

МИНИСТЕРСТВО ЗДРАВООХРАНЕНИЯ РЕСПУБЛИКИ БЕЛАРУСЬ  
БЕЛОРУССКИЙ ГОСУДАРСТВЕННЫЙ МЕДИЦИНСКИЙ УНИВЕРСИТЕТ  
КАФЕДРА МЕДИЦИНСКОЙ И БИОЛОГИЧЕСКОЙ ФИЗИКИ

**МЕДИЦИНСКАЯ  
И БИОЛОГИЧЕСКАЯ ФИЗИКА**  
**MEDICAL AND BIOLOGICAL  
PHYSICS**

Учебно-методическое пособие

*2-е издание*



Минск БГМУ 2013

УДК 577.3 (811.111)-054.6 (075.8)

ББК 28.707 (81.2 Англ-923)

М42

Рекомендовано Научно-методическим советом университета в качестве учебно-методического пособия 30.10.2013 г., протокол № 2

А в т о р ы: Л. В. Кухаренко, О. В. Недзьведь, М. В. Гольцев, В. Г. Лещенко, Г. К. Ильич

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**Медицинская** и биологическая физика = Medical and biological physics : учеб.-метод. пособие / Л. В. Кухаренко [и др.]. – 2-е изд. – Минск : БГМУ, 2013. – 240 с.

ISBN 978-985-528-901-3.

Издание содержит все разделы курса медицинской и биологической физики. В нем рассматриваются физические явления, лежащие в основе методов медицинской диагностики и лечения. Первое издание вышло в 2012 году.

Предназначено для студентов 1-го курса, изучающих медицинскую и биологическую физику на английском языке.

УДК 577.3 (811.111)-054.6 (075.8)

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Учебное издание

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Ответственный за выпуск В. Г. Лещенко  
Переводчики: Л. В. Кухаренко, О. В. Недзьведь  
Компьютерная верстка Н. М. Федорцовой

Подписано в печать 31.10.13. Формат 60×84/16. Бумага писчая «Снегурочка».

Ризография. Гарнитура «Times».

Усл. печ. л. 13,95. Уч.-изд. л. 12,92. Тираж 80 экз. Заказ 687.

Издатель и полиграфическое исполнение:  
учреждение образования «Белорусский государственный медицинский университет».

ЛИ № 02330/0494330 от 16.03.2009.

Ул. Ленинградская, 6, 220006, Минск.

**ISBN 978-985-528-901-3**

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# Chapter 1. MATHEMATICS FUNDAMENTALS

## 1.1. THE FUNCTION DERIVATIVE

In addition to knowing the value of a function  $f(x)$  at a particular  $x$ , one often wants to know how fast the function is changing with  $x$ . The *derivative of a function* represents an infinitesimal change in the function  $f(x)$  with respect to its variable  $x$ .

Consider a function  $y = f(x)$  at two points:  $x_0$  and  $x_0 + \Delta x$ :  $f(x_0)$  and  $f(x_0 + \Delta x)$ .

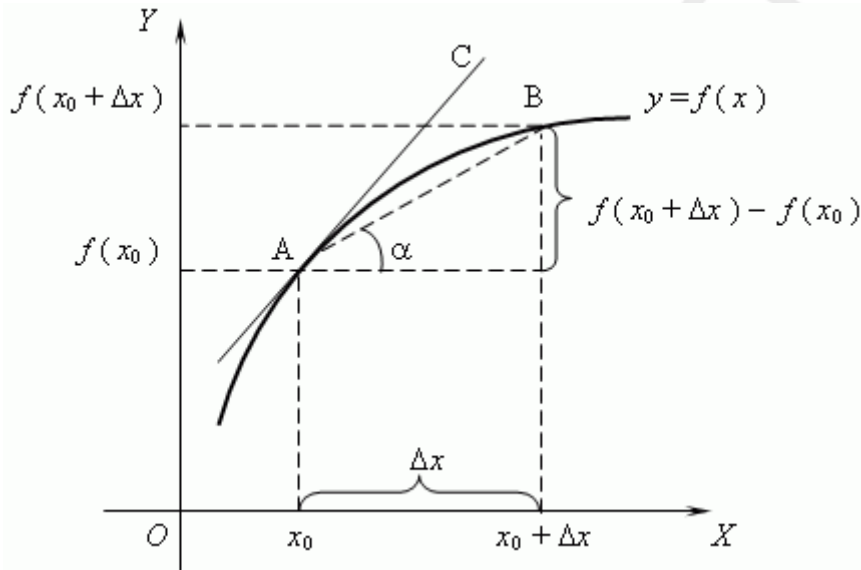


Fig. 1.1. Geometrical meaning of derivative

Here  $\Delta x$  means some small change of an argument, called an *argument increment*. Correspondingly a difference between the two values of a function:  $f(x_0 + \Delta x) - f(x_0)$  is called a *function increment*. Derivative of a function  $y = f(x)$  at a point  $x_0$  is the limit:

$$y' = \lim_{\Delta x \rightarrow 0} \frac{f(x_0 + \Delta x) - f(x_0)}{\Delta x}.$$

Derivative of a function  $f(x)$  is marked as:

$$y' = \lim_{\Delta x \rightarrow 0} \frac{\Delta y}{\Delta x}, \text{ or } \frac{dy}{dx} = \lim_{\Delta x \rightarrow 0} \frac{\Delta y}{\Delta x}. \quad (1.1)$$

$f'(x)$  is called «f-prime of x» and one can say that  $f(x)$  itself is differentiable at  $x$ , and that  $f(x)$  has a derivative.

Derivative of function has simple *geometrical meaning*. From fig.1.1 one can see, that for any two points  $A$  and  $B$  of the function graph:

$$\lim \frac{\Delta y}{\Delta x} = \frac{BC}{AC} = \operatorname{tg} \alpha, \quad (1.2)$$

where  $\alpha$  — a slope angle of the secant  $AB$ .

So, the difference quotient is equal to a secant slope. If to fix the point  $A$  and to move the point  $B$  towards  $A$ , then  $\Delta x$  will unboundedly decrease and approach 0, and the secant  $AB$  will approach the tangent  $AC$ . Hence, a limit of the difference quotient is equal to a slope of a tangent at point  $A$ .

A derivative of a function at a point is a slope of a tangent of this function graph at this point.

Consider a movement of a material point along a coordinate line. During the time interval from  $t_0$  till  $t_0 + \Delta t$  the point displacement is equal to:

$$s(t_0 + \Delta t) - s(t_0) = \Delta s,$$

and its *average velocity* is:

$$v_{aver} = \frac{\Delta S}{\Delta t}.$$

As  $\Delta t \rightarrow 0$ , then an average velocity value approaches the certain value, which is called an *instantaneous velocity*  $v(t_0)$  of a material point in the moment  $t_0$ . Thus,

$$u_{inst} = \lim_{\Delta t \rightarrow 0} \frac{\Delta S}{\Delta t} = \frac{ds}{dt} = S'. \quad (1.3)$$

Hence,  $v_{inst} = S'(t_0)$ , i. e. a derivative of a coordinate with respect to time is a instantaneous velocity.

Similarly to this, an acceleration is a derivative of a velocity with respect to time:

$$a = v'(t). \quad (1.4)$$

If some value  $y$  depends on the spatial coordinates  $x$ , the derivative  $dy/dx$  describes the rate of the spatial variation of  $y$ . The derivative of the spatial coordinate is called the *function gradient*.

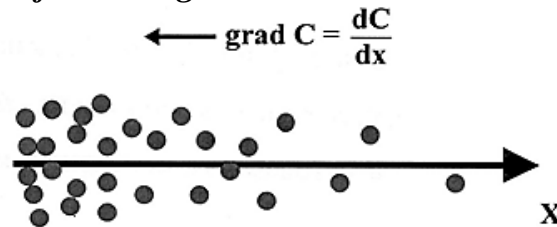


Fig. 1.2. The function gradient

For example, some substance is nonuniformly distributed along the axis  $x$ , thus its concentration is a function of  $x$  (fig. 1.2). Then the rate of change in concentration along the  $x$  axis derivative is defined. This value called the concentration gradient. Similarly, there are gradients of pressure, temperature and other variables. In physics and mathematics gradient is a vector, which is directed in the direction of increasing values  $y$ .

### Calculation of the derivative

In practice, once the derivatives of a few simple functions are known (table 1.1), the derivatives of other functions are more easily computed using rules for obtaining derivatives of more complicated functions from simpler ones.

Table 1.1

1) $C = \text{const}, (C)' = 0$	6) $(\cos x)' = -\sin x$
2) $(x^n)' = n \cdot x^{n-1}$	7) $(\operatorname{tg} x)' = \frac{1}{\cos^2 x}$
3) $(a^x)' = a^x \cdot \ln a$	8) $(\operatorname{ctg} x)' = -\frac{1}{\sin^2 x}$
3a) $(e^x)' = e^x$	9) $(\arcsin x)' = \frac{1}{\sqrt{1-x^2}}$
4) $(\log_a x)' = \frac{1}{x \cdot \ln a}$	10) $(\arccos x)' = -\frac{1}{\sqrt{1-x^2}}$
4a) $(\ln x)' = \frac{1}{x}$	11) $(\operatorname{arctg} x)' = \frac{1}{1+x^2}$
5) $(\sin x)' = \cos x$	

### Differentiation rules

The derivative of constant times a function is equal to the constant times the derivative of the function:

$$(Cu)' = C \cdot (u)'$$

**Sum rule:** the derivative of a sum of functions is equal to the sum of the function derivatives:

$$(u + v)' = u' + v'$$

**Product rule:** the derivative of a product of two functions is equal to the first function multiplies the derivative of the second one plus the second function multiplies the derivative of the first one:

$$(u \cdot v)' = u' \cdot v + u \cdot v'$$

**Quotient rule:** the derivative of the quotient of two functions is equal to the denominator multiplies the derivative of the numerator minus the numerator multiplies the derivative of the denominator all divided by the square of the denominator:

$$\left(\frac{u}{v}\right)' = \frac{u' \cdot v - v' \cdot u}{v^2}$$

**Chain rule:** if  $f$  is a function of  $g$  and  $g$  is a function of  $x$ , then the derivative of  $f$  with respect to  $x$  is equal to the derivative of  $f(g)$  with respect to  $g$  multiplies the derivative of  $g(x)$  with respect to  $x$ :

$$f'(x) = h'[g(x)] \cdot g'(x).$$

One can use chain rule for a composite function mean argument of which is also a function:  $h(x) = g(f(x))$ .

## 1.2. MAXIMA AND MINIMA OF FUNCTIONS

A function  $f(x)$  has a **local maximum** value at point  $A$ , if  $f(A)$  is greater than any function value in its immediate neighborhood. A function  $f(x)$  has

a **local minimum** value at point **B**, if  $f(b)$  is less than any function value in its immediate neighborhood. At each of these points the tangent to the curve is parallel to the x-axis so the derivative of the function is zero (fig. 1.3). The term local is used since these points are the maximum and minimum in this particular region. There may be others outside this region.

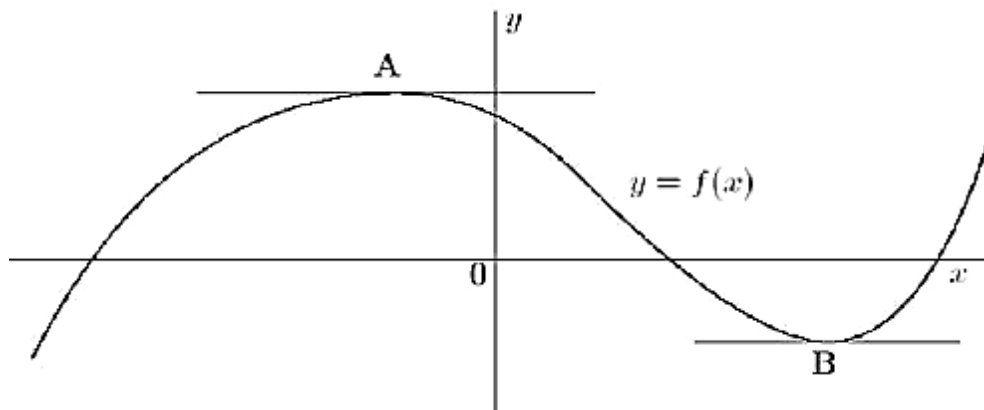


Fig. 1.3. Local maximum and minimum

If  $f(x)$  has a local maximum or minimum at point  $c$ , and if  $f'(c)$  exists, then

$$f'(c) = 0.$$

At points immediately to the left of a maximum the slope of the tangent is positive:  $f'(x) > 0$ . While at points immediately to the right the slope is negative:  $f'(x) < 0$ . In other words, at a maximum,  $f'(x)$  changes sign from  $+$  to  $-$ . At a minimum,  $f'(x)$  changes sign from  $-$  to  $+$ , respectively.

A point  $x$  at which either the function is not differentiable or its derivative is  $f'(x) = 0$  is called a **critical point**.

To find the maximum and minimum values of a function it is necessary:

1. To solve the algebraic equation:

$$f'(x) = 0.$$

The roots  $x_1, x_2, x_3 \dots$  of this equation are the critical points.

2. To calculate the second derivative  $f''(x)$  and definite its sign at the points.

If the second derivative is positive at a stationary point:  $f''(x_1) > 0$ , the point  $x_1$  is a local minimum; if it are negative:  $f''(x_2) < 0$ , the point  $x_2$  is a local maximum; if it is equal to zero:  $f''(x_3) = 0$ , it may or may not be a local extremum. In this case it is necessary to find a sign of the first derivative on the left side ( $x < x_3$ ) and on the right one ( $x > x_3$ ) from the  $x_3$ . If the sing on the left side is negative ( $-$ ) and on the right one is positive ( $+$ ) there is a local **minimum** at the point  $x_3$ . If the sing on the left side is positive ( $+$ ) and on the right one is negative ( $-$ ) there is a local **maximum** at the point  $x_3$ . And if the sing not changes there is no extremum at this point.

3. To determine a value of function in points of maximum and minimum.

### 1.3. DIFFERENTIAL OF A FUNCTION

The *differential of a function* represents the principal part of the change of a function  $y = f(x)$  with respect to changes of the independent variable. The differential  $dy$  is defined by:

$$dy = y' \cdot dx. \quad (1.5)$$

In other words, differential of function  $dy$  is the product of derivative function  $y'$  and an increment (a differential) of argument  $dx$ .

Differential  $dy$  of function is not equal to its increment  $\Delta y$  but it is regarded as a linear approximation to the increment of a function:

$$\Delta y \approx dy = y' \cdot dx.$$

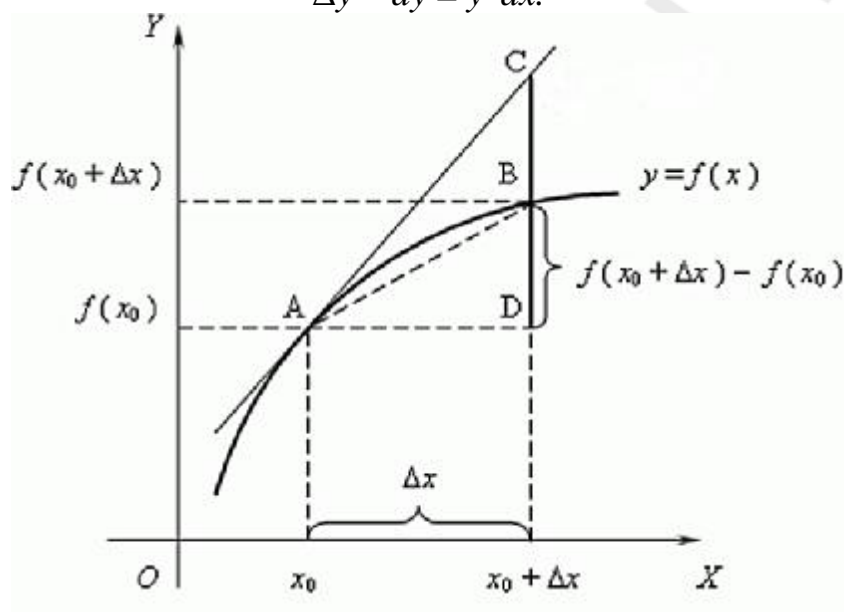


Fig. 1.4. Differential of function

In fig. 1.4. the function differential is  $dy = CD$ .

**Properties of the function differential.** A number of properties of the differential follow from the corresponding properties of the derivative.

**Linearity:** For constants  $a$  and  $b$  and differentiable functions  $f$  and  $g$ :

$$d(af + bg) = a \cdot df + b \cdot dg.$$

**Product rule:** For two differentiable functions  $f$  and  $g$ :

$$d(f \cdot g) = f \cdot dg + g \cdot df.$$

**Chain rule:** If  $y = f(u)$  is a differentiable function of the variable  $u$  and  $u = g(x)$  is a differentiable function of  $x$ , then:

$$dy = f'(u)du = f'(g(x)) \cdot g'(x)dx.$$

### 1.4. PARTIAL DERIVATIVES

In mathematics, a *partial derivative* of a function of several variables  $U(x,y,z)$  is its derivative with respect to one of those variables, with the others

held constant. The partial derivative of a function  $U(x,y,z)$  with respect to the variable  $x$  is variously denoted by

$$U'_x \text{ or } \frac{\partial U}{\partial x}.$$

We might also define partial derivatives of function  $U(x,y,z)$  as follows:

$$U'_x = \frac{\partial U(x,y,z)}{\partial x} = \lim_{\Delta x \rightarrow 0} \frac{U(x + \Delta x, y, z) - U(x, y, z)}{\Delta x}. \quad (1.6)$$

$$U'_y = \frac{\partial U(x,y,z)}{\partial y} = \lim_{\Delta y \rightarrow 0} \frac{U(x, y + \Delta y, z) - U(x, y, z)}{\Delta y}. \quad (1.7)$$

$$U'_z = \frac{\partial U(x,y,z)}{\partial z} = \lim_{\Delta z \rightarrow 0} \frac{U(x, y, z + \Delta z) - U(x, y, z)}{\Delta z}. \quad (1.8)$$

Calculating partial derivatives is usually just like calculating an ordinary derivative of one-variable calculus. One just has to remember with which variable the derivative is taken. To calculate  $\frac{\partial U}{\partial x}$  of function  $U(x,y,z)$  one can simply view  $y$  and  $z$  as being a fixed numbers and calculate the ordinary derivative with respect to  $x$ .

All the rules and formulas being true to the derivative of a function of one variable are true to a partial derivative.

### 1.5. PARTIAL DIFFERENTIALS, TOTAL DIFFERENTIAL OF FUNCTION

For functions of more than one independent variable, the partial differential of  $U(x,y,z)$  with respect to any one of the variables  $x$  is the principal part of the change in  $U(x,y,z)$  resulting from a change  $dx$  in that one variable. The partial differential is therefore:

$$dU_x = \frac{\partial U}{\partial x} dx.$$

The sum of all partial differentials is the **total differential** of function. For function  $U(x,y,z)$  the total differential  $dU$  is equal:

$$dU = U'_x \cdot dx + U'_y \cdot dy + U'_z \cdot dz, \text{ or}$$

$$dU = \frac{\partial U}{\partial x} dx + \frac{\partial U}{\partial y} dy + \frac{\partial U}{\partial z} dz. \quad (1.9)$$

Total differential is the principal part of the change in  $U(x,y,z)$  resulting from changes in the independent variables.



## 1.6. ANTIDERIVATIVE FUNCTION, INDEFINITE INTEGRAL

The process of solving for antiderivatives is opposite to (inverse) operation for differentiation. The function  $F(x)$  is called **antiderivative** function if the derivative of this function is equal to the initial function  $f(x)$ :

$$F'(x) = f(x).$$

**Examples:**

Since the derivative of  $x^2 + 4$  is  $2x$ , an antiderivative of  $2x$  is  $x^2 + 4$ .

Since the derivative of  $x^2 + 5$  is also  $2x$ , another antiderivative of  $2x$  is  $x^2 + 5$ .

Similarly, another antiderivative of  $2x$  is  $x^2 - 6$ .

In fact, every antiderivative of  $2x$  has the form  $x^2 + C$ , where  $C$  is constant:

$$F(x) = x^2 + C,$$

where  $C$  is an **arbitrary constant**.

Graphs of antiderivatives of a given function are vertical translations of each other; each graph's location depending upon the value of  $C$ .

Indefinite integral of a function  $f(x)$  is a set of all its antiderivatives, the process of finding an indefinite integral is called **integration**:

$$\int f(x)dx = F(x) + C.$$

**Features of the indefinite integral**

The process of differentiation and integration are inverses of each other:

$$(\int f(x)dx)' = f(x).$$

The integral of a sum or difference of functions is the sum or difference of the individual integrals. This rule can be extended to as many functions as we need.

$$\int (f(x) \pm g(x))dx = \int f(x)dx \pm \int g(x)dx$$

One can factor multiplicative constants out of indefinite integrals.

$$\int kf(x)dx = k \int f(x)dx$$

where  $k$  is any constant.

Some indefinite integrals can be finding with use of elementary functions (table 1.2).

Table 1.2

1. $\int x^n dx = \frac{x^{n+1}}{n+1} + C, (n \neq -1)$	6. $\int \cos x dx = \sin x + C.$
2. $\int \frac{dx}{x} = \ln x  + C.$	7. $\int \frac{dx}{\cos^2 x} = \operatorname{tg} x + C.$
3. $\int a^x dx = \frac{a^x}{\ln a} + C.$	8. $\int \frac{dx}{\sin^2 x} = -\operatorname{ctg} x + C.$

4. $\int e^x dx = e^x + C.$	9. $\int \frac{dx}{\sqrt{1-x^2}} = \arcsin x + C,  x  < 0.$
5. $\int \sin x dx = -\cos x + C.$	10. $\int \frac{dx}{1+x^2} = \arctg x + C.$

Sometimes it may be difficult or impossible to find an antiderivative which is an elementary function. There are different methods of integration in this case. The simplest methods are linear integration and integration by substitution.

**Linear integration** allows one to break complicated integrals into simpler ones.

*Example:*

$$\int (5x + \sin x) dx = \int 5x dx + \int \sin x dx = \frac{5x^2}{2} - \cos x + C.$$

### Integration by substitution

In calculus, the *substitution rule* is an important tool for finding antiderivatives and integrals. It allows to find the antiderivative for composite function (like the chain rule for differentiation).

*Example:*

$$\int \frac{\ln^5 x}{x} dx = \left[ \begin{array}{l} t = \ln x \\ dt = \frac{1}{x} dx \\ dx = x dt \end{array} \right] = \int t^5 dt = \frac{t^6}{6} + C = \frac{\ln^6 x}{6} + C.$$

## 1.7. DEFINITE INTEGRAL

The definition of the definite integral of the function  $f(x)$  with respect to  $x$  from  $a$  to  $b$  is known as the Newton–Leibniz formula:

$$\int_a^b f(x) dx = F(x) \Big|_a^b = F(b) - F(a), \quad (1.10)$$

where  $F(x)$  is the antiderivative of  $f(x)$ ,  $a$  and  $b$  are the limits of integration;  $a$  and  $b$  are called the lower and upper limits of integration respectively. With definite integrals, one can integrate a function between 2 points, and thus to find the precise value of the integral and there is no need for any unknown constant terms.

The notation  $F(x) \Big|_a^b$  means the following: at first substitute the upper limit  $b$  into the function  $F(x)$  to obtain  $F(b)$  and from  $F(b)$  we subtract  $F(a)$ , the value obtained by substituting the lower limit  $a$  into  $F(x)$ .

Main difference between indefinite and definite integrals is: the value of a definite integral is the *number*, whereas the value of the indefinite integral is the *set of function*.

## Features of the definite integral

1.  $\int_a^b f(x)dx = -\int_b^a f(x)dx.$
2.  $\int_a^b (f(x) + g(x))dx = \int_a^b f(x)dx + \int_a^b g(x)dx.$
3.  $\int_a^a f(x)dx = 0.$
4.  $\int_a^b kf(x)dx = k\int_a^b f(x)dx.$
5.  $\int_a^b f(x)dx = \int_a^c f(x)dx + \int_c^b g(x)dx.$

The definite integral can be used to find the area between a graph curve and the  $X$  axis, between two given values  $a$  and  $b$ :

$$Area = \int_a^b f(x)dx.$$

This area is called the *area under the curve* regardless of whether it is above or below the  $X$  axis (fig. 1.5).

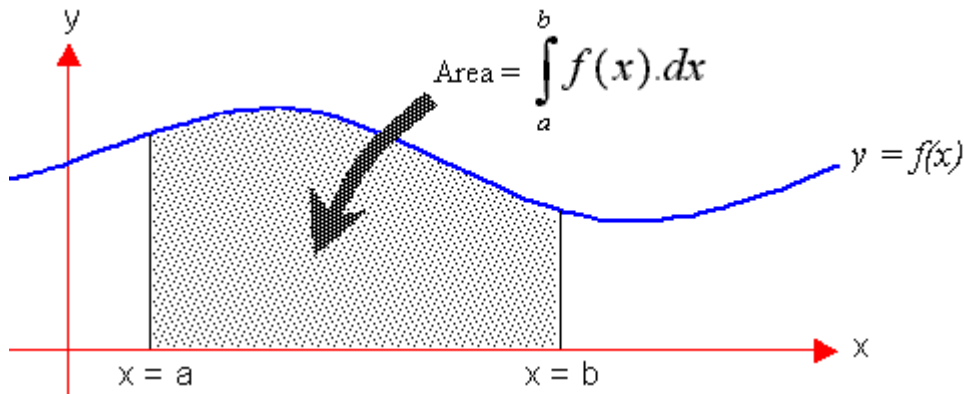


Fig. 1.5. Calculation of the area under a curve  $f(x)$

### Example 1:

Consider the integral  $\int_0^3 xdx$ . The area under the line is the triangle (fig. 1.6). The area of any triangle is half its base times the height. It is:  $S = \frac{1}{2} \cdot 3 \cdot 3 = \frac{9}{2}$ .

As expected, the integral yields the same result:

$$\int_0^3 xdx = \left. \frac{x^2}{2} \right|_0^3 = \frac{3^2}{2} - \frac{0^2}{2} = \frac{9}{2} - 0 = \frac{9}{2}.$$

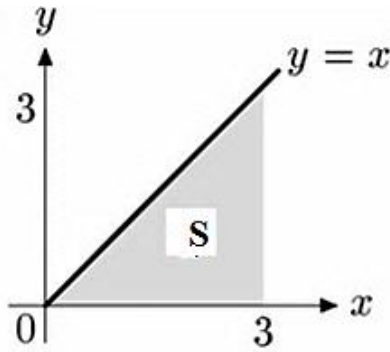


Fig. 1.6. The area  $S$  under the line  $y = x$

**Example 2:**

Calculate area  $S$  limited the curve  $y = x^2$ , axis  $x$  and lines  $x_1 = -1$  и  $x_2 = 2$ . On fig. 1.7 this area is cross-hatched.

$$S = \int_{-1}^2 x^2 dx = \left. \frac{x^3}{3} \right|_{-1}^2 = \frac{8}{3} - \left( -\frac{1}{3} \right) = \frac{9}{3} = 3.$$

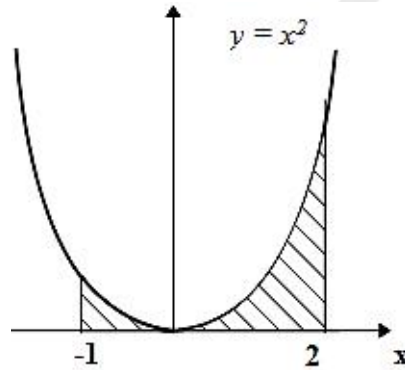


Fig. 1.7. The area  $S$  under the curve  $y = x^2$

### 1.8. DIFFERENTIAL EQUATIONS

A **differential equation** is an equation involving derivatives of an unknown function and possibly the function itself as well as the independent variable.

**Example:**

If an object of mass  $m$  is moving with acceleration  $a$  and being acted on with force  $F$  then Newton's second Law is:

$$F = ma.$$

Remained that acceleration  $a$  is a derivative of velocity  $v$  with respect to time or second derivative of a coordinate  $x$  with respect to time:

$$a = \frac{dv}{dt} = \frac{d^2x}{dt^2}.$$

So, with all these things in mind Newton's second Law can now be written as a differential equation:

$$F = m \frac{dv}{dt} = m \frac{d^2x}{dt^2}. \tag{1.11}$$

The **order** of a differential equation is the highest order of the derivatives of the unknown function appearing in the equation.

**Example:**

$y' = \sin(x)$  — is the **1<sup>st</sup> order** differential equations.

$y'' + y^3 + x = 0 \cdot y''$  — is the **2<sup>nd</sup> order** differential equation.

A **solution** to a differential equation is any function which satisfies upon substitution of this function and its derivatives into the differential equation. It is important to notice, that a solution to a differential equation is a **function**, unlike the solution to an algebraic equation which is (usually) a number. A solution of a differential equation with its constants undetermined is called a **general solution**. The solution of differential equation complete with the values of the constants is called a **particular solution**. For constants determination additional conditions are used. These conditions constrain values of the function at some particular value of the independent variable. For example, if the equation involves the velocity, the additional condition might be the initial velocity, the velocity at time  $t = 0$ .

**Example:**

$$\frac{dy}{dx} = x^2.$$

Separate the variables:  $dy = x^2 dx$ .

Integrate both sides:  $\int dy = \int x^2 dx$

A general solution:  $y = \frac{x^3}{3} + C$ .

Apply additional conditions: if  $x = 0$ , then  $y = 1$ .

Thus, the particular solution we are looking for is:  $y = \frac{x^3}{3} + 1$ .

**Questions:**

1. Give a definition of the derivative; explain its physical and geometrical meaning. What is a function gradient? What is the direction of a function gradient?
2. What is the physical meaning of the second derivative of way with respect to time?
3. What is an extremum of function? Formulate the stages of the extremum function investigation.
4. Give a definition of the differential of function of one variable. Demonstrate by means of graph a geometrical meaning of differential. Compare differential with a function increment.
5. Give a definition of the partial derivatives. What is their physical meaning?
6. What are partial differentials and total differential of function?
7. Give a definition of the antiderivative function. What is an indefinite integral?
8. Give a definition of the definite integral. What is the geometrical meaning of the definite integral?
9. Explain the Newton-Leibniz rule for definite integral calculation.
10. What is a differential equation? What determines the order of the differential equation? What is the solution of the differential equation?
11. What is a difference between a general solution and a particular solution? How to obtain a particular solution from general one?
12. How to check whether function is a solution of differential equation?

## Chapter 2. PROBABILITY THEORY

In the real world events cannot be predicted with total certainty. The best one can do is to say how likely they are to happen, using the idea of probability.

Probability theory is the branch of mathematics deals with analysis of *random events*, which may occur or may not occur. Examples of random events: the birth of girl in the family; the birth of a child with a predicted weight; the emergence of epidemic disease in the region in a certain period of time.

### 2.1. CLASSICAL (THEORETICAL) AND STATISTICAL (EMPIRICAL) PROBABILITY DEFINITION

For example, let's consider tossing a fair die. There are six possible numbers that could come up («outcomes»), and, since the die is fair, each one is equally likely to occur. So one can say each of these outcomes has probability  $1/6$ . Since the event «an odd number comes up» consists of exactly three of these basic outcomes, one can say the probability of «odd» is  $3/6$ , i. e.  $1/2$ .

More generally, if there is a situation in which there are  $n$  equally likely outcomes, and the event  $A$  consists of exactly  $m < n$  of these outcomes, one can say that the **classical** probability of the event  $A$  is:

$$P(A) = m/n. \quad (2.1)$$

This definition can be applied in a situation in which all possible outcomes and the outcomes in the events can be counted.

#### *Example:*

A box contains 3 red marbles, 1 blue marble, and 4 yellow marbles. One marble is drawn at random. There are now 8 equally likely marbles that can be drawn:

$$P(\text{draw one of the eight marbles and it is red}) = 3/8.$$

$$P(\text{draw one of the eight marbles and it is blue}) = 1/8.$$

$$P(\text{draw one of the eight marbles and it is yellow}) = 4/8.$$

So the *classical probability definition* is based on the physics of the experiment, but does not require the experiment to be performed. For example, we know that the probability of a balanced coin turning up heads is equal to 0,5 without ever performing trials of the experiment.

The probability of event accepts value between zero and unit:  $0 \leq P(A) \leq 1$ . If  $P(A) = 1$ , event  $A$  is certain event. A *certain event* is certain to occur. If  $P(A) = 0$ , it is impossible event. An *impossible event* has no chance of occurring. In other cases  $A$  is a random event and its probability  $0 < P(A) < 1$ .

#### *Examples:*

The Christmas will be celebrated on the 25th of December this year. This is a certain event.

When a number cube is rolled 7 is an impossible event.

The sunny day in London is a random event.

**Statistical probability.** Sometimes a situation may be too complex to understand the physical nature of it well enough to calculate probabilities. However, by running a large number of trials and observing the outcomes, we can estimate the probability. This is statistical (empirical) probability based on long-run relative frequencies and is defined as the ratio of the number of observed outcomes favourable to the event divided by the total number of observed outcomes. The larger the number of trials, the more accurate the estimate of probability.

The statistical probability is a limit of *relative frequency*:

$$P(A) = \lim_{N \rightarrow \infty} \frac{M}{N}. \quad (2.2)$$

where the value  $\frac{M}{N}$  is a relative frequency of event A.

Thus, *statistical probability* of event is a limit to which relative frequency of event tends at unlimited increase of the general number of tests.

For example, one tosses a coin, which might or might not be fair, 100 times and observes heads on 52 of the tosses. The relative frequency is 0,52. In case if the number of tosses aspire to  $\infty$  (for example, 1000) and number of head appearance is 498 the statistical probability is:

$$P(A) = \lim_{N \rightarrow \infty} \frac{498}{1000} = 0,5.$$

**Example:**

Experimenters roll two dice 50 times and record their results in the accompanying chart. What is the statistical probability of rolling a 7? What is the classical probability of rolling a 7? Compare statistical and classical probabilities.

In practise it was obtained: 3, 5, 5, 4, 6, 7, 7, 5, 9, 10, 12, 9, 6, 5, 7, 8, 7, 4, 11, 6, 8, 8, 10, 6, 7, 4, 4, 5, 7, 9, 9, 7, 8, 11, 6, 5, 4, 7, 7, 4, 3, 6, 7, 7, 7, 8, 6, 7, 8, 9.

Relative frequency is  $M/N = 13/50 = 26\%$ .

Classical probability is  $P_{\text{clas}} = 6/36 = 1/6 = 16.7\%$ .

## 2.2. TYPES OF RANDOM EVENTS

There are 3 main types of random events: disjoint events, independent events and dependent events.

1. Two events are *disjoint* if it is impossible for them to occur together.

**Example:** anyone cannot be both male and female, nor can they be aged 20 and 30.

Events  $M_1, M_2, \dots, M_k$  form the *full group of events* if at any tests there can be only one of them, and can't be any other events.

**Example 1:**

Getting a student on one test mark «1», or «2», or «3», or «4», or «5», or «6», or «7», or «8», or «9» or «10» — the events are disjoint, since one of these marks exclude the other on the same exam. These events form a full group of events.

**Example 2:**

Let  $P(A)$  is the probability of death for some diseases; it is known and is equal to 2%. Then the probability of a successful outcome in this disease is 98%. These events form full group of events.

2. Two or more events are **independent** if the occurrence of one of the events does not change the probability of the other events. That is, the events have no influence on each other. Two events **A** and **B** are independent if when one of them happens, it doesn't affect the other one happening or not.

**Examples:** choosing a marble from a jar and landing on heads after tossing a coin; choosing a 3 from a deck of cards, replacing it, and then choosing an ace as the second card.

If two events are independent then they cannot be disjoint.

3. Two or more events are **dependent** if the result of one event is affected by the result of other events. For dependent events **A** and **B** two types of probabilities are known: conditional probability and unconditional one.

The **conditional probability**  $P(B/A)$  of an event **B**, in relation to event **A**, is the probability that event **B** will occur given the knowledge that an event **A** has already occurred. The **unconditional probability**  $P(B)$  of an event **B** is the probability that event **B** will occur before an event **A**.

**Example:** taking out a marble from a bag containing some marbles and not replacing it, and then taking out a second marble are dependent events.

### 2.3. PROBABILITIES ADDITION AND MULTIPLICATION RULES

#### Probability addition rule:

1. When two events, **A** and **B**, are disjoint, the probability that event **A** or event **B** will occur is the sum of the probability of each event:

$$P(A \text{ or } B) = P(A) + P(B). \quad (2.3)$$

2. For some disjoint events  $M_1, M_2, \dots, M_k$ :

$$P(M_1 \text{ or } M_2 \text{ or } \dots \text{ or } M_k) = P(M_1) + P(M_2) + \dots + P(M_k).$$

3. For full group of events:

$$\sum_{i=1}^n P(M_i) = 1. \quad (2.4)$$

#### Example:

A glass jar contains 1 red, 3 green, 2 blue, and 4 yellow marbles. If a single marble is chosen at random from the jar, what is the probability that it is yellow or green?

The probability of extracting of yellow marble is:

$$P(\text{yellow}) = \frac{4}{10}.$$

The probability of extracting of green marble is:

$$P(\text{green}) = \frac{3}{10}.$$

The probability of extracting of yellow or green marble is:

$$P(\text{yellow or green}) = P(\text{yellow}) + P(\text{green}) = \frac{4}{10} + \frac{3}{10} = \frac{7}{10}.$$



### Probability multiplication rule for independent events:

1. If  $A$  and  $B$  are independent events, the probability of both events occurring is the product of the probabilities of the individual events:

$$P(A \text{ and } B) = P(A) \cdot P(B). \quad (2.5)$$

#### Example:

A drawer contains 3 red paperclips, 4 green paperclips, and 5 blue paperclips. One paperclip is taken from the drawer and then replaced. Another paperclip is taken from the drawer. What is the probability that the first paperclip is red and the second paperclip is blue?

Because the first paper clip is replaced, the sample space of 12 paperclips does not change from the first event to the second event. The events are independent.

$$P(\text{red and blue}) = P(\text{red}) \cdot P(\text{blue}) = \frac{3}{12} \cdot \frac{5}{12} = \frac{15}{144} = \frac{5}{48}.$$

2. For some disjoint events  $M_1, M_2, \dots, M_k$ :

$$P(M_1 \text{ and } M_2 \text{ and } \dots \text{ and } M_k) = P(M_1) \cdot P(M_2) \cdot \dots \cdot P(M_k).$$

### Probability multiplication rule for dependent events:

If  $A$  and  $B$  are dependent events, the probability joint appearance of two dependent events  $A$  and  $B$  is equal to product of the **unconditional** probability of first event on conditional probability of another one:

$$P(A \text{ and } B) = P(A) \cdot P(B/A) \quad (2.6)$$

or

$$P(B \text{ and } A) = P(B) \cdot P(A/B). \quad (2.6a)$$

In second case the first occurs event  $B$  and its probability is equal  $P(B)$  and for event  $A$  the conditional probability  $P(A/B)$  is realized.

#### Example:

A drawer contains 3 red paperclips, 4 green paperclips, and 5 blue paperclips. One paperclip is taken from the drawer and is not replaced. Another paperclip is taken from the drawer. What is the probability that the first paperclip is red and the second paperclip is blue?

Because the first paper clip is not replaced, the sample space of the second event is changed. The sample space of the first event is 12 paperclips, but the sample space of the second event is now 11 paperclips. The events are dependent.

$$P(\text{red and blue}) = P(\text{red}) \cdot P(\text{blue/red}) = \frac{3}{12} \cdot \frac{5}{11} = \frac{15}{132} = \frac{5}{44}.$$

## 2.4. BAYES FORMULA

Let the event of interest  $A$  happens under any of hypotheses  $H_i$  with a known conditional probability  $P(A/H_i)$ . Hypotheses  $H_1, H_2, \dots, H_n$  are known

(*prior probabilities*) and form full group of events:  $\sum_{i=1}^n P(H_i) = 1$ . Then

the conditional probability of the hypothesis  $H_i$ ; given that event  $A$  happened, is

$$P(H_i/A) = \frac{P(A/H_i) \cdot P(H_i)}{P(A/H_1)P(H_1) + \dots + P(A/H_n)P(H_n)}. \quad (2.7)$$

Formula (2.7) is known as **Bayes formula**. Bayes formula is an important method for calculation conditional probabilities. It is often used to calculate **posterior probabilities** (as opposed to prior probabilities) given observations.

For example, a patient is observed to have a certain symptom, and Bayes' formula can be used to compute the probability that a diagnosis is correct, given that observation. We illustrate this idea with details in the following example.

**Example:** Mammogram posterior probabilities.

Approximately 1 % of women aged 40–50 have breast cancer. A woman with breast cancer has a 90 % chance of a positive test from a mammogram, while a woman without has a 10 % chance of a false positive result. What is the probability  $P(C/A)$  a woman has breast cancer given that she just had a positive test?

The probability that the woman has breast cancer is equal:  $P(C) = 0,01$ ;

The probability that the woman has not breast cancer is equal:  $P(N) = 0,99$ ;

The probability of a positive test with breast cancer is equal:  $P(A/C) = 0,9$ ;

The probability of a positive test without breast cancer is equal:  $P(A/N) = 0,1$ .

$$P(C/A) = \frac{P\left(\frac{A}{C}\right) \cdot P(C)}{P\left(\frac{A}{C}\right) \cdot P(C) + P\left(\frac{A}{N}\right) \cdot P(N)} = \frac{0,9 \cdot 0,01}{0,9 \cdot 0,01 + 0,1 \cdot 0,99} = 0,083 \approx 8,3\%.$$

**Questions:**

1. What is a random event? Give a classical and statistical definition of a random event probability.
2. What types of random events do you know?
3. Formulate a probability addition rule. What type of random events can be used for this rule?
4. Which events form the full group of events? What is the sum of probabilities of full group of events?
5. Formulate a probability multiplication rule for independent events.
6. What are independent events? What is a conditional probability?
7. Formulate a probability multiplication rule for dependent events.
8. Present the Bayes formula; interpret a meaning of values in this formula.
9. How can Bayes formula be used for disease diagnostics problems?

### Chapter 3. RANDOM VARIABLES. DISTRIBUTION OF RANDOM VARIABLES

When the numerical value of a variable is determined by a chance event, that variable is called a **random variable**. As opposed to other mathematical variables, a random variable conceptually does not have a single, fixed value (even if unknown); rather, it can take on a set of possible different values, each with an associated probability. The value of the random variable will vary from trial to trial as the experiment is repeated.

There are two types of random variables: discrete and continuous.

A random variable is called **discrete random variable** if it may assume any of a specified list of exact values. For example, when two dice are rolled the total on the two dice will be 2, 3, ..., 12. The total on the two dice is a discrete random variable. This number cannot be 1,1 or 13. Within a range of numbers, discrete random variables can take on only certain values.

*Examples:* the number of children in a family, the number of patients in a doctor's surgery.

A random variable is called **continuous random variable** if it can assume an infinite number of possible values in the possible interval. Suppose the temperature in a certain city in the month of June in the past many years has always been between 25° to 35° centigrade. The temperature can take any value between the ranges 25° to 35°. The temperature on some day may be 25,13 °C or 25,14 °C or it may take any value between 25,13 °C and 25,14 °C. When we say that the temperature is about 30 °C, it means that the temperature lies between 29,5 °C and 30,5 °C. Any observation which is taken falls in the interval. In continuous random variable the value of the variable is located in some interval, the interval may be both small and big. The probability for continuous random variable is directly proportional to the value of this interval.

Examples include height, weight, the amount of glucose in an orange, the time required to run a mile.

### 3.1. DISCRETE PROBABILITY DISTRIBUTION

1. A probability distribution can be presented in a tabular form showing the values of the random variable  $X$  and the corresponding probabilities denoted by  $p(x_i)$  (table 3.1). Suppose a discrete random variable  $X$  can assume the values  $x_1, x_2, \dots, x_n$  with corresponding probabilities  $p(x_1), p(x_2), \dots, p(x_n)$ . The set of ordered pairs  $[x_1, p(x_1)], [x_2, p(x_2)], \dots, [x_n, p(x_n)]$  is called the **probability distribution** of discrete random variable.

Table 3.1

Values of random variable $x_i$	$x_1$	$x_2$	...	$x_i$	...	$x_n$
Probability $p(x_i)$	$p(x_1)$	$p(x_2)$		$p(x_i)$		$p(x_n)$

The probabilities  $p(x_i)$  must satisfy the **normalization condition**:

$$\sum_{i=1}^n p_i = p_1 + p_2 + \dots + p_n = 1. \quad (3.1)$$

2. The discrete probability distribution may also be described by the **probability polygon** (fig. 3.1):

The probability polygon concludes all possible values of a random variable  $x_i$  on a horizontal axis and probabilities  $p(x_i)$  corresponding them on a vertical axis.

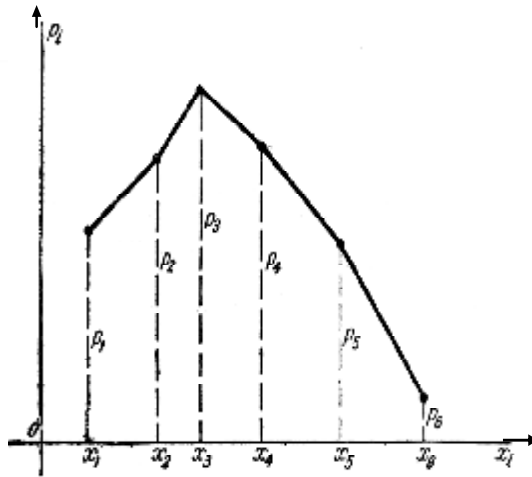


Fig. 3.1. The probability polygon

3. The discrete probability distribution can also be presented by some formula. One of these formulas as example is shown as:

$$P_k(n) = (1 - p)^{n-k} \cdot p^k.$$

In practise probability distribution more often is given by table.

### 3.2. CONTINUOUS PROBABILITY DISTRIBUTION. PROBABILITY DENSITY FUNCTION

A continuous probability distribution differs from a discrete probability distribution. The probability that a continuous random variable will assume a particular value is always zero. As a result, a continuous probability distribution cannot be expressed in tabular form.

The probability distribution of a continuous random variable is represented by a certain function  $f(x)$ , called the probability density function. The **probability density function** of a continuous random variable can be integrated to obtain the probability that the random variable takes a value in a given interval.

The probability density function  $f(x)$  must obey condition: the total probability for all possible values of the continuous random variable  $X$  is equal to 1:

$$\int_{-\infty}^{+\infty} f(x) dx = 1. \quad (3.2)$$

It is the **normalization condition** for continuous distribution.

The probability that value  $x$  takes values in the interval  $[x_1, x_2]$  can be found as:

$$P(x_1 < X < x_2) = \int_{x_1}^{x_2} f(x) dx. \quad (3.3)$$

In other words, the probability density function allow determine the probability that  $X$  takes values in any interval  $[x_1, x_2]$ . Graphically

probability  $P(x_1 < X < x_2)$  is the area under the probability density function curve from  $x_1$  to  $x_2$  as shown in fig. 3.2.

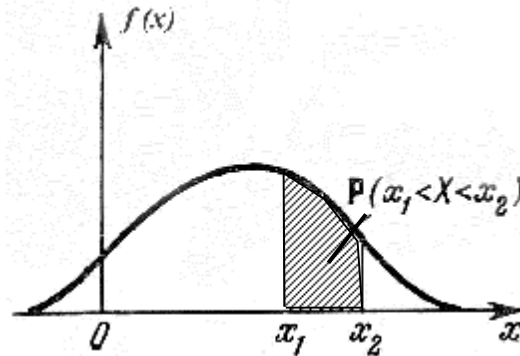


Fig. 3.2. Example of probability density curve for random variable  $x$

Function of probability distribution  $f(x)$  completely defines the distribution law of continuous random variables.

**Example:**

$$f(x) = \frac{2}{x^2} \text{ for } 1 \leq x \leq 2.$$

It necessary to find probability of  $X$  being between 1,5 and 2.

Let's check the fulfilment of normalization condition:

$$\int_1^2 \frac{2}{x^2} dx = 1.$$

To find the probability of  $X$  being between it is necessary to evaluate the following integral:

$$P(1,5 \leq x \leq 2) = \int_{1,5}^2 \frac{2}{x^2} dx = -\frac{2}{x} \Big|_{1,5}^2 = \frac{1}{3}.$$

So the probability of  $X$  being between 1,5 and 2 is equal to 1/3.

### 3.3. RANDOM DISTRIBUTION CHARACTERISTICS

There are following characteristics of random distribution: the central tendency and the dispersion.

#### Estimation of central tendency

The central tendency of a random distribution is an estimate of the «centre» of vales distribution. There are three major types of estimates of central tendency: 1) **expectation**; 2) **mode**; 3) **median**.

In probability theory, **expectation** (or population mean)  $\mu$  of a random variable is the weighted average of all possible values that this random variable can take on.

In case of a discrete random variable expectation  $\mu$  can be found as:

$$\mu = x_1 p_1 + x_2 p_2 + \dots + x_n p_n = \sum_{i=1}^n x_i p_i. \quad (3.4)$$

In case of a continuous random variable expectation  $\mu$  can be expressed as:

$$\mu = \int_a^b x \cdot f(x) dx. \quad (3.5)$$

**Mode  $Mo(X)$**  is a value that appears most often in a set of values. The mode of a discrete random variable is the value that is most likely to be sampled. The mode of a continuous random variable is the value  $x$  at which its probability density function attains its maximum value.

**Median  $Me(X)$**  for discrete distribution (simple ranged series) is the middle value if the number of values is odd and the mean of the two middle values, if the numbers of values is even. For continuous distributions median divides all distribution into two equal parts ( $Area_1 = Area_2$ ).

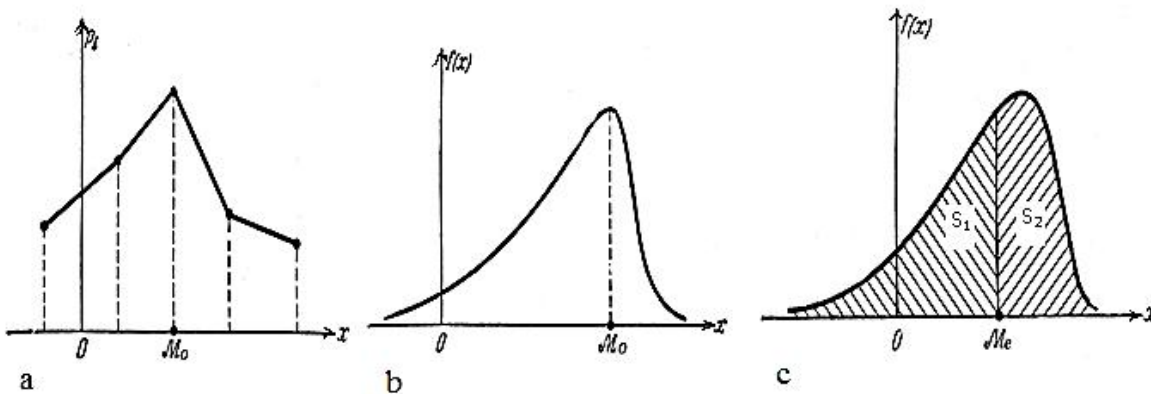


Fig. 3.3. Graphical representation of the random variable X:

*a* — discrete, indicating the mode of distribution; *b* — a continuous, indicating the mode of the distribution; *c* — continuous, indicating the median of the distribution

### Estimation of dispersion

The determination the center of the data set is one aspect observations. Another feature of the observations is as to how the observations are spread about the center. The observation may be closed to the center or they may be spread away from the center. If the observation are closed to the center (usually the arithmetic mean), one can say that dispersion is small. The dispersion is large if the observations are spread away from the center.

The statistical measure of dispersion is the **variance** of random variable  $x$  which is obtained by formula:

$$\sigma^2 = \mu [x - \mu(x)]^2 \quad (3.6)$$

or

$$\sigma^2 = \mu(x^2) - [\mu(x)]^2. \quad (3.6a)$$

For continuous random variables definite in the interval  $(a, b)$  the variance is given as:

$$\sigma^2 = \int_a^b [x - \mu(x)]^2 f(x) dx \quad (3.7)$$

or

$$\sigma^2 = \int_a^b x^2 f(x) dx - [\mu(x)]^2. \quad (3.7a)$$

Variance is measured in square units. To overcome the problem of dealing with squared units, statisticians take the square root of the variance to get the *standard deviation*  $\sigma$ : ( $\sigma = \sqrt{\sigma^2}$ ).

### 3.4. NORMAL DISTRIBUTION

The *normal* (or Gaussian) *distribution* is a continuous probability distribution that has a bell-shaped probability density function, known as the Gaussian function or informally the bell curve. For normal distribution the probability density function  $f(X)$  is given as

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{[x-\mu]^2}{2\sigma^2}}. \quad (3.8)$$

The parameter  $\mu$  is the expectation and  $\sigma$  is the standard deviation, both these parameters ( $\mu$  and  $\sigma$ ) completely determine probability density function  $f(X)$ .

Normal distribution is a symmetrical distribution. The graph of the normal distribution depends on two factors — the mean and the standard deviation. The mean of the distribution  $\mu$  determines the location of the centre of the graph, and the standard deviation  $\sigma$  determines the height and width of the graph. When the standard deviation is large, the curve is short and wide; when the standard deviation is small, the curve is tall and narrow but area under the curve is always equal to one (fig. 3.4). The maximal density of probability is equal to  $\frac{1}{\sigma\sqrt{2\pi}} \approx \frac{0,4}{\sigma}$  and corresponds to a mean  $\mu$ .

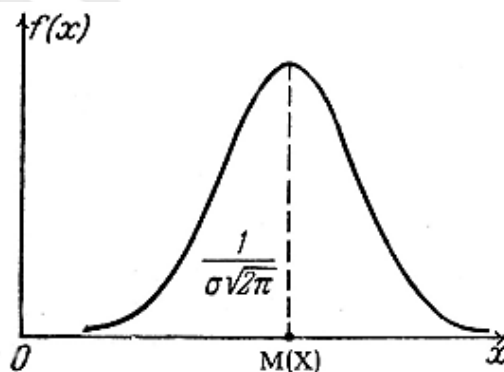


Fig. 3.4. Density curve for normal distribution

If the data distribution is approximately normal then about 68 % of the data values are within one standard deviation of the mean, about 95 % are within two standard deviations, and about 99,7 % lie within three standard deviations:

$$P(\mu - \sigma < x < \mu + \sigma) = 0,6827 = 68,27 \% \quad (3.9)$$

$$P(\mu - 2\sigma < x < \mu + 2\sigma) = 0,9545 = 95,45 \% \quad (3.10)$$

$$P(\mu - 3\sigma < x < \mu + 3\sigma) = 0,9973 = 99,73 \% \quad (3.11)$$

The formula (3.11) is known as *three-sigma rule* (fig. 3.5).

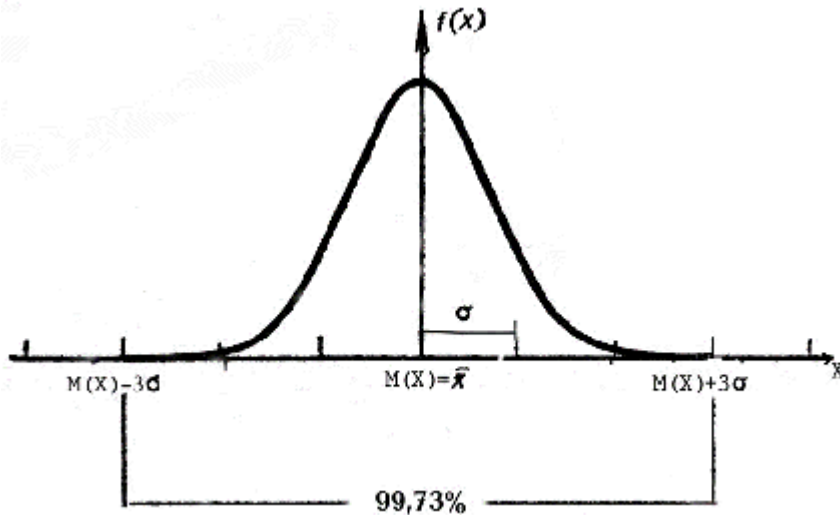


Fig. 3.5. Three-sigma rule

The mean, median, and mode of the normal distribution are the same:

$$\mu = \text{Mo}(x) = \text{Me}(x).$$

**Example:**

It is known the person pH blood is normally distributed quantity with mean 7,4 and a standard deviation 0,2. Find a range of pH values.

Let's use the three-sigma rule.

$$P(7,4 - 3 \cdot 0,2 < x < 7,4 + 3 \cdot 0,2) = 0,9973 = 99,73 \%.$$

With a probability of equal to 99,73 % it is possible to approve, that the range of the person's pH values makes 6,8÷8.

**Questions:**

1. What are the random variables? What are the differences between discrete and continuous random variables? Make examples.
2. How to specify probability distribution for discrete random variable? What is a normalization condition for the distribution for discrete random variable?
3. How to specify probability distribution for continuous random variable? What is a normalization condition in this case?
4. Give a definition of random distribution characteristics: expectation, mode, median, variance, standard deviation. Explain their meaning.
5. How to determine numeric parameters for discrete random variable distribution?
6. How to determine numeric parameters for continuous random variable distribution?
7. What features of continuous random variable normal distribution are known?



## Chapter 4. MATHEMATICAL STATISTICS FUNDAMENTALS

To know the taste of melons, not necessarily eat all of it  
(old Eastern wisdom)

### 4.1. GENERAL POPULATION AND SAMPLE

Mathematical statistics deals with gaining information from data. In practice, data often contain some randomness or uncertainty. Statistics handles such data using methods of probability theory.

**General population** is the set of all objects (units), on which scientists are going to draw conclusions in the study of specific problems. General population consists of all objects that should be considered. *General population* consists of all objects that should be considered. The composition of *the population* depends on the objectives of the study. Sometimes the *general population* is the entire population of a given region (for example, when we study the attitudes of potential voters to the candidate), usually given several criteria that determine the object of research.

In practice it is not possible to investigate all the objects of interest to us. Then apply *the sampling method* — that is, limited to examining only some parts of objects.

In statistics, a sample is a subset of a population. The sample represents a subset of manageable size. Samples are collected and statistics are calculated from the samples so that one can make inferences or extrapolations from the sample to on the entire population. However, this is necessary to select objects in the sample, subject to certain procedures. Without going into details, one can note that the **basic requirements for the sample** can be considered:

- representativeness (the ability to be a reflection of the general population);
- coincidence unit (each object the general population should have an equal probability of being selected);
- sufficiency level to obtain statistically significant results.

There are two types characteristics of the sample. A qualitative characteristic of the sample — which exactly one can choose and what methods of constructing the sample one can use for this. Quantification of the sample — how many cases we choose, in other words, the sample size.

**Sample size** is the number of cases included in the sample. From statistical considerations it is recommended that the number of cases is not less than 30–35. To calculate the sample size necessary to determine the permissible scope of sampling error, the level of confidence probability and the expected variance.

### 4.2. STATISTICAL SERIES TYPES

**Simple statistical series** is the set of values of variable  $X(x_i)$ , where  $i \in [1, n]$  which is presented as table 4.1.

Table 4.1

Number	1	2	...	$n$
Variant $x_i$	$x_1$	$x_2$	...	$x_n$

Resulting statistical material  $x_1, x_2 \dots x_i$  observation is the primary data on the size, subject of statistical analysis. Elements  $x_1, x_2 \dots x_i$  are called **variants**. Typically, such statistics are issued in the form of tables, charts, histograms, etc. If the sample volume  $n$  contains  $k$  various elements  $x_1, x_2 \dots x_k$ , and  $x_i$  found  $m_i$  times, the number of  $m_i$  is called the **frequency** of  $x_i$  element. And the ratio  $m_i/n = f_i$  is called the **relative frequency** of  $x_i$  element.

**Variational series** is a table whose first row contains the  $x_i$  elements in ascending order, and the second one contains their frequency  $m_i$  (or relative frequency  $f_i$ ). Variational series is presented in table 4.2.

Table 4.2

Variant, $x_i$ ( $x_1 < x_2 < x_3 \dots < x_k$ )	$x_1$	$x_2$	$x_3$	...	$x_k$	Control
Frequency, $m_i$	$m_1$	$m_2$	$m_3$	...	$m_k$	$\sum_{i=1}^k m_i = n$
Relative frequency, $f_i = \frac{m_i}{n}$	$\frac{m_1}{n}$	$\frac{m_2}{n}$	$\frac{m_3}{n}$	...	$\frac{m_k}{n}$	$\sum_{i=1}^k \frac{m_i}{n} = 1$

**Frequencies** (relative frequencies) **polygon** of sample is called a broken line with vertices  $(x_i, m_i)$  or  $(x_i, f_i)$  as illustrated in (fig. 4.1).

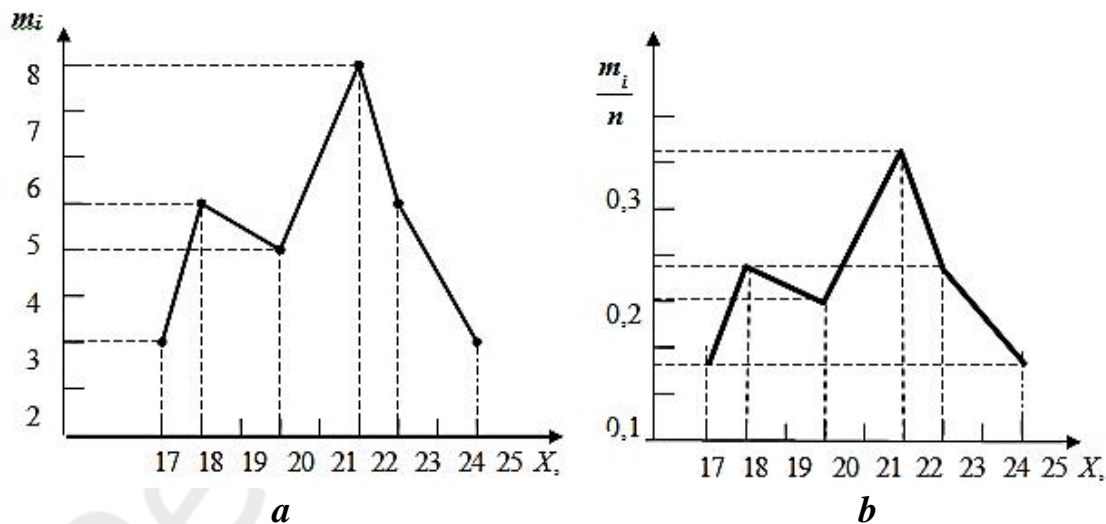


Fig. 4.1. a — frequencies polygon; b — relative frequencies polygon

**Ranked statistical series** is the series in the form of a decreasing or increasing on the value of the trait. **Rankings** is the process of converting a simple statistical series based on the ordering (clustering), the numerical values of the elements of a number of descending ( $x_1 > x_2 > \dots > x_i$ ) or ascending

( $x_1 < x_2 < \dots < x_i$ ), where  $i$  is the rank of the element ranked a number of values of variable  $i \in [1, n]$ . As a result of the transformation a ranked series is obtained.

Depending on the type of trait distinguish discrete and interval variational series. Depending on the amount of input data and the field of values of one-dimensional quantitative trait, the frequency distribution is also divided into discrete and interval. If a different version of the very many (10–15), these options are grouped by selecting a certain number of intervals, grouping and thus obtaining an interval frequency distribution. Algorithm for grouping data set consists of the following steps:

- 1) find the minimum and maximum variants;
- 2) the entire range of values of variable  $[x_{\min}, x_{\max}]$  is divided into intervals of equal length.

The number of intervals  $k$  is usually taken within 5–25. There are formulas for determining the «optimal» values of  $k$  and thus constructing the optimal allocation of frequencies:

$$k = \sqrt{n} \quad \text{or} \quad k \approx 1 + 3,32 \lg n. \quad (4.1)$$

For large  $n$ , this formula gives a lower bound for  $k$ .

- 3) find the interval width  $h$  and boundary points of each interval:

$$h = \frac{x_{\max} - x_{\min}}{k}; \quad (4.2)$$

- 4) find the boundary points of each

$$x_0 = x_{\min}, x_1 = x_0 + h, x_2 = x_1 + h, \dots, x_k = x_{\max};$$

- 5) calculate the number of variant  $m_i$ , caught in the interval, with the variants that come on the border ranges, refer only to one of the intervals.

The results are entered into the table (table 4.3).

Table 4.3

Interval	Frequency, $m_i$	Relative frequency, $m_i/n = f_i$
$x_0-x_1$	$m_1$	$m_1/n$
$x_1-x_2$	$m_2$	$m_2/n$
$x_2-x_3$	$m_3$	$m_3/n$
...	...	...
$x_{k-1}-x_k$	$m_k$	$m_k/n$

Let  $x$  is a continuous random variable with unknown probability density  $f(x)$ . To assess  $f(x)$  a sample  $x_1, x_2, \dots, x_n$  one can divide the range of values  $x$  at intervals of length  $h$ . Denote middle intervals  $x_i$ , and through  $m_i$  number of elements in the sample caught in a specified interval. Then  $f_i = \frac{m_i}{n h}$  is an assessment of the probability density at  $x_i$ . In the rectangular coordinate system are constructed rectangles with bases  $h$  and heights  $\frac{m_i}{n h}$ . Area of

a rectangle equals to the relative frequency. The resultant figure is called a *histogram* sampling (fig. 4.2).

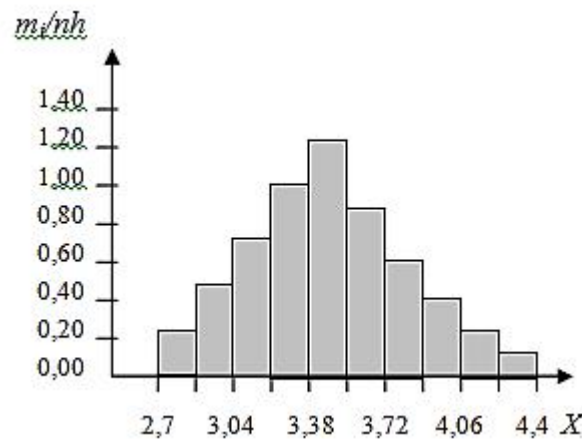


Fig. 4.2. Histogram sampling

### 4.3. GENERAL POPULATION PARAMETER ESTIMATION

Conducting a research project always involves some errors. A common mistake is to study the difference between the true value (in the general population) of the observed variable and its observed value (in the sample).

To reduce the influence of random errors someone can measure values of some quantity  $x$  several times. As a result of the measurements values of the quantity is obtained:

$$x_1, x_2, x_3, \dots, x_n.$$

With this sample, the result of measurements can be evaluated. Value that would be such an evaluation is denoted as  $\bar{x}$ . But as it is the importance of assessing the results of measurements would not represent the true value of the measured value, it is necessary to estimate its error. True value of  $x$  lies in the interval  $\bar{x} \pm \delta$ , which is called a *confidence interval* (the permissible deviation of the observed values from the truth). In this case the detected result of the measurements can be written in the form:

$$\mu = \bar{x} \pm \delta.$$

How frequently the observed interval contains the parameter of interest is determined by *confidence level*  $\gamma$ . Confidence level indicates the degree of confidence that the value of the observed element falls into the specified range of the confidence interval. Typically used  $\gamma = 95\%$  confidence level. To obtain more accurate data confidence level increases to  $\gamma = 99\%$ , but this entails a significant increase in sample size.

For example, measuring the length of a segment, the final result can be recorded in the form:

$$l = (8,34 \pm 0,02) \text{ mm}, (\gamma = 0,95).$$

This means that out of 100 chances  $-95$  for what the true value of the length of the segment lies in the range from 8,32 to 8,36 mm.

The half confidence interval can be calculated by the following formula:

$$\delta = t_{\gamma,n} \frac{S}{\sqrt{n}}. \quad (4.4)$$

In this case the lower and the upper confidence limits are:

$$\bar{x} \pm \delta = \bar{x} \pm t_{\gamma,n} \frac{S}{\sqrt{n}}, \quad (4.4a)$$

where  $t_{\gamma,n}$  is the **coefficient Student's** — special coefficient which depends on the confidence level  $\gamma$  and the number of measurements  $n$ ;  $S$  is the **sample standard deviation**, which may be calculated from the sample by using the following formula:

$$S^2 = \frac{\sum (x_i - \bar{x})^2}{n-1}. \quad (4.5)$$

The coefficient Student's  $t_{\gamma,n}$  is found from the special tables.

Proceeding on the same lines the 95 and 99 percent confidence limits may be stated as:

$$\bar{x} \pm \delta = \bar{x} \pm 1,96 \frac{S}{\sqrt{n}}, \quad (\gamma = 0,95) \quad (4.6)$$

$$\bar{x} \pm \delta = \bar{x} \pm 2,57 \frac{S}{\sqrt{n}}, \quad (\gamma = 0,99) \quad (4.6a)$$

**Example:**

A random sample of 64 students made an average score of 60, with a standard deviation of 15. Construct 99 % confidence interval estimation for the mean score of entire class.

It's known the following data:  $\bar{x} = 60$ ,  $S = 15$ ,  $n = 64$ ,  $t_{\gamma,n} = 2,57$  (from the table).

Using the formula for 99 % confidence interval may be written as:

$$\mu = \bar{x} \pm 2,57 \frac{S}{\sqrt{n}}.$$

The lower confidence limit is:

$$\bar{x} - 2,57 \frac{S}{\sqrt{n}} = 60 - 2,57 \frac{15}{8} = 60 - 4,82 = 55,18 \approx 55.$$

The upper confidence limit is:

$$\bar{x} + 2,57 \frac{S}{\sqrt{n}} = 60 + 2,57 \frac{15}{8} = 60 + 4,82 = 64,82 \approx 65.$$

Hence, the 99 % confidence interval estimate for the mean will be,  $55 < \mu < 65$ , i. e. the mean score is between 55 and 65.

#### 4.4. CORRELATION ANALYSIS

**Correlation** determines the degree of association between two statistical variables, for example, the correlation between the height of parents and their children. Correlations are useful because they can indicate a predictive relationship that can be exploited in practice.

**Scatter diagram** is a graphic picture of the sample data. The plotted points cluster around a straight line. This line is called the regression line obtained by

inspection. Making a scatter diagram and drawing a line or curve is investigation to assess the type of relationship between the variables. As long as the scattered points show closeness to a straight line of some direction, one can draw a straight line to represent the sample data (fig. 4.3, *a*, *b*). But when the points do not lie around a straight line, and from circle there is not any relationship between the two variables (fig. 4.3, *d*). If the plotted points cluster around a curve will be non-linear relationship between  $y$  and  $x$  (fig. 4.3, *c*)

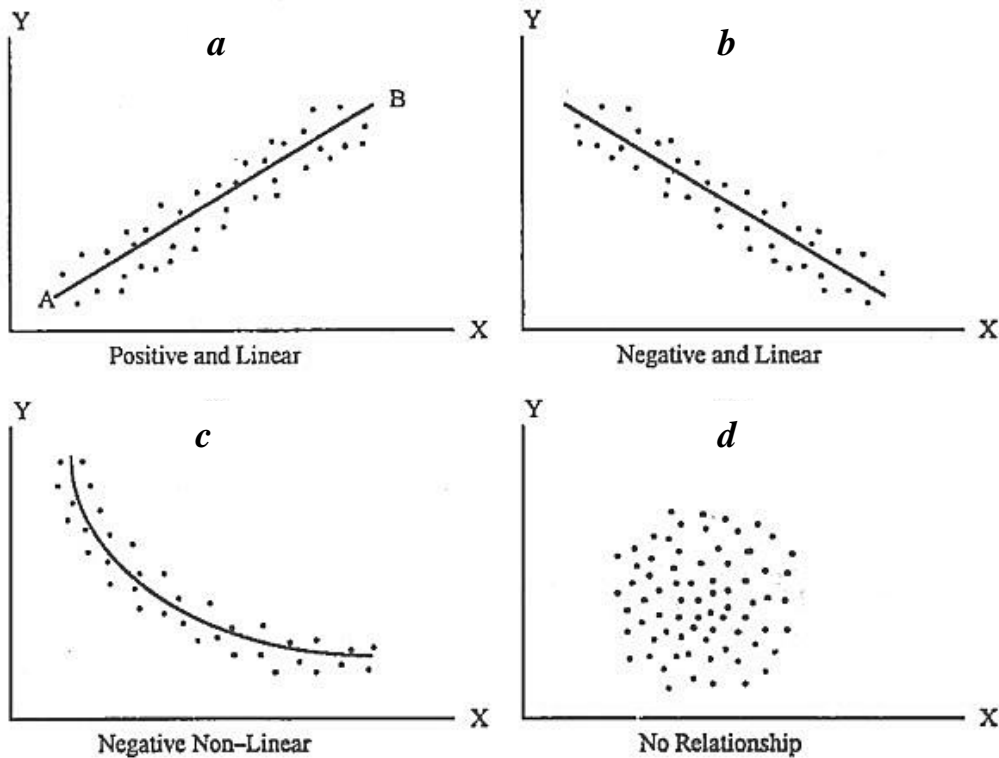


Fig. 4.3. Scatter diagrams

There are two ways to find out the correlation: a correlation coefficient and a scatter diagram. For linear association **correlation coefficient  $r$**  between two random variables  $x$  and  $y$  is defined as:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{X})(y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{X})^2 \cdot \sum_{i=1}^n (y_i - \bar{Y})^2}} \quad (4.7)$$

In general, correlation coefficients can range from  $-1$  to  $+1$  ( $-1 \leq r \leq 1$ ), with the magnitude and the sign of  $r$  representing the *strength* and *direction* respectively of the association between the two variables. Depends on the correlation coefficient sign distinguish positive (if value  $X$  increase the mean value  $Y$  increase too) and negative (if value  $X$  increase the mean value  $Y$  decrease) correlation. For  $|r| < 0,3$  the linear relationship between  $X$  and  $Y$  is

absent or extremely weak. Moderate correlation is observed when  $0,3 < |r| < 0,7$ . There is a strong correlation if  $0,7 < r < 1$ . There is a functional dependence between two variables if  $|r| = 1$ .

**Questions:**

1. Give definition of a general population and a sample. What does representative sample mean? What are the basic requirements for the sample?
2. What are a variant, simple statistical series, variational series?
3. What are the stages for variational series (discrete distribution) formation? How can variational series be represented graphically?
4. What are the stages for ranked statistical series (continuous distribution) formation? How ranked statistical series can be represented graphically?
5. Describe the central tendency and the dispersion characteristics for random variables.
6. Explain differences between sample parameters point estimate and sample parameters interval estimate.
7. What is confidence interval finding algorithm?
8. How to determine a required sample volume if the accuracy of interval estimate is known?
9. What is a correlation analysis major task?
10. What is a scatter diagram? What information about parameters correlation does this diagram contain?
11. How to calculate a correlation coefficient between parameters? What information does this coefficient contain?
12. What is the condition of reliable correlation coefficient?

## Chapter 5. BASICS OF BIOMECHANICS

### 5.1. DEFORMATION CHARACTERISTICS

One basic point in the study of the mechanics of deformable bodies is the resistive properties of materials. These properties relate the stresses to the strains and can only be determined by experiment.

When a sufficient load is applied to a structural material, it will cause the material to change shape. This change in shape and/or size is called deformation. **Deformation** is the transformation of a body from a reference configuration to a current configuration.

A temporary shape change that the object returns to its original shape and size is called **elastic deformation**. In other words, elastic deformation is recoverable after unloading. For example, rubber does large elastic deformation.

The deformation is called **plastic deformation**, if the size of the body is not fully recovered, that means there is a residual deformation. For example, copper, silver, and gold have rather large plastic deformation. Steel does, too, but not cast iron. Rubber, crystals, and ceramics have minimal plastic deformation ranges.

Accordingly, the **elasticity** is a physical property of materials which return to their original shape after the force that caused their deformation is no longer applied. **Plasticity** — the ability of material to non-reversible changes of shape in response to applied forces.

The main types of deformation are: compression, tension, bending, shift and torsion. In general, various types of deformation of the body can be reduced to two basic: *tensile deformation* and *shear deformation*.

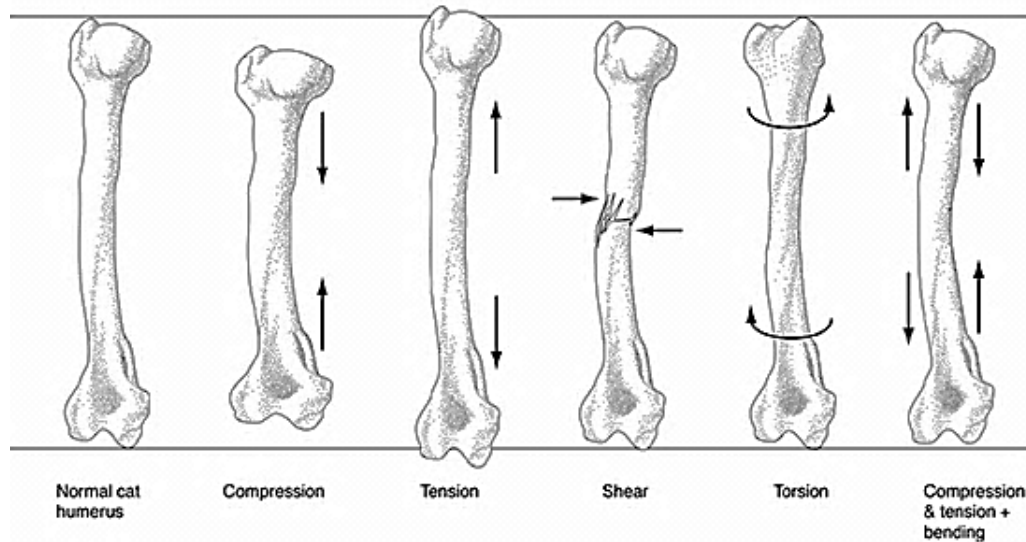


Fig. 5.1. Main types of deformation

It results from the net electrostatic attraction between the particles in a solid when it is deformed so that the particles are further apart from each other than when at equilibrium, where this force is balanced by repulsion due to electron shells; as such, it is the pull exerted by a solid trying to restore its original, more compressed shape. Tension is the opposite of compression.

Consider basic characteristics of a deformed body. *Absolute deformation* is the change in length:

$$\Delta l = l - l_0, \quad (5.1)$$

where  $l_0$  is the initial length. Absolute deformation has units of length.

*Strain* (relative deformation) is a normalized measure of deformation representing the displacement between particles in the body relative to a reference length. It is a dimensionless value, because it is only a ratio between two similar quantities:

$$\varepsilon = \frac{\Delta l}{l_0}, \text{ in per cent } \varepsilon = \frac{\Delta l}{l_0} \cdot 100 \%. \quad (5.2)$$

When a deforming force is applied on a body, it is deformed. The displaced molecules within the deformed body try to attain their normal position. This tendency gives rise to an internal force within the body. The force developed within the deformed body is called restoring force.

We may view a rod of any elastic material as a linear spring. Law that shows the relationship between restoring forces applied to a spring and its elasticity is called Hooke's law. *Hooke's Law* states that the restoring force of a spring is directly proportional to a small displacement.



Mathematically, Hooke's law states that:

$$F_e = k \times Dl, \quad (5.3)$$

where  $Dl$  is absolute deformation (the displacement) of the spring's,  $F$  is the restoring force exerted by the spring on that end,  $k$  is a coefficient called the *stiffness* or the spring constant (in SI units: N/m). A stiffness depends on geometrical size of sample.

The negative sign indicates that the force exerted by the spring is in direct opposition to the direction of displacement.

**Stress** is it is a measure of the average force per unit cross-section area of a surface within the body on which internal forces act:

$$\sigma = \frac{F}{A}. \quad (5.5)$$

Strain is measured in  $\text{N/m}^2$ .

So, stress is the force on unit of cross-section areas within a material that develops as a result of the externally applied force. Strain is the relative deformation produced by stress. **Hooke's Law** may also be expressed in terms of stress and strain: for relatively small stresses, stress is proportional to strain.

$$s = E \times e, \quad (5.6)$$

where  $E$  is Young's modulus.

**Young's modulus**, sometimes referred to as the *modulus of elasticity*  $E$ , it is numerical constant, which describes the elastic properties of a solid undergoing tension or compression in only one direction. The SI unit of modulus of elasticity is the Pascal ( $1 \text{ Pa} = 1 \text{ N/m}^2$ )

In general, elastic modulus is not the same as stiffness. Elastic modulus is a property of the constituent material; stiffness is a property of a structure, it depends on the geometric parameters. The formula for stiffness is:

$$k = \frac{ES}{l_0}. \quad (5.7)$$

So,  $k$  is directly proportional to the elastic modulus  $E$ , cross-sectional area of the sample  $S$  and inversely proportional to its length  $l_0$ .

## 5.2. STRESS-STRAIN DIAGRAM

In general, the relationship between stress and strain in the sample is complicated, depends on the material properties and not always obeys Hooke's law.

The graph between the strain developed in the solid and stress to which it is subjected is called the *stress-strain diagram*. Within region OA if the load is removed the specimen would return to its original length. On the segment OA the relationship between  $\sigma$  and  $\epsilon$  is direct, it corresponds to Hooke's law. The slope is equal to the Young's modulus:

$$\text{tga} = E.$$

A –  $\sigma_{PL}$  — **proportional limit** — above this point stress is not longer proportional to strain. Hooke's Law holds only on the linear segment OA.

B –  $\sigma_{EL}$  — **elastic limit** — the maximum stress that can be applied without resulting in permanent deformation when unloaded.

C –  $\sigma_{YL}$  — **yield limit** — the point at which the strain begins to increase very rapidly without a corresponding increase in stress. Beyond yield limit the increase in length is perfectly plastic.

CK — **proof stress** — the strain increases for very little or almost no increase in stress as in this segment.

D –  $\sigma_U$  — **ultimate strength** — as deformation continues, the stress increases until it reaches this point, the maximum stress the material can withstand. Beyond this point a neck forms where the local cross-sectional area decreases more quickly than the rest of the sample resulting in an increase in the true stress. Eventually the neck becomes unstable and the specimen ruptures (fractures).

E — **fracture** of specimen.

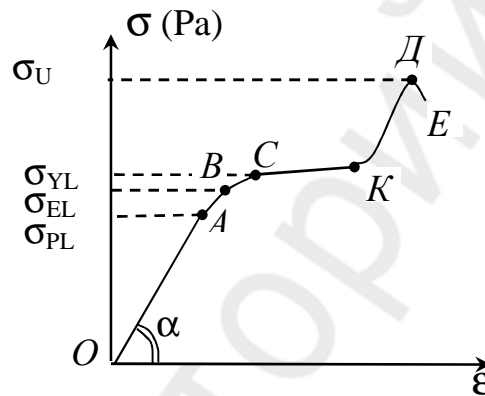


Fig. 5.2. Stress-strain diagram

Different materials clearly result in different stress-strain relationship. **Ductile materials** are capable of undergoing large strains (at normal temperature) before failure (damage). **Brittle materials** exhibit very little inelastic deformation. In fig. 5.3 the stress-strain diagram for ductile and brittle material is shown.

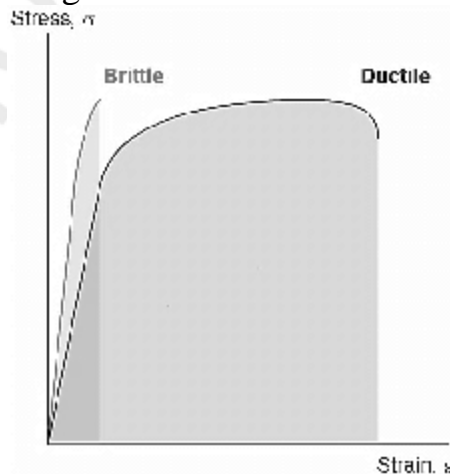


Fig. 5.3. The stress-strain diagram for ductile and brittle material

Another important characteristic of a deformable body is the Poisson ratio  $\mu$ . When a specimen of material is stretched in one direction, it tends to contract in the other two directions perpendicular to the direction of stretch. Conversely, when a sample of material is compressed in one direction, it tends to expand in the other two directions.

The **Poisson ratio** is the ratio of the fraction of expansion divided by the fraction of compression, for small values of these changes. It connects the longitudinal relative deformation  $\epsilon$  and transverse relative deformation  $\epsilon_1$  of the specimen:

$$\mu = -\frac{\epsilon_1}{\epsilon}. \quad (5.8)$$

These deformations always have different signs. For example, during the tension (fig. 5.4)

$$\epsilon = \frac{\Delta l}{l_0} > 0, \quad \epsilon_1 = \frac{\Delta d}{d_0} > 0,$$

during the compression:  $\epsilon < 0$ ,  $\epsilon_1 > 0$ , and Poisson ratio  $\mu$  is always positive.

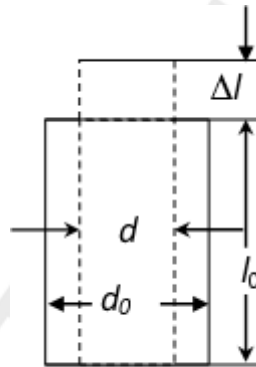


Fig. 5.4. The relation between longitudinal relative deformation and transverse relative deformation

$$\mu = -\frac{\epsilon_1}{\epsilon} > 0.$$

Poisson's ratio depends only on the properties of the material and determines the relative change in its volume  $V$ :

$$\frac{\Delta V}{V} = \epsilon(1 - 2\mu). \quad (5.8)$$

Most materials have Poisson ratio values ranging between 0 and 0,5. A perfectly incompressible material deformed elastically ( $\Delta V = 0$ ) at small strains would have a Poisson ratio of exactly 0,5.

On the molecular level, Poisson's effect is caused by slight movements between molecules and the stretching of molecular bonds within the material lattice to accommodate the stress. When the bonds elongate in the direction of

load, they shorten in the other directions. This behavior multiplied many times throughout the material lattice is what drives the phenomenon.

**Questions:**

1. Give a definition of a solid body deformation. What is the difference between elastic deformation and plastic one? Specify main types of deformation.
2. What is a quantitative measure of deformation? Call the units of a strain. Give a definition of a stress and indicate its units.
3. Show and analyze the Hooke's Law for tension (compression) deformation. What is the relation between stiffness and Young's modulus?
4. Show and analyze a stress-strain diagram. Determine proportional limit, elastic limit, yield limit, proof stress and ultimate strength.
5. Show and analyze the Hooke's Law for shear deformation. What is the Poisson ratio?

## Chapter 6. MECHANICAL OSCILLATIONS AND WAVES

### 6.1. HARMONIC OSCILLATIONS

Harmonic oscillation is the periodic process in which the parameter of interest is varied as sine or cosine. If there is no time-dependent force applied to the oscillator, then it is called a free oscillator.

The simple harmonic oscillator is a mass connected to some elastic object (spring) of negligible mass that is fixed at the other end and constrained so that it may only move in one dimension.

Fig. 6.1 shows a mass  $m$  connected to an elastic spring that is fixed at the other end and constrained so that it may only move in one dimension on smooth surface. If mass  $m$  will be displaced from the equilibrium position of a system (displacement  $x$ ) it will start periodically oscillate. The friction forces and air resistance are ignored. Let's find the law, according to which the coordinate  $x$  changes with time  $x = f(t)$ .

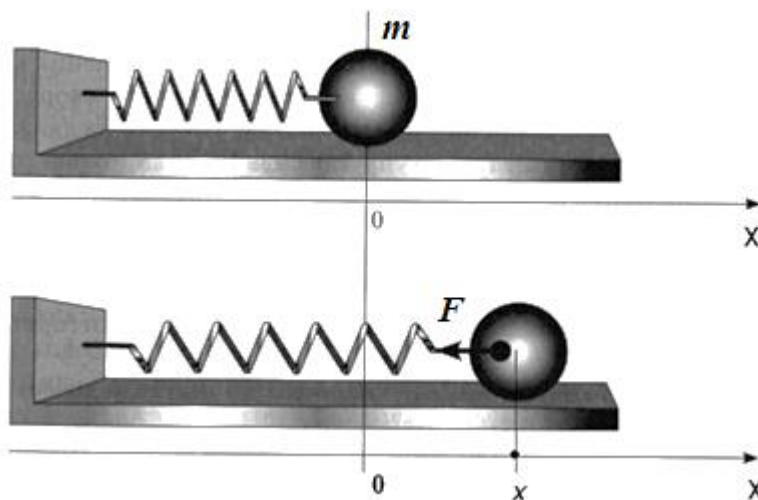


Fig. 6.1. Oscillations of negligible mass  $m$  connected to spring

The force acting in this system is elasticity force, which is directly proportional to the displacement of mass from the equilibrium position of a system  $x$  and it will point in the opposite direction (a condition known as Hooke's Law):

$$F = -kx.$$

In this case the Newton's Law, combined with Hooke's law for the behavior of a spring, states the following:  $m\mathbf{\ddot{a}} = \mathbf{\dot{F}}$ , or in projection on horizontal axis  $x$ :  $ma_x = -kx$ , where  $k$  is the spring constant,  $m$  is the mass,  $x$  is the position of the mass, and  $a$  is its acceleration.

The *velocity*  $v$ , or the rate of change of the position with time, is defined as:

$$u = \frac{dx}{dt}.$$

The *acceleration*  $a$ , or the rate of change of the velocity, is

$$a = \frac{du}{dt} \Rightarrow a = \frac{d^2x}{dt^2}.$$

So, we've obtained the second order linear differential equation (DE). And its solution gives us the displacement of the mass as a function of time. This DE describes the free harmonic oscillation:

$$m \frac{d^2x}{dt^2} = -kx \tag{6.1}$$

↓

$$m \frac{d^2x}{dt^2} + kx = 0.$$

Denoting  $\omega_0^2 = \frac{k}{m}$ , one can write

$$\frac{d^2x}{dt^2} = -\omega_0^2 x \quad \text{or} \quad \frac{d^2x}{dt^2} + \omega_0^2 x = 0. \tag{6.2}$$

The solution of this equation is *harmonic* function of type:

$$x = A \sin(\omega_0 t + \varphi_0). \tag{6.3}$$

So, it is the general solution of the free harmonic oscillations, where  $A$  is the amplitude;  $\omega_0 = \sqrt{k/m}$  is the angular frequency and  $\varphi_0$  is the initial phase of oscillation;  $(\omega_0 t + \varphi_0)$  is the phase of oscillation;  $t$  is the running time. The period of oscillation  $T$  is equal  $T = 2\pi\sqrt{m/k}$ ;  $n = 1/T$  is the frequency of oscillation.

The energy associated with a harmonic oscillator is just the sum of the kinetic  $E_k$  and potential  $E_p$  energies. For a mass on a spring the total energy is:

$$E = E_k + E_p = \frac{mu^2}{2} + \frac{kx^2}{2}. \tag{6.4}$$

The potential energy stored in a spring is just  $E_p = \frac{kx^2}{2}$  since the force is given by Hooke's Law. The displacement of a harmonic oscillator can be written  $x = A_0 \sin(\omega_0 t + \varphi_0)$  and the velocity expression then becomes

$$v = \frac{dx}{dt} = A_0 \omega_0 \cos(\omega_0 t + \varphi_0).$$

Substituting  $\omega_0^2 = k/m$ , the total energy can be written:

$$E = \frac{1}{2} m A_0^2 \omega_0^2 [\cos^2(\omega_0 t + \varphi_0) + \sin^2(\omega_0 t + \varphi_0)] = \frac{1}{2} m A_0^2 \omega_0^2. \quad (6.5)$$

Harmonic vibration energy is directly proportional to amplitude  $A$  square and depends on angular frequency  $\omega$ .

## 6.2. DAMPED HARMONIC OSCILLATIONS

Let's find the law, according to which the coordinate changes as a function of time, when a body makes the oscillations overcoming the force of friction (fig. 6.2).

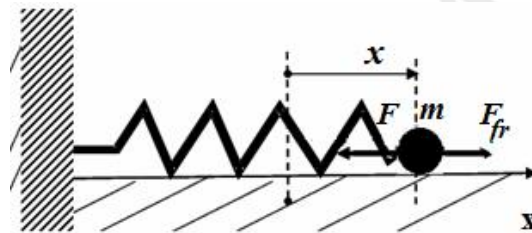


Fig. 6.2. Oscillations of negligible mass  $m$  overcoming the friction force  $F_{fr}$

For this reason, it is necessary to form and solve the equation, where it is necessary to take into account the force of friction. The force of friction  $F_{fr}$  is always directed opposite a moving body, that is to say:  $F_{fr} \sim u \Rightarrow F_{fr} = -ru$ , where  $r$  is the coefficient of proportionality,  $v$  is the velocity.

In this case one can write the Newton's second Law of motion:

$$m\ddot{a} = \dot{F} + \dot{F}_{fr}.$$

In the projections on horizontal axis OX along which an oscillatory process occurs, the equation will take the type:

$$ma = -kx - ru.$$

Or, in the differential form:  $m \frac{d^2 x}{dt^2} = -r \frac{dx}{dt} - kx$  (6.6)

$$\Downarrow$$

$$m \frac{d^2 x}{dt^2} + r \frac{dx}{dt} + kx = 0$$

$$\frac{d^2x}{dt^2} + \frac{r}{m} \frac{dx}{dt} + \frac{k}{m} x = 0.$$

Taking into account that  $\frac{r}{m} = 2\beta$ ;  $\frac{k}{m} = \omega_0^2$ , one can obtain:

$$\frac{d^2x}{dt^2} + 2\beta \frac{dx}{dt} + \omega_0^2 x = 0 \quad (6.7)$$

The general solution of this DE is the function:

$$x = A_0 e^{-\beta t} \sin(\omega t + \varphi_0), \quad (6.8)$$

where  $\beta = \frac{r}{2m}$  is called the damping factor,  $r$  is the coefficient of drag. The rate of the amplitude decreasing of damped harmonic oscillations is characterized by a damping factor  $\beta$ . The more damping factor  $\beta$  the faster oscillation damping. The equation (6.8) shows that displacement  $x$  is varied as a sine and the oscillation amplitude decrease with time exponentially:

$$A = A_0 e^{-\beta t}.$$

$\omega = \sqrt{\omega_0^2 - \beta^2}$  is the damping frequency. The oscillation process takes place if  $(\omega_0^2 - \beta^2) > 0$ . Fig. 6.3 represents the damped harmonic oscillation.

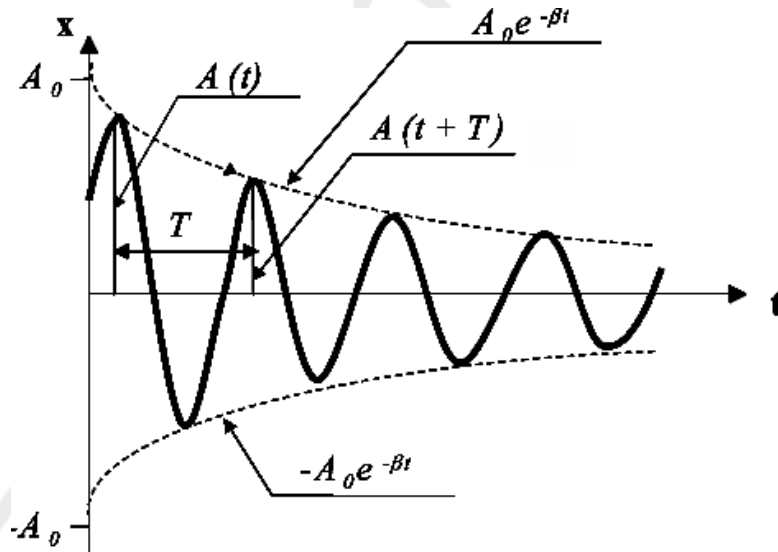


Fig. 6.3. Displacement  $x$  dependence on time  $t$  during damped harmonic oscillation

In practice an oscillation damping is characterized by *the damping ratio*  $\delta$ :

$$\delta = \frac{A(t)}{A(t+T)}. \quad (6.9)$$

The damping ratio is a measure describing how oscillations in a system decay after a disturbance. The damping ratio is also related to *the logarithmic*

**decrement  $\lambda$ .** The logarithmic decrement  $\lambda$  is defined as the natural logarithm of the ratio of any two subsequent amplitudes:

$$\lambda = \ln \delta = \ln \frac{A_0 e^{-\beta t}}{A_0 e^{-\beta(t+T)}} = \ln e^{\beta T} = \beta T. \quad (6.10)$$

### 6.3. THE FORCED HARMONIC OSCILLATIONS

**Let's consider** a damped harmonic oscillator driven by some time-dependent external applied force  $F_e = F_0 \sin \Omega t$ , where  $F_0$  is the driving force amplitude.

In this case the Newton's Law can be written as

$$m \frac{d^2 x}{dt^2} = -kx - r \frac{dx}{dt} + F_0 \sin \Omega t. \quad (6.11)$$

Noting  $\omega_0^2 = \kappa/m$ ,  $2\beta = r/m$  and  $f_0 = F_0/m$ , the second order linear differential equation can be written as follows:

$$\frac{d^2 x}{dt^2} + 2\beta \frac{dx}{dt} + \omega_0^2 x = f_0 \sin \Omega t. \quad (6.12)$$

Fig. 6.4 shows a function, which is a solution of the DE (6.12).

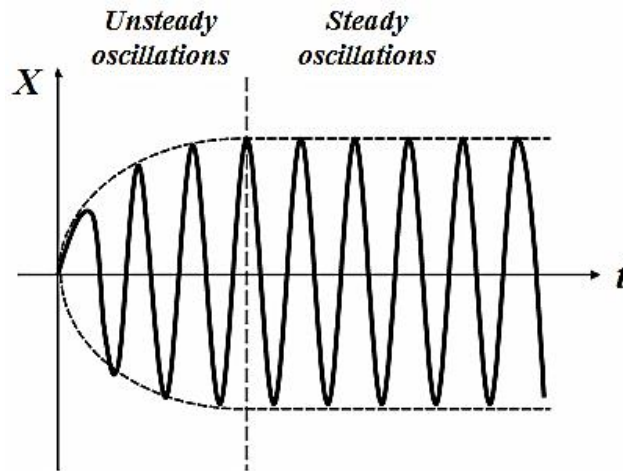


Fig. 6.4. Displacement  $x$  dependence on time  $t$  during forced harmonic oscillation

The equation solution consists of two parts  $X_1$  and  $X_2$ . The first one corresponds to unsteady oscillations, the second one — to steady oscillations:

$$X = X_1 + X_2.$$

For the steady oscillations displacement is varied as a sine function with driving force frequency  $\Omega$ :

$$X_2 = A \sin(\Omega t + \varphi). \quad (6.13)$$

Steady amplitude  $A$  depends on frequency of a natural oscillations  $\omega_0$ , a damping factor  $\beta$ , driving force characteristics ( $f_0, \Omega$ ):

$$A = f_0 / \sqrt{(\omega_0^2 - \Omega^2)^2 + 4\beta^2 \Omega^2}. \quad (6.14)$$



The amplitude has maximum value when a driving force frequency is determined by equation:

$$\Omega = \Omega_{res} = \sqrt{\omega_0^2 - 2\beta^2}. \quad (6.15)$$

**Mechanical resonance** is the tendency of a mechanical system to oscillate at larger amplitude (to absorb more energy) when a driving force **frequency  $\Omega$**  is determined by equation (6.15).

#### 6.4. SUPERPOSITION OF HARMONIC OSCILLATIONS

The superposition of two harmonic (sinusoidal) oscillations  $X_1 = A_1 \sin(\omega t + j_1)$  and  $X_2 = A_2 \sin(\omega t + j_2)$  with the same frequency  $\omega$  gives another harmonic (sinusoidal) oscillation  $X = X_1 + X_2$  with the same frequency  $\omega$  (but with a different amplitude and phase displacement):

$$X = X_1 + X_2 = A_1 \sin(\omega t + j_1) + A_2 \sin(\omega t + j_2) = A \sin(\omega t + j). \quad (6.16)$$

The frequency of oscillation being obtained by superposition of harmonic oscillations with the same frequency is equal the frequency of added oscillations. Resulting amplitude  $A$  depends on  $A_1$  and  $A_2$  amplitudes and initial phase displacement  $j_1$  and  $j_2$ :

$$A = \sqrt{A_1^2 + A_2^2 + 2A_1 A_2 \cos(\varphi_2 - \varphi_1)}. \quad (6.17)$$

The initial phase  $j$  of resulting oscillation is determined by the following equation:

$$\text{tg} \varphi = \frac{A_1 \sin \varphi_1 + A_2 \sin \varphi_2}{A_1 \cos \varphi_1 + A_2 \cos \varphi_2}. \quad (6.18)$$

By superposing harmonic (sinusoidal) oscillations  $X_1 = A_1 \sin(\omega_1 t + j_1)$  and  $X_2 = A_2 \sin(\omega_2 t + j_2)$  with different frequencies  $\omega_1$  and  $\omega_2$  one can obtain a periodic function (fig. 6.5). Periodic function of the time  $x(t) = x(t + T)$  is a function which repeat their course after a definite interval of time.

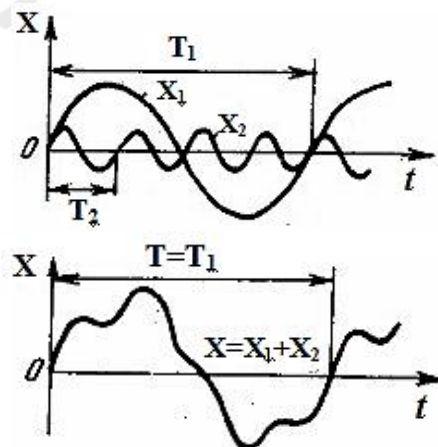


Fig. 6.5. The superposition of two harmonic vibrations  $X_1$  and  $X_2$  with different frequencies  $\omega_1$  and  $\omega_2$  (periods  $T_1$  and  $T_2$ )

## 6.5. THE FOURIER THEOREM

According to the Fourier theorem any periodic function  $x(t) = x(t + T)$  (fig. 6.6) may be expressed as the sum of harmonic components at integer multiples of the fundamental frequency  $\nu = 1/T$  (or angular frequency  $\omega = 2\pi\nu$ ) (a series of sine and cosine terms called the Fourier series).

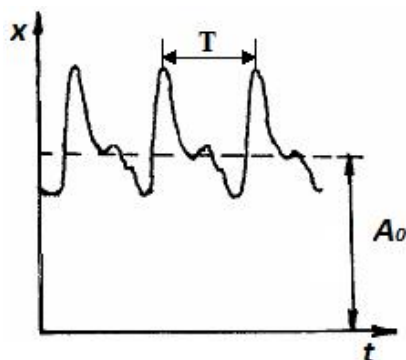


Fig. 6.6. The complex oscillation with a constant component  $A_0$

Each of sine and cosine term has specific amplitude and phase coefficients known as Fourier coefficients. In the brief description the Fourier theorem can be written as:

$$x(t) = A_0 + \sum_{k=1}^{\infty} A_k \sin(k\omega t + \varphi_k), \quad (6.19)$$

where  $A_0$  is a constant component periodical function (in many cases it can be equal to zero);  $A_k \sin(k\omega t + \varphi_k)$  are harmonic components with amplitude  $A_k$ , angular frequency  $k\omega$  and initial phase  $\varphi_k$ . The first term (at  $k = 1$ ) describes harmonic of the fundamental frequency  $\omega$ . Others components (at  $k = 2, 3, \dots$ ) are called overtones:  $2\omega, 3\omega, 4\omega, \dots$ .

Frequency range from  $\omega$  to  $\omega_k = k\omega$  is called the frequency spectrum of complex oscillation. Oscillation frequency spectrum and the corresponding harmonic amplitudes determine the harmonic spectrum of the complex oscillation (fig. 6.7).

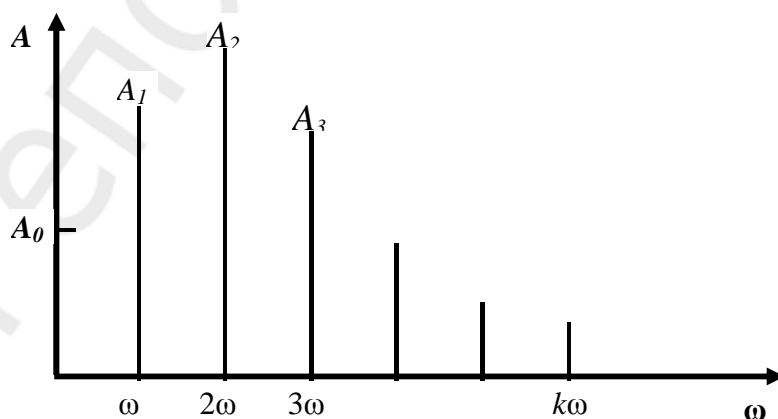


Fig. 6.7. The harmonic spectrum of the complex oscillation

A standard result of Fourier analysis is that a function has a harmonic spectrum if and only if it is periodic.

### 6.6. MECHANICAL WAVES. THE WAVE EQUATION

A mechanical wave is a process of mechanical oscillations propagation in the elastic medium. The wave is characterized by the transfer of energy without the transfer of matter. Transverse waves are those with vibrations perpendicular to the direction of the propagation of the wave; examples include waves on a string, and electromagnetic waves. Longitudinal waves are those with vibrations parallel to the direction of the propagation of the wave; examples include most sound waves. Mathematically, the most basic wave is the harmonic wave (or sinusoid), described by the equation:

$$S = A \sin \omega \left( t - \frac{x}{u} \right), \quad (6.20)$$

where  $A$  is the amplitude of the wave (the maximum distance from the highest point of the disturbance in the medium (the crest) to the equilibrium point during one wave cycle);  $x$  is the space coordinate;  $t$  is the time coordinate;  $\omega$  is the angular frequency, and  $u$  is the wave velocity.

The basic characteristics of a wave are:

- the wavelength  $\lambda$  is the distance between two sequential crests (or troughs), and generally is measured in meters:

$$\lambda = v T;$$

- the amplitude  $A$  is the maximum distance from the highest point of the disturbance in the medium (the crest) to the equilibrium point during one wave cycle;

- the period  $T$  is the time for one complete cycle of an oscillation of a wave and is measured in seconds;

- the frequency  $\nu$  is the number of periods per unit time (per second) and is measured in Hertz. These are related by  $\nu = \frac{1}{T}$ ;

- the angular frequency  $\omega$  represents the frequency in radians per second.

It is related to the frequency by  $\omega = 2\pi\nu = \frac{2\pi}{T}$ .

Thus the wave equation can be written as:

$$S = A \sin 2\pi \left( \frac{t}{T} - \frac{x}{\lambda} \right) \quad (6.21)$$

Wave propagates in a medium with a velocity  $u$  determined by only the elastic modulus  $E$  and medium density  $\rho$ :

$$u = \sqrt{\frac{E}{\rho}} \quad (6.22)$$

The wave process is associated with transference of the energy  $E$  in space. The process of energy transference is characterized by energy flux  $\Phi$ . In the case of uniform transfer of energy  $E$  the energy flux  $\Phi$  can be written as:

$$\Phi = \frac{E}{t}. \quad (6.23)$$

In general, the energy flux  $\Phi$  is a derivative of energy with respect to time:

$$\Phi = \frac{dE}{dt}.$$

$\Phi$  is the total rate of energy transfer and is measured in Watt ( $W = J \cdot s^{-1}$ ).

Wave intensity  $I$  (density of energy flux) is rate of energy transfer  $\Phi$  per unit area  $S$  perpendicular to the wave propagation. Or other words, wave intensity  $I$  is a vector quantity whose component perpendicular to any surface equals the energy transported across that surface by some medium per unit area per unit time:

$$I = \frac{\Phi}{S} = \frac{E}{St}. \quad (6.24)$$

The unit of intensity  $I$  is  $W \cdot m^{-2} = J \cdot m^{-2} \cdot s^{-1}$ .

## 6.7. THE DOPPLER EFFECT

The Doppler effect is observed whenever the source of waves is moving with respect to an observer. A change in the observed frequency of a wave, as of sound or light, occurring when the source and observer are in motion relative to each other, with the frequency increasing when the source and observer approach each other and decreasing when they move apart. The relative changes in frequency can be explained as follows. When the source of the waves is moving toward the observer, each successive wave crest is emitted from a position closer to the observer than the previous wave. Therefore each wave takes slightly less time to reach the observer than the previous wave. Therefore the time between the arrival of successive wave crests at the observer is reduced, causing an increase in the frequency. While they are travelling, the distance between successive wave fronts is reduced; so the waves «bunch together». Conversely, if the source of waves is moving away from the observer, each wave is emitted from a position farther from the observer than the previous wave, so the arrival time between successive waves is increased, reducing the frequency. The distance between successive wave fronts is increased, so the waves «spread out».

In general, when the source and detector of wave are in motion with the velocity  $v_s$  and  $v_d$  correspondingly the perceived wave frequency by detector can be written as:

$$v_d = \frac{v_w \pm v_d}{v_w \mp v_s}, \quad (6.25)$$

where  $v_w$  is the wave velocity in a medium.

Doppler effect is used to measure changes in sound waves therefore it is used to diagnose conditions related to circulation and blood flow. The Doppler ultrasound can actually measure how fast or slow blood is moving, which can indicate a circulatory problem. Blood clots can be found using Doppler ultrasound because the ultrasound will be able to detect slower blood flow or a lack of blood flow where the clot is located. Doppler ultrasound can also be used to identify narrowed arteries, plaque buildup in the blood vessels, or blocked arteries.

The fig. 6.8 shows a Doppler transducer placed on the skin and aimed at an angle,  $\theta$ , towards a blood vessel, which contains blood flowing with a velocity of  $v_b$  m/s, at any instant. The transducer emits ultrasound waves of frequency,  $n_s$ , and echoes generated by moving reflectors in the blood, e. g. red blood cells, have a frequency,  $n_r$ . The difference between these two frequencies,  $\Delta n$ , is related to the velocity of the flowing reflectors through the following equation:

$$v_r - v_s = \Delta v = \frac{2v_s v_b \cos \theta}{v},$$

where  $v$  is speed of sound in blood.

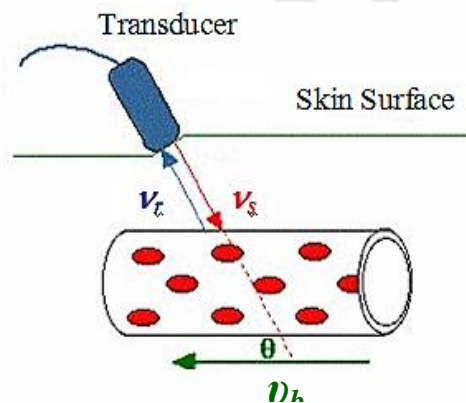


Fig. 6.8. Illustration of blood flow detection using the Doppler effect with ultrasound waves

An advantage of Doppler ultrasound is that it can be used to measure blood flow within the heart without invasive procedures such as cardiac catheterization.

**Questions:**

1. Write harmonic oscillations equation and formula for displacement.
2. Write formula for displacement in the case of damped harmonic oscillations. What is the logarithmic decrement? What is the relation between a logarithmic decrement and a damping factor?
3. What parameters a forced harmonic oscillations frequency depends on?
4. Explain a phenomenon of resonance. What are the conditions of the resonance appearance?
5. Formulate the Fourier theorem. What is the harmonic spectrum of the complex oscillation?
6. Write the mechanical wave equation. Explain meaning of values in this equation.
7. What parameters the wave intensity depends on?
8. Explain the Doppler effect. How is it used for blood flow detection?

## Chapter 7. ACOUSTIC

Acoustics plays two important roles in study of medical and biological physics. First, human hear sound and thereby sense what is happening in their environment. Second, physicians use sound and ultrasound waves for diagnostics and therapy. This chapter provides a brief introduction to the physics of sound and the medical uses of ultrasonic imaging.

### 7.1. PHYSICAL AND PHYSIOLOGICAL SOUND PROPERTIES

Sound is a mechanical longitudinal wave, transmitted through an elastic medium. It can travel through any material medium with a speed that depends on the properties of the medium. As the waves travel, the particles in the medium vibrate producing changes in density and pressure along the direction of motion of the wave. When the air vibrations reach the ear, they cause the eardrum to vibrate; this produces nerve impulses that are interpreted by the brain.

Sound waves are divided into three categories that cover different frequency ranges. **Audible waves** are waves that lie within the range of sensitivity of the human ear. They can be generated in a variety of ways, such as by musical instruments, human vocal cords, and loudspeakers. Normally, young human can beings detect sounds ranging from 16 to 20 000 Hz. **Infrasound** has frequencies below the audible range ( $< 16$  Hz). **Ultrasound** has frequencies above the audible range ( $> 20\ 000$ Hz).

The **velocity of the sound wave** depends on the medium properties through which the sound is traveling. If the medium has a Young modulus  $E$  and density  $\rho$ , the velocity  $v$  of sound waves in that medium is:

$$v = \sqrt{\frac{E}{\rho}}. \quad (7.1)$$

Sound will travel faster in solids than in liquids, and faster in liquids than in gases, because the solids are more difficult to compress than liquids, while liquids in turn are more difficult to compress than gases. The velocity of sound also depends on the temperature of the medium. Sound waves have velocity in the air 340 m/s, in water and soft tissues — 1500 m/s, in bones 3000–6000 m/s.

Sounds are divided into tones, noise and sonic booms. A **simple** (pure) **tone** is a harmonic signal which has one frequency, although its intensity may vary. A simple tone is given by a tuning fork or electronic signal generator.

A **complex tone** is a periodical signal and consists of two or more simple tones. The tone of lowest frequency  $v_0$  is called the **fundamental**; the others are called **overtones** (fig. 7.1, *a*). The first tone is called **fundamental tone**, the other tones with frequencies such as  $2v_0$ ,  $3v_0$ , ... are called **overtones** or **harmonics** and they determine the quality of the sound.

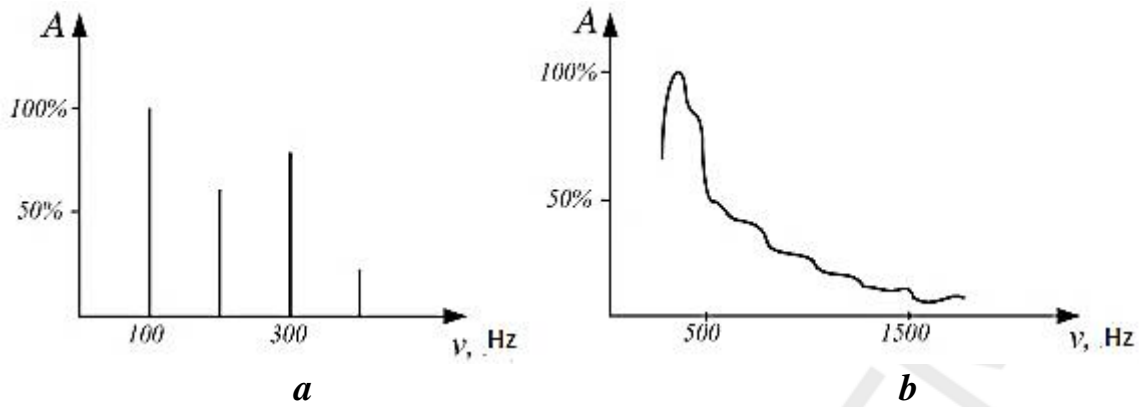


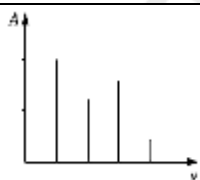
Fig. 7.1. Different types of sounds:  
*a* — complex tone; *b* — noise

**Noise** is a non-periodical complex signal that contains a wide continuous audible spectrum (fig. 7.1, *b*).

The **sonic boom** is a short sound effect (such as explosion), with very high intensity. Thunder is a type of natural sonic boom.

The sound has physical characteristics as mechanical wave and physiologic characteristics as human perception. Loudness, pitch and timbre are some of the terms which are used to describe the sound we hear. Sound physical and physiologic characteristics are given in table 7.1.

Table 7.1

Physical characteristics	Physiologic characteristics
Intensity, $I$ , $W/m^2$ , $I = \frac{E}{S \cdot t}$	Loudness, $E$ , phones
Frequency, $\nu$ , Hz	Pitch
 Harmonic spectrum	Timbre

The **intensity**  $I$  of the sound wave has been defined as the energy which transmitted through a unit area perpendicular to the direction of sound propagation per unit time. It is given by:

$$I = \frac{E}{S \cdot t}, \tag{7.2}$$

where  $E$  is the energy,  $S$  is the area,  $t$  is the time.

Unit of the intensity is  $W/m^2$ .

The **loudness** is a subjective characteristic describing the strength of the ear's perception of a sound. The ear does not respond linearly to sound intensity. That is, a sound which is a million times more powerful than another does not evoke a million times higher sensation of loudness. Relation between loudness and intensity is logarithmic.

The *pitch* of a sound is the ear's response to frequency. The pitch increases with frequency increases. There is, however, no simple mathematical relationship between pitch and frequency.

The *timbre* is mainly determined by the harmonic spectrum of sound. It characterizes tone quality and color.

## 7.2. AUDITION DIAGRAM

The human ear can detect sound at frequencies between 16 and 20 000 Hz. Within this frequency range the response of the ear is not uniform. The ear is most sensitive to frequencies between 1000 and 3000 Hz, and its response decreases toward both higher and lower frequencies.

The sensitivity of the ear varies with the frequency content and the quality of a sound. Perceived loudness is directly related to the intensity of the sound wave reaching our ear. However, it is hard to measure. Because the range of intensities is so wide, it is convenient to use a logarithmic scale, where the *intensity level* is defined by the equation:

$$L = n \lg \frac{I}{I_0}. \quad (7.3)$$

The intensity level  $L$  is measured in decibels (dB) if  $n = 10$  and in bels if  $n = 1$ .

In formula 7.3 the constant  $I_0$  is the lowest intensity that the human ear can detect at  $\nu = 1000$  Hz:

$$I_0 = 10^{-12} \text{ W/m}^2.$$

It is called the *threshold of hearing*. The intensity at which a sound begins to evoke pain is the *threshold of pain*:

$$I \approx 10 \text{ W/m}^2.$$

The threshold of pain corresponds to an intensity level of

$$L = 10 \lg \frac{10}{10^{-12}} = 10 \lg 10^{13} = 130 \text{ dB}.$$

and the threshold of hearing corresponds to  $L = 10 \lg \frac{10^{-12}}{10^{-12}} = 0 \text{ dB}$ .

Sound intensities above the threshold of pain may cause permanent damage to the eardrum and ossicles. Ear plugs are recommended whenever sound levels exceed 90 dB. Recent evidence suggests that «noise pollution» may be a contributing factor to high blood pressure, anxiety, and nervousness.

Fig. 7.2 shows how the normal threshold of hearing (lower curve) depends upon the frequency of a pure tone. The curve is an average for many normal subjects. The upper curve is an equal loudness contour. The curve was obtained as an average for many normal subjects and it joins together points which correspond to sounds that give the same subjective loudness.



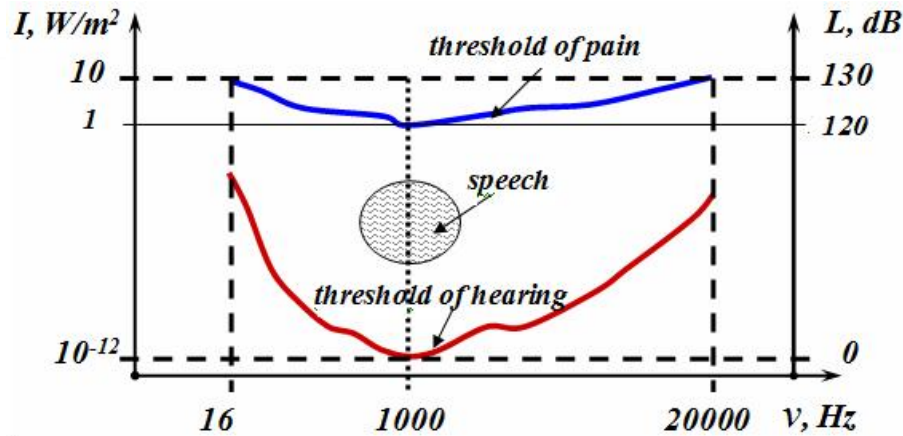


Fig. 7.2. Audition diagram

### 7.3. THE WEBER-FECHNER LAW

The *Weber-Fechner's Law* represents the relation between the magnitude of physical stimulus and the magnitude of psychological perception: **The relationship between *stimulus* and *perception* is logarithmic.** In acoustic it is the relationship between loudness and sound intensity.

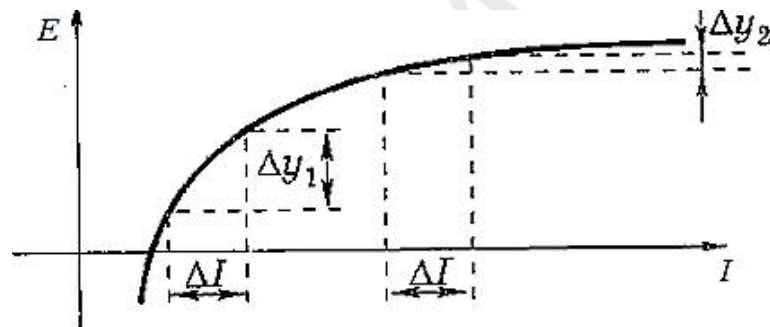


Fig. 7.3. Relationship between loudness  $E$  and sound intensity  $I$

This means that if the sound intensity is low, then a slight increase in intensity (the value of  $\Delta I$ ) leads to a significant increase in the loudness (the value  $\Delta y_1$  in fig. 7.3). As soon as the sound intensity is slightly higher than the threshold, a sound sensation appears. If the sound intensity is high, its increase by the same value  $\Delta I$  makes a small increase in the loudness ( $\Delta y_2$  in fig. 7.3).

**Loudness level** (often called simply the **loudness**)  $E$  associated with the intensity level by formula:

$$E = kL, \quad (7.4)$$

where  $k$  is the coefficient of proportionality that depends on the frequency and intensity of sound.

Loudness  $E$  is measured in **phones**. By definition, 1 phon is equal to 1 dB at a frequency of 1 kHz. For other frequencies ratio between the level of intensity and loudness can be determined using the equal loudness curves (fig. 7.4).

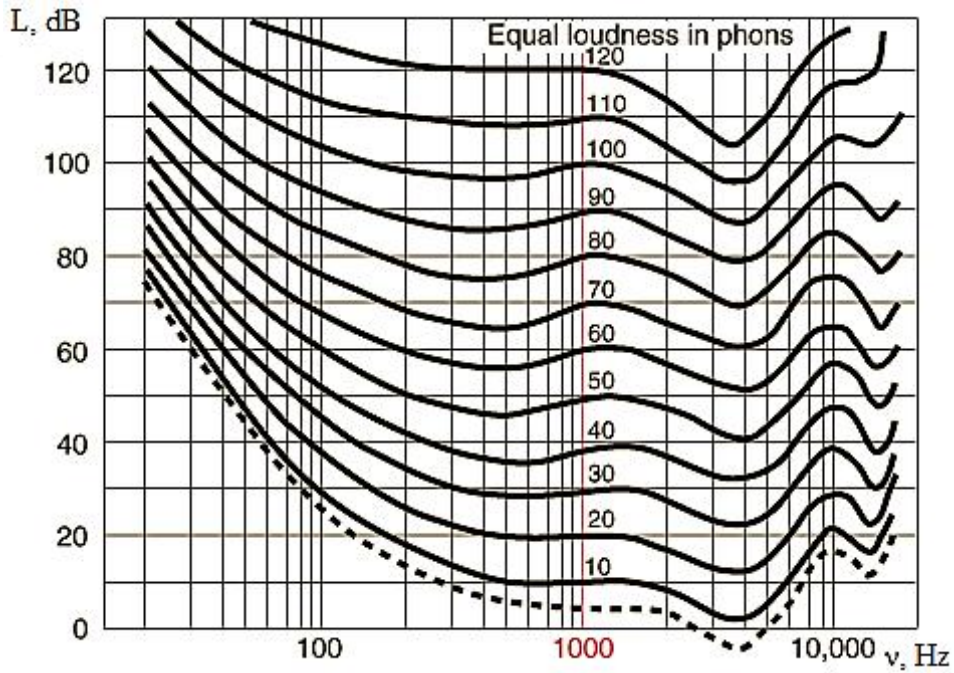


Fig. 7.4. Equal loudness curves

#### 7.4. ACOUSTIC WAVE REFLECTION AND ABSORPTION

Whenever a sound wave encounters a material with a different density, there will be some sound **reflection** off the boundary and some **transmission** into the new medium (fig. 7.5).

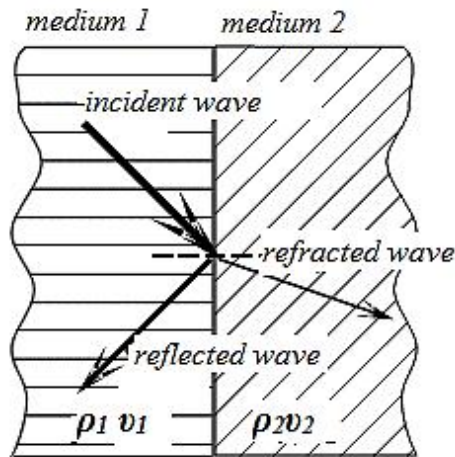


Fig. 7.5. Acoustic wave reflection and absorption

The waves will always reflect in such a way that the angle at which they approach the boundary equals the angle at which they reflect off the boundary. This is known as the law of reflection.

The reflection coefficient ( $R$ ) is determined by a ratio intensity of reflected wave to intensity of incident one:  $R = I_{ref} / I_{inc}$ . Its value depends on density of the mediums  $\rho_1$  and  $\rho_2$  as well as on acoustic wave velocity in these mediums  $v_1$

and  $v_2$ . The medium characteristic *acoustic impedance*  $Z$  ( $\text{N}\cdot\text{s}/\text{m}^3$  or  $\text{Pa}\cdot\text{s}/\text{m}$ ) is determined as:

$$Z = \rho \cdot v, \quad (7.5)$$

where  $\rho$  is the density of the medium ( $\text{kg}/\text{m}^3$ ), and  $v$  is the sound speed ( $\text{m}/\text{s}$ ).

Taking into account that  $v = \sqrt{E/\rho}$ , characteristic acoustic impedance  $Z$  can be defined as

$$Z = \sqrt{E/\rho}. \quad (7.6)$$

At normal incidence the reflection coefficient ( $R$ ) is equal:

$$R = \left( \frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2 \text{ or } R = \left( \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1} \right)^2. \quad (7.7)$$

The greater the difference between acoustic impedances, the larger the reflection coefficient is.

When the sound wave propagates through the medium its intensity  $I$  decreases due to absorption and diffusion. The law of the wave intensity decreasing is given by formula:

$$I = I_0 e^{-kx}, \quad (7.8)$$

where  $I$  is the wave intensity after passing of distance  $x$  in a medium;  $I_0$  is the incident wave intensity;  $k$  is the absorption coefficient ( $\text{m}^{-1}$ ).

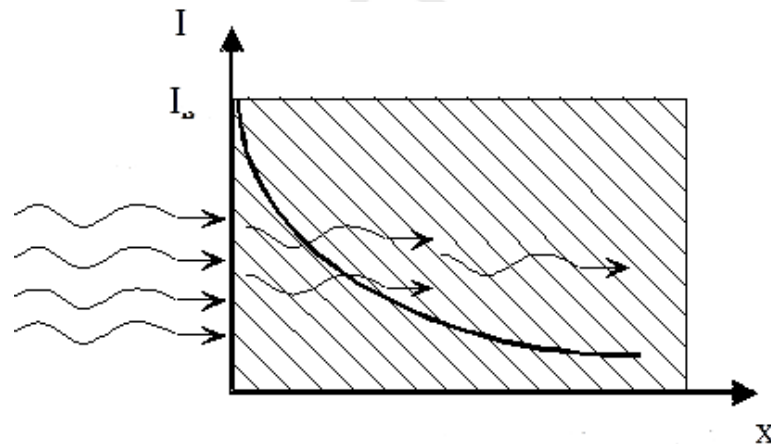


Fig. 7.6. Propagating sound waves through the medium

## 7.5. ULTRASOUND IN DIAGNOSTIC AND THERAPEUTIC APPLICATIONS

*Diagnostic ultrasonography* is an ultrasound-based diagnostic imaging technique used to visualize subcutaneous body structures including tendons, muscles, joints, vessels and internal organs for possible pathology or lesions. It is possible to perform both diagnosis and therapeutic procedures, using ultrasound to guide interventional procedures (for instance biopsies or drainage of fluid collections).

Ultrasonography (sonography) uses a probe containing one or more acoustic transducers to send pulses of sound into a material. Whenever a sound

wave encounters a material with a different density (acoustical impedance), part of the sound wave is reflected back to the probe and is detected as an echo. The time it takes for the echo to travel back to the probe is measured and used to calculate the depth of the tissue interface causing the echo. The greater the difference between acoustic impedances, the larger the echo is. If the pulse hits gases or solids, the density difference is so great that most of the acoustic energy is reflected and it becomes impossible to see deeper. This is a reason why it is impossible to recognize tissues under hollow organs. The frequencies used for medical imaging are generally in the range of 0,5 to 15 MHz. Higher frequencies have a correspondingly smaller wavelength, and can be used to make sonograms with smaller details with high spatial resolution. However, the attenuation of the sound wave is increased at higher frequencies, so in order to have better penetration of deeper tissues, a lower frequency is used. The choice of frequency is a trade-off between spatial resolution of the image and imaging depth: lower frequencies produce less resolution but image deeper into the body. Sonography is effective for imaging soft tissues of the body. Superficial structures such as muscles, tendons, testes, breast and the neonatal brain are imaged at a higher frequency, which provides better axial and lateral resolution. Deeper structures such as liver and kidney are imaged at a lower frequency with lower axial and lateral resolution but greater penetration.

The speed of sound is different in different materials. However, the sonographic instrument assumes that the acoustic velocity is constant at 1540 m/s. An effect of this assumption is that in a real body with non-uniform tissues, the beam becomes somewhat de-focused and image resolution is reduced.

Four different modes of ultrasound are used in medical imaging. These are:

- **A-mode:** A-mode is the simplest type of ultrasound. A single transducer scans a line through the body with the echoes plotted on screen as a function of depth. Therapeutic ultrasound aimed at a specific tumor or calculus is also A-mode, to allow for pinpoint accurate focus of the destructive wave energy;

- **B-mode:** in B-mode ultrasound, a linear array of transducers simultaneously scans a plane through the body that can be viewed as a two-dimensional image on screen;

- **M-mode:** M stands for motion. In m-mode a rapid sequence of A-mode scans whose images follow each other in sequence on screen in horizontal direction enables doctors to see and measure range of motion, as the organ boundaries that produce reflections move relative to the probe;

- **Doppler mode:** this mode makes use of the Doppler effect in measuring and visualizing blood flow. By calculating the frequency shift of a particular sample volume, for example a jet of blood flow over a heart valve, its speed and direction can be determined and visualised. This is particularly useful in cardiovascular studies (sonography of the vascular system and heart) and essential in many areas such as determining reverse blood flow in the liver

vasculature in portal hypertension. Most modern sonographic machines use pulsed Doppler to measure velocity.

Most ultrasound procedures are done using a transducer on the surface of the body, but improved diagnostic confidence is often possible if a transducer can be placed inside the body. For this purpose, specialty transducers, including endovaginal, endorectal, and transesophageal transducers are commonly employed. Very small transducers can be mounted on small diameter catheters and placed into blood vessels to image the walls and disease of those vessels.

**Therapeutic applications** use ultrasound to bring heat or agitation into the body. Therefore much higher energies are used than in diagnostic ultrasound. For therapeutic applications maximum acceptable intensity is

$I_{\max} \approx 1 \frac{W}{s \cdot m^2}$ . In many cases the range of frequencies used are also very different (0,8–3 MHz).

Ultrasound may be used to clean teeth in dental hygiene. Ultrasound sources may be used to generate regional heating and mechanical changes in biological tissue, e. g. in occupational therapy, physical therapy and cancer treatment. However the use of ultrasound in the treatment of musculoskeletal conditions has fallen out of favor. Focused ultrasound may be used to generate highly localized heating to treat cysts and tumors (benign or malignant). This is known as Focused Ultrasound Surgery (FUS) or High Intensity Focused Ultrasound (HIFU). These procedures generally use lower frequencies than medical diagnostic ultrasound (from 250 kHz to 2000 kHz), but significantly higher energies. HIFU treatment is often guided by magnetic resonance imaging. Focused ultrasound may be used to break up kidney stones by lithotripsy. Ultrasound may be used for cataract treatment by phacoemulsification. Additional physiological effects of low-intensity ultrasound have recently been discovered, e. g. its ability to stimulate bone-growth and its potential to disrupt the blood-brain barrier for drug delivery.

As with all imaging modalities, ultrasonography has in list of positive and negative attributes. Strengths of this method are as follows. It images muscle, soft tissue, and bone surfaces very well and is particularly useful for delineating the interfaces between solid and fluid-filled spaces. It renders «live» images, where the operator can dynamically select the most useful section for diagnosing and documenting changes, often enabling rapid diagnoses. Live images also allow for ultrasound-guided biopsies or injections, which can be cumbersome with other imaging modalities. It shows the structure of organs. It has no known long-term side effects and rarely causes any discomfort to the patient. Equipment is widely available and comparatively flexible. Small, easily carried scanners are available; examinations can be performed at the bedside.

On the other hand, the method has some weaknesses. Sonographic devices have trouble penetrating bone. For example, sonography of the adult brain is

very limited though improvements are being made in transcranial ultrasonography. Sonography performs very poorly when there is a gas between the transducer and the organ of interest, due to the extreme large reflection. For example, overlying gas in the gastrointestinal tract often makes ultrasound scanning of the pancreas difficult, and lung imaging is not possible (apart from demarcating pleural effusions). Even in the absence of bone or air, the depth penetration of ultrasound may be limited depending on the ultrasound frequency. Consequently, there might be difficulties imaging structures deep in the body, especially in obese patients. The method is operator-dependent. A high level of skill and experience is needed to acquire good-quality images and make accurate diagnoses. There is no scout image as there is with computer tomography and magnetic resonance imaging. Once an image has been acquired there is no exact way to tell which part of the body was imaged.

**Questions:**

1. What are the sound waves? What determines the sound velocity?
2. Which physical characteristics determine physiological sound characteristics?
3. What is a threshold of hearing? What does it depend on?
4. Formulate the Weber-Fechner Law. What is the relation between the intensity level and the loudness? What are units for intensity level and loudness?
5. What is acoustic impedance? What the reflection coefficient on the interface depends on?
6. Write the absorption law for acoustic waves in medium.
7. Describe ultrasound production and registration methods. Explain physical basics for the methods.
8. What is the essence of ultrasound diagnostics methods?
9. Why different frequencies are used for ultrasound diagnostics of different organs?

## **Chapter 8. PROPERTIES OF LIQUIDS. SURFACE FENOMENA**

### **8.1. SURFACE TENSION**

Surface tension is a tendency of liquids to reduce their exposed surface to the smallest possible area. A drop of water, for example, tends to assume the shape of a sphere. The phenomenon is attributed to cohesion, the attractive forces acting between the molecules of the liquid. The molecules within the liquid are attracted equally from all sides, but those near the surface experience unequal attractions and thus are drawn toward the center of the liquid mass by this net force (fig. 8.1). The tension force acting in the surface of a liquid tends to minimize the area of the surface. These centrally directed tension forces cause the droplet to assume a spherical shape, thereby minimizing both the free energy and surface area. As a result, the surface of the liquid tends to keep its smallest possible area, for the given volume. Water droplets tend to be spherical because the sphere has the smallest surface area for its volume.

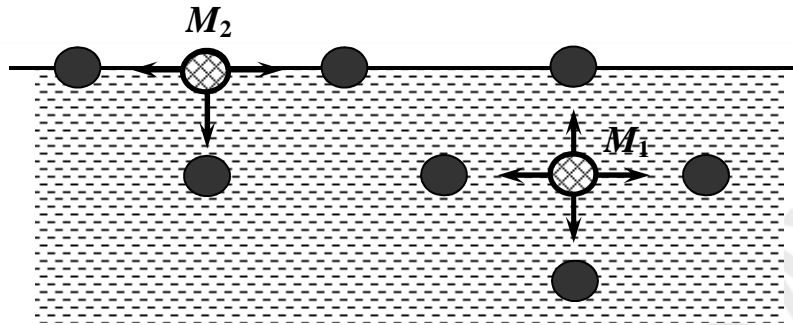


Fig. 8.1. In the body of a liquid, the time-averaged force exerted on any given molecule  $M_1$  by its neighbors is zero. In the surface of a liquid ( $M_2$ ), the situation is quite different; beyond the free surface, there exist no molecules to counteract the forces of attraction exerted by molecules in the interior for molecules in the surface

Surface tension, represented by the symbol  $\sigma$ , is defined as the tension force  $F$  along a line of unit length  $l$ , where the force is parallel to the surface but perpendicular to the line:

$$\sigma = \frac{F}{l}. \quad (8.1)$$

The surface tension is therefore measured in N/m.

An equivalent definition of the surface tension is work done per unit area.

$$\sigma = \frac{A}{S}. \quad (8.2)$$

As such, in order to increase the surface area of a mass of liquid by an amount,  $\Delta S$ , a quantity of work,  $A = \sigma \Delta S$ , is needed. This work  $A$  is stored as potential energy  $W_s$ . The total tension potential energy is given by the surface tension times the surface area,

$$W_s = \sigma S,$$

so it is minimum for the smallest surface area (since mechanical systems try to find a state of minimum potential energy), hence a droplet of water tends to take a spherical shape, which has the minimum surface area for a given volume. Consequently surface tension can be also measured in SI system as joules per square meter ( $J/m^2$ ).

For water at 20 °C,  $\sigma = 0,073$  N/m, while at 100 °C,  $\sigma = 0,059$  N/m, as increasing temperature decreases the surface tension (the attractive force between water molecules). Soapy water has a surface tension reduced by a factor of 4 or 5. Water itself is a pretty power solvent, so it can dissolve most sources of dirt. The fluid in our lung has a similar surface tension, of 0,05 N/m, a bit too large to allow the lungs to expand freely. In fact the lungs secretes a substance that can reduce the surface tension of that liquid by a factor of 10 when the lungs are fully expanded. Table 8.1 shows the surface tension of various liquids.

Table 8.1

Liquid	Temperature, °C	Surface tension, $\sigma$ , N/m
Water	0	0,0756
Water	20	0,0725
Water	100	0,0589
Ethanol	20	0,0223
Mercury	20	0,47
Milk	20	0,050
Urine	20	0,066

Measurement of surface tension is important for diagnosis. For example, the surface tension of urine in normal state is 66 mN/m and in disease state is 56 mN/m.

### 8.2. PHENOMENON OF THE WETTING AND NONWETTING OF SOLIDS BY LIQUIDS

Surface forces, or more generally, interfacial forces, govern such phenomena as the wetting or nonwetting of solids by liquids, the capillary rise of liquids in fine tubes and wicks, and the curvature of free-liquid surfaces.

The surface of a liquid at contact with the surface of a solid makes an angle. Measured between the tangent to the liquid surface at the point of contact with the solid surface and the solid surface, the angle is called contact (wetting) angle,  $\theta$ , theta. The fig. 8.2 shows phenomena of the wetting and nonwetting of solids by liquids.

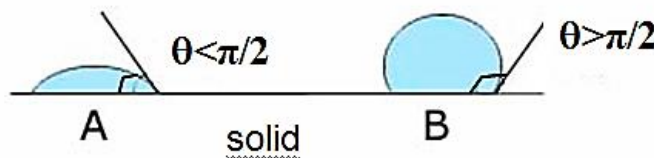


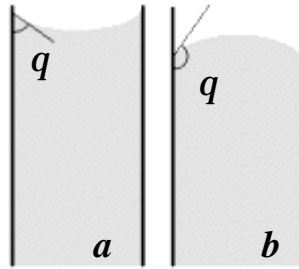
Fig. 8.2. Phenomena of the wetting (A) and nonwetting (B) of solids by liquids

If  $\theta < 90$  degrees, like for water and glass, the cohesive force (the attractive force between the molecules of the liquid, so the surface tension) is weaker than the adhesive force (between the liquid and the solid surface). In this case the liquid is said to «wet» the surface of the solid. Vice-versa if  $\theta > 90$  degrees, like between mercury and glass (mercury has  $\sigma = 0,465$  N/m, almost 7 times larger than water) the cohesive force is larger than the adhesive force. Let's consider a droplet on the surface of some material. If the cohesive force is dominant over the adhesive force, the droplet can be close to spherical, and does not «wet» the surface of the solid. Water-proof or water-repellent materials are such that the adhesive force is very small, so water beads up and does not easily penetrate the material. On the contrary, detergent reduces the cohesive force (the surface tension), and the water can more easily penetrate the material.



Surfaces which are wetting by liquids are called hydrophilic surfaces and surfaces which are nonwetting by liquids are called hydrophobic ones.

If a liquid is in a container, then besides the liquid/air interface at its top surface, there is also an interface between the liquid and the walls of the container. The surface tension between the liquid and air is usually different (greater than) its surface tension with the walls of a container. And where the two surfaces meet, their geometry must be such that all forces balance.

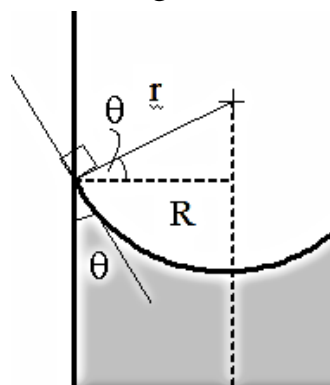


*Fig. 8.3.* The contact angle  $\theta$  of liquid in a vertical tube:  
 $a$  — phenomena of the wetting;  $b$  — phenomena of the nonwetting

Surface tension occurs during a gas-liquid interface, but if that interface comes in contact with a solid surface — such as the walls of a container — the interface usually curves up or down near that surface. Such a concave or convex surface shape is known as a meniscus (fig. 8.3). A convex meniscus occurs when the molecules of the liquid have a stronger attraction to each other than to the container. This may be seen between mercury and glass. Conversely, a concave meniscus occurs when the molecules of the liquid attract those of the container. This can be seen between water and glass.

### 8.3. LAPLACE PRESSURE

In a sufficiently narrow tube of circular cross-section (radius  $R$ ), the interface between liquid and air forms a meniscus that is a portion of the surface of a sphere with radius  $r$  (fig. 8.4).



*Fig. 8.4.* Spherical meniscus with radius of curvature  $r$ ;  $R$  is the capillary radius;  $\theta$  is the wetting angle

The pressure jump across this surface is:

$$\Delta p = \frac{2\sigma}{r}, \quad (8.3)$$

where  $\Delta P$  is so called Laplace pressure;  $\sigma$  is the surface tension;  $r$  is the radius of curvature. The pressure difference  $\Delta P$  is proportional to the surface tension  $\sigma$  and inversely proportional to the effective radius  $r$  of the interface, it also depends on the contact (wetting) angle  $\theta$  of the liquid on the surface of the capillary. Laplace pressure arises from the surface tension of a liquid at its interface with a gas in a solid container. This additional pressure  $\Delta P$  is directed to the center of curvature. Laplace pressure is responsible for water being drawn into a wick or capillary made of a hydrophilic material such as glass; for water rising in a capillary, the pressure is lower below the meniscus (in the water).

In medicine formula for Laplace pressure is used in the context of respiratory physiology, in particular alveoli in the lung, where a single alveolus is modeled as being a perfect sphere. In this context, the pressure differential is a force pushing inwards on the surface of the alveolus. The Law of Laplace states that there is an inverse relationship between surface tension and alveolar radius. It follows from this that a small alveolus will experience a greater inward force than a large alveolus, if their surface tensions are equal. In that case, if both alveoli are connected to the same airway, the small alveolus will be more likely to collapse, expelling its contents into the large alveolus. This explains why the presence of surfactant lining the alveoli is of vital importance. Surfactant reduces the surface tension on all alveoli, but its effect is greater on small alveoli than on large alveoli. Thus, surfactant compensates for the size differences between alveoli, and ensures that smaller alveoli do not collapse.

An embolism — from the Greek *émbolos* meaning «stopper» or «plug» — is the term that describes a condition where an object called an embolus is created in one part of the body, circulates throughout the body, and then blocks blood flowing through a vessel in another part of the body. Emboli (plural of embolus) are not to be confused with thrombi (plural of thrombus), which are clots that are formed and remain in one area of the body without being carried throughout the bloodstream.

#### 8.4. CAPILLARITY

Capillarity or capillary action is rise or fall of liquid in a small passage or tube (fig. 8.5). When a glass tube of small internal diameter is inserted into water, the surface water molecules are attracted to the glass and the water level in the tube rises. The narrower the tube, the higher the water rises.

Capillarity can be explained by considering the effects of two opposing forces: adhesion, the attractive (or repulsive) force between the molecules of the liquid and those of the tube, and cohesion, the attractive force between the molecules of the liquid. Adhesion causes water to wet a glass tube and thus

causes the water's surface to rise near the container's walls until there is a sufficient mass of water for gravitational forces to be equal to the intermolecular forces. The equilibrium condition can also be written as  $\Delta P = \rho gh$ , where  $\Delta P$  is the additional Laplace pressure,  $\rho$  is the liquid density,  $g$  is the gravitational acceleration,  $h$  is the height of liquid raising. Thus the height of liquid raising  $h$  can be calculated as:

$$h = \frac{\Delta p}{\rho g} = \frac{2\sigma}{\rho g R} = \frac{2\sigma \cos \theta}{\rho g r}. \quad (8.4)$$

Connection between the radius of curvature  $r$  and the capillary radius  $R$  has been taken into account in equation (8.4):  $R = r/\cos\theta$ .

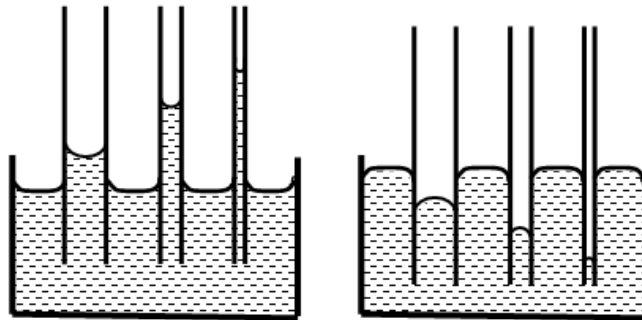


Fig. 8.5. Capillary action is liquid rise for wetting liquid or liquid fall for nonwetting one in a small tube

The contact length (around the edge) between the top of the liquid column and the tube is proportional to the diameter of the tube, while the weight of the liquid column is proportional to the square of the tube's diameter, so a narrow tube will draw a liquid column higher than a wide tube.

Conversely, if a glass tube is inserted into mercury, the level of the liquid in the tube falls. The mercury does not wet the tube and in this case cohesive force dominant over adhesive force, so the column of liquid in equilibrium is below the surrounding level.

Notice that capillary action is what allows plants to grow, as they need to bring up water well above the ground level. It is also what makes absorbent materials like sponges and paper towels absorb so well.

## 8.5. METHODS OF SURFACE TENSION MEASUREMENT

### Pendant drop test

Surface tension can be measured using the pendant drop method. A simple way to form a drop is to allow liquid to flow slowly from the lower end of a vertical tube of small diameter  $d$  (fig. 8.6). The surface tension  $\sigma$  of the liquid causes the liquid to hang from the tube, forming a pendant. When the drop exceeds a certain size it is no longer stable and detaches itself. The falling liquid is also a drop held together by surface tension. The basic premise of the drop

method is that surface tension can be calculated from physical drop characteristics as it forms at the end of a capillary tip of known external radius.

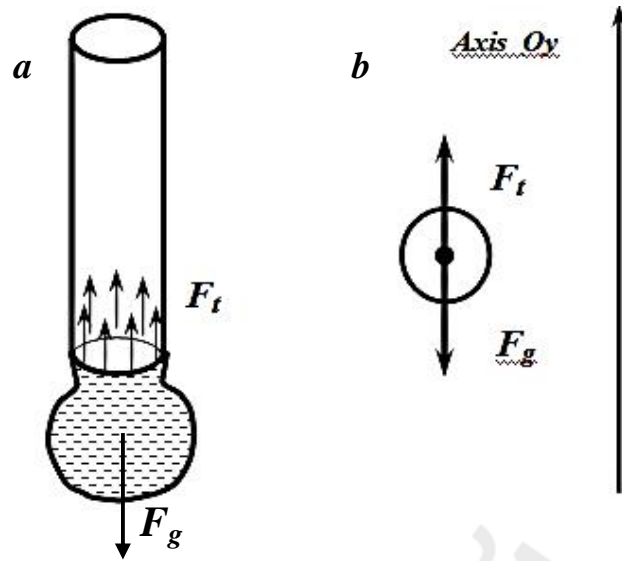


Fig. 8.6. The pendant drop method (a). There are two forces acting on the drop: the tension force ( $F_t = \sigma l$ ) and the force due to gravity ( $F_g = mg$ ) (b)

Thus a drop of liquid is suspended from the end of a tube by surface tension. The force due to surface tension is proportional to the length of the boundary between the liquid and the tube, with the proportionality constant usually denoted  $\sigma$ . Since the length of this boundary is the circumference of the tube, the force due to surface tension is given by:

$$F_t = \sigma l,$$

where  $l = 2\pi r = \pi d$  — is the length of the boundary between the liquid and the tube, where  $d$  is the tube diameter.

When drop hangs from the end of the tube the net force (the force due to gravity ( $F_g = mg$ ) plus the force due to surface tension ( $F_t = \sigma l$ ), acting on drop is equal zero. One can write that:

$$mg = \sigma 2\pi r. \quad (8.5)$$

This relationship is the basis of a convenient method of measuring surface tension. Thus:

$$\sigma = \frac{mg}{2\pi r}. \quad (8.6)$$

### The ring method

The du Noüy ring method is one technique by which the surface tension of a liquid can be measured. The advantage of this method is that the surface tension can be determined directly from the force required to pull the ring from a liquid (fig. 8.7). Surface tension for the ring method is the mechanical force  $F = F_t + mg$  necessary to lift a platinum ring of known wire radius  $R_1$  and ring radius  $R_2$  from the solution surface.

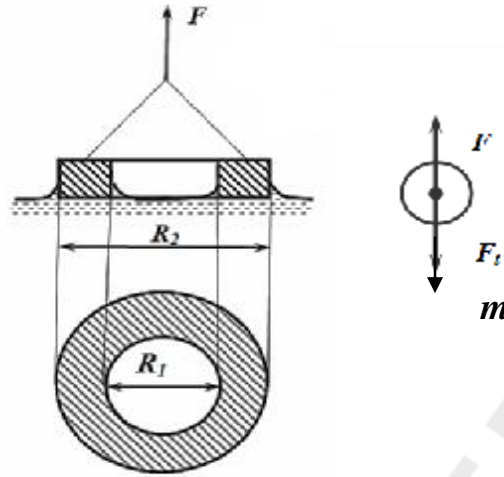


Fig. 8.7. Using the ring method the surface tension can be determined directly from the force ( $F$ ) required to pull the ring from a liquid. Surface tension for the ring method is the mechanical force necessary to lift a platinum ring of known wire radius  $R_1$  and ring radius  $R_2$

The force ( $F$ ) required to raise the ring from the liquid's surface is measured and related to the liquid's surface tension ( $\sigma$ ). The equation describing this process is:

$$\sigma = \frac{F - mg}{l} = \frac{F - mg}{2\pi R_1 + 2\pi R_2}. \quad (8.7)$$

#### Maximum bubble pressure method

The maximum bubble pressure method is based on the maximum pressure in a capillary or a maximum pressure difference between two capillaries of different radii necessary to produce and detach a bubble from the capillary tip immersed in test solution. Maximum bubble pressure measuring apparatus for surface tension is shown in fig. 8.8.

Under pressure  $P_{\text{atm}} - P_1 = \Delta P$  a bubble from the capillary tip immersed in test solution is produced. The pressure drop  $\Delta P$  was created in the system by opening a tap is measured by the manometer. Thus,  $\Delta P = \rho gh$ . Laplace pressure arising from the surface tension of a liquid is equal:

$$\Delta p = \frac{2\sigma}{r}.$$

Thus, one can write:

$$\rho gh = \frac{2\sigma}{r}. \quad (8.8)$$

The same procedure can carry out with etalon liquid, for example distilled water, and obtain

$$\rho gh_0 = \frac{2\sigma_0}{r} \quad (8.8a)$$

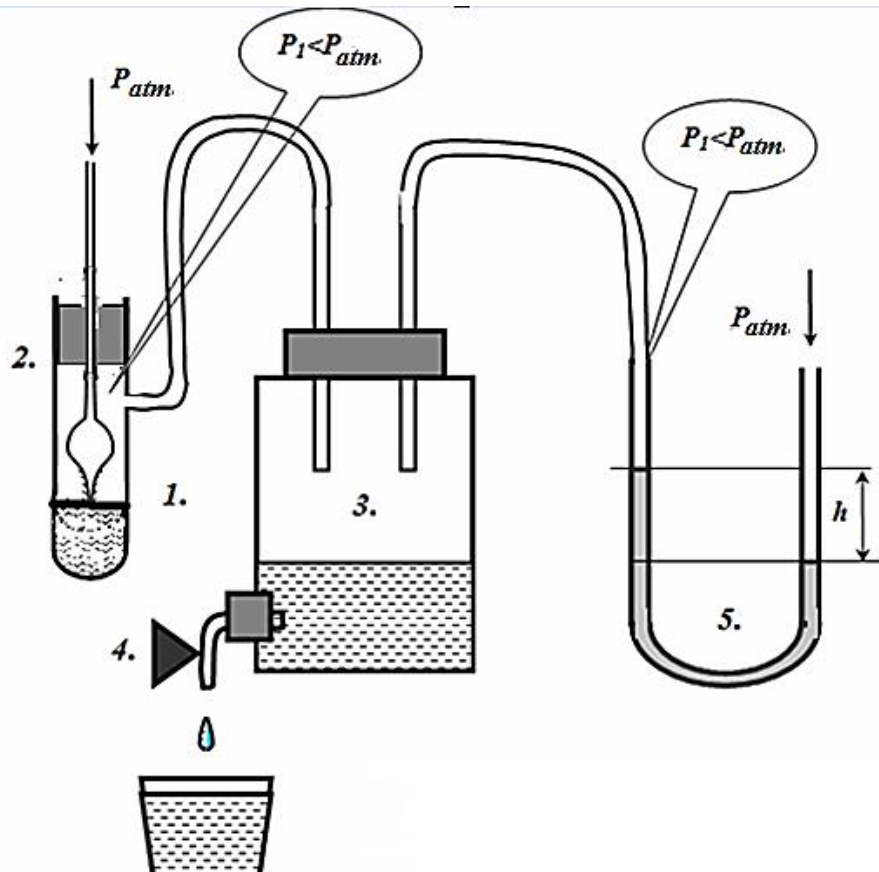


Fig. 8.8. Maximum bubble pressure measuring apparatus for surface tension:  
 1 — is the tube containing liquid under investigation; 2 — is the capillary tip immersed in test liquid; 3 — is the corked jar containing water; 4 — is the tap; 5 — is the manometer

The attitude of these two equations (8.7) and (8.7a) is equal:

$$\frac{h}{h_0} = \frac{\sigma}{\sigma_0}$$

Thus equation for surface tension of test liquid is obtained:

$$\sigma = \sigma_0 \frac{h}{h_0} \quad (8.9)$$

**Questions:**

1. What is the reason of surface tension energy? What the surface energy depends on?
2. What is the physical meaning of surface tension coefficient? What it depends on? What are its units?
3. Give the definition of surface tension forces. What are the units of surface tension forces?
4. Write Laplace formula for an additional pressure under curved surface.
5. Explain the wetting and nonwetting phenomena. What is the contact (wetting) angle?
6. How to calculate the height of liquid raising in capillary?
7. What is the embolism? What are the conditions of its appearance?
8. Describe the surface tension coefficient determination methods.

## Chapter 9. BIOPHYSICAL PRINCIPLES OF BIORHEOLOGY AND HEMODYNAMICS

### 9.1. CONTINUITY EQUATION

Continuity equation represents the law of conservation of mass. Consider fluid flowing through a tube consisting of two segments with cross-sectional areas  $S_1$  and  $S_2$ . The volume of incompressible fluid flowing per the same time through any point in the tube is constant. It is given by the formula:

$$S_1 \cdot v_1 \cdot t = S_2 \cdot v_2 \cdot t,$$

where  $S_1$  and  $S_2$  are cross-sectional areas,  $v_1$  and  $v_2$  are velocities for different cross-sections.

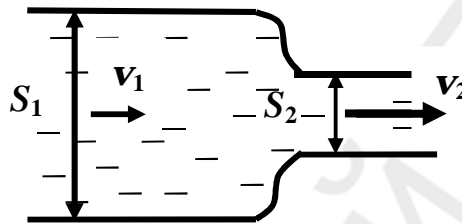


Fig. 9.1. Continuity equation

On the basis of this formula, the **continuity equation** can be written:

$$S_1 \cdot v_1 = S_2 \cdot v_2 \text{ or } S \cdot v = \text{const.} \quad (9.1)$$

It states that the product of the area and the fluid velocity at all points along the tube is a constant for an incompressible fluid.

Two different characteristics commonly are used as measures of fluid flow: volumetric flow rate and linear average velocity. **Linear average velocity**  $v$  is the way what particle passes per unit time:

$$v = \frac{L}{t}. \quad (9.2)$$

Linear velocity is measured in m/s.

**Volumetric flow rate**  $Q$  is one of the most widely used characteristic for liquids.  $Q$  is determined as the volume of flow per unit time:

$$Q = \frac{V}{t}. \quad (9.3)$$

Volumetric flow rate is measured in  $\text{m}^3/\text{s}$ ,  $\text{l/s}$ .

For flow of fluids in pipes the velocity will not be constant over the cross-sectional area of flow, yet some measure of the fluid velocity is often of interest. The linear average velocity  $v$  is defined to be the volumetric flow rate  $Q$  divided by the cross-sectional area of flow:

$$v = \frac{Q}{S}. \quad (9.4)$$

It is another statement for continuity equation for hemodynamics: in any cross-section of the cardiovascular system, the volumetric flow rate is

the constant:  $Q = \text{const}$ . It means more narrow the vessel, the faster the velocity of flow is (fig. 9.2).

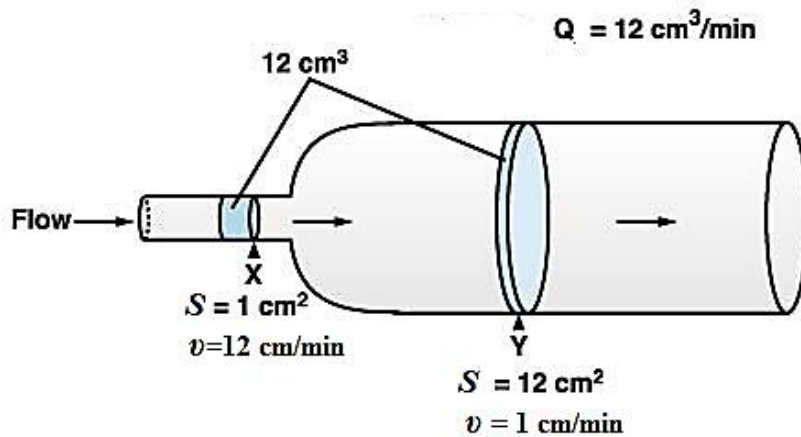


Fig. 9.2. Volumetric flow rate in different parts of the tube

The same is observed in the cardiovascular system: the greater the total vascular cross-sectional area, the lower the velocity. Volumetric flow rate, however, remains constant (fig. 9.3).

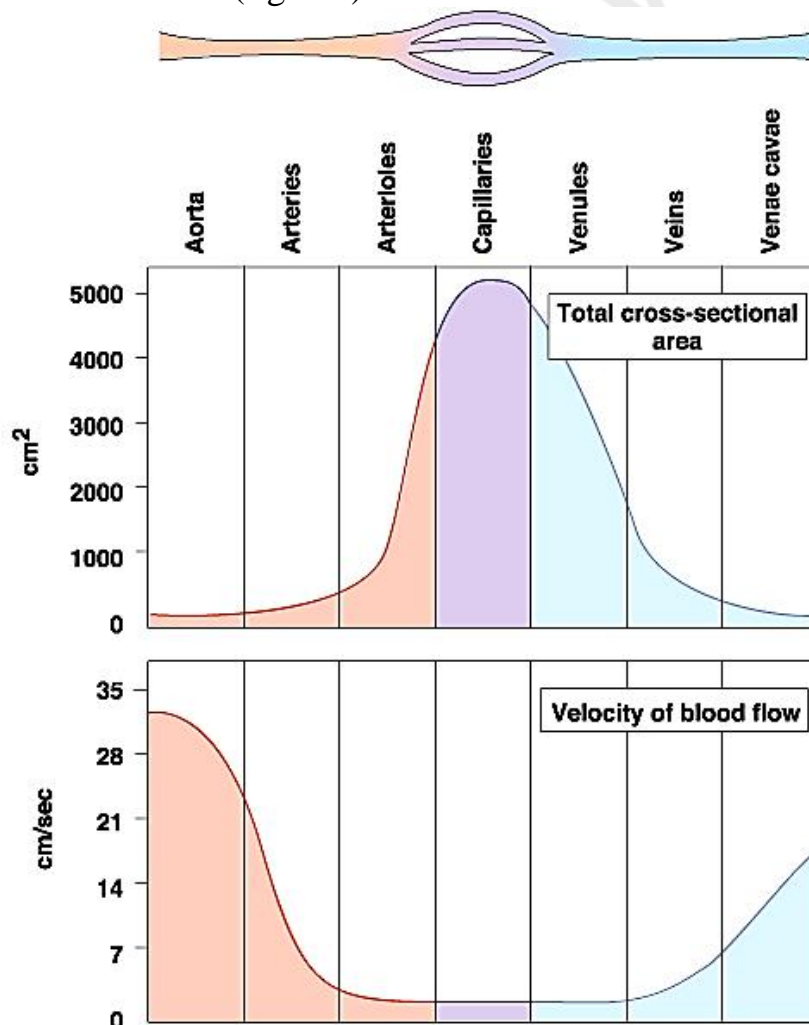


Fig. 9.3. Volumetric flow rate equality in different parts of the cardiovascular system



## 9.2. BERNOULLI'S EQUATION

**Bernoulli's equation** is one of the most important and useful equations in hemodynamics. This equation gives the relationship between velocity, pressure and elevation in a streamline. Bernoulli's equation has some restrictions in its applicability, they are: friction losses are negligible; the fluid is incompressible; the fluid flow is laminar and steady state.

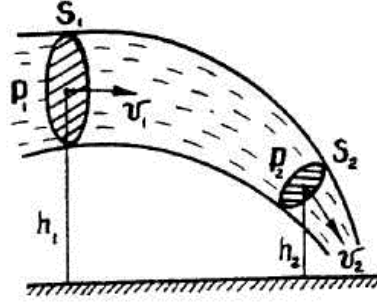


Fig. 9.4. For Bernoulli's equation derivation

Let's consider incompressible liquid into the smooth tube (fig. 9.4). Two cross-sections with area  $S_1$  and  $S_2$  are selected. The centers of cross-sections are located on heights  $h_1$  and  $h_2$ , linear velocities are  $v_1$  and  $v_2$ , pressures in fluid are  $P_1$  and  $P_2$  correspondingly. Total energy of fluid in every cross-section is the same, it can be written as:

$$\frac{mv_1^2}{2} + P_1V + mgh_1 = \frac{mv_2^2}{2} + P_2V + mgh_2, \quad (9.5)$$

where  $\frac{mv^2}{2}$  is the kinetic energy of fluid,  $PV$  is the fluid potential energy, which is defined by the liquid pressure,  $mgh$  is the potential energy, provided by the location of the liquid at a height  $h$ .

The energy of a moving fluid is more useful in applications when it is expressed as the energy per unit of volume:

$$\frac{\rho v_1^2}{2} + \rho gh_1 + P_1 = \frac{\rho v_2^2}{2} + \rho gh_2 + P_2, \quad (9.6)$$

where  $\rho$  is the fluid density,  $v$  is the fluid velocity,  $g$  is the acceleration of gravity,  $h$  is the height above a reference surface.

In this formula  $\frac{\rho v^2}{2}$  is a **dynamic pressure**,  $\rho gh$  is a **hydrostatic pressure**,  $P$  is a **static pressure** in the fluid.

If the elevation of the fluid remains constant, or if the change in elevation is small enough to not change the gravitational potential energy of the fluid appreciably, then the potential energy term can be ignored:

$$\frac{\rho v_1^2}{2} + P_1 = \frac{\rho v_2^2}{2} + P_2. \quad (9.7)$$

This expression specifies that, in laminar flow, the sum of the pressures has the same value at all points along a streamline.

In a person with advanced arteriosclerosis, the Bernoulli effect produces a symptom called *vascular flutter*. In this situation, the artery is constricted as a result of accumulated plaque on its inner walls. To maintain a constant flow rate, the blood must travel faster than normal through the constriction. If the blood speed is sufficiently high in the constricted region, the artery may collapse under external pressure, causing a momentary interruption in blood flow. At this moment, there is no Bernoulli effect, and the vessel reopens under arterial pressure. As the blood rushes through the constricted artery, the internal pressure drops and again the artery closes. Such variations can be heard with a stethoscope. If the plaque becomes dislodged and ends up in a smaller vessel that delivers blood to the heart, the person can suffer a heart attack (fig. 9.5).

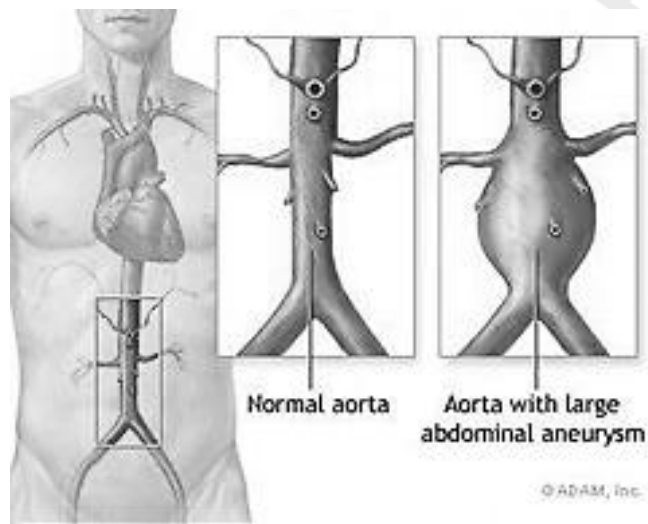


Fig. 9.5. Normal aorta and aorta with aneurysm

An *aneurysm* is caused by the weakening of the arterial wall where a bulge occurs and the cross-section of a vessel increases considerably. An analysis as before will show that the flow velocity  $v$  will be reduced at the cross-section of an aneurysm and the pressure  $P$  will increase. The higher pressure may cause further expansion of the cross-section, which can lead to the bursting of the vessel at that site.

### 9.3. FLUID VISCOSITY

Informally, viscosity is the quantity that describes a fluid's resistance to flow. Fluids resist the relative motion of immersed objects through them as well as to the motion of layers with different velocities within them.

Formally, *viscosity* (represented by the symbol  $\eta$  «eta») is the ratio of the shearing stress ( $F/S$ , where  $F$  is a shearing force,  $S$  is contact area between the liquid layers) to the velocity gradient or shear rate  $dv/dx$  in fluid. The more usual form of this relationship, called *Newton's equation*, states that

the resulting shear of a fluid is directly proportional to the force applied and inversely proportional to its viscosity:

$$\frac{F}{S} = \eta \frac{dv}{dx} \quad (9.8)$$

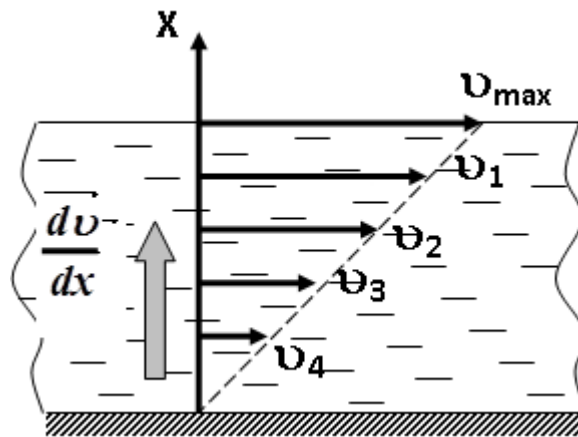


Fig. 9.6. The velocity gradient in fluid

Consider the experiment shown in fig 9.6. The top plate is moved with constant velocity  $v$  by the action of shearing force  $F$ , and the bottom plate is kept in place (velocity is zero). The result is that the different layers of the fluid move with different velocities. The difference in velocity in the different fluid layers causes a shearing action (friction) between them. The rate of shear  $\gamma$  is the relative displacement of one fluid layer with respect to the next. In general, the shear rate is the slope of the velocity profile as shown in fig 9.4. The units of shear rate (velocity gradient) are  $1/s$ .

The units of viscosity are  $Pa \cdot s = Ns/m^2$  or *Poise*. Ten poise are equal to one pascal second [ $Pa \cdot s$ ]:  $10 P = 1 Pa \cdot s$ , making the centipoise [ $cP$ ] and millipascal second [ $mPa \cdot s$ ] identical.

Fluids with a straight relationship between shear stress and shear rate are called **Newtonian fluids**, i. e., viscosity does not depend on shear stress or shear rate. Viscosity is sometimes called dynamic viscosity in contrast to the kinematic viscosity, which is defined as viscosity divided by density  $\eta/\rho$ . Water and plasma are Newtonian fluids.

**Non-Newtonian fluids** flow properties differ from those of Newtonian fluids. Most commonly the viscosity of non-Newtonian fluids is dependent on shear rate. Blood as are many commonly found substances such as ketchup, toothpaste, paint, and shampoo are non-Newtonian fluids.

#### 9.4. POISEUILLE'S EQUATION

Let's consider that viscous liquid laminar flows through smooth tube with length  $L$  and radius  $r$  (fig. 9.7). Its volume depends on the fluid flow time  $t$ ,

the pressure drop  $\Delta P$ , the radius  $r$ , and inversely depends on the length  $L$  and the viscosity  $\eta$ . It can be written as formula:

$$V = \frac{\pi r^4 (P_1 - P_2)}{8\eta L} t. \quad (9.9)$$

Dividing both parts of the equation by  $t$ , one can obtain **Poiseuille's equation**:

$$Q = \frac{\pi r^4 (P_1 - P_2)}{8\eta L}, \quad (9.9a)$$

where  $Q$  is the volumetric flow rate.

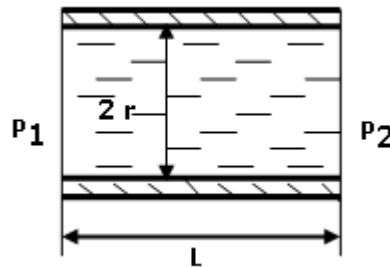


Fig. 9.7. Poiseuille's equation

The assumptions of the equation are that the flow is laminar viscous and incompressible and the flow is through a constant circular cross-section that is significantly longer than its diameter.

The Poiseuille's equation is also can be written in a simpler form as the **Hagen–Poiseuille Law**:

$$Q = \frac{P_1 - P_2}{X}.$$

The value  $X$  in this formula is the **hydrodynamic resistance** is:

$$X = \frac{8\eta L}{\pi r^4}. \quad (9.10)$$

Poiseuille's Law corresponds to Ohm's law for electrical circuits ( $I = \frac{V}{R}$ ), where the pressure drop  $\Delta P$  is analogous to the difference of potentials  $\Delta\phi$  and volumetric flow rate  $Q = \frac{V}{t}$  is analogous to the current  $I = \frac{q}{t}$ . This similarity is represented in table 9.1:

Table 9.1

Type	Hydraulic	Electric
Quantity	Volume $V$ [m <sup>3</sup> ]	Charge $q$ [C]
Potential	Pressure $p$ [Pa = J/m <sup>3</sup> ]	Potential $\phi$ [V = J/C]
Flux	Current $Q$ [m <sup>3</sup> /s]	Current $I$ [A = C/s]
Flux density	Velocity $v$ [m/s]	Current density $j$ [C/(m <sup>2</sup> ·s) = A/m <sup>2</sup> ]

Just as electric resistance, the general flow resistance of concatenated blood vessels is equal to the amount of the resistance of these vessels.

$$X_{gen} = X_1 + X_2 + \dots + X_n. \quad (9.11)$$

In case of parallel connection (arterioles, capillaries, veins) the general flow resistance decreases:

$$\frac{1}{X_{gen}} = \frac{1}{X_1} + \frac{1}{X_2} + \dots + \frac{1}{X_n}. \quad (9.12)$$

That is why, for instance, arterioles are of the greatest resistance: the influence of small radius (the first reason of resistance increase) predominates over the influence of parallel arterioles in the cardiovascular systems.

As the resistance of the vessels also depends on the blood viscosity, which increases toward the walls of blood vessels, the value of blood resistance will depend on the general area of blood vessels. For example, in the arterioles the blood flow rate (the third reason) is high — just a little bit less than the blood flow rate in the aorta — whereas the general area of the internal walls of the arterioles results in the increased blood resistance.

## 9.5. METHODS OF VISCOSITY MEASUREMENT

A **viscometer** (also called *viscosimeter*) is an instrument used to measure the viscosity of a fluid.

### 9.5.1. Falling sphere viscometers

Stokes' Law is the basis of the falling sphere viscometer, in which the fluid is stationary in a vertical glass tube (fig. 9.6). This law is an expression for the frictional (drag) force exerted on spherical objects:

$$F_d = 6\pi\eta r v, \quad (9.13)$$

where  $F_d$  is the drag force of the fluid on a sphere,  $\eta$  is the fluid viscosity,  $v$  is the velocity of the sphere relative to the fluid, and  $r$  is the radius of the sphere.

A sphere of known size and density is allowed to descend through the liquid.

Fig. 9.8 shows three forces acting on the sphere;  $F_b$ ,  $F_d$ , and  $mg$ . The first two forces arise from the buoyancy effect of displacing the fluid in question, and from the viscous drag of the fluid on the sphere, respectively. Both forces act upwards — buoyancy tending to « float » the sphere  $F_b$  and the drag force  $F_d$  resisting the acceleration of gravity. The only force acting downwards is the body force resulting from gravitational attraction  $mg$ . By summing forces in the vertical direction one can write the following equation (at uniform falling of sphere):

$$F_b + F_d = mg.$$

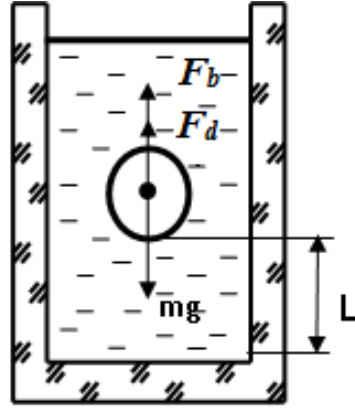


Fig. 9.8. Falling sphere viscometer

The buoyancy force is simply the weight of displaced fluid. The volume of a sphere ( $V_s$ ) is:

$$V_s = \frac{4}{3}\pi r^3.$$

Combining this volume with the mass density of the fluid,  $\rho_{fl}$ , one can now write the buoyancy force as the product:

$$F_b = \frac{4}{3}\pi r^3 \rho_{fl} g,$$

where  $g$  is the gravitational acceleration and  $r$  is the radius of the sphere. Combining all of the previous relationships that describe the forces acting on the sphere in a fluid the following expression is obtained:

$$\frac{4}{3}\pi r^3 \rho_{fl} g + 6\pi\eta r v = mg. \quad (9.14)$$

If correctly selected, it reaches terminal velocity, which can be measured by the time it takes to pass two marks on the tube. Knowing the terminal velocity  $v$ , the radius  $r$  and density of the sphere  $\rho_s$ , and the density of the liquid  $\rho_{fl}$ , formula (9.14) can be used to calculate the viscosity of the fluid:

$$\eta = 2(\rho_s - \rho_{fl})r^2 g / 9v, \quad (9.15)$$

where  $v$  is the sphere's settling velocity (m/s) (vertically downwards as  $\rho_s > \rho_{fl}$ ),  $r$  is the Stokes radius of the particle (m),  $g$  is the gravitational acceleration ( $m/s^2$ ),  $\rho_s$  is the density of the sphere ( $kg/m^3$ ),  $\rho_{fl}$  is the density of the fluid ( $kg/m^3$ ), and  $\eta$  is the (dynamic) fluid viscosity (Pa s).

### 9.5.2. U-tube viscometers

These devices also are known as glass capillary viscometers or *Ostwald viscometers*, named after Wilhelm Ostwald. Ostwald viscometers measure the viscosity of a fluid with a known density. In one arm of the U-tube is a vertical section of precise narrow bore (the capillary) (fig. 9.9). Above this is a bulb, with its reservoir lower down on the other arm. In use, liquid is drawn into the upper bulb by suction, and then allowed to flow down through

the capillary. Two marks (one above and one below the upper bulb) indicate a known volume  $V$ .

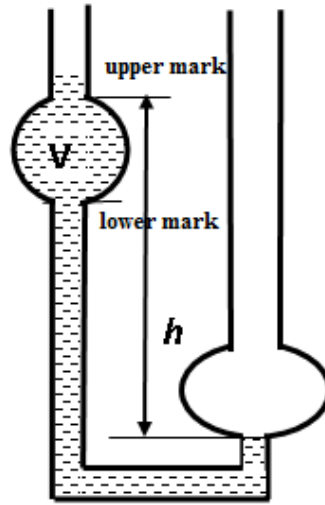


Fig. 9.9. U-tube viscometer

For test liquid (water) this volume can be expressed as:

$$V = \frac{\pi r^4 \rho_0 g h}{8 \eta_0 L} t_0. \quad (9.16)$$

For liquid under investigation there will be *the same* volume ( $V = V$ ), which can be written as:

$$V = \frac{\pi r^4 \rho g h}{8 \eta L} t. \quad (9.17)$$

Thus in order to determine the viscosity of liquid under investigation it's necessary to measure time required for test liquid  $t_0$  and for liquid under investigation  $t$  to flow through this volume. Set equal to right of expressions (9.16) and (9.17), one can get the formula for determining the viscosity of tested liquid:

$$\eta = \eta_0 \frac{\rho t}{\rho_0 t_0}, \quad (9.18)$$

where  $\rho$  and  $\rho_0$  are the densities of investigated and test liquids correspondently.

### 9.5.3. Rotational viscometers

The main feature of this method is that it gives possibility to find the viscosity dependence on gradient velocity:  $\eta = f(dv/dx)$ . It is very important for non-Newtonian fluids particularly for blood.

There are a variety of rotational viscometers. Consider the principle of action of one of them. It consists of two cylinders with a common axis of rotation (fig. 9.10). The inner cylinder is suspended by a thread, and the external can be rotated about its longitudinal axis with adjustable angular velocity  $\omega$ . The gap between the cylinders is filled with the test non-Newtonian liquid, such

as blood. Due to the viscosity of the fluid the inner cylinder begins to rotate and reaches equilibrium at particular angle of rotation  $\theta$ . This angle can be easily measured. The higher the viscosity of the fluid  $\eta$  and the angular velocity  $\omega$ , the greater the angle of rotation:

$$\theta = k \eta \omega,$$

where  $k$  is instrumental constant.

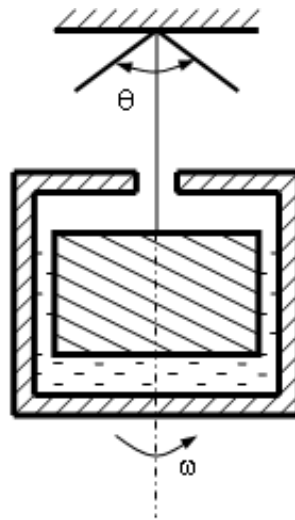


Fig. 9.10. Rotational viscometer

## 9.6. FACTORS AFFECTING BLOOD VISCOSITY

Blood consists of plasma and cellular elements, such as the red blood cells, white blood cells, platelets. The viscosity of whole blood in normal state is 4–5 mPa·s and in disease state is 1,7–22,9 mPa·s. The viscosity of blood thus depends on the number of factors.

Viscosity is strongly dependent on **temperature**. As the temperature of the fluid increases its viscosity decreases. A increase of 1 °C in temperature yields a 2 % decrease in viscosity. Thus in a cold foot blood viscosity is much higher than in the brain. Nevertheless temperature dependence of viscosity has complicated character. The temperature change may course change of platelet aggregation extent, some change in blood structure.

Thus the viscosity of blood depends on the viscosity of the plasma, in combination with the **hematocrit (Ht)**. The hematocrit is the percentage by volume of red blood cells in a given sample of whole blood. For example, an hematocrit of 25 % means that there are 25 milliliters of red blood cells in 100 milliliters of blood. Normal results of hematocrit vary, but in general are as follows:

- Male: 40,7–50,3 %;
- Female: 36,1 – 44,3 %.

Higher hematocrit implies higher viscosity. The relation between hematocrit and viscosity is complex (fig. 9.11).



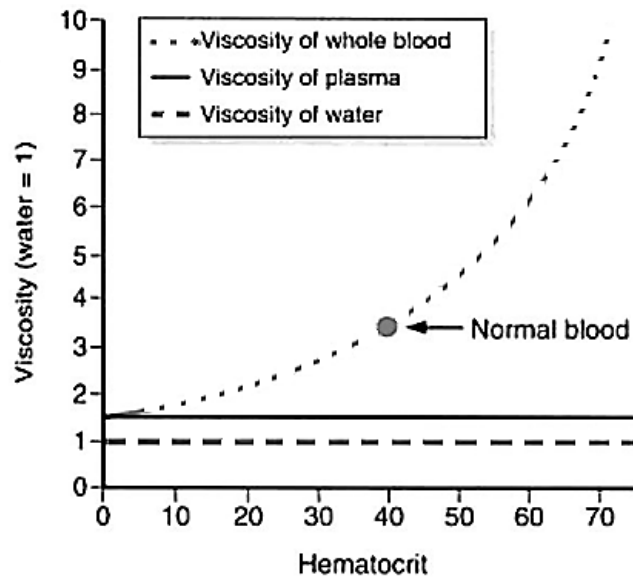


Fig. 9.11. Dependence blood viscosity on the hematocrit

The viscosity of blood depends on its **velocity gradient**. More exactly formulated, when velocity gradient (shear rate) increases viscosity decreases. In large and medium size arteries shear rates are higher than  $100 \text{ s}^{-1}$ , so viscosity is practically constant. For extremely low shear rates formation of red blood cells aggregates may occur, thereby increasing viscosity to very high values (fig. 9.12).

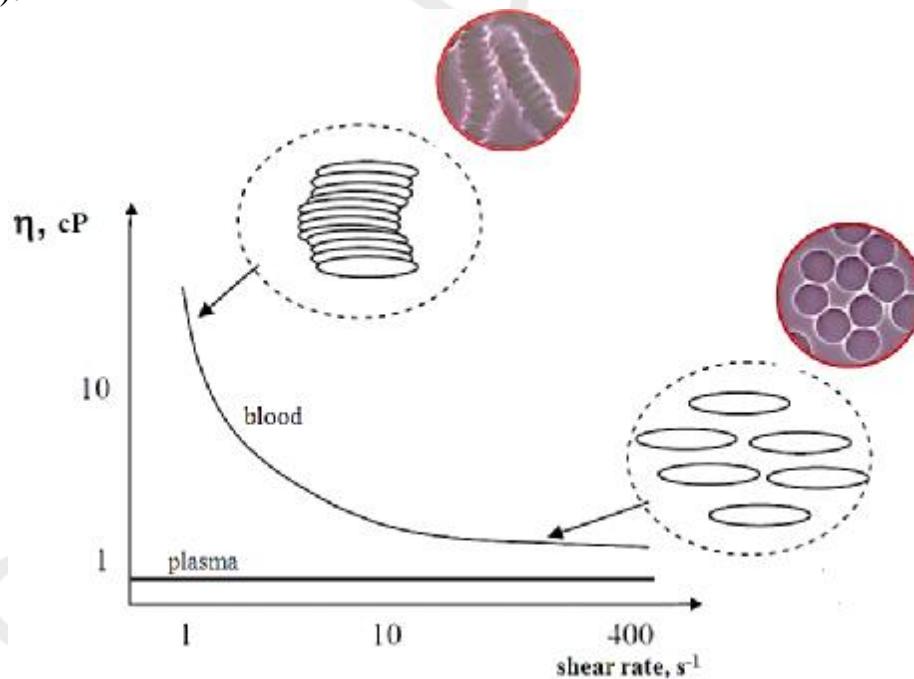


Fig. 9.12. Dependence blood viscosity on shear rate

The viscosity of blood depends on **orientation** of red blood cells in the direction of the flow. For Newtonian liquid the maximum velocity is found on the center of the vessel's cross-section (fig. 9.13, a).

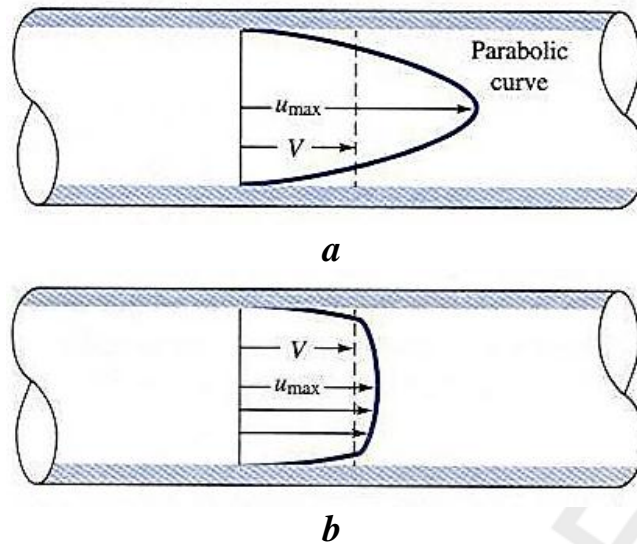


Fig. 9.13. Velocity profile for Newtonian liquid (a) and for blood (b)

For the blood moving through the vessels, the velocity profile has a more flat shape (fig. 9.13, b).

### 9.7. LAMINAR AND TURBULENT FLOW, REYNOLDS NUMBER

At *laminar flow* one layer of fluid moves past another with no transfer of matter from one to another. *Turbulent flow* is type of fluid flow in which the fluid undergoes irregular fluctuations, or mixing (fig. 9.14).

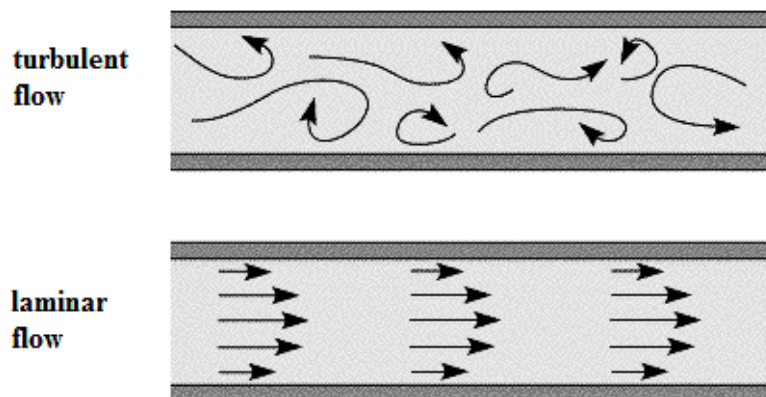


Fig. 9.14. Laminar and turbulent flow

The Reynolds number characterizes whether flow conditions lead to laminar or turbulent flow. The *Reynolds number* is the most important dimensionless number in fluid dynamics providing a criterion for dynamic similarity. It is named after Osborne Reynolds. Typically it is given as follows:

$$Re = \frac{\rho v d}{\eta}, \quad (9.19)$$

where *Re* is the *Reynolds number* and  $\rho$  fluid density, *d* — diameter of the vessel, *v* — mean fluid velocity,  $\eta$  — dynamic fluid viscosity.

Laminar flow within smooth pipes, for example, will occur when the Reynolds number is below the critical Reynolds number of  $Re_{crit, pipe} = 2300$  and turbulent flow will happen when it is above 2300. The Reynolds number depends on the pipe diameter and the mean fluid velocity  $v$  within the pipe. The value of 2300 has been determined experimentally and a certain range around this value is considered the transition region between laminar and turbulent flow.

For blood the critical Reynolds number is varied from 1600 to 900. It should be emphasized that flow in the circulatory system is normally laminar, although flow in the aorta can destabilize briefly during the deceleration phase of late systole; however, this time period is generally too short for flow to become fully turbulent. Turbulent flow may occur in large blood vessels, but the distensible vessel wall and arterial narrowing diminish the disturbances in flow. Certain disease conditions can produce turbulent blood flow, particularly downstream of a vessel narrowing or distal to defective heart valves. Such a flow can damage the vessel wall and contribute to the further progression of a disease.

### 9.8. PULSE WAVE

When the heart ejects blood into the aorta during systole, at first the proximal part of the aorta becomes distended, because aorta is elastic. The walls of large arteries are composed of smooth muscle cells, collagen fibers and elastine fibers. They give to arteries the ability to distend and recoil.

Because of these elastic properties, the arterial system dampens the dramatic pressure changes created when the ventricle ejects blood into the aorta (fig. 9.15). As the aorta close to the heart distend with each ventricular contraction, the reservoir is formed. After that during diastole the aorta near to the heart contracts and pushes blood along the aorta. Large arteries also function as pressure reservoirs; when they are expanded, they store pressure in their walls.

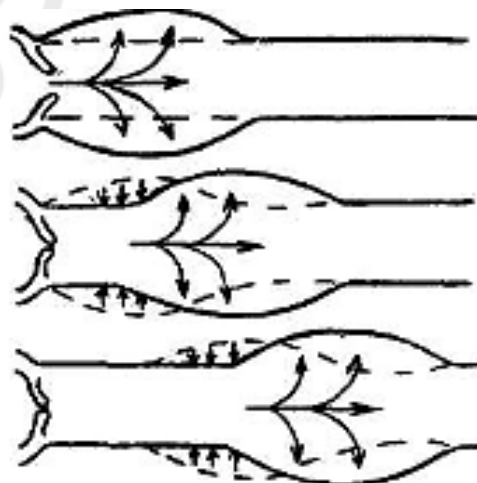


Fig. 9.15. Pulse wave

Then next part of the aorta distends and the wave of distention moves along the aorta. This wave of pressure is called a **pulse wave**. The pulse wave velocity is:

$$v = \sqrt{\frac{E \cdot h}{\rho \cdot d}}, \quad (9.20)$$

where  $E$  is the Young modulus,  $h$  is the vascular wall thickness,  $d$  is the diameter of vessel,  $\rho$  is the blood density.

The more rigid the wall of the artery, the faster the wave moves. The velocity of pulse wave in the aorta is 4 to 6 m/sec; in the artery 8 to 12 m/sec. In general, the greater the compliance of each vascular segment, the slower the velocity.

Let's compare the velocity of the pulse wave and blood velocity in the aorta. The velocity of transmission of the pressure pulse is much larger than the velocity of blood flow. It occurs because the pulse wave is simply a moving wave of pressure.

As the heart beats, the blood pressure rises and falls. The maximum pressure during the cardiac cycle is the **systolic pressure** (fig. 9.16). The lowest blood pressure between the pulses is called the **diastolic pressure**. The **mean pressure** of the pulsating blood at heart level is:

$$P = \frac{\int_0^T P(t) dt}{T}, \quad (9.21)$$

where  $T$  is pressure pulse period, so it is not simple average pressure.

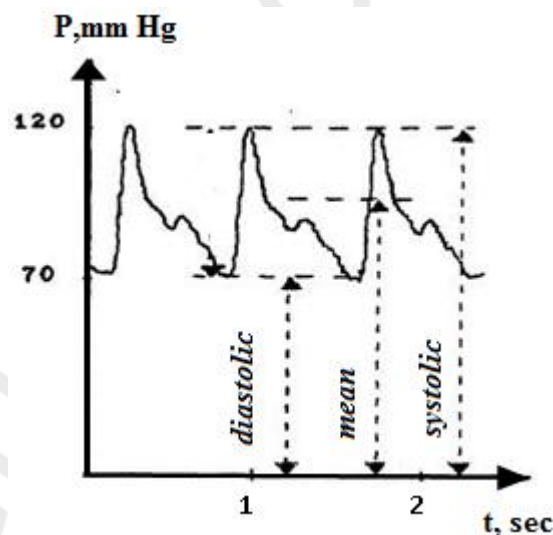


Fig. 9.16. Blood pressure dependence on time

In a young healthy individual the systolic pressure is about 120 mm Hg and the diastolic pressure is about 80 mm Hg. The mean pressure of the pulsating blood at heart level is near 100 mm Hg.

## 9.9. DISTRIBUTION OF BLOOD PRESSURE IN CARDIOVASCULAR SYSTEM

Because the heart pumps blood continually into the aorta, the mean pressure in the aorta is high, averaging about 100 mm Hg. Also, because heart pumping is pulsatile, the arterial pressure alternates between a systolic pressure and a diastolic pressure.

The large arteries elastically recoil and release pressure which propels the blood forward into smaller arteries. Even though the large pressure waves generated by the ventricles are truncated by the distension of the aorta and other large arteries, the pulsatile flow of blood still occurs through smaller arteries and arterioles because of the pulsatile recoil of the larger arteries. Only when the blood reaches the capillaries does the pulsing smooth to a continuous laminar flow (fig. 9.17).

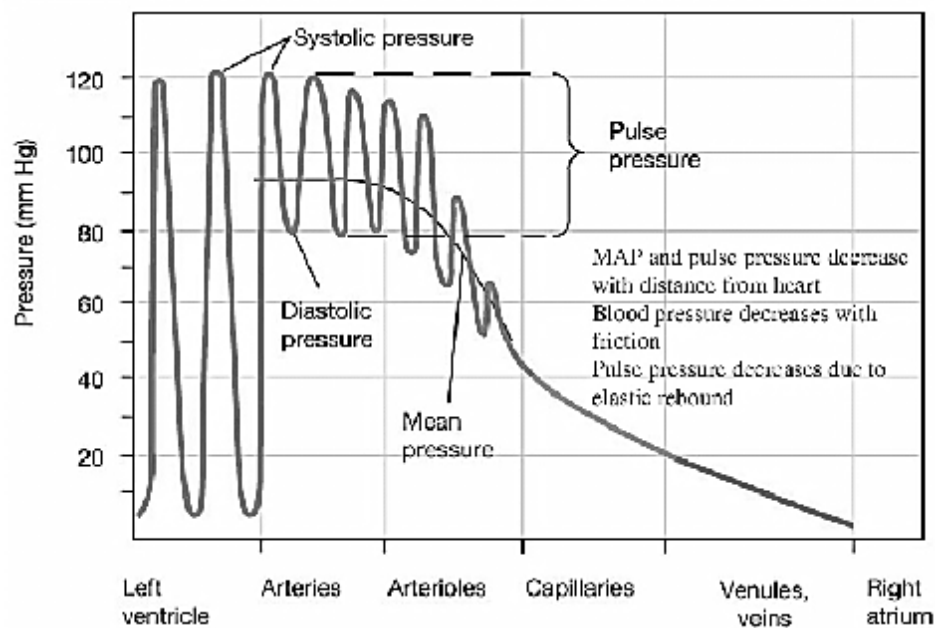


Fig. 9.17. Distribution of blood pressure in cardiovascular system

We define the hydrostatic resistance  $R$  in a segment of the circulatory system as the ratio of pressure difference across the segment to the flow. The smaller the radius of a vessel, the larger the resistance to fluid flow. The main arteries in the body have a relatively large radius. Therefore, the pressure drop along the arteries is small. The size of the arteries decreases, resistance to flow increases. The blood flow in arteries is also reduced; the pressure drop is much larger. The most pressure drop occurs in arterioles.

Immediately following the arterioles are the capillaries. Though the radii of the capillaries are very small, the network of capillaries have the largest surface area in the vascular network. They are known to have the largest surface area in the human vascular network. The larger the total cross-sectional area, the lower the mean velocity as well as the pressure. The pressure in the capillaries is low enough for nutrients can diffuse easily through pores of the capillary walls to

the tissue cells. In the capillaries the average blood pressure is only about 30 mm Hg.

The pressure drops still lower in the veins. The mean pressure falls below 0 mm Hg by the time it reaches veins what empty into the right atrium of the heart.

Since the pressure drop in the main arteries is small, when the body is horizontal, the average arterial pressure is approximately constant throughout the body. If a person is standing erect, the blood pressure in the arteries is not uniform in the various parts of the body. The weigh of the blood affects on the pressure at various locations.

### 9.10. BLOOD PRESSURE MEASUREMENT

The arterial blood pressure is an important indicator of the health of an individual. It almost always is measured in millimeters of mercury (mm Hg). Blood pressure can be measured most directly by inserting a vertical glass tube into an artery and observing the height to which the blood rises but this method is obviously not satisfactory for routine clinical examination.

**Auscultatory method** — is routine method for determining systolic and diastolic arterial pressures. A stethoscope is placed over the artery and a blood pressure cuff is inflated around the upper arm (fig. 9.18).

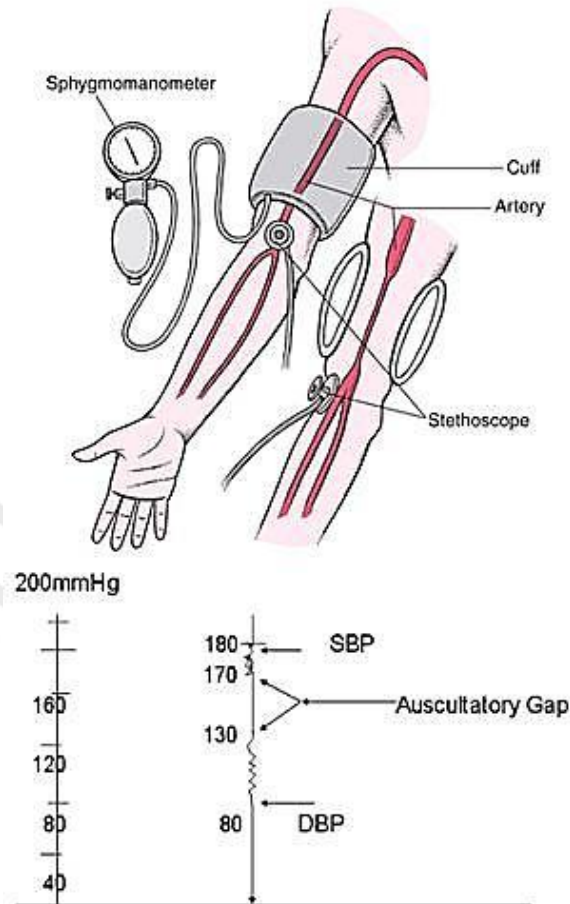


Fig. 9.18. Auscultatory method

The cuff compresses the arm, pressure in the cuff elevates greater than systolic pressure, and blood can not pass. As long as this cuff pressure is higher than systolic pressure, the artery remains collapsed so that no blood jets into the distal artery during any part of the pressure cycle. No sounds are heard from the artery with the stethoscope. Then the cuff pressure decreases. Just as soon as the pressure in the cuff falls below systolic pressure, blood begins to slip through the artery beneath the cuff during the peak of systolic pressure, and one begins to hear tapping sounds from the artery in synchrony with the heartbeat. These sounds are called **Korotkoff sounds**. The cause of Korotkoff sounds is turbulence in the vessel beyond the cuff. As soon as these sounds begin to be heard, the pressure level indicated by the manometer connected to the cuff is about equal to the systolic pressure. Then, finally, when the pressure in the cuff falls to equal diastolic pressure, the artery no longer closes during diastole, which means that the basic factor causing the sounds (the jetting of blood through a squeezed artery) is no longer present. Therefore, the sounds suddenly disappear. One notes the manometer pressure when the Korotkoff sounds disappear; this pressure is about equal to the diastolic pressure.

### 9.11. HEART WORK AND HEART POWER

The energy in the flowing blood is provided by the pumping action of the heart. Heart work during one cardiac contraction consists of right ventricular work and left ventricular work:

$$A = A_l + A_r.$$

Right ventricular work is normally about 0,2 of the left ventricle work:

$$A_r = 0,2 A_l$$

$$A = 1,2 A_l$$

The work of the left ventricle is spent to overcome the pressure forces of blood into the vascular system and the transmission of the kinetic energy to blood. So this work consists of static component and kinetic component:

$$A_{st} = P_a V_s,$$

where  $P_a$  is blood pressure in aorta,  $V_s$  is systolic volume.  $P = 100 \text{ mm Hg} = 13,3 \text{ kPa}$  и  $V_c = 60 \text{ ml} = 6 \cdot 10^{-5} \text{ m}^3$ ,  $\Rightarrow A_{st} \approx 0,8 \text{ J}$ .

$$A_k = \frac{mv^2}{2} = \frac{\rho V_s v^2}{2},$$

if  $\rho = 1,05 \cdot 10^3 \text{ kg/m}^3$ ,  $v = 0,5 \text{ m/s}$ , then  $A_k = 0,008 \text{ J}$ .

Total work of hear during one beat is written as:

$$A = 1,2(PV_c + \frac{\rho V_c \cdot v^2}{2}) \approx 1\text{J}. \quad (9.22)$$

#### Questions:

1. Give the definition of the linear flow velocity and the volumetric flow rate? What is the relation between them?
2. What is the meaning of the continuity equation?

3. Write Bernoulli's equation and characterize it.
4. Describe viscous fluid flow features. Write Newton's equation. What is the fluid viscosity? What are the units of the fluid viscosity?
5. What are the differences between Newtonian fluids and non-Newtonian ones? Make examples of these fluids.
6. Write Poiseuille's Equation. How to determine the vessel hydrodynamic resistance?
7. Compare advantages and disadvantages of viscosity determination methods.
8. What Reynolds number describes? Write the formula for Reynolds number.
9. Specify blood viscosity values for norm and for pathological processes.
10. In which part of cardiovascular system does the most of the pressure drop occur? Why?
11. Write the pulse wave velocity formula. Compare the pulse wave velocity values for the aorta, arteries and veins.
12. In which parts of cardiovascular system is turbulent flow of blood observed?
13. Calculate heart work during one cardiac contraction. What is the heart power?

## Chapter 10. PHYSICAL PROPERTIES AND FUNCTIONS OF THE BIOLOGICAL MEMBRANE

### 10.1. STRUCTURE AND PHYSICAL PROPERTIES OF THE BIOLOGICAL MEMBRANE

All biological cells are surrounded by a plasma membrane. In 1972, S. Singer and G. Nicolson proposed the Fluid Mosaic Model of membrane structure. The cytoplasmic membrane consists of phospholipids or glycolipids, cholesterol and protein molecules. Molecules of lipids consist of polar heads (the phosphate radical or glycerol that is soluble in water) and non-polar tails (the fatty acid radical that are insoluble in water) (fig. 10.1). Such molecules are called ***amphiphilic***. The head of a phospholipid is attracted to water (it is ***hydrophilic***), due to its polar nature. The nonpolar tail is the ***hydrophobic***.

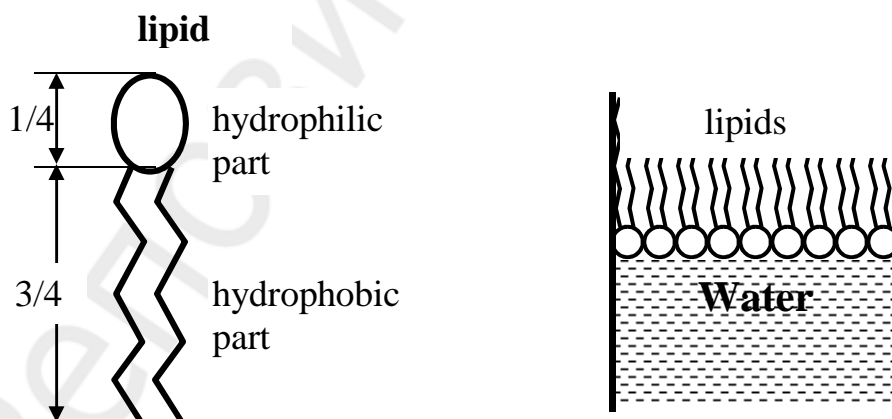


Fig. 10.1. Lipid molecule schematic representation and behavior of lipids on the water surface

Depending on lipid concentration and the lipid type there are some self-organizing structures what lipids assume include ***monolayers, micelles, and vesicles***. Self-assembly occurs due to thermodynamics. If the phospholipids are



in water (or other polar solution) the tails will want to be «away» from the solution. They could all go to the top (like oil on water), or they could have the tails point toward each other (fig. 10.2).

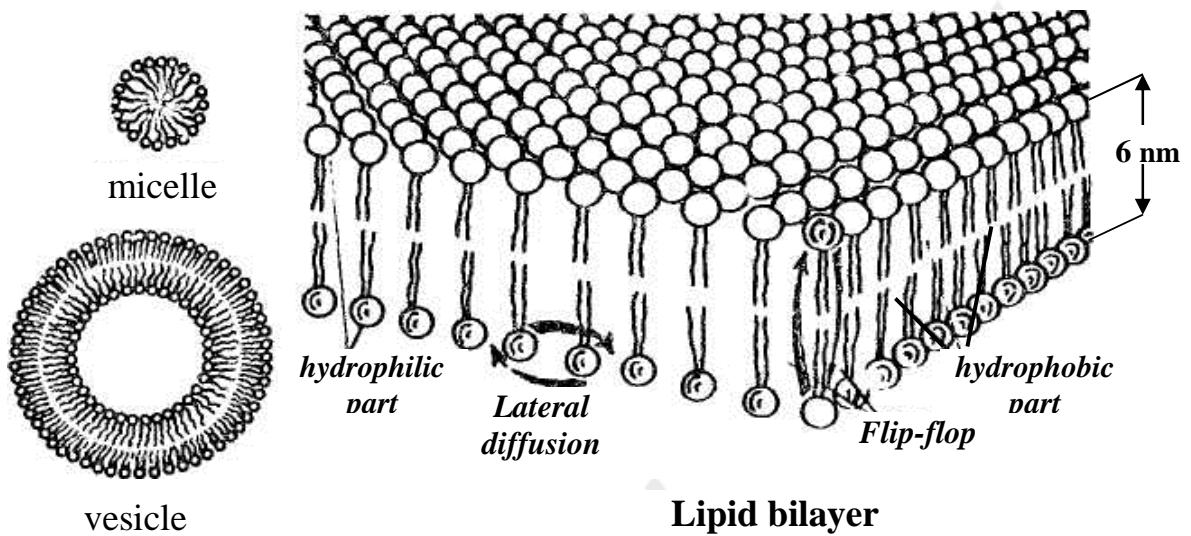


Fig. 10.2. Types of self-organization of lipids in water

The phospholipid bilayer is arranged so that the polar parts of the molecules form the outermost and innermost surface of the membrane while the non-polar parts form the center of the membrane. The lipids of membrane are similar to liquid crystal in which the fluidity and plasticity of liquids referred to symmetry of crystal. The liquid-crystalline properties of membranes are explained by the fact that lipids are in molten state in case of normal blood-heat.

Except lipid molecules plasma membrane contains proteins and carbohydrates. Membrane proteins are divided into two categories, integral and peripheral, depending on their location in the membrane.

Proteins that go through the membrane are called integral or transmembrane proteins. They have hydrophobic (non-polar amino acids with alpha helix coiling) regions within the interior of the membrane and hydrophilic regions at either membrane surface. The interior and exterior «faces» of transmembrane proteins are comprised of different tertiary domains, as is the hydrophobic «core». Some integral proteins become «anchored» within the phospholipid bilayer by covalently bonding to fatty acids. Peripheral proteins are attached to the surface of the membrane, often to the exterior hydrophilic regions of the transmembrane proteins (fig. 10.3). On the interior surface, peripheral proteins typically are held in position by the cytoskeleton. On the exterior, proteins may attach to the extracellular matrix. Peripheral proteins help give animal cell membranes strength.

Usually *carbohydrates* are located on the extracellular surface of the plasma membrane. The membrane thickness is 8–9 nm.

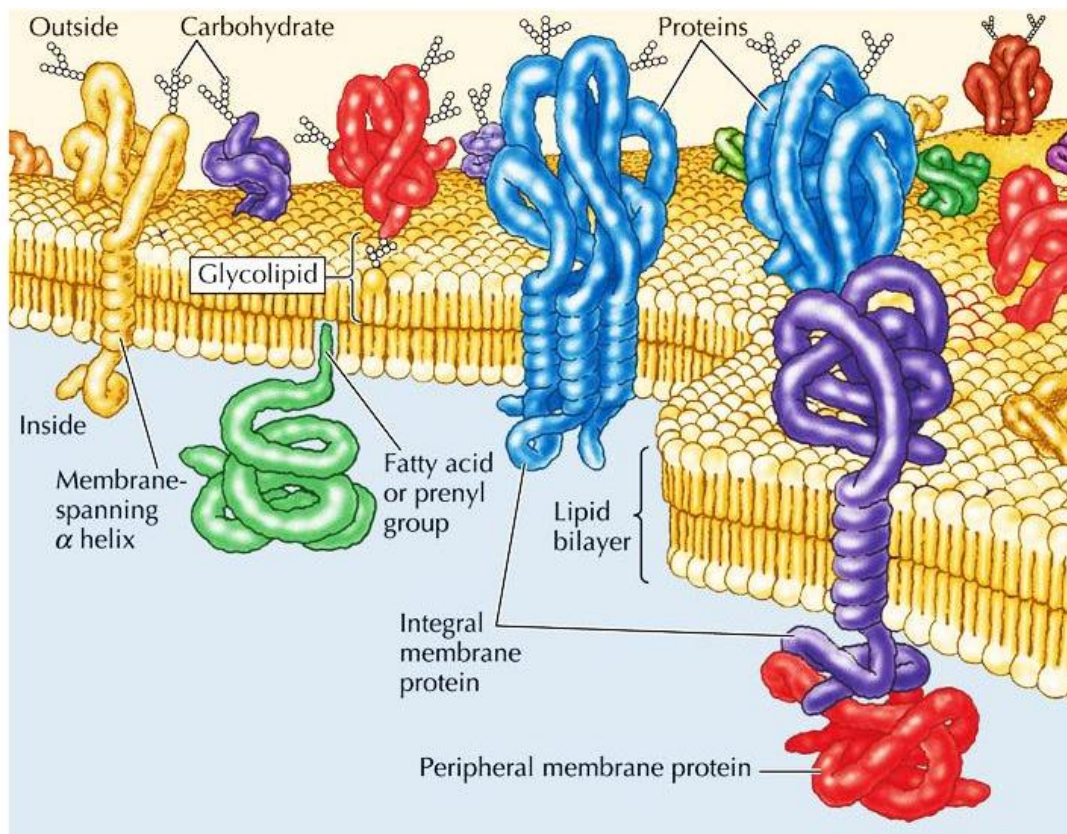


Fig. 10.3. Plasma membrane structure

## 10.2. TYPES OF LIPIDS AND PROTEINS MOTION IN THE CELL MEMBRANE

The cell membrane is not solid/static/fixed but rather elastic and adaptable to changing needs. Lipids and proteins are in constant thermal motion in the membrane. No strong bonds between neighboring phospholipids, so they fluidly move past one another. The lipids are mobile within their half of the lipid bilayer. Chaotic movements of lipids and proteins along the membrane surface are called *the lateral diffusion*. The rate of lipids lateral diffusion is about  $5 \mu\text{m/s}$ . The rate of lateral diffusion of proteins is much less than lipids due to their large mass.

Lipids and proteins are participating in the rotational motion, called *the rotational diffusion*. The rotation angular velocity at normal temperatures for phospholipids is high ( $\sim 10^9 \text{ rad/s}$ ) and for proteins it is much less. For example, for rhodopsin the rotation angular velocity  $v$  is equal to  $10^6 \text{ rad/s}$ .

The transition of lipids from one membrane monolayer to another (this transition is called *flip-flop*) is very unlikely and happens very rarely, as in this case, the polar head must pass through the hydrophobic inner region of the membrane, where it is not soluble. The probability of such *flip-flop* transitions is  $10^{10}$  times smaller than the probability of lateral diffusion. *Flip-flop* movement needs enzymes (flippases) to speed flip-flop.

Protein mobility can vary greatly. Some proteins are free to move. Others may be tethered to structures in the cytoplasm or extracellular spaces, thus restricting their movement. Some types of cell junctions (e. g., tight junctions) can restrict protein movements to a specific membrane domain.

### 10.3. TRANSPORT OF MOLECULES AND IONS THROUGH THE MEMBRANE

The cytoplasmic membrane is a selectively permeable membrane that determines what goes in and out of the cell (fig. 10.4).

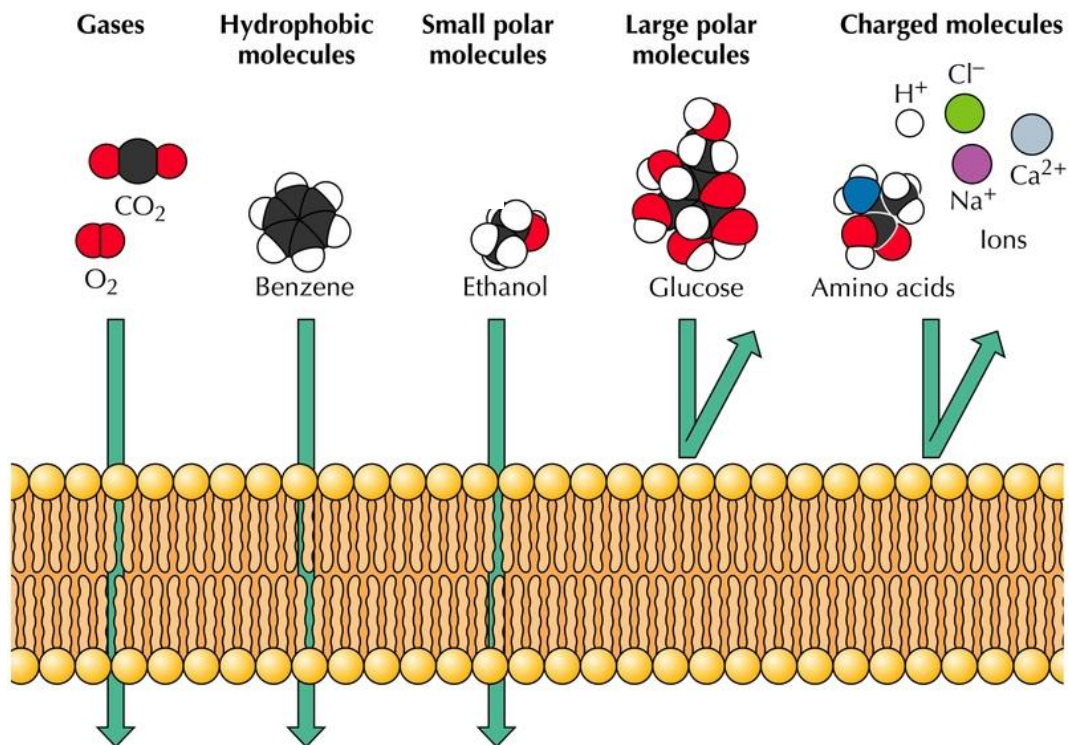


Fig. 10.4. Movement of substances across cell membranes

Water-soluble ions generally pass through small pores in the membrane. All other molecules require carrier molecules to transport them through the membrane. There are two major types of the membrane transport: **passive and active**.

Transport of substances through the membrane is called *passive* if it does not expend metabolic energy stored in the cell. Passive transport does not require the electrochemical energy of the hydrolysis ATP — adenosine triphosphate. The main types of the passive transport are the following:

- 1) simple diffusion through the membrane lipid bilayer;
- 2) simple diffusion through a protein channels- pores in membrane;
- 3) facilitated diffusion through the membrane with the help of special carrier molecule.

**Diffusion** is a spontaneous process of substances penetration from an area of higher concentration to an area of lower concentration due to the energy of

thermal motion. The main driving force for passive transport is the gradient of concentration (more exactly — electrochemical potential gradient) across the membrane.

### **Simple diffusion through the lipid bilayer**

One of the most important factors that determine how rapidly a substance diffuses through the lipid bilayer is the lipid solubility of the substance. Hydrophobic molecules and (at a slow rate) very small uncharged polar molecules can diffuse through the lipid bilayer. For instance, the lipid solubilities of oxygen, nitrogen, carbon dioxide, and alcohols are high, so that all these can dissolve directly in the lipid bilayer and diffuse through the cell membrane. For obvious reasons, the rate of diffusion of these substances through the membrane is directly proportional to their lipid solubility. Especially large amounts of oxygen can be transported in this way; therefore, oxygen is delivered to the interior of the cell almost as though the cell membrane did not exist. Membrane permeability for nonpolar organic compounds is high, since the membrane lipids are well dissolved nonpolar substance. Large polar molecules and ions cannot pass through phospholipid bilayer. One can conclude:

- membrane permeability for the organic molecules decreases when the number of polar groups (hydroxyl, carboxyl and amine) increase;
- membrane permeability for the organic molecules increases when the number of non-polar groups (methyl, ethyl and phenyl) increase.

### **Simple diffusion through a protein channel**

Inorganic polar molecules and ions are insoluble in lipids, so they can pass through the membrane only if there are special channels — pores that exist in the membrane. However, the number of such channels is relatively small, so the membrane permeability for ions and polar compounds is in a hundred times worse than for non-polar compounds.

An ion channel is an integral membrane protein or more typically an assembly of several proteins. The size, shape and charge of each channel acts a *selective filter* that allows only certain types of ions to pass. Some types of channel proteins are always open. They allow specific ions to continually pass through the pore's selective filter using the kinetic energy of the ions. Other channel proteins are gated. Access to the ion is governed by «gates», which can be opened or closed by chemical or electrical signals, or mechanical force, depending on the dimensions of channel (fig. 10.5). If the conformational state of protein channels depends on difference in ionic charges on two sides of membrane, the channels are called *voltage-gated channels*. If the conformational state depends on binding of specific molecule (ligand) to outer or inner surface of channels, the channels are called *chemically-gated channels*.

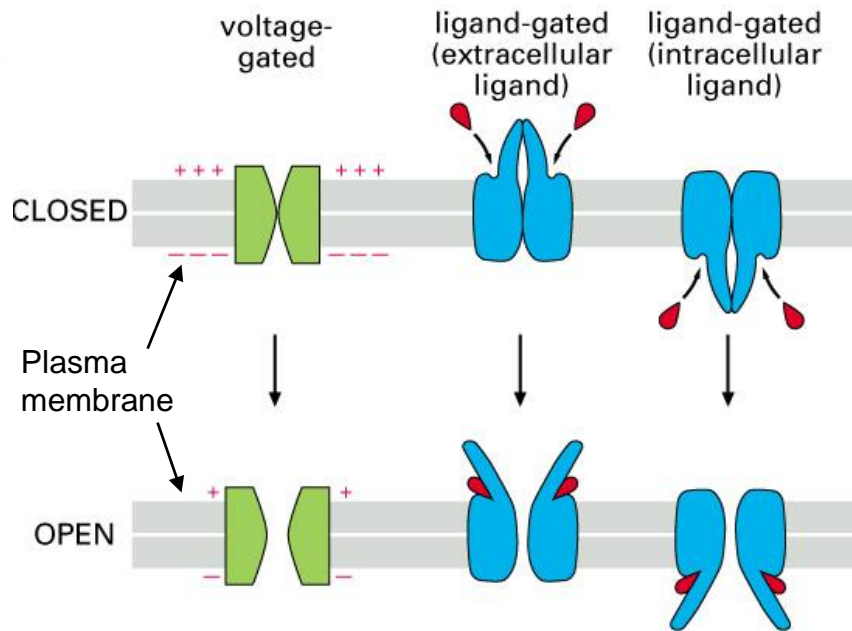


Fig. 10.5. The gating of ion channels

### Facilitated diffusion (by carrier molecule)

Facilitated diffusion is also called carrier-mediated diffusion because a substance transported in this manner diffuses through the membrane with a specific carrier protein helping it to do so. That is, the carrier facilitates the diffusion of the substance to the other side.

There are two kinds of facilitated diffusion:

1) **transfer of a substance with a movable carrier** — a carrier molecule is combined with the transported substance on one side of the membrane, and with it moves through the lipid bilayer to the other side of the membrane;

2) **relay transfer** — in this case, the carrier molecules do not make shuttle movements in the membrane and are embedded in the membrane of each other, forming a bridge to it. Capturing a substance transported, extreme carrier molecule transfers it neighboring molecule, and so on «in the relay».

Facilitated diffusion involves proteins known as carriers, which are specific for a certain type of ions and can transport substances in either direction across the membrane. However, unlike channels, they facilitate the movements of solutes across the membrane by physically binding to them on one side of the membrane and releasing them on the other side. The direction of the solute's net movement simply depends on its concentration gradient across the membrane. If the concentration is greater in the cytoplasm, the solute is more likely to bind to the carrier on the cytoplasmic side of the membrane and be released on the extracellular side, and there will be a net movement from inside to outside.

A characteristic feature of carrier-mediated transport is that its rate is saturable. Facilitated diffusion differs from simple diffusion through an open channel in the following important way: although the rate of diffusion through

an open channel increases proportionately with the concentration gradient of the diffusing substance, in facilitated diffusion if the concentration gradient of a substance is progressively increased, the rate of transport of the substance will increase up to a certain point and then level off. Further increases in the gradient will produce no additional increase in rate. The reason for this is that there is a limited number of carriers in the membrane. When the concentration of the transported substance is raised high enough, all of the carriers will be in use and the capacity of the transport system will be saturated. This difference between simple diffusion and facilitated diffusion is demonstrated in fig. 10.6, showing that as the concentration gradient of the substance increases, the rate of transport continues to increase proportionately, but there is a limitation of facilitated diffusion to the  $v_{\max}$  level.

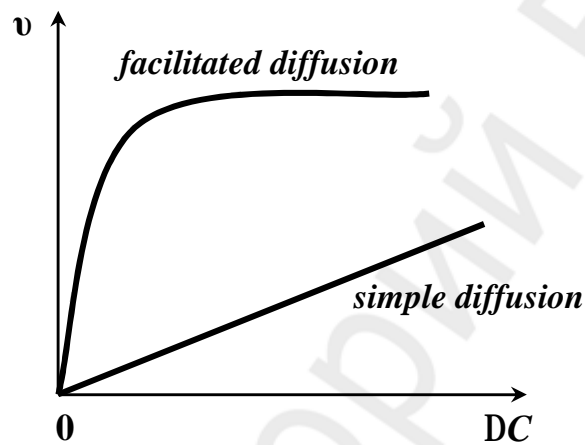


Fig. 10.6. The transfer rate  $v$  dependence on the transported molecule concentration difference  $\Delta C$  across the membrane in simple and facilitated diffusion

Carrier-mediated diffusion has *three essential characteristics*:

- it is specific, with only certain molecules or ions transported by a given carrier;
- the direction of net movement being determined by the relative concentrations of the transported substance inside and outside the cell;
- it may become saturated if all of the protein carriers are in use.

Among the most important substances that cross cell membranes by facilitated diffusion are glucose and most of the amino acids.

#### 10.4. MATHEMATICAL DESCRIPTION OF THE PASSIVE TRANSPORT

Electrochemical potential is the free energy of one mole of solution. Free energy is the thermodynamic potential, which determines the ability of a physical-chemical system to perform useful work. All useful work that can be done in one mole of a substance is due to decrease of its electrochemical potential. For solutions of substances electrochemical potential can be expressed as

$$\mu = \mu_0 + RT \ln C + ZF\phi, \quad (10.1)$$

$\mu_0$  is the part of chemical potential of one mole of solution which is determined by the energy of chemical bonds of the solute with the solvent;  $R$  is the universal gas constant;  $T$  is the absolute temperature of the solution;  $C$  is the molar concentration of the solute;  $Z$  is the electric charge of the dissolved ions, which is expressed in units of electron charge;  $F$  is the Faraday number;  $\varphi$  is the electric potential of the solution.

Let's imagine that the membrane separates two solutions of identical composition but different ion concentration (fig. 10.7).

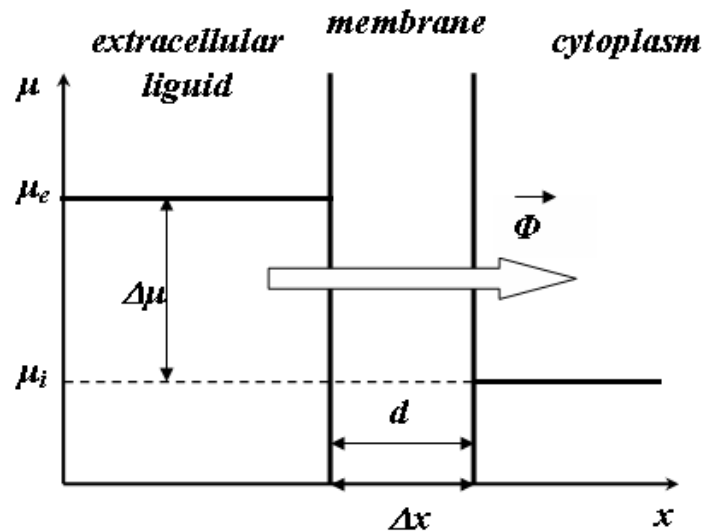


Fig. 10.7. Connection between the diffusion flux direction and the electrochemical potential distribution across the membrane

If the values of electrochemical potential on both sides of the membrane are different  $\mu_e \neq \mu_i$ , then the system is thermodynamic non-equilibrium. In this case electrochemical potential gradient appears across the membrane:  $d\mu/dx = \Delta\mu/d$ , where  $d$  is the membrane thickness.

The thermodynamic equilibrium of system is characterized by the equality of thermodynamic potentials including electrochemical ones:  $\mu_e = \mu_i$ . The process of transition from the non-equilibrium to equilibrium state in the case of biological membranes is always accompanied by substance diffusion from the region of greater value of the electrochemical potential into the region with its lower value.

Mathematically, the process of substance transfer is described by the **Theorell equation**:

$$\vec{\Phi} = -CU \frac{d\mu}{dx}, \quad (10.2)$$

where  $\Phi$  is the diffusion flux density (amount of substance transported through the unit membrane area per second);  $C$  is molar concentration of the solution;  $U$  is the mobility;  $d\mu/dx$  is the electrochemical potential gradient.

Let's find the electrochemical potential gradient  $d\mu/dx$ . Taking into account that on both sides of biomembranes solvent is always the same — water, so  $\mu_{oi} = \mu_{oe} = \text{const}$ , one can obtain:

$$\frac{d\mu}{dx} = RT \frac{1}{C} \frac{dC}{dx} + ZF \frac{dj}{dx}. \quad (10.3)$$

Let's substitute this expression (3) in (1) and write **Nernst-Planck equation** describing diffusion of ions across the membrane:

$$\vec{\Phi} = -URT \frac{dC}{dx} - CUZF \frac{dj}{dx}. \quad (10.4)$$

First summand in this equation describes diffusion which is due to the concentration gradient  $dC/dx$ , second summand describes electrodiffusion which is due to electric potential gradient  $d\phi/dx$  through membrane.

In case of the uncharged particles diffusion ( $Z = 0$ ) the second term in the equation (10.4) vanishes and the passive transport of such substances is described by **Fick Law**:

$$\vec{\Phi} = -D \frac{dC}{dx}, \quad (10.5)$$

where  $D$  is the diffusion coefficient. The diffusion coefficient depends on the mobility of the substance  $U$  and the absolute temperature of the medium  $T$ :

$$D = URT. \quad (10.6)$$

It is possible to simplify Fick equation, if concentration gradient is expressed as

$$dC/dx \sim \Delta C/\Delta x = |C_i - C_e|/d, \quad (10.7)$$

where  $d$  is the membrane thickness;  $C_i$  and  $C_e$  are concentration absolute values on the interior and exterior membrane surfaces:

$$\Phi = p |C_i - C_e|, \quad (10.8)$$

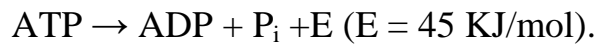
where coefficient  $p = D/d$  is **permeability coefficient**.

## 10.5. ACTIVE TRANSPORT OF IONS

Active transport typically moves molecules or ions through a membrane from low their concentration to high in the direction of increasing the electrochemical potential. Passive transport of substances has always gone from the region of large values of the electrochemical potential to the region of its lower values, resulting in electrochemical potential gradient decreases. Active transport of substances is going in the opposite direction and leads to an increase of the electrochemical potential difference on both side of the membrane, so energy is required. Active transport is mediated by carrier proteins that undergo conformational changes in order to move substance across membranes. Many of



the carrier proteins involved in active transport are referred to as pumps. The ATP-dependent pump uses the energy derived from adenosine triphosphate (ATP) hydrolysis to adenosine diphosphate (ADP) and inorganic phosphate ( $P_i$ ):



Active transport of substances can be divided into two types:

- 1) active transport of ions;
- 2) active transport of organic compounds, mainly amino acids and carbohydrates.

All ATP-dependent pumps (ATPases) share a common feature. They transport substances from the side where they are less concentrated to the side where they are more concentrated by utilizing the free energy associated with ATP hydrolysis. There are several types of ATPases, and they function by distinct mechanisms. The best-studied ATPase is the Na, K-ATPase, also known as the sodium-potassium pump.

The sodium-potassium (Na-K) pump is a transport process that pumps sodium ions outward through the cell membrane of all cells and at the same time pumps potassium ions from the outside to the inside (fig. 10.8). This pump is responsible for maintaining the sodium and potassium concentration differences across the cell membrane as well as for establishing a negative electrical voltage inside the cells.

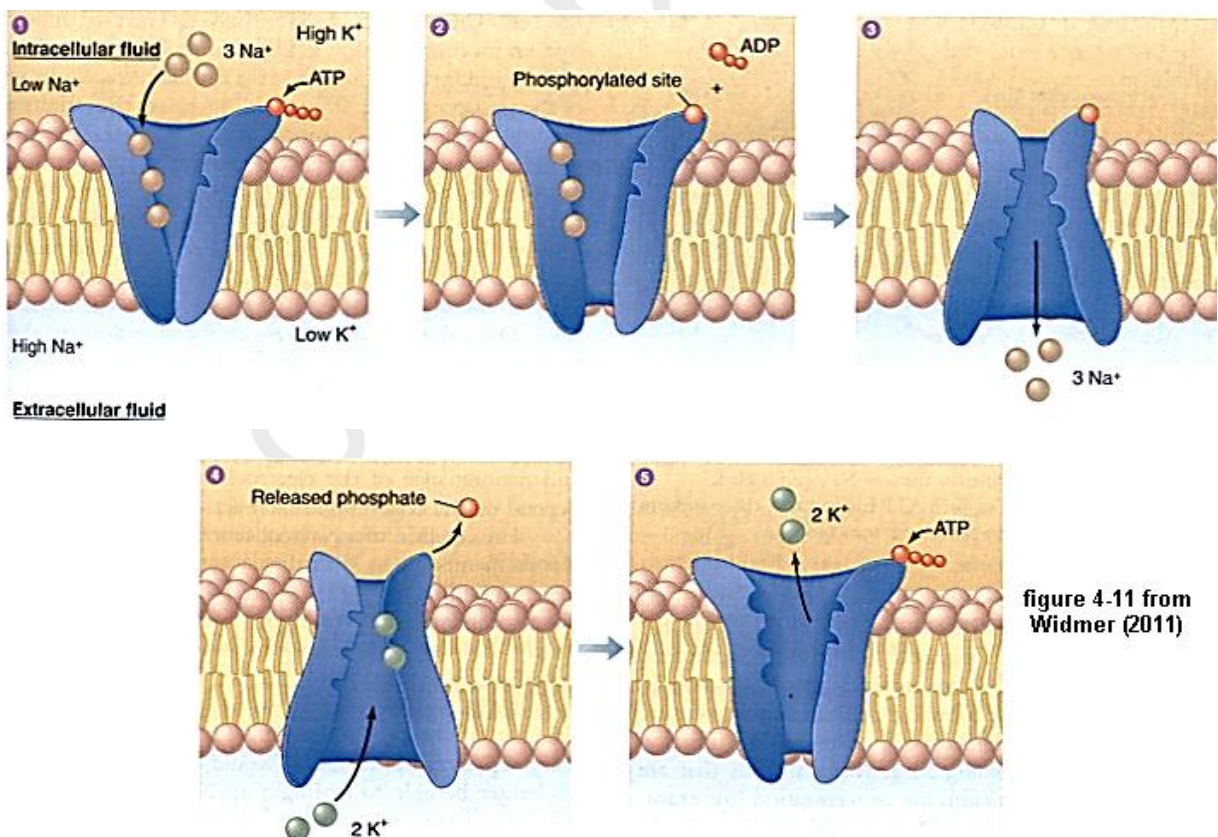


figure 4-11 from Widmer (2011)

Fig. 10.8. Scheme of the sodium-potassium pump

During one cycle of pumping, the sodium-potassium pump exports three ions of sodium and imports two ions of potassium through the cell membrane.

After binding sodium ions on the interior of the cell, ATP is hydrolyzed and the phosphate is transferred to the pump protein. The phosphorylated protein undergoes a conformational change, delivering the sodium ions to the exterior of the cell and exchanging them for potassium ions. The protein is then dephosphorylated and undergoes an additional conformational change, returning to its original state and delivering the potassium ions to the interior of the cell. The fact that the Na-K pump moves three  $\text{Na}^+$  ions to the exterior for every two  $\text{K}^+$  ions to the interior means that one positive charge is moved from the interior of the cell to the exterior for each cycle of the pump. This creates positivity outside the cell but leaves a deficit of positive ions inside the cell; that is, it causes *negativity on the inside*.

**Questions:**

1. Characterize the cell membrane lipids physical properties. What are cell membrane lipids and proteins functions?
2. Describe types of the lipids and proteins motion in the cell membrane (lateral diffusion, rotational diffusion, flip-flop).
3. What passive transport types across cell membrane are known?
4. Which substances can move across cell membranes? Specify membrane channels properties.
5. What is a facilitated diffusion? Describe facilitated diffusion types.
6. What is the meaning of electrochemical potential? Write the Theorell equation, Nernst-Planck equation and Fick Law. What is the cell membrane permeability?
7. What is the active transport? Explain ions active transport mechanism by the sodium-potassium pump example.

## **Chapter 11. MEMBRANE POTENTIALS OF THE CELL**

The cell membrane acts as a barrier which prevents the intracellular fluid from mixing with the extracellular fluid. These two solutions have different concentrations of their ions. Furthermore, this difference in concentrations leads to a difference in charge of the solutions. This creates a situation whereby one solution is more positive than the other. The membrane potential ( $\varphi_m$ ) of an excitable cell is defined as the potential at the inner surface ( $\varphi_i$ ) relative to that at the outer ( $\varphi_e$ ) surface of the membrane, i. e.  $\varphi_m = (\varphi_i) - (\varphi_e)$ . This definition is independent of the cause of the potential, and whether the membrane voltage is constant, periodic, or nonperiodic in behavior. If the potential outside is taken to be zero, then the interior resting membrane potential varies from  $-60$  mV to  $-100$  mV depending on the type of cell.

A nerve cell conducts an electrochemical impulse because of membrane potential changes. These changes allow movement of ions through the membrane, setting up currents that flow through the membrane and along the cell. Similar impulses travel along muscle cells before they contract.

## 11.1. THE NERNST EQUATION

Find the equilibrium membrane potential, which arises due to the diffusion of ions through the cell membrane. Suppose that in a rest the membrane is permeable to one type of ion ( $K^+$ ). The concentration of potassium ions is higher inside cells than outside due to the active transport of potassium ions. Most cells have potassium-selective ion channel proteins that remain open all the time. There will be net movement of positively-charged potassium ions through these potassium channels with a resulting accumulation of excess negative charge inside of the cell. The outward movement of positively-charged potassium ions is due to its diffusion and continues until enough excess negative charge accumulates inside the cell to form a membrane potential which can balance the difference in concentration of potassium between inside and outside the cell. «Balance» means that the electrical potential that results from the build-up of ionic charge, and which impedes outward diffusion, increases until it is equal in magnitude but opposite in direction to the tendency for outward diffusive movement of potassium. This balance point (the equilibrium state) is characterized by the equality of electrochemical potentials on both sides of the membrane  $\mu_e = \mu_i$  and the net transmembrane flux (or current) of  $K^+$  is zero ( $\Phi_{K^+} = 0$ ).

The electrochemical potential inside cell can be written as

$$\mu_i = \mu_{0i} + RT \ln C_i + ZF\phi_i$$

and the electrochemical potential outside is

$$\mu_e = \mu_{0e} + RT \ln C_e + ZF\phi_e.$$

The chemical potential of the water is the same on both sides  $\mu_{0i} = \mu_{0e}$ , and condition of the equilibrium state has the form:

$$RT \ln C_i + ZF\phi_i = RT \ln C_e + ZF\phi_e.$$

This equation can be rearranged to give:

$$RT(\phi_i - \phi_e) = RT(\ln C_i - \ln C_e).$$

The Nernst equation for equilibrium membrane potential is obtained from the last equation:

$$\phi_i - \phi_e = -\frac{RT}{ZF} \ln \frac{C_i}{C_e}, \quad (11.1)$$

where  $\phi_i - \phi_e$  is the equilibrium potential for ion;  $R$  is the universal gas constant;  $T$  is the absolute temperature;  $Z$  is the number of elementary charges;  $F$  is the Faraday constant;  $C_e$  is the extracellular concentration of ion;  $C_i$  is the intracellular concentration of ion.

The equilibrium potential for a given ion depends only upon the concentrations on either side of the membrane and the temperature. The Nernst equation is widely used in physiology to relate the concentration of ions on either side of a membrane to the electrical potential difference across the membrane. Usually the outside solution is set as the zero voltage ( $\phi_e = 0$ ).

Then the difference between the inside voltage and the zero voltage is determined. At physiological temperature, about 29,5 °C, and physiological concentrations (which vary for each ion), the calculated equilibrium potentials are approximately +67 mV for Na<sup>+</sup>, +90 mV for K<sup>+</sup>, -86 mV for Cl<sup>-</sup> and +123 mV for Ca<sup>2+</sup>.

## 11.2. RESTING MEMBRANE POTENTIAL

In mammalian cells sodium Na<sup>+</sup>, potassium K<sup>+</sup> and chloride Cl<sup>-</sup> ions play large roles for the resting membrane potential. The resting membrane potential is determined by the equilibrium potentials for every ion to which the membrane is permeable, weighted by the permeability ( $P$ ), via the Goldman–Hodgkin–Katz voltage equation:

$$\varphi_m = -\frac{RT}{F} \ln \frac{P_K C_i(K^+) + P_{Na} C_i(Na^+) + P_{Cl} C_e(Cl^-)}{P_K C_e(K^+) + P_{Na} C_e(Na^+) + P_{Cl} C_i(Cl^-)}, \quad (11.2)$$

where  $R$ ,  $T$ , and  $F$  are as above;  $P_K$ ,  $P_{Na}$ ,  $P_{Cl}$  are the membrane permeabilities for K<sup>+</sup>, Na<sup>+</sup>, Cl<sup>-</sup> ions, respectively;  $C_e(K^+)$ ,  $C_e(Na^+)$ ,  $C_e(Cl^-)$  are the extracellular concentrations for K<sup>+</sup>, Na<sup>+</sup>, Cl<sup>-</sup> ions, respectively;  $C_i(K^+)$ ,  $C_i(Na^+)$ ,  $C_i(Cl^-)$  are the intracellular concentrations for K<sup>+</sup>, Na<sup>+</sup>, Cl<sup>-</sup> ions, respectively. If the permeabilities of Na<sup>+</sup> and Cl<sup>-</sup> are zero, the membrane potential reduces to the Nernst potential for K<sup>+</sup> (as  $P_K = P_{tot}$ ). Usually, under resting conditions  $P_{Na}$  and  $P_{Cl}$  are not zero, but they are much smaller than  $P_K$ , which renders  $\varphi_m$  close to the equilibrium potential for potassium. Normally, permeability values are reported as relative permeabilities with  $P_K$  having the reference value of one (because in most cells at rest  $P_K$  is larger than  $P_{Na}$  and  $P_{Cl}$ ). Hodgkin and Katz experimentally found that for the giant axon of squid the attitude of the membrane permeability for K<sup>+</sup>, Na<sup>+</sup> and Cl<sup>-</sup> ions in a rest is  $P_K : P_{Na} : P_{Cl} = 1 : 0,04 : 0,45$ . Medical conditions such as hyperkalemia in which blood serum potassium (which governs  $[K^+]_e$ ) is changed are very dangerous since they offset the equilibrium potential for potassium, thus affecting resting membrane potential  $\varphi_m$ . This may cause arrhythmias and cardiac arrest.

Because the electric field in the resting cell is zero, there is no net charge in the fluid. Positive ions are neutralized by negative ions everywhere except at the membrane. A layer of charge on each surface generates an electric field within the membrane and a potential difference across it. Measurements with a microelectrode show that the potential within the cell is about 60–100 mV less than outside. If the potential outside is taken to be zero, then the interior resting potential is (-60) – (-100) mV. If the potential drops 80 mV and if the membrane thickness is 8 nm, then the electric field within the membrane is assumed to be constant:

$$E = \frac{\varphi_0}{d} = \frac{80 \text{ mV}}{8 \text{ nm}} = \frac{80 \cdot 10^{-2} \text{ V}}{8 \cdot 10^{-9} \text{ m}} = 10^7 \frac{\text{V}}{\text{m}}. \quad (11.3)$$

### 11.3. ACTION POTENTIAL IN EXCITABLE CELLS

All cells exhibit a potential difference across the cell membrane. Nerve cells and muscle cells are excitable. They have the ability to generate and propagate electrical signals. The origin of the membrane potential is the same in nerve cells as in muscle cells. In both cell types, the membrane generates an impulse as a consequence of excitation. This impulse propagates in both cell types in the same manner.

An action potential is the brief reversal in the potential difference across a plasma membrane (as of a nerve cell or muscle fiber) that occurs when a cell has been activated by a stimulus (fig. 11.1).

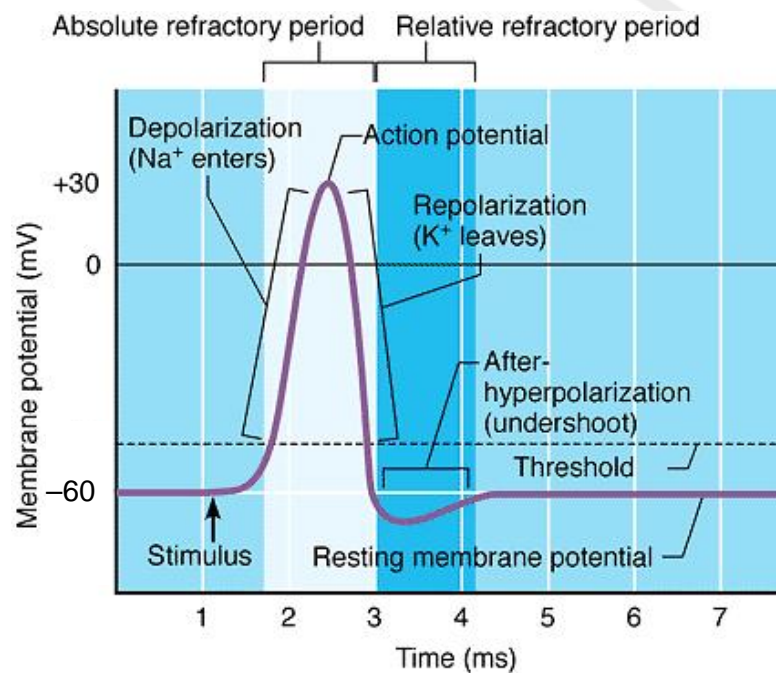


Fig. 11.1. Schematic representation of an action potential in an excitable cell

The course of the action potential can be divided into five parts: the rising phase, the peak phase, the falling phase, the undershoot phase, and finally the refractory period. When the excitable cell membrane is stimulated so that the membrane potential rises and reaches the threshold, the sodium and potassium ionic permeabilities of the membrane change. The sodium ion permeability increases very rapidly at first, allowing sodium ions to flow from outside to inside, making the inside more positive. During the rising phase the membrane potential  $\phi_m$  depolarizes (becomes more positive). The sharp rise in membrane potential and sodium permeability correspond to the rising phase of the action potential. Hodgkin and Katz experimentally found that for the giant axon of squid the attitude of the membrane permeability for  $K^+$ ,  $Na^+$  and  $Cl^-$  ions during the rising phase is  $P_K : P_{Na} : P_{Cl} = 1 : 20 : 0,45$ .

The point at which depolarization stops is called the peak phase. At the peak of the action potential, the sodium permeability is maximized and

the membrane potential is nearly equal to the sodium equilibrium voltage  $\varphi_{\text{Na}}$ . At this stage, the membrane potential reaches a maximum.

Subsequent to this, there is a falling phase. The same raised voltage that opened the sodium channels initially also slowly shuts them off, by closing their pores; the sodium channels become inactivated. This lowers the membrane's permeability to sodium, driving the membrane potential back down. At the same time, the raised voltage opens voltage-sensitive potassium channels; the increase in the membrane's potassium permeability drives the membrane potential  $\varphi_m$  towards the potassium equilibrium voltage  $\varphi_K$ . The efflux of potassium ions decreases the membrane potential thus returning the membrane potential to its resting value or hyperpolarizes the cell. Combined, these changes in sodium and potassium permeability cause the membrane potential  $\varphi_m$  to drop quickly, repolarizing the membrane and producing the «falling phase» of the action potential.

The raised voltage opened many more potassium channels than usual, and these do not close right away when the membrane returns to its normal resting voltage. The potassium permeability of the membrane is transiently unusually high, driving the membrane potential  $\varphi_m$  even closer to the potassium equilibrium voltage  $\varphi_K$ . Hence, there is an undershoot, a hyperpolarization, that persists until the membrane potassium permeability returns to its usual value. The undershoot phase is the point during which the membrane potential becomes temporarily more negatively charged than when at rest. While at rest, following activation, the Na-K pump restores the ion concentrations inside and outside the membrane to their original values.

Each action potential is followed by a refractory period, which can be divided into an absolute refractory period, during which it is impossible to evoke another action potential, and then a relative refractory period, during which a stronger-than-usual stimulus is required. These two refractory periods are caused by changes in the state of sodium and potassium channel molecules. When closing after an action potential, sodium channels enter an «inactivated state», in which they cannot be made to open regardless of the membrane potential — this gives rise to the absolute refractory period. Even after a sufficient number of sodium channels have transitioned back to their resting state, it frequently happens that a fraction of potassium channels remains open, making it difficult for the membrane potential to depolarize, and thereby giving rise to the relative refractory period. Because the density and subtypes of potassium channels may differ greatly between different types of neurons, the duration of the relative refractory period is highly variable.

Duration of the depolarization is small in any cases. For nerve cells and muscle cells this duration is 0,5–1 ms. Duration of the repolarization depends essentially on the type of cells: for the nerve cells and skeletal muscle cells duration of the repolarization is 0,5–10 ms, for the heart muscle cells — about 300 ms.

The action potential amplitude is equal to the sum of absolute values of the resting potential  $\phi_0$  and the maximum achieved membrane potential  $\phi_{\max}$  and is  $\sim 90\text{--}120$  mV:

$$\phi_a = \phi_{\max} - \phi_0 = \phi_{\max} + |\phi_0|. \quad (11.4)$$

Currents produced by the opening of voltage-gated channels in the course of an action potential are typically significantly larger than the initial stimulating current. Thus the amplitude, duration, and shape of the action potential are largely determined by the properties of the excitable membrane and not the amplitude or duration of the stimulus. The action potentials are generated anew along excitable stretches of membrane and propagate without decay.

#### 11.4. PROPAGATION OF ACTION POTENTIAL ALONG AN UNMYELINATED AXON

The nerve cell may be divided on the basis of its structure and function into three main parts:

- the cell *body*, also called the *soma*;
- numerous short processes of the *soma*, called the *dendrites*;
- the single long nerve fiber, the *axon*.

The long nerve fiber, the *axon*, transfers the signal from the cell body to another nerve or to a muscle cell. The long cylindrical axon has properties that are in some ways similar to those of an electric cable. Its diameter may range from less than one micrometer ( $1\ \mu\text{m}$ ) to as much as 1mm for the giant axon of “a squid; in humans the upper limit is about  $20\ \mu\text{m}$ . Pulses travel along it with speeds ranging from  $0.6$  to  $100\ \text{m s}^{-1}$ , depending, among other things, on the diameter of the axon. The axon core may be surrounded by either a membrane (for an unmyelinated fiber) or a much thicker sheath of fatty material (myelin) that is wound on like tape.

Let’s consider the action potential propagation along unmyelinated axon. At resting potential there is positive charge on the outside of axon membrane and negative charge on the inside, with high sodium ion concentration outside and high potassium ion concentration inside (fig. 11.2).

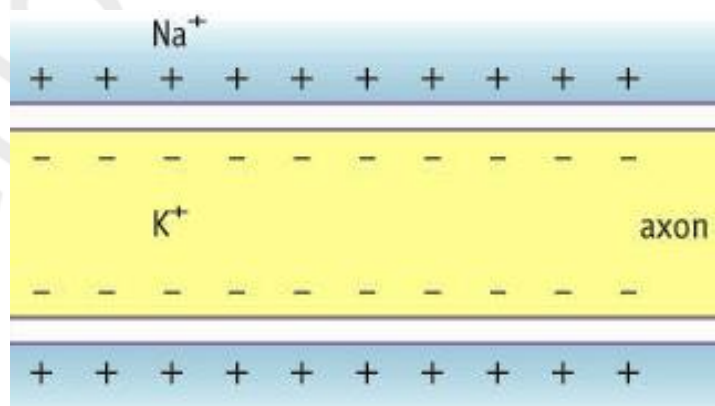


Fig. 11.2. Unmyelinated axon in a rest. There is no net transport of the ion through the membrane

If the membrane stimulus is insufficient to cause the membrane potential to reach the threshold, then the membrane will not activate. The response of the membrane to this kind of stimulus is essentially passive. If the excitatory stimulus is strong enough, the membrane potential reaches the threshold, and the membrane produces a characteristic electric impulse, the nerve impulse. This potential response follows a characteristic form regardless of the strength of the transthreshold stimulus. When stimulated, voltage-dependent sodium ion channels open, and sodium ions flow into the axon, depolarizing the membrane. The potential difference ( $\phi_{\max} - \phi_0$ ) between excited and unexcited regions of an axon would cause small currents, called local circuit currents, to flow between them in such a direction that they stimulate the unexcited region (fig. 11.3).

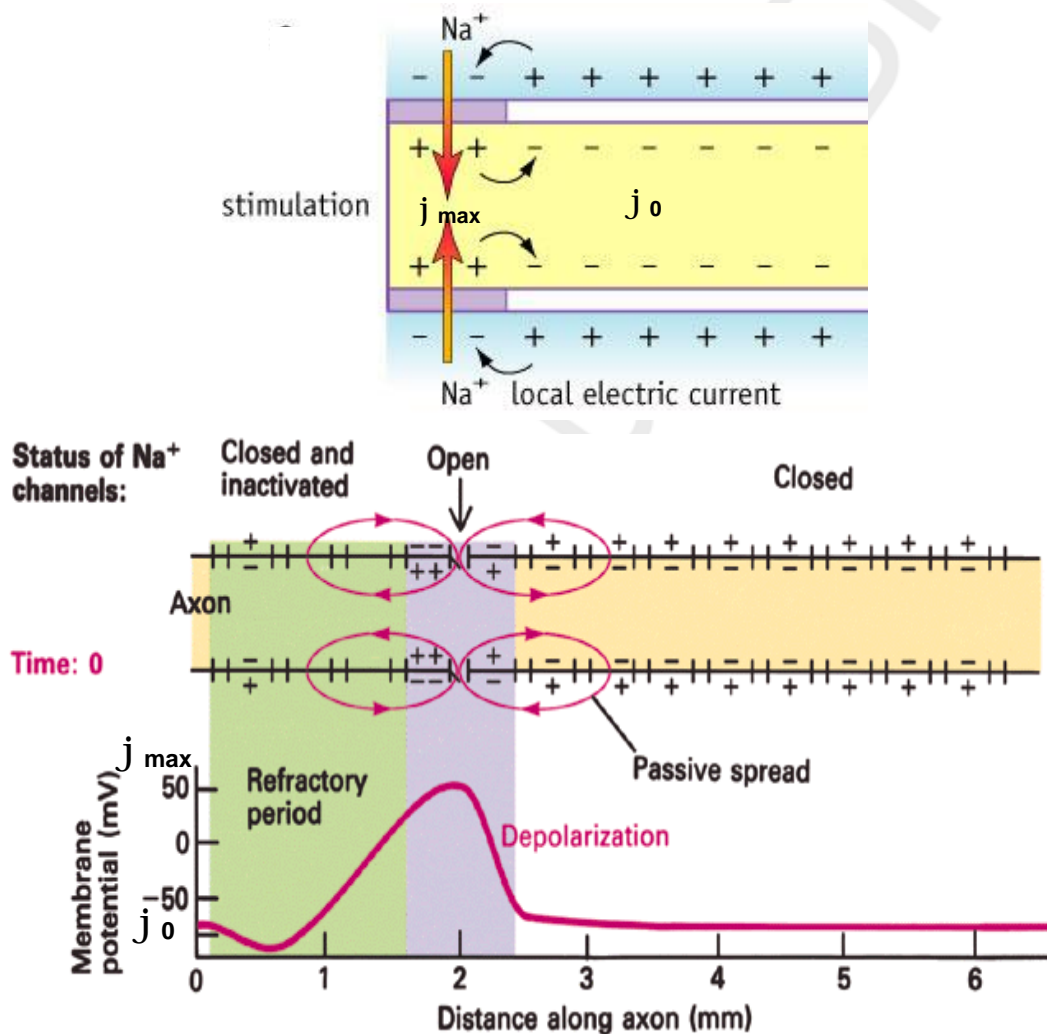


Fig. 11.3. The propagation of action potential along an unmyelinated axon

Meanwhile, in the earlier excited region potassium ions leave the axon, repolarizing the membrane. The currents flowing inwards at a point on the axon during an action potential spread out along the axon, and depolarize the adjacent sections of its membrane (fig. 11.4). The action potential generated at the axon propagates as a wave along the axon.



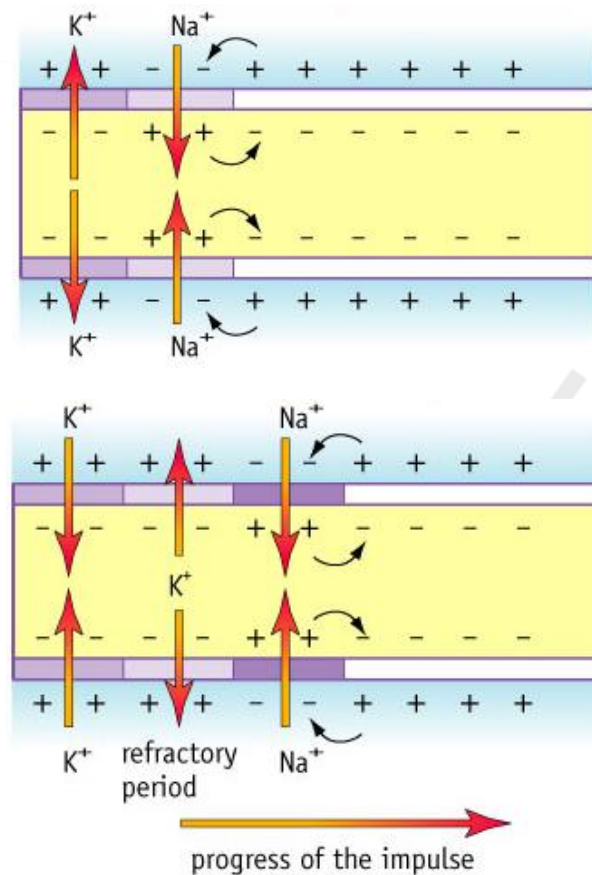


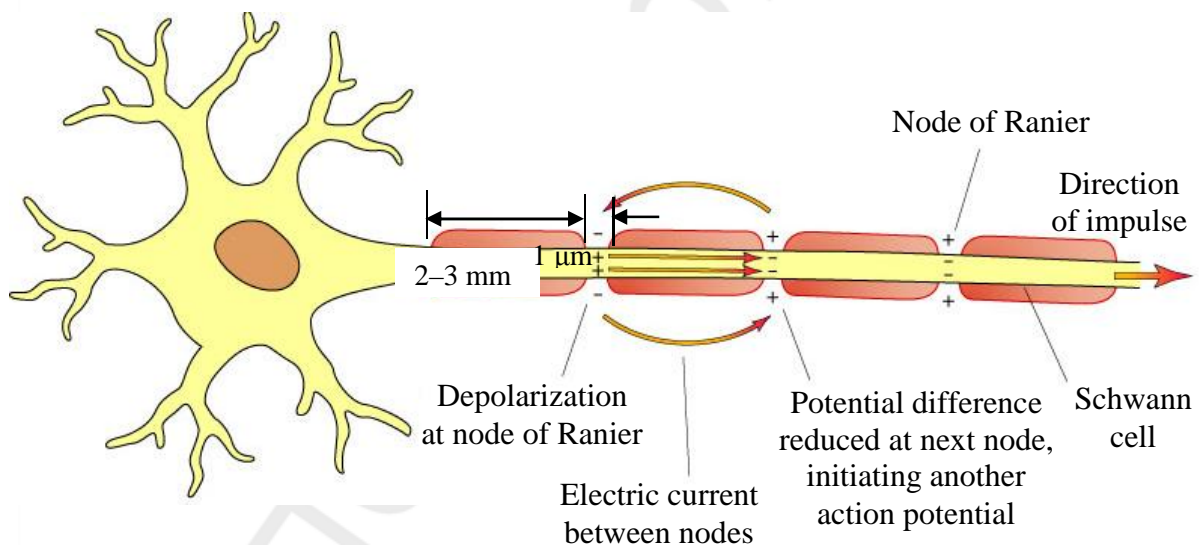
Fig. 11.4. The propagation of action potential along an unmyelinated axon

An important physical property of the axon membrane is the change in sodium conductance due to activation. The higher the maximum value achieved by the sodium conductance, the higher the maximum value of the sodium ion current and the higher the rate of change in the membrane voltage. The result is a higher gradient of voltage, increased local currents, faster excitation, and increased conduction velocity. The decrease in the threshold potential facilitates the triggering of the activation process. Conduction speed can be increased by reducing the internal resistance of the axon. Impulse transmission can be speeded up by increasing the diameter of the axon. However, there are limitations on the size of an axon. Transmission speed can reach 25 m per sec if the diameter of the unmyelinated axon is 1 mm.

### 11.5. PROPAGATION OF ACTION POTENTIAL ALONG A MYELINATED AXON

The evolutionary need for the fast and efficient propagation of electrical signals in nervous system resulted in appearance of myelin sheaths around neuronal axons. The myelin sheath is not continuous but divided into sections with the size of 2–3 mm, separated at regular intervals by the nodes of Ranvier with the length of  $1\mu\text{m}$ . A typical human nerve might contain twice as many unmyelinated fibers as myelinated. The myelin gives a faster impulse conduction speed for a given axon radius.

A myelinated axon, surrounded by the myelin sheath, can produce a nerve impulse only at the nodes of Ranvier. This myelin sheath makes the axon impermeable to ions so they are unable to diffuse between the tissue fluid and the neurone, so action potentials cannot be generated by the myelinated regions (it acts as an insulator). Action potentials can only be generated at the nodes of Ranvier, so the local currents involved in nerve impulse transmission flow over longer distances. An action potential at one node of Ranvier causes inwards currents that depolarize the membrane at the next node, provoking a new action potential there; the action potential appears to «hop» from node to node. Thus action potential seems to «jump» from node to node, as illustrated in fig. 11.5. Since the intervening parts of the axon membrane do not have to be successively depolarised it takes less time for the action potentials to pass from node to node. This results in nerve impulse transmission that is much faster, the consequence of which is that smaller myelinated nerves can transmit impulses much faster than larger unmyelinated ones (120 m/sec compared to 25 m/sec along unmyelinated axon). Another advantage of this is that energy is saved as sodium potassium pumps are only required at specific points along the axon. Such a propagation is called saltatory conduction. The process of excitation and conduction in myelinated nerve fibers is characterized by its discontinuous and saltatory features.



*Fig. 11.5.* Propagation of action potential along a myelinated axon

The cytoplasm of an axon is electrically conductive and because myelin inhibits charge leakage through the membrane, depolarization at one node of Ranvier is sufficient to elevate the voltage at a neighboring node to the threshold for action potential initiation. Even if one node is damaged, transmission can still effectively bypass that node. Nodes of Ranvier contain a significantly higher density of voltage-gated sodium channels than is found in unmyelinated axons (4 orders of magnitude higher).

**Questions:**

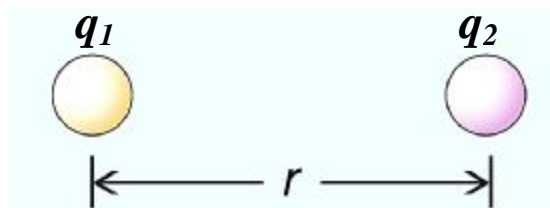
1. How are resting membrane potential generated?
2. Obtain the Nernst Equation.
3. What ions specify the cell membrane potentials? Write the Goldman-Hodgkin-Katz voltage equation. What does the Goldman-Hodgkin-Katz voltage equation describe?
4. What is the condition of cell excitement?
5. What processes occur in cell membrane during action potential generation?
6. Characterize depolarization phase and repolarization one. Give the graph for action potential.
7. What determines the sodium channel permeability?
8. What are the refractory periods? Describe the types and duration of the refractory periods for different cells.
9. Describe the propagation of action potential along an unmyelinated axon.
10. Characterize the propagation of action potential along a myelinated axon.

## **Chapter 12. ELECTRICAL FIELDS OF THE ORGANS AND TISSUES. METHODS OF THEIR REGISTRATION**

### **12.1. ELECTRICAL FIELD AND ITS CHARACTERISTICS**

The fundamental unit of electric charge ( $e$ ) is the charge carried by the electron and its unit is coulomb. Electron  $e$  has the charge magnitude  $1,6 \times 10^{-19}$  Coulomb (C). In nature, the electric charge of any system is always an integral multiple of the least amount of charge. It means that the quantity can take only one of the discrete set of values. The charge,  $q = ne$  where  $n$  is an integer. Electric charges can neither be created nor destroyed. According to the law of conservation of electric charge, the total charge in an isolated system always remains constant. The total electric charge of a system is equal to the algebraic sum of electric charges located in the system.

When the charges are likely there is a repulsive force between them and, opposite, when the charges are unlikely, there is attractive force between them. The force between two charged bodies was studied by Coulomb in 1785. Coulomb's law states that the force of attraction or repulsion between two point charges is directly proportional to the product of the charges and inversely proportional to the square of the distance between them. The direction of forces is along the line joining the two point charges. Let  $q_1$  and  $q_2$  be two point charges placed in air or vacuum at a distance  $r$  apart (fig. 12.1).



*Fig. 12.1.* Two point charges  $q_1$  and  $q_2$  placed in air or vacuum at a distance  $r$  apart

Then, according to Coulomb's law,

$$F = k \frac{q_1 q_2}{\epsilon r^2}. \quad (12.1)$$

The electrostatic force  $F$  between two point charges  $q_1$  and  $q_2$  is directly proportional to the product of the charges and inversely proportional to the square of the distance  $r$  between them, where  $k = 9 \cdot 10^9 \frac{\text{N} \cdot \text{m}^2}{\text{C}^2}$  and  $\epsilon$  is absolute permittivity.

Electric field is said to exist in the region of space around a charged object: the source is charge. Electric field due to a charge is the space around the test charge in which it experiences a force. The presence of an electric field around a charge cannot be detected unless another charge is brought towards it. When a test charge  $q_0$  is placed near a charge  $q$ , which is the source of electric field, an electrostatic force  $F$  will act on the test charge (fig. 12.2).

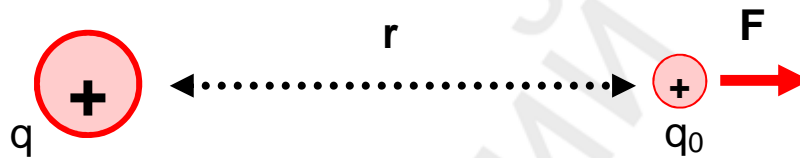


Fig. 12.2. A test charge  $q_0$  is placed near a charge  $q$ , which is the source of electric field, an electrostatic force  $F$  acts on the test charge

If a positive charge  $q$  is fixed at some point in space, any other positive charge  $q_0$  (test charge) which is brought close to it will experience a repulsive force. The repulsive force  $F$  is directly proportional to the test charge  $q_0$  (in each point of electric field):

$$F \sim q_0, \text{ or } \Rightarrow \vec{F} = \vec{E}q_0. \quad (12.2)$$

Thus, the ratio

$$\vec{E} = \frac{\vec{F}}{q_0} \quad (12.3)$$

does not depend on the point charge  $q_0$  and is called the **electric field strength** or **electric field intensity**.

The electric field strength  $E$  at a point in space is defined as the electric force  $F$ , acting on a positive test charge  $q_0$ , placed at that point divided by the magnitude of the charge. It is a vector quantity. The unit of electric field intensity is  $\text{N C}^{-1}$ .

The concept of field lines was introduced by Michael Faraday as an aid in visualizing electric and magnetic fields. The electric field line is an imaginary straight or curved path along which a unit positive charge tends to move in an electric field. The electric field lines of the point positive and negative charges are shown in fig. 12.3.

Properties of the electric field lines are:

- the electric field lines start from positive charge and terminate at negative charge;
- the electric field line never intersect;
- the tangent to a electric field line at any point gives the direction of the electric field ( $E$ ) at that point;
- the number of lines per unit area, through a plane at right angles to the lines, is proportional to the magnitude of  $E$ . This means that, where the electric field lines are close together,  $E$  is large and where they are far apart,  $E$  is small.

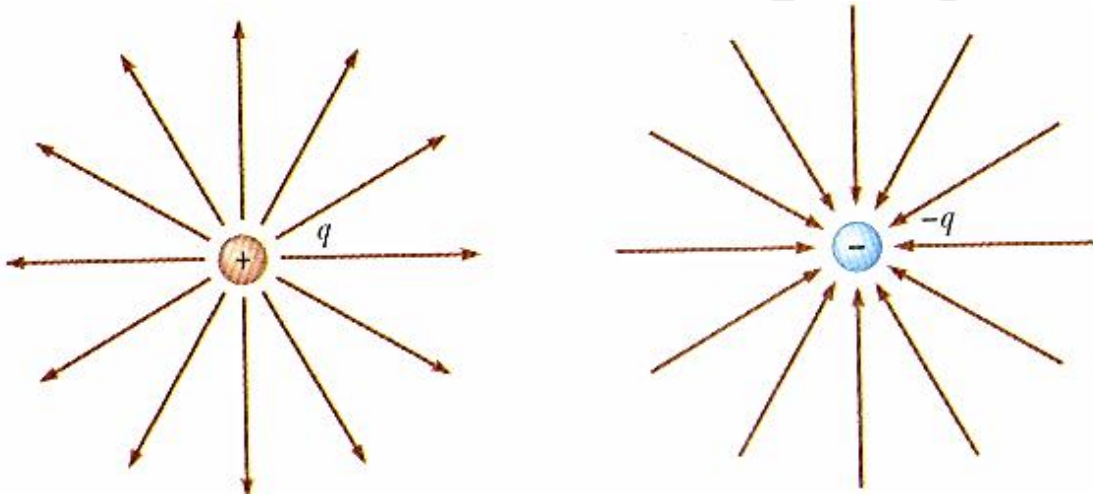


Fig. 12.3. The electric fields lines of the point positive and negative charges

Let  $q$  be the point charge placed at point O in air (fig. 12.4). A test charge  $q_0$  is placed at point A at a distance  $r$  from  $q$ .

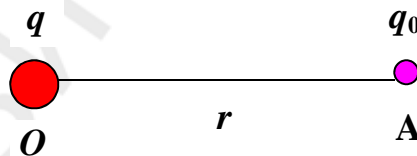


Fig. 12.4. A test charge  $q_0$  is placed at point A at a distance  $r$  from the point charge  $q$  placed at point O

According to Coulomb's law, the force acting on  $q_0$  due to  $q$  is:

$$F = k \frac{qq_0}{\epsilon r^2}. \quad (12.4)$$

The electric field at a point A is, by definition, the force per unit test charge.

$$E = \frac{F}{q_0} = k \frac{q}{\epsilon r^2}. \quad (12.5)$$

If there are a number of stationary charges (fig. 12.5)  $q_1, q_2, q_3, \dots, q_n$ , the net electric field at a point is the vector sum of the individual electric fields due to each charge. It is **the principle of superposition**:

$$\vec{E} = \vec{E}_1 + \vec{E}_2 + \vec{E}_3 + \dots + \vec{E}_n. \quad (12.6)$$

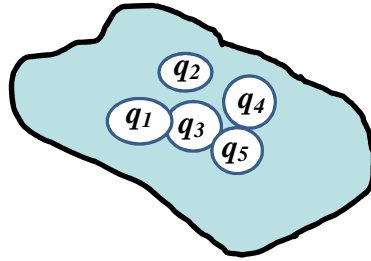


Fig. 12.5. A number of stationary charges  $q_1, q_2, q_3, \dots, q_n$

The work  $A$  done by an electric force  $F$  or «field» in moving a positive test charge  $+q_0$  along the electric field line at a distance  $d$  is:

$$A = F \cdot d = q_0 \cdot E \cdot d. \quad (12.7)$$

Therefore, any test charge in electric field is said to have an electric potential energy:  $W_{\text{pot}} = A \sim q_0$ , which is directly proportional to the magnitude of the charge  $q_0$ . The electric potential energy depends upon the charge placed in the electric field. To quantify the potential energy in terms of only the field itself it is more useful to define it per unit charge:

$$j = \frac{W_{\text{pot}}}{q_0}. \quad (12.8)$$

Electric potential  $\phi$  is potential energy per unit charge. Electric potential  $\phi$  is a scalar characteristic of an electric field, independent of any other charges. Unit of electric potential  $\phi$  is Volt (V) (1 Volt = 1 Joule per Coulomb (J/C)).

The potential from a collection of  $n$  charges is just the algebraic sum of the potential due to each charge separately (this is much easier to calculate than the net electric field, which would be a vector sum). Potential due to a group of point charges:

$$\phi = \phi_1 + \phi_2 + \phi_3 + \dots + \phi_n. \quad (12.9)$$

If all the points of a surface are at the same electric potential, then the surface is called an equipotential surface.

In case of an isolated point charge, all points equidistant from the charge are at same potential. Thus, equipotential surfaces in this case will be a series of concentric spheres with the point charge as their centre (fig. 12.6). The potential will however be different for different spheres.

If the charge is to be moved between any two points on an equipotential surface through any path, the work done is zero. This is because the potential difference between two points A and B is defined as  $\phi_B - \phi_A = W_{AB} / q$ . If  $\phi_B = \phi_A$  then  $W_{AB} = 0$ . Hence the electric field lines must be normal to an equipotential surface.

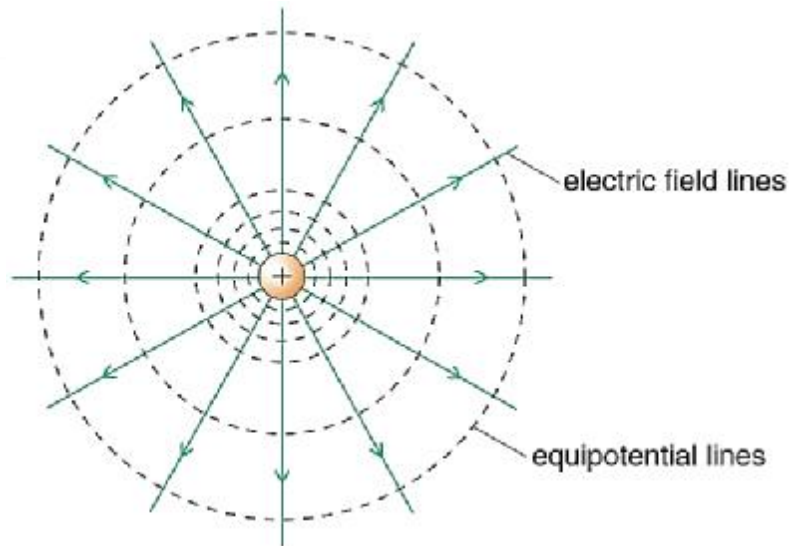


Fig. 12.6. The equipotential lines and electric field lines

Let  $+q$  be an isolated point charge situated in air at point  $O$ .  $B$  is a point at a distance  $r$  from  $+q$ . The electric potential  $\phi$  at the point  $B$  due to the charge  $+q$  is the total work done in moving a unit positive charge from infinity to that point:

$$\phi = k \frac{q}{\epsilon r}. \quad (12.10)$$

Suppose charge  $q_0$  is moved from point **1** to point **2** through a region of space described by electric field  $E$  (fig. 12.7).

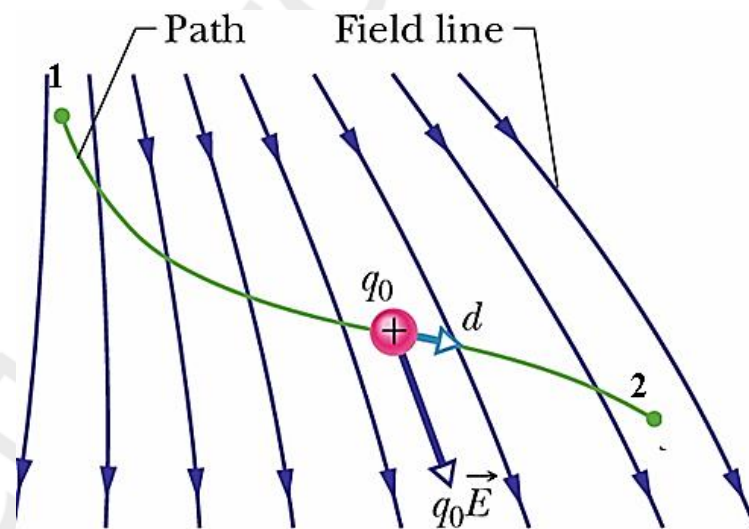


Fig. 12.7. The charge  $q_0$  is moved from point **1** to point **2** through a region of space described by electric field  $E$

The work  $A$  done by the electric field in bringing the charge  $q_0$  from point **1** to point **2** can be written:

$$A = W_{\text{pot1}} - W_{\text{pot2}} = q_0 (\phi_1 - \phi_2) = q_0 U. \quad (12.11)$$

The potential difference  $U$  between point **1** and point **2** is:

$$U = \varphi_1 - \varphi_2 = E \cdot d. \quad (12.12)$$

The potential difference between two points in an electric field is defined as the amount of work done in moving a unit positive charge from one point to the other against the electric force. The unit of potential difference  $U$  is volt. The potential difference between two points is 1 volt if 1 joule of work is done in moving 1 Coulomb of charge from one point to another against the electric force. The electric potential in an electric field at a point is defined as the amount of work done in moving a unit positive charge from infinity to that point against the electric forces. The work  $A$  does not depend upon the exact path chosen to move charge from point **1** to point **2** and is determined by the potential difference between point **1** and point **2**.

The electric field is equal to the negative gradient of potential:

$$\vec{E} = -\text{grad}\varphi. \quad (12.13)$$

The negative sign in the formula indicates that the electric field is pointing to the direction of decreasing potential. The unit of electric intensity can also be expressed as  $\text{V} \cdot \text{m}^{-1}$ .

## 12.2. ELECTRIC DIPOLE AND ITS FIELD

A system of two equal and opposite ( $q^+$  and  $q^-$ ) charges separated by a certain distance  $l$  is called an electric dipole (fig. 12.8). It has an electric dipole moment  $P$ .  $P$  is a vector that points from the negative charge to the positive charge.

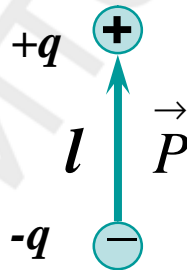


Fig. 12.8. A system of two equal and opposite  $q^+$  and  $q^-$  charges separated by a certain distance  $l$

**Dipole moment**  $P$  is a measure of the strength of electric dipole. The magnitude of the dipole moment is given by the product of the magnitude of the one of the charges  $q$  and the distance  $l$  between them:

$$\vec{P} = q \vec{l}. \quad (12.14)$$

The unit of dipole moment  $P$  is C m.

Let  $A$  be the point at a distance  $r$  from the midpoint of the dipole  $O$  and  $\theta$  be the angle between  $AO$  and the axis of the dipole. Let  $r_1$  and  $r_2$  be the distances of the point  $A$  from  $+q$  and  $-q$  charges respectively (fig. 12.9).



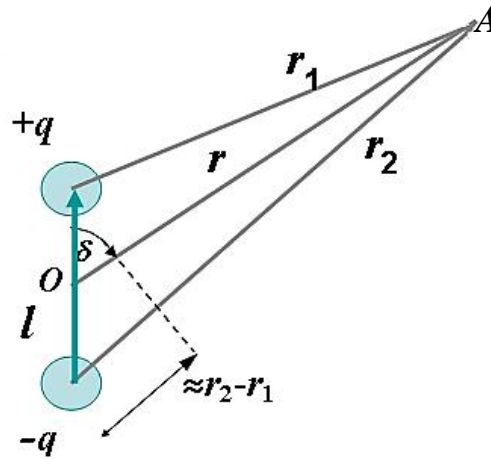


Fig. 12.9. Potential of dipole field.  $r_1$  and  $r_2$  are the distances of the point A from  $+q$  and  $-q$  charges respectively

Total potential  $\phi_A$  at point A due to dipole is an algebraic sum of potential  $\phi_+$  at point A due to charge  $(+q)$  and potential  $\phi_-$  at point A due to charge  $(-q)$ :

$$\phi_A = \phi_+ + \phi_- = k \frac{q}{\epsilon r_1} - k \frac{q}{\epsilon r_2} = k \frac{q}{\epsilon} \cdot \left( \frac{1}{r_1} - \frac{1}{r_2} \right) \approx k \frac{q}{\epsilon} \frac{(r_2 - r_1)}{r^2}.$$

Rewrite this for special case  $r \gg l$ :  $(r_2 - r_1) \approx l \cos \delta$ .

Then, electric potential at a point due to an electric dipole is determined by formula:

$$\phi_A = k \frac{ql \cos \delta}{\epsilon r^2} = k \frac{p \cos \delta}{\epsilon r^2}. \quad (12.15)$$

Electric field lines and equipotential surfaces for the dipole are illustrated on fig. 12.10.

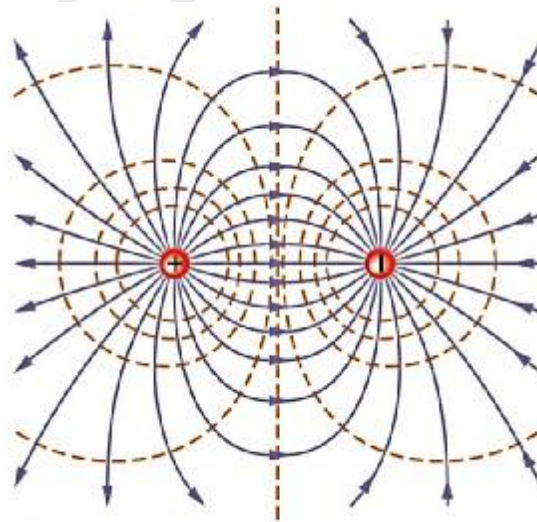


Fig. 12.10. Electric field lines and equipotential surfaces of the dipole

The dashed lines represent equipotential (points of equal potential) lines and the solid lines are the electric field lines.

The potential difference  $U_{AB}$  between point  $A$  and point  $B$  created by dipole (fig. 12.11) is directly proportional to the projection of the dipole moment  $P \cos \alpha$  on the line connecting these points and inversely proportional to the square of the distance  $r$  between the dipole and line:

$$U_{AB} = 2k \frac{p \sin \frac{\beta}{2} \cos \alpha}{\epsilon r^2} \sim \frac{p \cos \alpha}{r^2}. \quad (12.16)$$

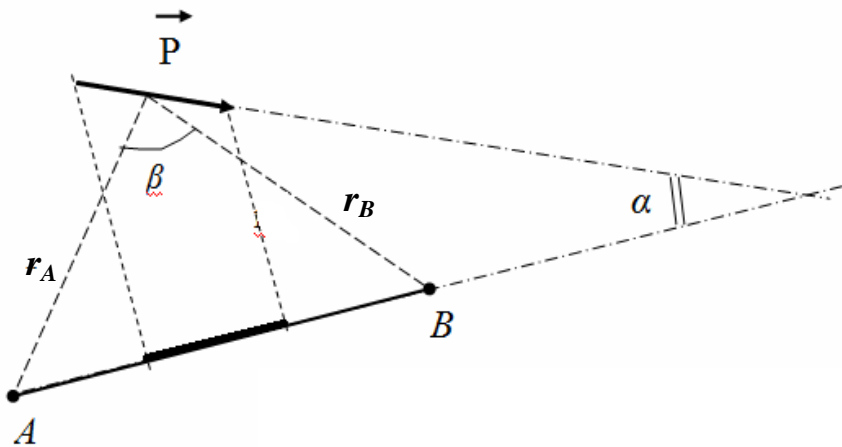


Fig. 12.11. Connection between the dipole moment  $P$  and potential difference  $U_{AB}$ . Points  $A$  and  $B$  are located at a distances  $r_A$  and  $r_B$  from dipole with the dipole moment  $P$

### 12.3. ELECTROCARDIOGRAPHY

An electrocardiogram (ECG) is a recording of electrical activity (potentials) produced by the conduction system and the myocardium of the heart during its depolarization made from electrodes placed on the surface of the skin.

The beating heart generates an electric signal that can be used as a diagnostic tool for examining some of the functions of the heart. This electric activity of the heart can be approximately represented as a vector quantity (an equivalent dipole) called the electric heart vector (fig. 12.12). The heart consists of an electric dipole with dipole moment  $P$  located in the partially conducting medium of the thorax. In electrocardiography this dipole moment is known as the cardiac vector. As we progress through a cardiac cycle, the magnitude and direction of  $P$  vary because the dipole field varies.

In 1901 a Dutch physiologist, Willem Einthoven, developed a galvanometer that could record the electrical activity of the heart. He found that a tracing can be produced as action potentials spread between negatively and positively charged electrodes. A third electrode serves to ground the current. He found that tracings varied according to the location of the positive and negative electrodes, and subsequently described three angles or leads in the form of a triangle with the heart in the middle. This is known today as Einthoven's triangle, and the three electrode arrangements are known as the standard limb leads I, II, and III (fig. 12.13). If the two electrodes are located on different equal-potential lines

of the electric field of the heart, a nonzero potential difference or voltage is measured.

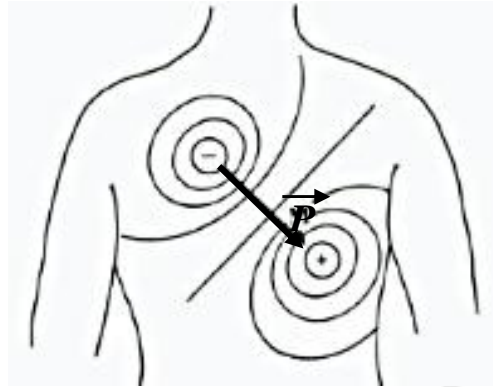


Fig. 12.12. The heart can be approximately represented as a vector quantity (an equivalent dipole) called the electric heart vector with dipole moment  $P$  located in the partially conducting medium of the thorax

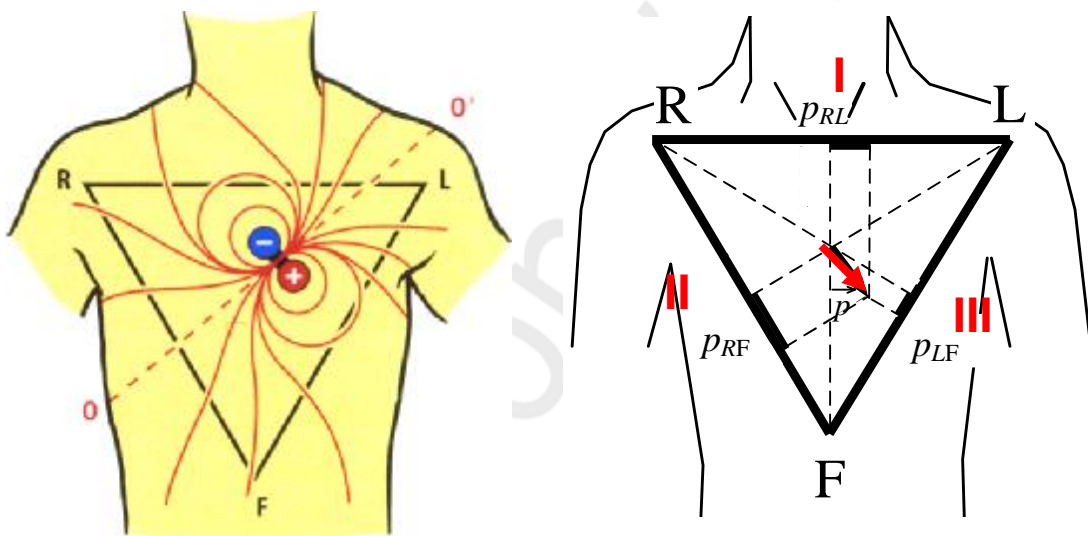


Fig. 12.13. Einthoven's triangle with three standard limb leads (I, II, and III)

Thus, Einthoven's triangle is a hypothetical triangle created around the heart when electrodes are placed on both arms and the left leg. The heart is considered to be at the center of an equilateral triangle, each corner of which serves as the location for an electrode for two leads to the ECG recorder. The three standard limb leads are I, II, and III. Lead I records the potential difference between right arm and left arm. Lead II records the potential difference between right arm and left leg. Lead III records the potential difference between left arm and left leg.

According to Einthoven's law these lead voltages have the following relationship:

$$U_{II}(t) = U_{I}(t) + U_{III}(t). \quad (12.17)$$

As research continued throughout the 20th century, additional arrangements were discovered that enable physicians to analyze electrical events as they

spread in many directions through the heart. Today, the cardiologist uses a 12-lead ECG system consisting of the following 12 leads, which are:

- I, II, III — three bipolar limb;
- $\alpha$ VR,  $\alpha$ VL, and  $\alpha$ VF — augmented unipolar limb leads;
- V<sub>1</sub>, V<sub>2</sub>, V<sub>3</sub>, V<sub>4</sub>, V<sub>5</sub>, V<sub>6</sub> — six chest leads.

Three augmented unipolar limb leads are used for frontal plane measurements (fig. 12.14). Three additional limb leads  $\alpha$ VR,  $\alpha$ VL, and  $\alpha$ VF are obtained by measuring the potential between each limb electrode and the Wilson central terminal.

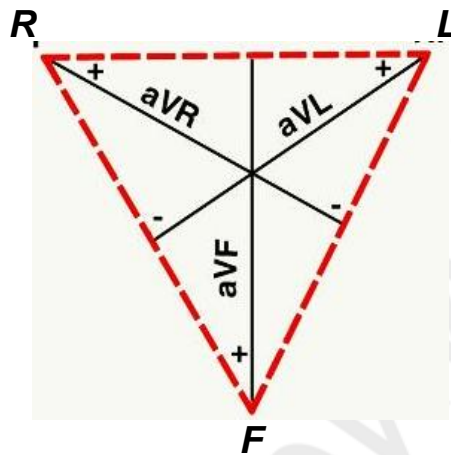


Fig. 12.14. Augmented unipolar limb leads —  $\alpha$ VR,  $\alpha$ VL, and  $\alpha$ VF

For measuring the potentials close to the heart, Wilson introduced the precordial leads (chest leads) in 1944. These leads, V<sub>1</sub>–V<sub>6</sub> are located over the left chest as described in the fig. 12.15. Each of the six precordial leads is unipolar (1 electrode constitutes a lead) and is designed to view the electrical activity of the heart in the horizontal or transverse plane.

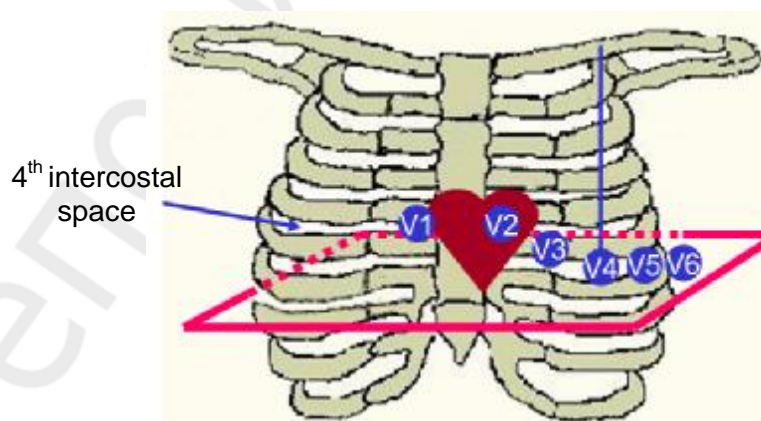


Fig. 12.15. Six chest leads V<sub>1</sub>–V<sub>6</sub>

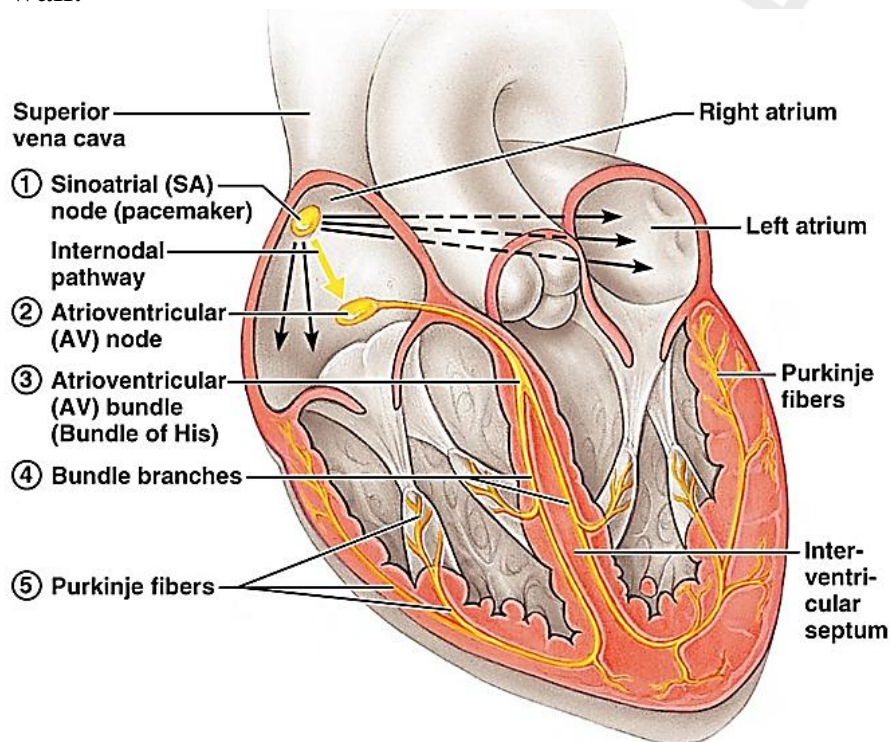
### Cardiac conduction system

To fully appreciate electrical impulses and the information provided by an ECG, let's review fundamental concepts regarding electrical membrane

potentials. All cardiac cell membranes are positively charged on their outer surfaces because of the relative distribution of cations. This resting membrane potential is maintained by an active transport mechanism called the sodium-potassium pump. When the cell is stimulated, ion channels open, allowing a sudden influx of sodium and/or calcium ions and thereby reversing the resting potential. This period of depolarization is very brief because sodium channels close abruptly, denying further influx of sodium. Simultaneously, potassium channels open and allow intracellular potassium to diffuse outward while sodium ions are actively pumped out. This reestablishes a positive charge to the outside of the membrane, a process called repolarization that returns the membrane to its resting membrane potential. The processes of depolarization and repolarization are referred to collectively as an action potential. This event self-propagates as an impulse along the entire surface of a cell and from one cell to another, provided that their membranes are connected.

Mechanical contraction of the heart is caused by the electrical excitation of the myocardial cells. The heart is largely autonomous having the ability to initiate its own beat with a regular period, so that it will continue to beat after being removed from the body. Cells capable of initiating electrical activity are called pacemaker cells, and exist in several places throughout the heart. Only those pacemaker cells with the fastest rate of pacemaker discharge control the electrical activity of the entire heart. The region of tissue with the shortest period of spontaneous electrical activity is the sinoatrial (SA) node which is located on the atrial wall near the junction of the superior vena cava and the right atrium (fig. 12.16). Action potentials are normally generated here at the rate of 60 to 100 per minute. From the SA node, the action potential is propagated from cell to cell through firstly the right atrium, followed closely by the left atrium at a conduction velocity of approximately  $1\text{ m s}^{-1}$  until it reaches the atrioventricular (AV) node. The AV node consists of similar pacemaker-type cells as are found in the SA node but, because they beat spontaneously at a slower rate (approximately 40 to 55 beats per minute), they are paced by the excitation propagating from the SA node. In the event that the SA node is removed or destroyed, or that conduction is slowed through the atria, the cells in the AV node will take over as pacemaker for the ventricles. Conduction through the AV node is at a much slower rate (around  $0,05\text{ m s}^{-1}$ ) giving time for the atria to contract and pump blood into the ventricles before the action potential conducts through the ventricles and causes them to contract. Under normal conditions, the AV node is the only electrical connection between the atria and the ventricles with electrical propagation exciting the bundle of His' which forms the upper portion of the ventricular conduction system and runs down the right side of the septum. This common bundle divides after a short distance into right and left bundle branches. The right branch continues down the right septal wall, and the left perforates the septum and splits into two (or

three) further main branches on the left septal wall. All of these branches then continue to subdivide into a complex network of fibres called the Purkinje fibre network, spreading across the endocardial surface of both ventricles and into the subendocardial region of the ventricular myocardium. Due to this extensive arrangement of Purkinje fibres, the septum (except its basal region) is activated first and normally pushes in towards the left ventricular wall. The papillary muscles are also activated early thereby preventing the AV valves from inverting during systole. The fast conduction of approximately  $1,5$  to  $4 \text{ m s}^{-1}$  through the bundle branches and Purkinje fibres cause the entire endocardium to be excited almost simultaneously. The apical regions contract first and the basal regions are usually the last regions to be excited. Excitation spreads outwards through the ventricular wall at a rate of approximately  $0,3$  to  $0,5 \text{ m s}^{-1}$ , and the first epicardial region to be excited is the thinnest portion of the right ventricular wall.



*Fig. 12.16.* The conduction system of the heart:

sinoatrial node (SA node) is the «pacemaker», located in right atrial wall causes depolarization and contraction of the atria, and depolarization of the AV node; atrioventricular node (AV node) — there is a slight delay at the AV node to allow the atria to contract completely before the ventricles contract, after the delay the bundle of His (AV bundle) depolarizes within the atrioventricular septum; Bundle branches (right and left) — carry the depolarization to the purkinje fibers in the right and left ventricles; purkinje fibers — depolarize and contract the ventricles

### **The ECG tracing**

A typical normal signal recorded between two electrodes is shown in fig. 12.17. The baseline of an ECG tracing is called the isoelectric line and

denotes resting membrane potentials. The main features of this wave form are identified by the letters *P*, *Q*, *R*, *S*, and *T*. The shape of these features varies with the location of the electrodes. A trained observer can diagnose abnormalities by recognizing deviations from normal patterns.

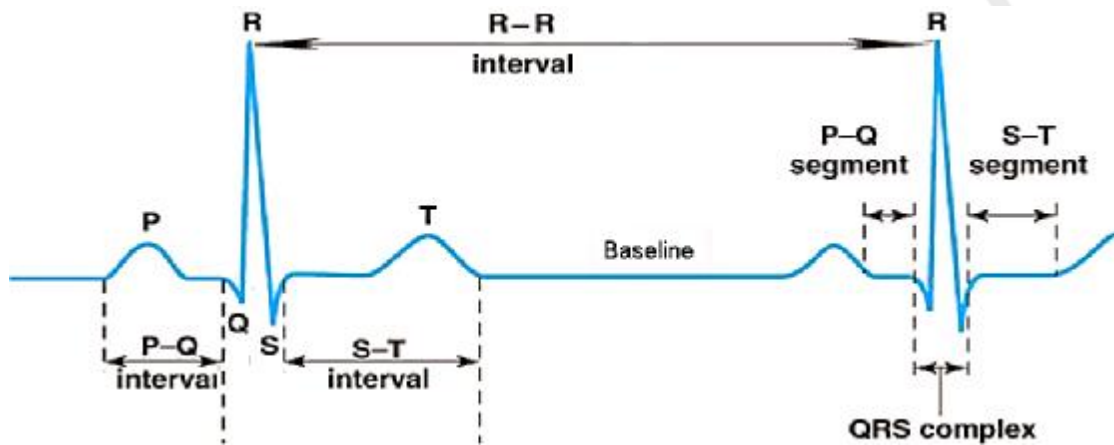


Fig. 12.17. The ECG with interval and segment measurements

**The P Wave and Atrial Depolarization.** Atrial excitation results from a wave of depolarization that originates in the SA node and spreads over the atria.

**The PQ Segment and Atrioventricular Conduction.** After the P wave, the ECG returns to the baseline present before the P wave. The ECG is said to be isoelectric when there is no deflection from the baseline established before the P wave. During this time, the wave of depolarization moves slowly through the AV node, the AV bundle, the bundle branches, and the Purkinje system. The isoelectric period between the end of the P wave and the beginning of the QRS complex, which signals ventricular depolarization is called the PQ segment.

**The QRS Complex and Ventricular Depolarization.** The QRS complex is larger than P wave because of greater muscle mass of ventricles. The depolarization wave emerges from the AV node and travels along the AV bundle (bundle of His), bundle branches, and Purkinje system; these tracts extend down the interventricular septum. The small downward deflection produced on the ECG is the Q wave. The normal Q wave is often so small that it is not apparent. The wave of depolarization spreads via the Purkinje system across the inside surface of the free walls of the ventricles. The Q, R, and S waves together are known as the QRS complex and show the progression of ventricular muscle depolarization. The duration of the QRS complex is roughly equivalent to the duration of the P wave, despite the much greater mass of muscle of the ventricles. The relatively brief duration of the QRS complex is the result of the rapid, synchronous excitation of the ventricles.

**The ST Segment.** The ST segment is the period between the end of the S wave and the beginning of the T wave. The ST segment is normally isoelectric, or nearly so.

**The T Wave and Ventricular Repolarization.** Repolarization, like depolarization, generates a dipole because the voltage of the depolarized area is different from that of the repolarized areas. The T wave has a longer duration than the QRS complex because repolarization does not proceed as a synchronized, propagated wave. Instead, the timing of repolarization is a function of properties of individual cells, such as numbers of particular  $K^+$  channels.

**The QT Interval.** The QT interval is the time from the beginning of the QRS complex to the end of the T wave. If ventricular action potential and QT interval are compared, the QRS complex corresponds to depolarization, the ST segment to the plateau, and the T wave to repolarization (fig. 12.18). The relationship between a single ventricular action potential and the events of the QT interval are approximate because the events of the QT interval represent the combined influence of all of the ventricular action potentials. The QT interval measures the total duration of ventricular activation.

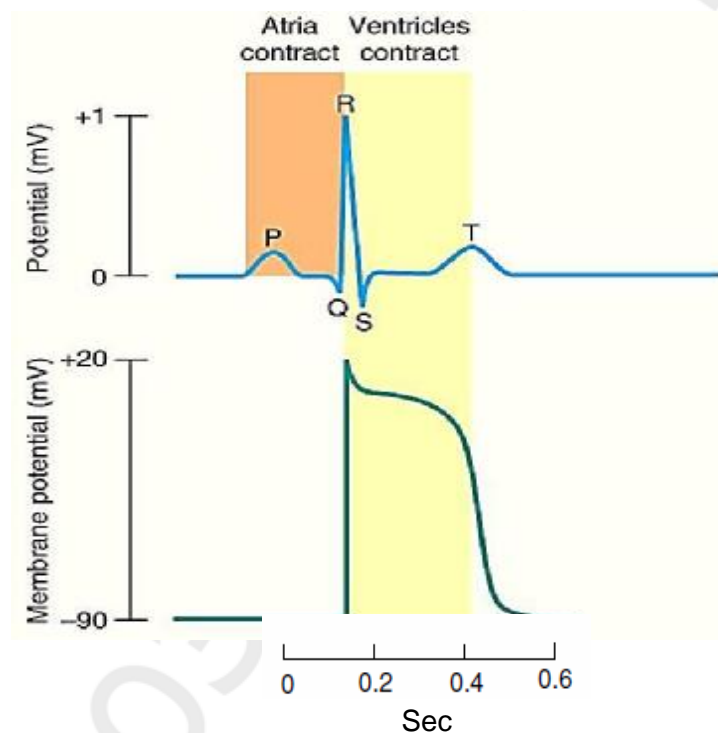


Fig. 12.18. The ECG and action potential of myocardial cell in ventricles

**Questions:**

1. What types of electric charges are known? Specify their units. Write Coulomb's Law.
2. What are the main characteristics of the electric field? Write formulas for electric field strength and potential.
3. What is the relation between the electric field strength and potential?
4. What is the electrical dipole? How to calculate electric potential at a point due to an electric dipole? Write the formula.
5. Write formula for the potential difference between two points created by dipole.
6. Why do certain organs and tissues create electrical fields? What determines the fields? What is the integral electric organ vector? What is the electrogram?



7. What are Einthoven's theory fundamentals? What are standard bipolar limb leads; augmented unipolar limb leads?

8. Give the approximated ECG. Specify which the physiological processes related to main waves and intervals of ECG.

## Chapter 13. ELECTROCONDUCTIVITY OF TISSUES AND LIQUIDS FOR DIRECT CURRENT

### 13.1. DIRECT CURRENT IN ELECTROLYTES

The current is defined as the rate of flow of charges across any cross sectional area of a conductor. The conditions for current flow are following: the presence of free charge carriers and the presence of an electric field. If a net charge  $q$  passes through any cross section of a conductor in time  $t$ , then the current  $I = q/t$ , where  $q$  is in coulomb and  $t$  is in second. The current  $I$  is expressed in ampere (A). If the rate of flow of charge is not uniform, the current varies with time and the instantaneous value of current  $i$  is given by  $i = dq/dt$ . Current is a scalar quantity. The direction of conventional current is taken as the direction of flow of positive charges or opposite to the direction of flow of electrons. When the current in a circuit has a constant magnitude and direction the current is called direct current (DC).

Current density at a point is defined as the quantity of charge passing per unit time through unit area, taken perpendicular to the direction of flow of charge at that point. The current density  $j$  for a current  $I$  flowing across a conductor having an area of cross section  $S$  is

$$j = \frac{I}{S}. \quad (13.1)$$

Current density  $j$  is a vector quantity. It is expressed in  $A \cdot m^{-2}$ .

George Simon Ohm established the relationship between potential difference and current, which is known as Ohm's Law. The law states that, at a constant temperature, the steady current flowing through a conductor is directly proportional to the potential difference between the two ends of the conductor:

$$I = \frac{U}{R}. \quad (13.2)$$

The current  $I$  is measured in amperes, the voltage  $U$  in volts and the resistance  $R$  in ohms ( $\Omega$ ).

The resistance of a conductor  $R$  is directly proportional to the length of the conductor  $l$  and is inversely proportional to its area of cross section  $S$ :

$$R = \frac{\rho l}{S},$$

where  $\rho$  is called specific resistance or electrical resistivity of the material. The unit of  $\rho$  is  $\Omega \cdot m$ .

### Ohm's law from an electromagnetic field point of view

To derive Ohm's Law at a point from Ohm's Law for resistors, it is necessary to relate the circuit quantities (voltage  $U$  and current  $I$ ) to the field quantities (electric field strength  $E$  and current density  $j$ ).

After substitution of resistance  $R = \frac{\rho l}{S}$  into the equation of Ohm's it is easy to obtain:  $I = \frac{US}{\rho l}$ .

Taking into account that  $j = \frac{I}{S}$  and  $E = \frac{U}{l}$ , one can write equation for current density  $j$ :  $j = \frac{E}{\rho}$ .

The reciprocal of electrical resistivity, is called electrical conductivity  $\sigma$ :  $\sigma = \frac{1}{\rho}$ .

The unit of conductivity  $\sigma$  is siemens [S] = [ $\Omega^{-1} \text{ m}^{-1}$ ].

Thus, Ohm's Law at a point can be obtained as:

$$j = \sigma E. \quad (13.4)$$

### The electric current in electrolytes

Let's find the dependence of electrical conductivity of the electrolyte's properties. In conductive liquids both positive and negative charges (ions of both signs) carry current.

Consider a cylindrical conductive liquids with a charge carrier density of  $n = n_+ + n_-$  in which a current  $I$  is flowing. This constitutes an average drift velocity  $v_+$ ,  $v_-$  of each charge carrier.

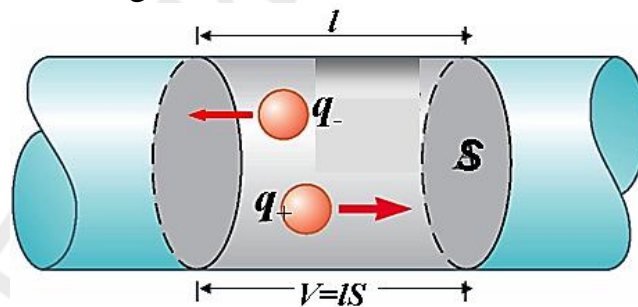


Fig. 13.1. The selected volume of the electrolyte

Each charge carrier (positive  $q_+$  or negative  $q_-$  ion) moves on average a distance  $l$ :  $l_+ = v_+ t = \mu_+ E t$  and  $l_- = v_- t = \mu_- E t$ , where mobility is velocity of the charge carrier per electrical field strength.

The total charge  $Q = Q_+ + Q_-$  transferred during time  $t$  through the cross-sectional area  $S$  is:

$$Q = Q_+ + Q_- = q_+ n_+ S l_+ + q_- n_- S l_- = (q_+ n_+ \mu_+ + q_- n_- \mu_-) S t E. \quad (13.5)$$

The equation for current density  $j$  can be written as:

$$j = \frac{I}{S} = \frac{Q}{St} = \frac{(q_+n_+\mu_+ + q_-n_-\mu_-)StE}{St} = (q_+n_+\mu_+ + q_-n_-\mu_-)E. \quad (13.6)$$

Therefore the conductivity  $\sigma$  of an electrolyte is equal:

$$\sigma = q_+n_+\mu_+ + q_-n_-\mu_-. \quad (13.7)$$

The charge and concentration of the positive and negative ions is equal in the case of dissociation:  $|q_+| = |q_-| = q$  and  $n_+ = n_- = \alpha n$ , where  $\alpha$  is the coefficient of the dissociation.

The equation for electrolyte conductivity  $\sigma$  can be written as:

$$\sigma = qn\alpha(\mu_+ + \mu_-). \quad (13.8)$$

Thus, the conductivity  $\sigma$  depends on the value of the ion charge  $q$ , concentration  $n$ , coefficient of the dissociation  $\alpha$  and mobility of the ions  $\mu$ .

### 13.2. FEATURES OF ELECTRICAL CONDUCTIVITY OF BIOLOGICAL TISSUES

Biological tissue, actually display some characteristics of both insulators and conductors because they contain dipoles as well as charges that can move, but in a restricted manner. For materials that are heterogeneous in structure, charges may become trapped at interfaces.

Mechanism of direct current passing through the living tissue is presented in fig. 13.2.

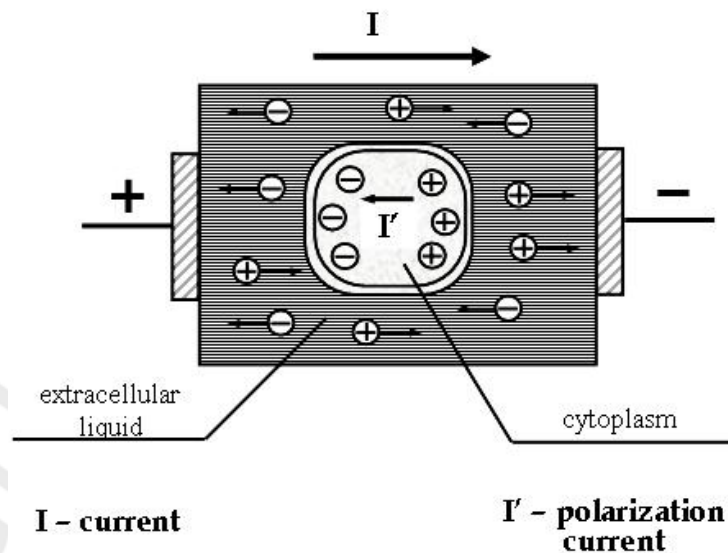


Fig. 13.2. The movement of ions in extracellular liquid and cytoplasm.  $I$  is the principal current;  $I'$  is the interstitial polarization current

The principal tissue current is determined by ions motion in the extracellular liquid under the applied potential difference. Inside cellular structures positive and negative ions start to move in opposite directions under the applied field.

Since the cellular membranes have low conductivity the equal signs ions are accumulated on cell membranes so generating polarization zones and field inside tissues. Charge separation takes place within the cell structures and the opposite direction potential difference appears causing interstitial polarization current. Interstitial polarization appears, which causes appearance of opposite direction current in relation to principal current. It creates additional resistance to active current.

Electrical properties of tissues and organs differ greatly. Epidermis, conjunctive tissues, bone without periosteum, chordas have a high electrical resistance. These tissues can be related to dielectrics. Body liquid media have low-resistance and good electric conductivity. The following tissues have small direct-current resistance: cerebrospinal fluid, blood, blood plasma, extracellular fluids.

### 13.3. SOME THERAPEUTIC METHODS BASED ON THE USE OF DIRECT CURRENT

**Galvanization** is a method of direct current medical use: low voltage current (less than 80 V) and small amperage (less than 50 mA). A maximum value of current density used is  $0,1 \text{ mA/sm}^2$ . Stainless steel, conductive rubber or fabric is used as electrodes. Gaskets are necessary to eliminate the possibility of chemical burn patient electrolysis products formed between the electrode and the skin during the course of DC.

The primary physical mechanisms of direct current action on tissue is caused by the motion of the ions, their separation and the change in ion concentrations in different tissue cells. When a direct current is applied to the tissue by means of two electrodes, the ions will move away from or towards the electrodes: the cations (+) will move towards the cathode (-) and the anions (-) will move towards the anode (+). Polarization is provided by accumulation of equal signs ions on plasmolemma, basement membranes and fascias different surfaces, interstitial polarization appears, which causes appearance of opposite direction current in relation to principal current. It creates additional resistance to active current, but at the same time these zones are places of the most active current action (after epidermis). Simultaneously with ions movement electric current modifies membrane permeability of tissues and increases passive transport of large protein molecules and other matters. Moreover, physiological diffusion and osmosis in human tissues are intensified due to DC action.

The thermal effect is negligible when galvanization is used as the current density is low (less than  $0,1 \text{ mA/sm}^2$ ).

**Iontophoresis** is a process of delivery of ionic (charged) drugs into the body by the use of electric current. Iontophoresis is an alternative to oral or parenteral (e. g., needle injection) methods of drug delivery. This method is called electropharmacological because of combination of physical (electrical current) and chemical (ionic (charged) drugs) factors. This factors together

increase effects of each other. Electric current acting on the receptors of tissue excites them and effect of the medicine may be increased or weakened. The drug effect is more significant even in small concentration under current acting. Low amperage currents appear to be more effective as a driving force than currents with higher intensities.

The drug is administered through an electrode (active) which has the same charge as the drug. This is very important. If the polarity of the electrode is not the same as the ions, then penetration through the skin may not occur. During the procedure drug goes not so deeply and is concentrated in skin, partly in subcutaneous fat. It is possible to make a superficial pathological region of a high concentration drug and to have a local effect. Iontophoresis has wide applications in dermatology, ophthalmology, allergic conditions even in cardiac and neurological situations, but its greatest advantage is in the transport of protein or peptide drugs which are very difficult to transport transdermally due to their hydrophilicity and large molecular size.

**Questions:**

1. Derive Ohm law in differential form.
2. What is the relation between electrical conductivity and electrical resistivity?
3. What is the interstitial polarization current? What is the reason of its appearance?
4. Whether the physiotherapy based on the direct current is attended by noticeable heat effect? Why?
5. What are differences between galvanization and iontophoresis?

## **Chapter 14. THE ALTERNATING CURRENT. THE ELECTRICAL IMPEDANCE OF LIVING TISSUE**

### **14.1. MAIN CHARACTERISTICS OF THE ALTERNATING CURRENT**

The alternating currents (AC) varying according to harmonic law have the most important practical significance. The instantaneous value of voltage and current is given by:

$$U = U_m \sin \omega t; \quad I = I_m \sin(\omega t + \varphi), \quad (14.1)$$

where  $U_m$  is the amplitude value of voltage;  $I_m$  is the amplitude value of current;  $\omega = 2\pi n = 2\pi/T$ ;  $\omega$  is angular frequency (radians/sec);  $n$  is the frequency (measured in Hertz, 1/sec);  $T$  is the period;  $\varphi$  is the phase difference between current and voltage (radians).

Averaged over the period magnitudes of alternating currents and voltages ( $I_{eff}$  and  $U_{eff}$ ) determine their effect and are called effective values of an AC.  $I_{eff}$  and  $U_{eff}$  are related to the amplitude values of AC ( $U_m$  and  $I_m$ ) by the following expressions:

$$U_{eff} = \frac{U_m}{\sqrt{2}}; \quad I_{eff} = \frac{I_m}{\sqrt{2}}. \quad (14.2)$$

The average power  $P$  of an AC circuit is also called the true power of the circuit and is given by:

$$P = I_{eff}U_{eff}\cos\varphi; P = \frac{1}{2}I_mU_m\cos\varphi, \quad (14.3)$$

where  $\cos\varphi$  is the power factor. The average power  $P$  depends strongly on the phase difference  $\varphi$  between current and voltage.

### 14.2. AC CIRCUIT WITH RESISTOR

Let an alternating source of voltage be connected across a resistor of resistance  $R$  (fig. 14.1).

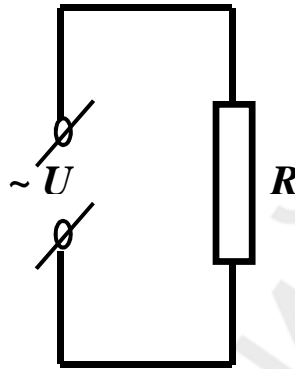


Fig. 14.1. AC circuit with a resistor

The instantaneous value of the applied voltage  $U$  is:

$$U = U_m\sin\omega t. \quad (14.4)$$

The current  $I$  through the circuit at the instant  $t$ :

$$I = \frac{U}{R} = \frac{U_m}{R}\sin\omega t = I_m\sin\omega t. \quad (14.5)$$

Equation (14.5) gives the instantaneous value of current in the circuit containing  $R$ . From the expressions of voltage and current given by equations (14.4) and (14.5) it is evident that in a resistive circuit, the applied voltage and current are in phase with each other (fig. 14.2). Average power  $P$  ( $j = 0$  and  $\cos\varphi = 1$ ) is maximal:

$$P_R = I_{eff}U_{eff} = \frac{1}{2}I_mU_m.$$

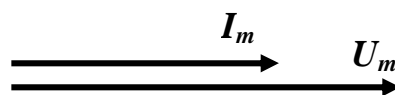


Fig. 14.2. The phasor diagram of AC circuit with a resistor representing the phase relationship between the current and the voltage

### 14.3. AC CIRCUIT WITH A CAPACITOR

An alternating source of voltage is connected across a capacitor of capacitance  $C$  (fig. 14.3). It is charged first in one direction and then in the other direction.

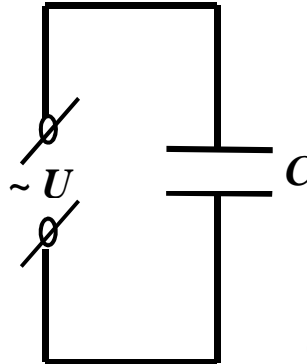


Fig. 14.3. AC circuit with a capacitor

The charge  $q$  in the capacitor will vary according to the law:

$$q = CU = CU_m \sin \omega t.$$

But the current  $I$  is the time derivative of the charge:

$$I = \frac{dq}{dt} = CU_m \omega \cdot \cos \omega t = I_m \sin \left( \omega t + \frac{\pi}{2} \right) \quad (14.6)$$

where  $I_m = C\omega U_m$ .

$$X_C = \frac{U_m}{I_m} = \frac{1}{\omega C} \quad (14.7)$$

is the resistance offered by the capacitor. It is called capacitive reactance.

From equation (14.4), it follows that in an AC circuit with a capacitor, the current leads the voltage by a phase angle of  $\pi/2$  and average power  $P_c = 0$  ( $\varphi = \pi/2$ ,  $\cos \varphi = 0$ ). This is represented graphically in fig. 14.4.

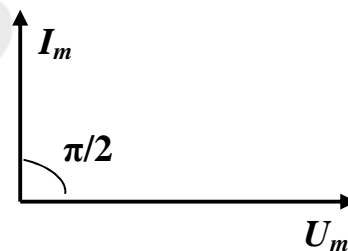


Fig. 14.4. The phasor diagram of AC circuit with a capacitor representing the phase relationship between the current and the voltage

### 14.4. AC CIRCUIT WITH AN INDUCTOR

Let an alternating source of voltage be applied to a pure inductor of inductance  $L$  (fig. 14.5). The inductor has a negligible resistance  $R = 0$ .

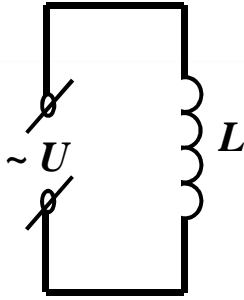


Fig. 14.5. AC circuit with an inductor

Due to an alternating voltage that is applied to the inductive coil, a self induced emf is generated which opposes the applied voltage:

$$\mathcal{E}_L = -L \frac{dI}{dt} = -U_m \sin \omega t.$$

The solution of this differential equation for current is:

$$I = -\frac{U_m}{\omega L} \cdot \cos \omega t = I_m \sin(\omega t - \frac{\pi}{2}). \quad (14.8)$$

$$X_L = \omega L \quad (14.9)$$

is the resistance offered by the inductor.

It is clear from equation (14.8) that in an AC circuit containing a pure inductor the current  $I$  lags behind the voltage  $U$  by the phase angle of  $\pi/2$  and average power  $P_L = 0$  ( $\varphi = -\pi/2$ ,  $\cos \varphi = 0$ ). This fact is presented graphically in fig. 14.6.

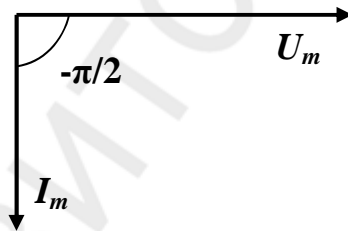


Fig. 14.6. The phasor diagram of AC circuit with an inductor representing the phase relationship between the current and the voltage

### 14.5. RESISTOR, INDUCTOR AND CAPACITOR IN SERIES

Let an alternating source of voltage  $U$  be connected to a series combination of a resistor of resistance  $R$ , inductor of inductance  $L$  and a capacitor of capacitance  $C$  (fig. 14.7).

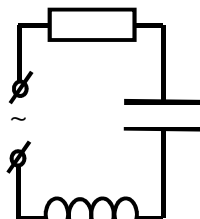


Fig. 14.7. The series LCR circuit



The expression

$$Z = \frac{U_m}{I_m} = \sqrt{R^2 + (X_C - X_L)^2} = \sqrt{R^2 + \left(\frac{1}{\omega C} - \omega L\right)^2} \quad (14.10)$$

is the net effective opposition offered by the combination of resistor, inductor and capacitor known as the impedance of the circuit and is represented by  $Z$ . Its unit is ohm.

The amplitude value of current in a series  $RLC$  circuit is given by

$$I_m = \frac{U_m}{Z} = \frac{U_m}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}}. \quad (14.11)$$

At a particular value of the angular frequency, the inductive reactance and the capacitive reactance will be equal to each other (i. e.)  $\omega L = \frac{1}{\omega C}$ , so that the impedance becomes minimum and it is given by  $Z = R$  i. e.  $I$  is in phase with  $U$ . The particular frequency  $\omega_{res} = \frac{1}{\sqrt{LC}}$  at which the impedance of the circuit becomes minimum and therefore the current becomes maximum is called resonant frequency of the circuit (fig. 14.8). Maximum current flows through the circuit, since the impedance of the circuit is merely equal to the ohmic resistance of the circuit. i. e.  $Z = R$ .

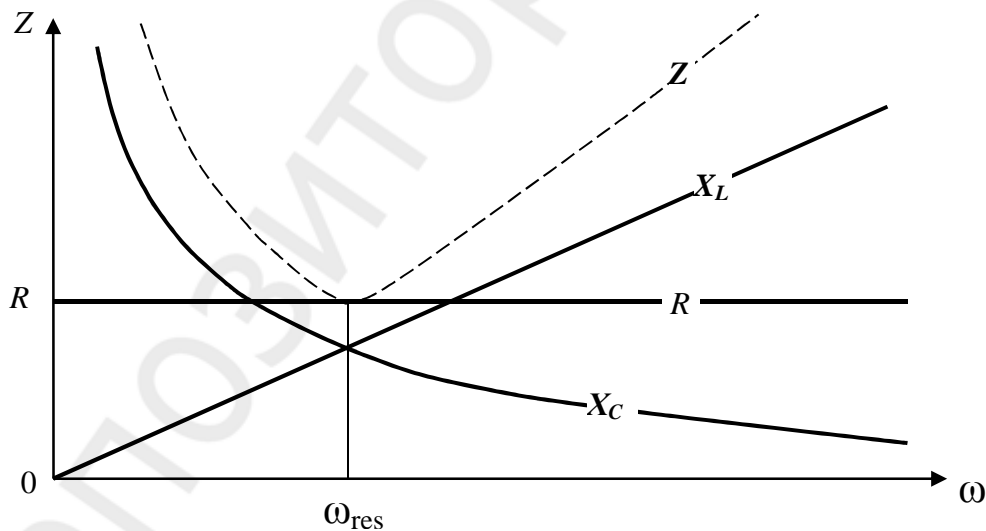


Fig. 14.8. Dependence of ohmic resistance  $R$ , inductive reactance  $X_L$ , and the capacitive reactance  $X_C$  and impedance  $Z$  on current frequency

## 14.6. ELECTRICAL IMPEDANCE OF BIOLOGICAL TISSUES FOR ALTERNATING CURRENT

The cell is the basic unit of living tissues. Its basic structure (a phospholipid bilayer membrane that separates the intracellular medium from the extracellular medium) determines the tissue electrical impedance.

From the electrical point of view, the extracellular medium can be considered as a liquid electrolyte (ionic solution). By far, the most important ions are  $\text{Na}^+$  (~140 mM) and  $\text{Cl}^-$  (~100 mM). Thus, the electrical properties depend on all physical or chemical parameters that determine their concentration or mobility.

The cell membrane has a passive role (to separate the extra and the intracellular media (the lipid bilayer)) and an active role (to control the exchange of different chemical species (ionic channels and pumps)). Its intrinsic electrical conductance is very low and it can be considered a dielectric.

In the case of the intracellular medium, the important charge carriers are  $\text{K}^+$ , protein- and  $\text{HPO}_4^{2-} + \text{SO}_4^{2-} +$  organic acids. Besides the ions and other charged molecules, inside the cell it is possible to find numerous membrane structures with a completely different electrical response. These membranes are formed by dielectric materials and their conductivity is very low. Thus, the impedance of the intracellular medium must be a mixture of conductive and capacitive properties. However, for simplification, it is generally accepted that the intracellular medium behaves as a pure ionic conductor.

The electrical behavior of biological tissues can be modeled with a series of nested RC circuits where C is a pseudo-capacitance (fig. 14.9). It is known that the electrical impedance of biological tissue decreases with increasing current frequency and this dependence on frequency is due to the cell membrane, which behaves like a capacitor (fig. 14.10). The extracellular and intracellular constituents of tissue can be related to the electrical equivalent circuit, as shown in figure.

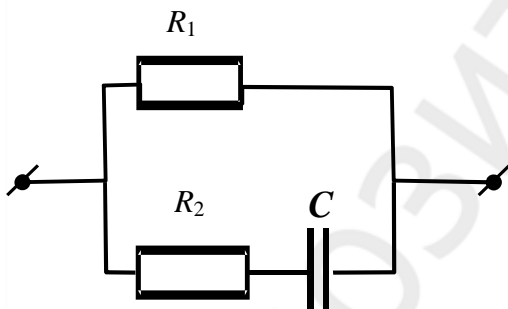


Fig. 14.9. The equivalent circuit of living tissue

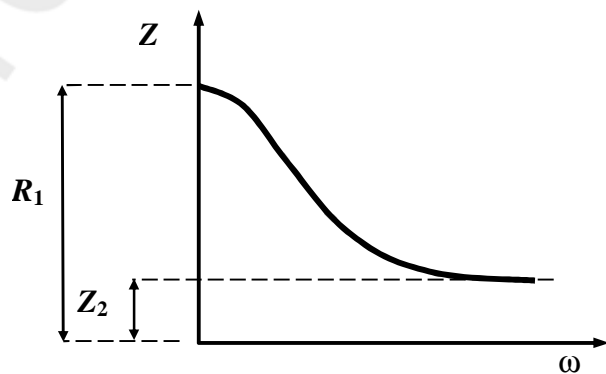


Fig. 14.10. A typical dependence of living tissue impedance on the current frequency

Electrical model of biological tissue concludes resistance  $R_1$  of the extracellular space, resistance  $R_2$  of the intracellular space and membrane pseudo-capacitance  $C$ .

At low frequencies (< 1 kHz) the current is blocked by the capacitance and the current is only capable to flow through  $R_1$ . At high frequencies (> 1 MHz) the membrane capacitance is no impediment to the current and it flows indiscriminately through the extra and intracellular media.

The impedance  $Z$  for this circuit is determined by:

$$Z = \frac{R_1 \sqrt{R_2^2 + X_c^2}}{\sqrt{(R_1 + R_2)^2 + X_c^2}}. \quad (14.12)$$

At very high frequencies  $X_c = \frac{1}{\omega C} \rightarrow 0$  the expression for the impedance is:

$$Z_2 = \frac{R_1 R_2}{R_1 + R_2} \quad (14.13)$$

At medium and high frequencies the impedance  $Z$  can be written as:

$$Z = \sqrt{R_2^2 + \left(\frac{1}{\omega C}\right)^2}. \quad (14.14)$$

The electrical impedance of a living tissue can be continuously measured in order to determine its patho-physiological evolution. The ratio of the impedance value at low and high frequencies is called polarization coefficient  $K$  (fig. 14.11):

$$K = \frac{Z_L (\nu = 10^3 \text{ Hz})}{Z_H (\nu = 10^6 \text{ Hz})} > 1. \quad (14.15)$$

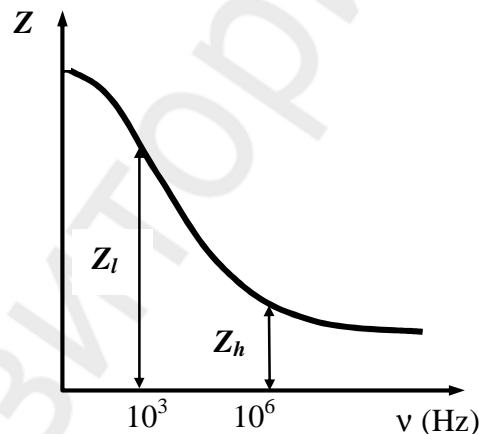


Fig. 14.11. The determination of tissue viability

Measurement of polarization coefficient allows healthy tissues to be differentiated from pathological (malignant and benign) tissues with high reliability. The structure of biological tissue can be assessed impedancometrically during surgical intervention.

**Questions:**

1. What is an alternating current? What are the amplitude, instantaneous and averaged over the period voltage and current values?
2. What is the phasor diagram? What is it used for?
3. Describe a relationship between an alternating current, a voltage and a power in circuit with a resistor; with an inductor; with a capacitor?
4. Describe a relationship between an alternating current, a voltage and a power in a series combination of an inductor, a capacitor and a resistor.

5. What is an electric impedance? Write the formula.
6. Describe the dependence of living tissue impedance on the current frequency. Give the equivalent circuit of living tissue and characterize.
7. What is a polarization coefficient? What does it characterize?

## **Chapter 15. ELECTROSTIMULATION OF THE TISSUES AND ORGANS**

The response of excitable cells to naturally occurring or artificial stimuli is a subject of great importance in understanding natural function of nerve and muscle, because most stimuli are produced by the natural system itself. Electrostimulation is the application of various types of low-frequency ( $\nu \leq 200$  Hz) electrical current to stimulate the body's organs and systems for clinical diagnosis, therapy, and rehabilitation. A current, arising from an external stimulator or natural source, is introduced into a cell or its neighborhood. The current creates transmembrane voltage in nearby membrane. The membrane responds passively (i. e., with constant membrane resistance), so long as the voltage produced is below a threshold level. When the threshold level is reached, the membrane responds with an action potential, or some other active response. Very often electrostimulation is used in order to provide neurostimulating and voluntary and involuntary muscle stimulation activity, to help strengthen muscles and improves their tone, to stimulate secretory and motoric function of the gastrointestinal tract. The clinical effects of electrostimulation are anti-inflammatory, analgesic, sedative, tranquilising, spasmolytic, asodilating, metabolic.

For electrodiagnostics and electrostimulation realization the pulse electrical current of various form is used. The rectangular pulse currents have the most simple form and are used for nervous system stimulation. Pulse can be defined as an isolated electrical event separated by a finite time from the next event, or represents a finite period of charged particle movement.

### **15.1. CHARACTERISTICS OF A RECTANGULAR PULSE**

For a complete description of the rectangular form pulse current (fig. 15.1) it is necessary to indicate its amplitude and the two time parameters: pulse duration and pulse period (or interpulse interval).

Pulse amplitude ( $I_0$ ): is the maximal magnitude of a pulse parameter, such as the voltage, current; [mA].

Pulse duration ( $t_u$ ): is the period of time during which a pulse is present; [ms].

Interpulse interval ( $t_0$ ): is the time between the end of one pulse and the beginning of the next pulse in a series, or other words  $t_0$  is the period of time between pulses during which there is no current flow; [ms].

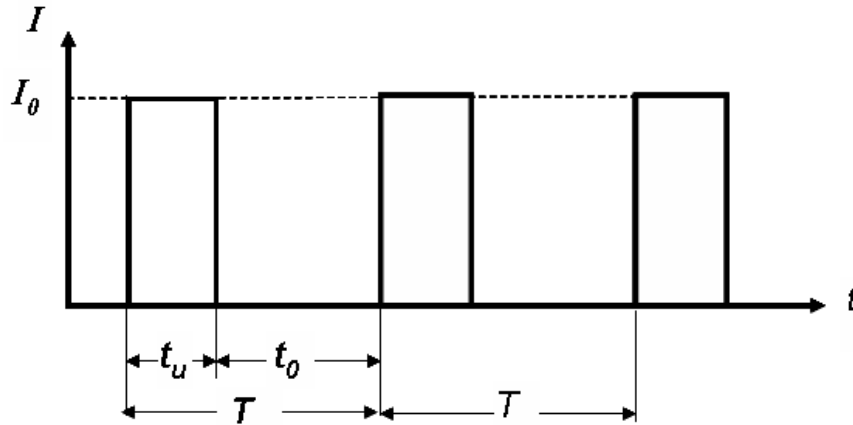


Fig. 15.1. The rectangular form pulse current and its parameters

Period ( $T$ ): the period is equal to the pulse duration plus the interpulse interval; [ms]:

$$T = t_u + t_0. \quad (15.1)$$

Pulse repetition frequency or frequency  $n$  is the number of pulses per time unit (e. g. seconds) [Hz]:

$$n = \frac{1}{T}. \quad (15.2)$$

The fill factor  $k$  is defined as the ratio of the pulse duration ( $t_u$ ) to the period ( $T$ ) of a rectangular pulse. The fill factor is the proportion of time during which a current is operated. The fill factor can be expressed as a ratio or as a percentage:

$$k = \frac{t_u}{T}. \quad (15.3)$$

The duty cycle  $Q$  shows how many times pulse period is more than a pulse duration:

$$Q = \frac{T}{t_u} = \frac{t_u + t_0}{t_u} = 1 + \frac{t_0}{t_u}. \quad (15.4)$$

## 15.2. CHARACTERISTICS OF AN ARBITRARY PULSE

For an arbitrary pulse current description (fig. 15.2) it is necessary to enter some additional parameters characterizing the shape of the pulse. For this purpose the auxiliary lines are drawn at  $0,1 I_0$  and  $0,9 I_0$ .

Pulse rise time ( $t_{rt}$ ): is the period of time during which a pulse rises from ten percent of its amplitude value ( $0,1 \cdot I_0$ ) to 90 percent of its amplitude value ( $0,9 \cdot I_0$ ).

Pulse fall time ( $t_{ft}$ ): is the period of time during which a pulse falls from ninety percent of its amplitude value ( $0,9 \cdot I_0$ ) to ten percent of its amplitude value ( $0,1 \cdot I_0$ ).

Pulse peak time ( $t_{pt}$ ): is the period of time during which a pulse  $I \geq 0,9 I_0$ .

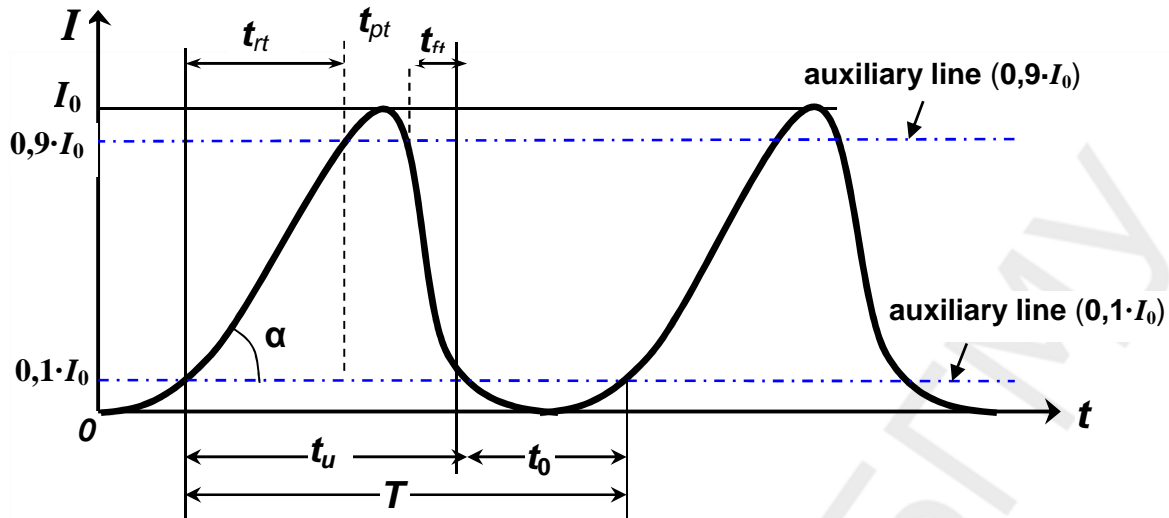


Fig. 15.2. The arbitrary pulse current and its parameters

Steepness of the pulse ( $K$ ) determines the rate of current rise in the time from  $0,1 \cdot I_0$  to  $0,9 \cdot I_0$ :

$$K = \frac{0,9I_0 - 0,1I_0}{t_{rt}} = \frac{0,8I_0}{t_{rt}} = \operatorname{tg}\alpha \quad (15.5)$$

In this case the pulse duration  $t_u$  can be obtained as a sum:

$$t_u = t_{rt} + t_{pt} + t_{ft}. \quad (15.6)$$

### 15.3. WEISS–LAPICQUE LAW

In electrical stimulation, current induced must be of sufficient amplitude and duration to bring excitable cells to the threshold of depolarization. The lowest current disturbance that causes tissue excitation is called the threshold current  $I \geq I_{thr}$ . If the stimulus is lower than the threshold, no activation will be initiated. But current magnitude does not exceed the let-go current:

$$I_{thr} < I < I_{let-go}. \quad (15.7)$$

The threshold current  $I_{thr}$  dependence on the rectangular pulse duration  $t_u$  is given by Weiss–Lapicque Law:

$$I_{thr} = \frac{a}{t_u} + b, \quad (15.8)$$

where  $a$  and  $b$  are constants depending on the types of living tissue.

The minimum current  $I_{chr}$  required above a certain threshold for tissues stimulation is inversely proportional to the duration of the electrical pulse  $t_u$ . A plot of the inverse relationship between the threshold stimulus current-pulse amplitude and its duration is known as the strength-duration curve (fig. 15.3).

Lapicque introduced two new terms to define the tissue stimulation threshold:

– **the rheobase  $R$**  is the lowest current required to reach threshold as the stimulation duration grows long (conceptually, as  $t_u \rightarrow \infty$ ).

– the **chronaxie**  $t_{chr}$  is that pulse duration at which the threshold value is twice that of the rheobase.

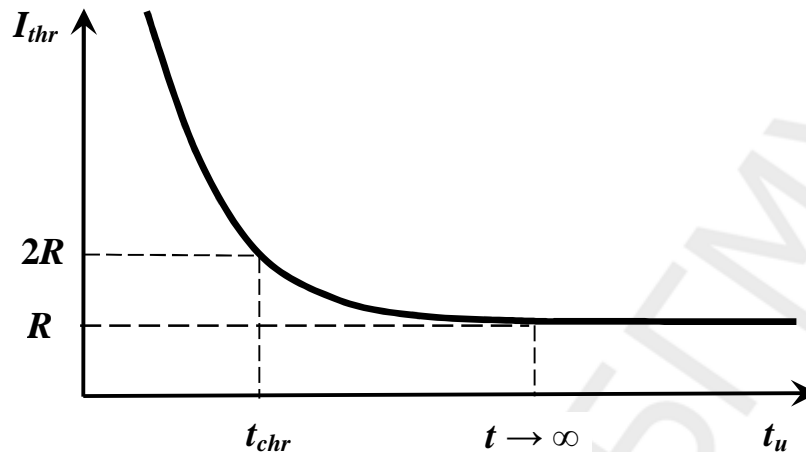


Fig. 15.3. The strength-duration curve shows the inverse relationship between the lowest stimulus current pulse required to produce a response versus its duration

Values of the constants ( $a$  and  $b$ ) can be related to rheobase  $R$  and chronaxie  $t_{chr}$ , which are determined experimentally.

1. If  $t_u \rightarrow \infty$ , the threshold current  $I_{thr}$  is equal to rheobase  $R$ :

$$I_{thr} \rightarrow b, \text{ it means } b = R. \quad [b] = mA$$

2. If  $t_u = t_{chr}$ , then  $I_{thr} = 2R$ , and according to Weiss–Lapicque Law:

$$2R = \frac{a}{t_{chr}} + R.$$

$$\text{Thus, } a = Rt_{chr}. \quad [a] = C \quad (15.9)$$

### The pulse duration $t_u$

The pulse duration should be  $t_u \geq t \rightarrow \infty$ , than in this case the threshold is minimum (is equal to rheobase). The pulse duration  $t_u$  depends on the types of living tissue.

### The pulsed current frequency $n$

For tissues electrical excitation it is necessary that pulse period should be more than the absolute refractory period  $T_{ref}$ . The absolute refractory period  $T_{ref}$  is the time during which the cell can not be excited by any stimulus. That is why the maximal excitation cell frequency is  $\nu_{max} = 1/T_{ref}$ .

For neural tissue  $\nu_{max} = 500 \div 1000 \text{ Hz}$  ( $T_{ref} = 1 \div 2 \text{ ms}$ );

for skeletal muscle  $\nu_{max} = 100 \div 200 \text{ Hz}$  ( $T_{ref} = 5 \div 10 \text{ ms}$ );

for heart muscle  $\nu_{max} = 3,3 \text{ Hz}$  ( $T_{ref} = 300 \div 350 \text{ ms}$ ).

### Steepness of the pulse $K$

The dependence of threshold current  $I_{thr}$  on the rate of pulse steepness increase is reflected in *the Law of Du Bois–Reymond*: a motor nerve responds, not to the absolute value, but to the alteration of value from moment to moment,

of the electric current; rate of change of intensity of the current is a factor in determining its effectiveness.

The threshold current value  $I_{thr}$  decreases when pulse steepness  $K$  increases.

#### 15.4. ELECTRICAL STIMULATION OF THE HEART MUSCLE

Defibrillation is used to treat cardiac arrest or fibrillation loss of coordinated contraction of heart muscle fibers. Death occurs in minutes if left untreated. Fibrillation is arrhythmia resulting from an abnormal spread of excitation, causing parts of the myocardium to contract while other regions of the cardiac muscle are relaxing. The functional fragmentation can be both localized in atria and in ventricles. In ECG the fluctuation associated to ventricular fibrillation are very irregular, changing rapidly in frequency, shape and amplitude. Cardiac arrest is the complete cessation of cardiac activity, either electrical, mechanical, or both.

**Defibrillation** involves the application of a powerful single current pulse of duration  $t_u = 2\text{--}5\text{ ms}$  to the heart which leads to depolarization of the most of the heart cells simultaneously, which often reestablishes coordinated contractions and a normal sinus rhythm.

Parameters of the electric pulse used are:

- on the chest: voltage  $U = 5\text{--}7\text{ kV}$ , current  $I \sim 1\text{ A}$ ;
- on the heart of the nude: voltage  $U = 1,5\text{--}2,5\text{ kV}$ , current  $I \sim 1\text{ A}$ .

#### **Cardioverter-defibrillator**

Cardioversion is used in persons who have heart rhythm problems (arrhythmias), which can cause the heart to beat too fast (tachycardia) or too slowly (bradycardia). There are implantable cardioversion defibrillation and external defibrillator. An implantable cardioverter-defibrillator (often called an ICD) is a device that briefly passes an electric current through the heart. It is implanted in the chest to constantly monitor and correct abnormal heart rhythms (arrhythmias). Pacing circuit consists of a power source (pulse generator), one or more conducting (pacing) leads, and the myocardium (fig. 15.4). Electrical signal (stimulus) travels from the pacemaker, through the leads, to the wall of the myocardium. Myocardium is “captured” and stimulated to contract. External defibrillators are typically used in hospitals or ambulances, but are increasingly common outside the medical areas. As automated external defibrillators become safer and cheaper. There are synchronized cardioversion and non-synchronized one, automated defibrillator and semi-automated defibrillator. Parameters of the electric pulse used for heart stimulation are: pulse duration  $t_u = 0,5\text{--}8\text{ ms}$ ; frequency  $n = 1\text{--}1,2\text{ Hz}$ ; voltage  $U \sim 6\text{ V}$ ; current  $I \sim 1\text{--}10\text{ mA}$ .



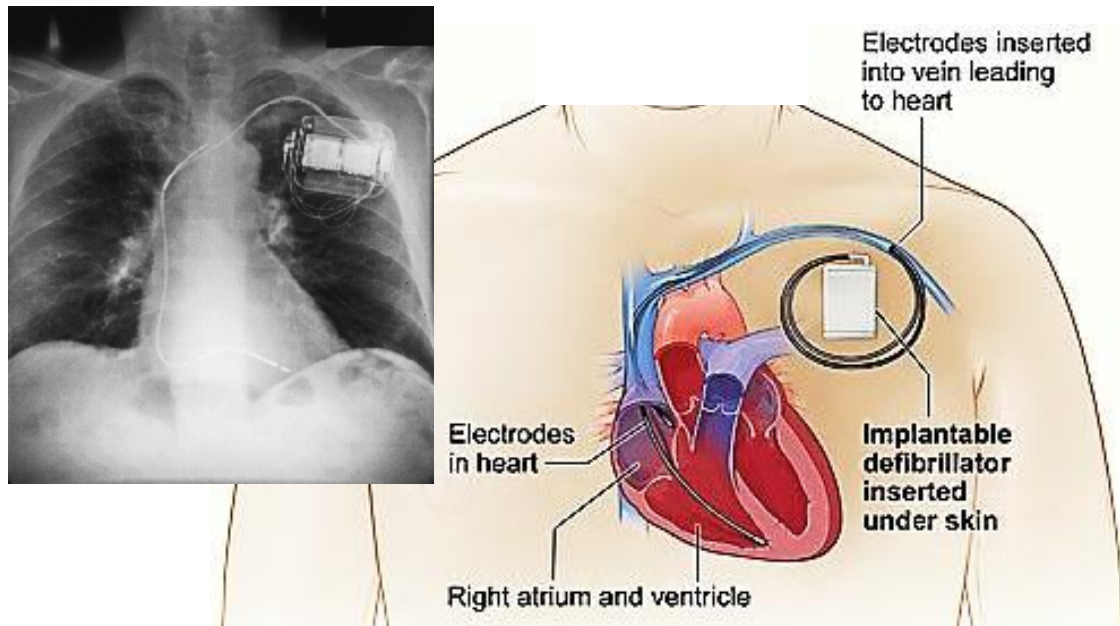


Fig. 15.4. Implantable cardioversion defibrillation

**Questions:**

1. What is the electrostimulation?
2. What is the electrical current used for electrostimulation?
3. Describe parameters of a rectangular pulse.
4. Specify main characteristics of an arbitrary pulse.
5. What do electrostimulation pulse duration, frequency and amplitude depends on?
6. Give the strength-duration curve and characterize it.
7. What are the rheobase and the chronaxie?
8. Write Weiss–Lapicque Law. What is a relationship between the law constants and the rheobase and the chronaxie?
9. Explain the Law of Du Bois-Reymond.
10. What is the defibrillation method? Specify main parameters and features the method.

## Chapter 16. HIGH FREQUENCY ELECTROMAGNETIC FIELDS USE IN MEDICINE

Therapeutic heating causes vasodilation, increases the rate of enzymatic biological reactions, increases nerve conduction velocity, and increases soft tissue extensibility. These physiologic effects underlie the benefits of therapeutic heating for promoting tissue healing, reducing pain and increasing range of motion.

The tissue can be heated due to the effect of electric current. When an electric current is passed through a tissue, the tissue gets heated up and here the electrical energy is converted into heat energy. The heat  $Q$  produced in a tissue is directly proportional to the tissue resistance  $R$ , the duration of the electric current action  $t$  and to the square of the applied current  $I$ :

$$Q = I^2 R t. \quad (16.1)$$

Let's  $j$  is current flux density i. e. current flowing through a unit area:

$$j = \frac{I}{S}. \quad (16.2)$$

The effectiveness of any thermal procedures is determined by the specific heat  $q$ . The specific heat  $q$  is the heat produced in a tissue unit volume per unit time:

$$q = \frac{Q}{Vt}. \quad (16.3)$$

### 16.1. DIATHERMY

**Diathermy** is a form of physical therapy in which deep heating of tissues is accomplished by the use of high-frequency electrical current. Diathermy equipment uses two large electrodes placed at each side of the body (fig. 16.1). Value of applied current  $I$  is 1–2 A and frequency  $\nu$  is 0,5–2,0 MHz.

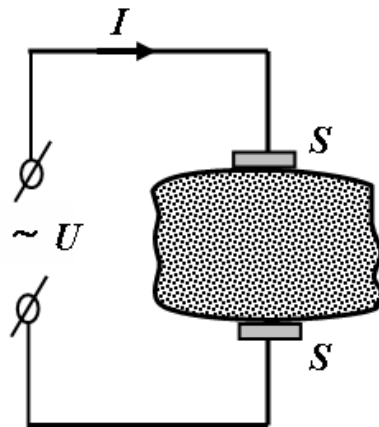


Fig. 16.1. Scheme of diathermy

In order to determine which tissues are warmed by diathermy let's write the following equation:

$$q = \frac{Q}{Vt} = \frac{I^2 R t}{Vt} = \frac{I^2 \rho l}{S l S} = \frac{I^2 \rho}{S^2} = j^2 \rho, \quad (16.4)$$

where  $\rho$  is electrical resistivity (also known as specific electrical resistance).

The higher the tissue resistivity, the more heat will be released in the tissue when the current passes through it. From the equation it follows that for the same current density in the diathermy, the tissue with high resistivity better is heated, i. e. skin and subcutaneous adipose tissue.

Surgical diathermy is based on diathermy and divided into cutting tissue and coagulating tissue. In surgical diathermy the area of one electrode (as a pointed probe) is much more smaller then another one (fig. 16.2). Since area of electrode inversely proportional to current density  $j = \frac{I}{S}$ , the current density is very high at the point of contact between the probe and the tissue.

In the monopolar technique, a strong thermal effect is produced at the narrow active electrode (tip of the electrosurgical knife) due to an increase in current density. The bipolar technique is used mainly in micro- and neurosurgery, and it can only be used for coagulation. A bipolar active electrode (forceps) is used, whereby both poles have contact with the surgical field. A neutral electrode is not required.

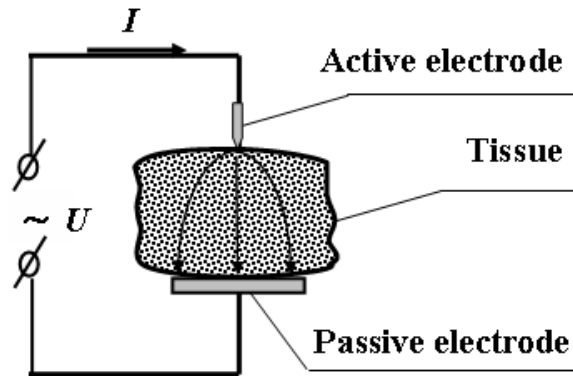


Fig. 16.2. Monopolar technique of surgical diathermy

In the case of tissue electrosection current density  $j$  is equal to  $\sim 40 \text{ mA/mm}^2$  and in the case of tissue coagulation current density  $j$  is equal to  $\sim 6\text{--}10 \text{ mA/mm}^2$ . Electrocoagulation is ideal for clotting small blood vessels (less than 2 to 3 mm in diameter) in deep and superficial surgery. Usually, a 2- to 5-mm metallic sphere at the end of a treatment electrode is the optimal tip for hemostasis of small vessels. In electrosection, the electrode is used to cut tissue. An electrode tip in the shape of a fine needle, wire loop, diamond, ellipse, or triangle is advanced slowly through the tissue, causing a steam envelope to advance around the tip and producing a smooth cutting effect with little sense of pressure against the tissue by the operator.

This minimization of power produces a specimen with minimal heat damage along its margins and clinical wound healing the same as when surgical steel blades are used. The specimen should be acceptable for pathologic interpretation compared with specimens produced with laser techniques. Wound edges can be approximated with sutures when an excisional biopsy is performed. Cosmetic results are similar to those seen with scalpel and suturing.

## 16.2. INDUCTOTHERMY

**Inductothermy** is a form of physical therapy in which deep tissues heating based on using an oscillating magnetic field  $B = B_0 \sin 2\pi \nu t$  with frequency  $\nu = 10\text{--}20 \text{ MHz}$ . The effect of deep heating of tissues and organs is based on using a spiral or helix of wire (a coil) to produce an oscillating magnetic field within the body which will induce currents having the same effect (fig. 16.3). The frequency employed is usually 13,56 MHz ( $\nu = 13,56 \text{ MHz}$ ). The magnetic field, penetrating the tissues, induces in them electrical currents named as

induction currents, vortical currents or currents Foucault. The more is the electroconductivity of a tissue, the current of greater force is formed in it. The occurrence of vortical currents is accompanied by heating of tissues. Thus to induce a current into the underlying tissue and organs strong and rapidly changing magnetic field must be generated by the coil.

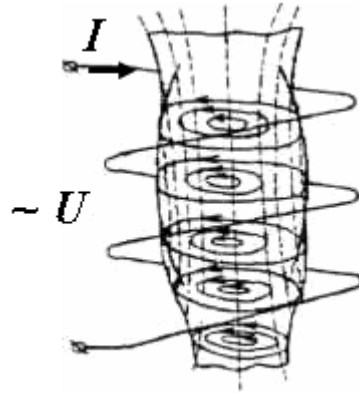


Fig. 16.3. Scheme of inductothermy

Faraday law can be explained by the current generated in the closed loop circuit if an electric conductor, which forms a closed circuit, is linked by a time-varying magnetic flux  $\Phi$ . This current is due to the electromotive force ( $\varepsilon$ ) induced by the time-varying flux. The magnitude of  $\varepsilon$  depends upon the rate of the magnetic flux change  $d\Phi/dt$ . The direction of  $\varepsilon$  is such that the time-varying magnetic field is always opposite to that of  $d\Phi/dt$ . Therefore,

$$\varepsilon = -\frac{d\Phi}{dt}, \quad (16.5)$$

where  $\varepsilon$  is an electromotive force [V],  $\Phi$  is a magnetic flux [Wb],  $t$  is a time [s]. Magnetic flux  $\Phi$  can be written as  $\Phi = BS$ , where  $B$  is a magnetic field,  $S$  is an area.

Induced Foucault current  $I$  can be written as:

$$I = \frac{\varepsilon}{R}. \quad (16.6)$$

In order to determine which tissues are warmed by inductothermy let's write the following equation:

$$q = \frac{Q}{Vt} = \frac{\varepsilon^2 R t}{R^2 V t} = \frac{\varepsilon^2 t}{\frac{\rho l}{S} S t} = \frac{\varepsilon^2}{\rho l^2}, \quad (16.7)$$

where  $\rho$  is electrical resistivity.

Thus, the less resistivity of tissue, the more intensively it will be heated up. First of all blood, lymph, tissue fluid will be heated up. Tissues with a high resistivity are less heated under inductothermy.

### 16.3. ULTRA HIGH FREQUENCY THERAPY

**Ultra high frequency therapy** (UHF-therapy) is a form of physical therapy in which deep heating of tissues based on using an oscillating electric field  $E = E_0 \sin 2\pi \nu t$  ( $E$  is electrical field strength) ( $\nu = 30\text{--}60$  MHz). The frequency employed is usually 40,68 MHz.

To obtain the vibrations of various frequencies the generator of high frequencies is used in physiotherapy devices. The basic element of such device is the LC circuit (or oscillating circuit) (fig. 16.4).

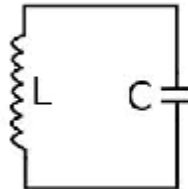


Fig. 16.4. Scheme of oscillating circuit

An oscillating circuit is a resonant circuit that consists of an inductor  $L$  and a capacitor  $C$ . When connected together, an electric current can alternate between them at the circuit's resonant frequency. An LC circuit can store electrical energy vibrating at its resonant frequency. A capacitor stores energy in the electric field between its plates, depending on the voltage across it, and an inductor stores energy in its magnetic field, depending on the current through it.

Physiotherapy devices consist of technical and therapeutic LC circuits (fig. 16.5). In order to have effective heating of tissues technical and therapeutic circuits have to work in resonance:  $T_{\text{tech}} = T_{\text{ther}}$  i. e. oscillation periods of technical and therapeutic circuits should be equal.  $C_{\text{ther}}$  is a variable tuning capacitor which is used to adjust the resonant frequency to the desired value.

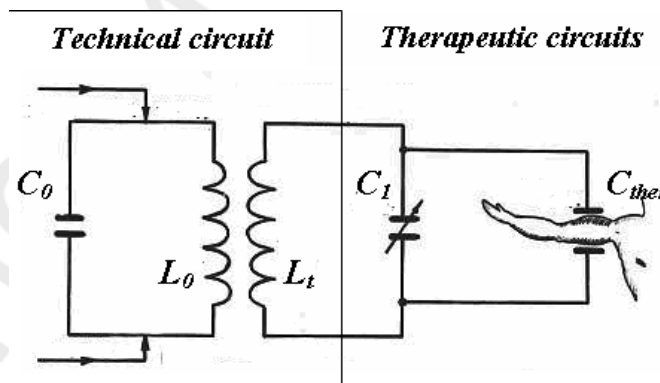


Fig. 16.5. Scheme of technical and therapeutic circuits of apparatus for UHF-therapy

The specific heat  $q$  produced in conductive tissue under the UHF-therapy action can be characterized as:

$$q = \frac{Q}{Vt} = \frac{U^2 R t}{R^2 V t} = \frac{U^2 t}{\frac{\rho l}{S} S t} = \frac{U^2}{\rho l^2} = \frac{E^2}{\rho}. \quad (16.8)$$

The specific heat  $q$  produced in dielectric tissue under the UHF-therapy action can be written as:

$$q = \varepsilon\varepsilon_0 E^2 \omega \operatorname{tg} \delta, \quad (16.9)$$

where  $\varepsilon$  is a permittivity of medium,  $\varepsilon_0$  is a permittivity of vacuum,  $E$  is electrical field strength,  $\omega$  is frequency,  $\operatorname{tg} \delta$  is dielectric loss tangent.

The most significant difference between these two expressions is that the heating of electrolytes does not depend on frequency and dielectric heating increases with an increase of the electromagnetic field frequency (fig. 16.6).

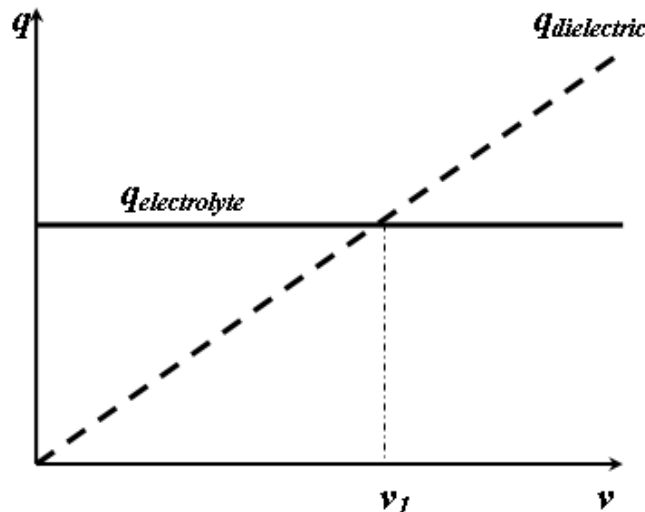


Fig. 16.6. Frequency dependence of specific heat for electrolyte and dielectric under the UHF-therapy action

At frequencies  $\nu < \nu_1$  electrolyte heated more than dielectric, and at frequencies  $\nu > \nu_1$  dielectric heated more effectively. At frequencies  $\nu = 30\text{--}60$  MHz the electrical field energy is absorbed mainly in tissues having the large capacitor resistance that is in tissues badly conducting an electrical current i. e. in dielectric tissues.

#### 16.4. THE MICROWAVE THERAPY

**The microwave therapy** is an influence on tissues of organism by a variable electromagnetic field of super high frequency (microwave)  $\nu = 300\text{--}2500$  MHz.

**Centimeter wave therapy** is a form of physical therapy in which tissues heating is based on using an electromagnetic waves with frequency  $\nu = 2375$  MHz. In this case wave length  $\lambda$  is equal to  $\sim 12$  cm ( $\lambda = c/\nu$ ). It is necessary to dose centimeter wave therapy because of standing waves formation. They are formed at reflection of a wave from border of two environments and imposing reflected on the next falling wave. Such process occurs repeatedly in the same place. Under the laws of physics the «standing» wave is formed in case if distance between borders of two environments makes more than a quarter of length of

a wave. This situation can arise at thickness of subcutaneous fatty layer more than 2 cm. At formation of «standing» waves there is a significant local increase of temperature of a tissue down to a burn. This overheating of a tissue is accompanied by sensation of bursting open, burning, rheumatic pains that requires immediate reduction of a doze of influence or termination of procedure. The uncontrollable overheating can arise at influence on hydropic tissue. That can lead to local burn inside of body. The energy of microwaves is absorbed mainly by molecules of water; their dielectric permeability in this connection is insignificant. Deep of penetration is ~ 3–5 cm.

**Decimeter wave therapy** is a form of physical therapy in which tissues heating is based on using an electromagnetic waves with frequency  $\nu = 460$  MHz. Length wave  $\lambda$  is equal to ~ 65 cm ( $\lambda = c/\nu$ ). The microwaves of a decimeter range are approximately 2 times less intensively reflected by a surface of skin. They to a lesser degree, than wave of a centimetric range, are absorbed by water, as the phenomena of a resonance of dipoles of water at this frequency of an electromagnetic field are less expressed. The energy of these waves in process of penetration into depth of tissues fades twice more slowly in comparison with centimetricwaves. This therapy is used for heating tissues containing H<sub>2</sub>O. Deep of penetration is ~ 8–9 cm.

**Hyper frequency therapy:**  $\nu = 3 \cdot 10^{10} - 3 \cdot 10^{11}$  MHz. Length wave  $\lambda$  is equal to ~ 1–10 mm ( $\lambda = c/\nu$ ). This therapy is used for obtaining nonheating tissue effect (resonance energy absorption). The study of hyper frequency therapy reactions has resulted in representation about oscillator effect, which is considered as specific, characteristic for the certain frequency of fluctuations. The absorption of energy of electromagnetic waves in tissues due to fluctuation of ions does not depend on their frequency; the absorption due to molecules is increased with increase of frequency of fluctuations. This increase occurs up to the frequency, determined for even one molecule, and in the maximal degree will be shown at concurrence of frequency of theen closed fluctuations to own frequency of fluctuations of molecules (phenomenon of a resonance, resonant frequency). It was found out, that there is «shaking» of lateral circuits of protein molecules, their relaxation.

### 16.5. DARSONVALISATION

**Darsonvalisation** is the influence by a variable pulse sine wave electrical current of high frequency ( $\nu = 110$  KHz), high voltage ( $U = 10-30$  kV) and small current ( $I = 10-15$  mA), the frequency of pulses is 50 Hz, amplitude of a current in each pulse gradually accrues and decreases, i. e. the electrical current is modulated on amplitude. The high voltage is made to tissues with the help of a glass vacuum electrode, in which air is rarefied up to 0,1–0,5 mm mercury (fig. 16.7). The name of this electrode is condenser. A condenser has resistance of  $R = 10^6-10^7$  Om.

$$I = \frac{U}{R} = \frac{20 \times 10^3 V}{10^7 \text{ Ohm}} = 20 \times 10^{-4} \text{ A.}$$

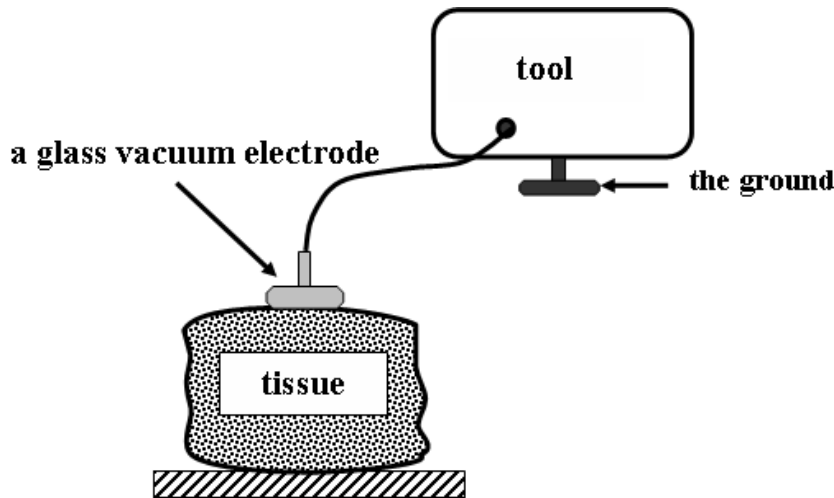


Fig. 16.7. Scheme of darsonvalisation

Under action of a high voltage air in an electrode is ionized, the electrical current passes through the ionized gas. It is possible to assimilate conducting part of electrode and a body of the patient to facings of the condenser, the glass is dielectric. At transition of an electrical current from the ionized gas and capacity of a glass plate on air arises the spark discharge — disruption of the condenser, and then the electrical current through the patient goes to the ground. The basic biophysical processes: the effect darsonvalism is connected with irritating action of the spark discharge on superficial layers of a skin and mucous environments. As the current of very small force is used, the heating of tissues does not occur. Basic physiological reactions and medical action in case of local darsonvalism are local or have segmentation character. The silent electrical category irritates nervous receptors, causing their functional changes, those results in small sedative analgesic effect.

**Questions:**

1. What electromagnetic wave diapason is used for high-frequency heating?
2. Give the diathermy parameters. Which tissues are warmed under diathermy.
3. What is the surgical diathermy? Describes monopolar technique and bipolar one.
4. What are inductothermy parameters? Which tissues are warmed under this procedure?
5. What is the ultra high frequency therapy? Which tissues are warmed more in the ultra high frequency electric field?
6. Explain technical and therapeutic circuits function in ultra high frequency device.
7. What is a basic of tissues heating under microwave therapy and centimeter wave one? Which tissues are warmed more during the procedures? What is the danger under centimeter wave therapy?
8. What is the darsonvalisation? What is the therapeutic effects mechanism?



## Chapter 17. BIOPHYSICAL SIGNALS MONITORING

### 17.1. THE SENSORS

Some important biosignals do not have the character of the electrical potential or voltage (blood pressure, core body temperature, blood flow, cerebrospinal fluid pressure). The monitoring can be carried out only with the sensors transforming that signal as a physical quantity to some form of the electrical signal. Sensors are devices, which transform measured parameter into electrical signal.

There are two major types of sensors: active and passive. **Active sensors** generate electric current or voltage directly in response to measured parameter (physical stimulus, such as thermal energy, electromagnetic energy, acoustic energy, pressure, magnetism, or motion). Amplitude or frequency of generated signal is proportional to measured parameter. Examples of active sensors are thermocouples and piezoelectric accelerometers. Thermocouples produce a voltage related to a measured temperature of two metals and if the two junctions are at different temperatures, electricity is generated. **Passive sensors** produce a change in some their electrical characteristics, such as resistance, capacitance, or inductance, as a result of measured parameter action. These usually require additional electrical energy. The examples of passive sensors are resistance temperature detectors and thermistors.

Sensors have following characteristics:

– **the sensitivity** of the sensor is the minimum input of physical parameter that will create a detectable output change. This is defined as the ratio of the incremental output ( $\Delta y$ ) to incremental input ( $\Delta x$ ), i. e.

$$S = \frac{\Delta y}{\Delta x}.$$

In some sensors, the sensitivity is defined as the input parameter change required to produce a standardized output change. In others, it is defined as an output voltage change for a given change in input parameter;

– **the measured range (MR)** of the sensor is the maximum and minimum values of applied parameter that can be measured. The measured range is defined as the difference of the maximum input and the minimum input,  $x_{\max} - x_{\min} = \text{MR}$ ;

– **the accuracy** of the sensor is the maximum difference that will exist between the actual value (which must be measured by a primary or good secondary standard) and the indicated value at the output of the sensor. The accuracy describes the closeness with which the measurement approaches the true value of the variable being measured. And it is given by

$$\varepsilon_a = \frac{x_m - x_t}{x_t} \cdot 100\%,$$

where  $x_t$  is a true value,  $x_m$  is a measured value. The accuracy can be expressed either as a percentage of full scale or in absolute terms;

– **the resolution:** it is defined as the smallest incremental change in the input that would produce a detectable change in the output. This is often expressed as percentage of the measured range, MR. For a detectable output  $\Delta y$ , if the minimum change in  $x$  is  $\Delta x_{\min}$ , then the maximum resolution is

$$R_{\max} = \frac{\Delta x_{\min}}{x_{\max} - x_{\min}} \cdot 100\%.$$

– **the response time** can be defined as the time required for a sensor output to change from its previous state to a final settled value within a tolerance band of the correct new value. Sensors do not change output state immediately when an input parameter change occurs. Rather, it will change to the new state over a period of time, called the response time.

## 17.2. SENSORS OF TEMPERATURE

There are many different sensors of temperature, but three find particularly wide application to biomedical problems — the resistance temperature detector, thermistors, and thermocouples.

**The thermocouple** is a temperature sensor which generates an electrical voltage or electromotive force directly dependent on the temperature without an additional power source because of its thermo-electric properties. Thermocouple systems are based on the thermoelectric effect, discovered in 1821 by Thomas Seebeck. Seebeck found that when two different metals were joined and a temperature difference was present, a voltage was produced. Thermocouples contain two electrical conductors made of different materials which are connected at one end. The end of the conductors which will be exposed to the process temperature is called the measurement junction. The point at which the thermocouple conductors end (usually where the conductors connect to the measurement device) is called the reference junction (fig. 17.1). When the measurement and reference junctions of a thermocouple are at different temperatures, a millivolt electromotive force is formed within the conductors. Knowing the type of thermocouple used, the magnitude of the millivolt electromotive force within the thermocouple, and the temperature of the reference junction allows the user to determine the temperature at the measurement junction.

The electromotive force generated by the thermocouple is largely proportional to the difference between the temperature of the object under test and the reference temperature:

$$\varepsilon = \alpha(T_2 - T_1), \quad (17.1)$$

where  $\varepsilon$  is the electromotive force,  $\alpha$  is the coefficient of proportionality,  $T_2 - T_1$  is the temperature difference.

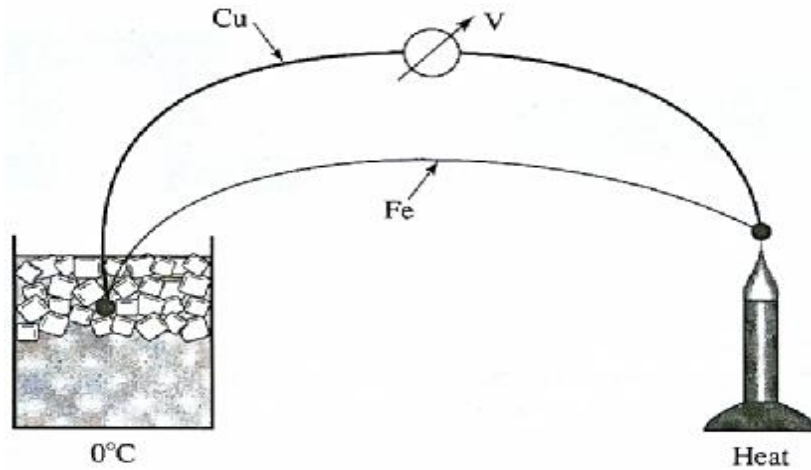


Fig. 17.1. Schematic representation of temperature measurement with the thermocouples

**The resistance temperature detector**, or the RTD, employs the property that the electrical resistance of metals varies with temperature. The electric resistance of a piece of metal or wire generally increases as the temperature of that electric conductor increases (fig. 17.2). A linear approximation to this relationship is given by

$$R = R_0[1 + \alpha(T - T_0)], \quad (17.2)$$

where  $R_0$  is the resistance at temperature  $T_0 = 0$ ;  $\alpha$  is the temperature coefficient, which depends only on the nature of the metal and  $T$  is the temperature at which the resistance is being measured.

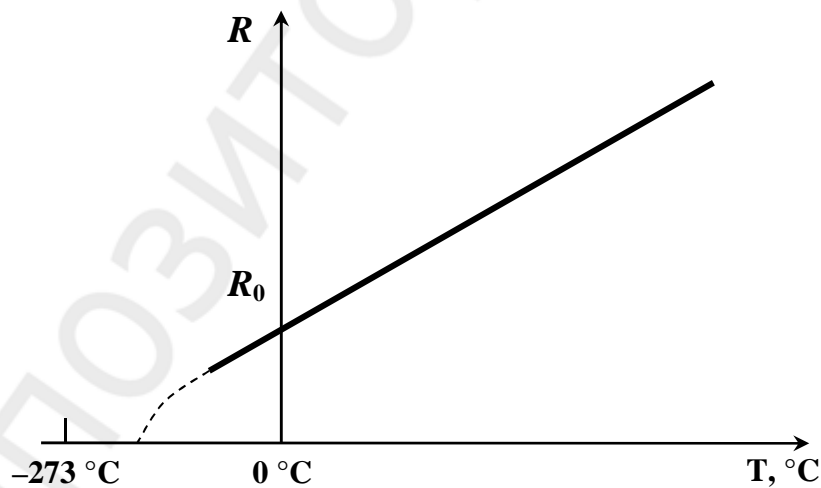


Fig. 17.2. Resistance versus temperature for a typical conductor

The temperature coefficient of resistance is widely used to characterize

$$\text{RTD: } TCR = \frac{1}{R_0} \frac{dR}{dT}.$$

The unit of TCR is  $1/K^0$ .

RTD are positive temperature coefficient (PTC) sensors whose resistance increases with temperature. The main metals in use are platinum and nickel. The RTD exhibits behavior which is more accurate and more linear over wide temperature ranges than a thermocouple. Unlike a thermocouple, however, an RTD is a passive sensor and requires current excitation to produce an output voltage.

Similar in function to the RTD, **thermistors** are constructed of solid semiconductor materials. The electric resistance of a typical intrinsic (non doped) semiconductor decreases exponentially with the absolute temperature  $T(^{\circ}\text{K})$  (fig. 17.3):

$$R(T) = Ae^{B/T}, \quad (17.3)$$

where  $A$  (Ohm) and  $B$  ( $^{\circ}\text{K}$ ) are constants depending only on the semiconductor material being used in thermistor.

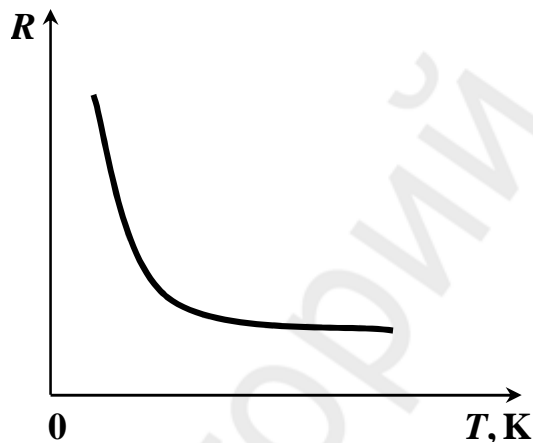


Fig. 17.3. Resistance versus temperature for a typical semiconductor

The most commonly used thermistors are those with a negative temperature coefficient. The thermistor high sensitivity allows it to detect minute variations in temperature which could not be observed with an RDT or thermocouple. The temperature coefficient of thermistors does not decrease linearly with increasing temperature as it does with RDTs; therefore, linearization is required for all but the narrowest of temperature ranges. Thermistors have the most sensitivity but are the most non-linear.

Let's compare a structure of semiconductors and conductors. A metal consists of a lattice of atoms, each with a shell of electrons. This can also be known as a positive ionic lattice. The outer electrons are free to dissociate from their parent atoms and travel through the lattice, creating a «sea» of electrons, making the metal a conductor. A conductor may be described as a substance in which the number of «free» electrons per unit volume is the same order of magnitude as the number of atoms per unit volume. When an electrical potential difference (a voltage) is applied across the metal, the electrons drift from one end of the conductor to the other under the influence of the electric field. Semiconductors are materials which lie between conductors and insulators. Let's

consider silicon as an example of semiconductors. Silicon forms crystal of the diamond type in which there is a co-valent bond between the atoms. Each atom shares its electrons with four other atoms, making a cubic lattice. When the thermal energy of the system is zero in a perfect crystal, all the electrons are in their proper positions and the substance is an insulator. With increasing temperature an increasing fraction of the electrons is displaced by thermal movement. In a pure metallic conductor the electrons are «free» even when the material contains no thermal energy. The proximity of the atoms, coupled with the small binding forces, leave the valency electrons «floating» in the material. As the temperature increases the kinetic energy of the atoms increases, and the electrons driven through the material by an electric field suffer larger energy losses at collisions and their mobility is therefore diminished. Thus the electric resistance of metal increases as the temperature increases. The opposite is the case with a semiconductor because the number of electrons increases with temperature. The electric resistance of intrinsic semiconductor decreases as the temperature increases.

### 17.3. BIOPOTENTIAL AMPLIFIER

Biopotential signals usually have amplitudes of the order of a few millivolts or less. Such signals must be amplified to levels compatible with recording and display devices. Amplifiers are an important part of modern instrumentation systems for measuring biopotentials. The essential function of a biopotential amplifier is to take a weak electric signal of biological origin and increase its amplitude so that it can be further processed, recorded, or displayed (fig. 17.4).

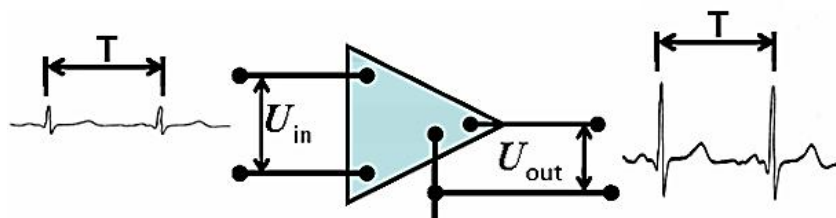


Fig. 17.4. Scheme of ECG signal amplifying

Thus, the amplifier is an electric device that increases the input voltage ( $U_{in}$ ) (power  $P_{in}$ , current  $I_{in}$ ) by a factor  $K$ ; that is, the output voltage  $U_{out}$  (power  $P_{out}$ , current  $I_{out}$ ) is  $U_{out} = KU_{in}$ ;  $P_{out} = KP_{in}$ ;  $I_{out} = KI_{in}$ . The amplification factor (gain)  $K$  is determined by the ratio of the output and input voltages (power, current). Depending on the nature of the input and output signals, one can have different types of amplifier gain: current gain (current out/current in); voltage gain (voltage out/voltage in), power gain (power out/power in):

$$K = \frac{I_{out}}{I_{in}}; \quad K = \frac{U_{out}}{U_{in}}; \quad K = \frac{P_{out}}{P_{in}}. \quad (17.4)$$

Main requirement for the amplifier is to increase signal amplitude without distortion of the signal form.

The biosignals can be considered as periodic ones. The signal is periodic if signal waveshape is repeated periodically. Any periodic biosignal can be written as a Fourier series. According to the Fourier theorem any periodic function may be expressed as the sum of harmonic components at integer multiples of the fundamental frequency  $\nu_0 = 1/T$  (or angular frequency  $\omega_0 = 2\pi\nu_0$ ). (a series of sine and cosine terms called the Fourier series). Each of sine and cosine term has specific amplitude and phase coefficients known as Fourier coefficients:

$\varepsilon(t) = a_0 + a_1\cos(\omega_0t + \varphi_1) + a_2\cos(2\omega_0t + \varphi_2) + \dots + a_n\cos(n\omega_0t + \varphi_n)$  (17.5)  
or in the brief description

$$\varepsilon(t) = a_0 + \sum_{m=1}^n a_m \cos(m\omega_0t + \varphi_m), \quad (17.6)$$

where  $a_0$  is a constant signal component (in many cases it can be equal to zero);  $a_m\cos(m\omega_0t + \varphi_m)$  are harmonic signal components with amplitude  $a_m$  ( $m = 1, 2, 3, \dots, n$ ), angular frequency  $m\omega_0$  and initial phase  $\varphi_m$ . The first term (at  $m = 1$ ) describes harmonic of the fundamental frequency  $\nu_0$ . This fundamental frequency  $\nu_0$  is equal to the frequency of investigated biosignal and is called fundamental tone. Others components (at  $m = 2, 3, \dots, n$ ) are called overtones.

Frequency range from  $\nu_0$  to  $\nu_n = n\nu_0$  is called the frequency spectrum of signal. Signal frequency spectrum and the corresponding harmonic amplitudes determine the harmonic spectrum of the biosignal under consideration (fig. 17.5).

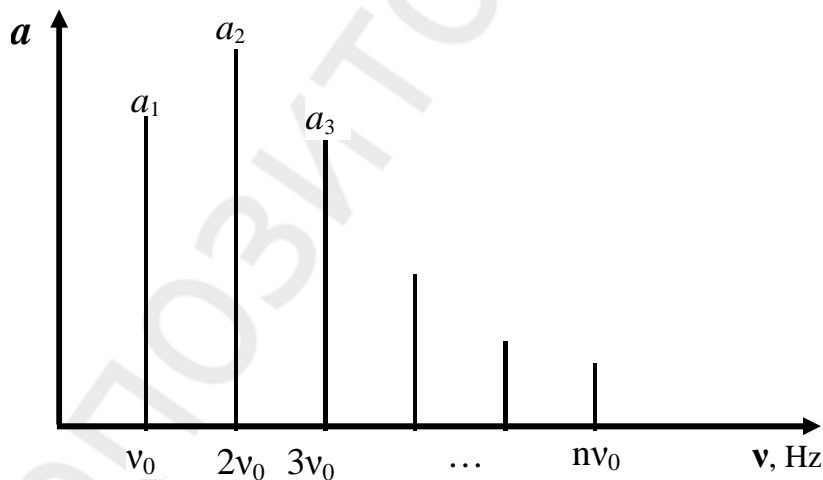


Fig. 17.5. The harmonic spectrum of the periodic signal

In order to satisfy the basic requirement for an amplifier (input signal amplitude increase without distortion of its form) gain  $K$  of the various harmonics of the amplified signal should be the same. In this case gain  $K$  is constant and does not depend on frequency:  $K_0 = K_1 = K_2 = \dots = K_n = \text{const} = K$ , if the initial phase of the harmonics do not change with amplifying. The output signal will be a new periodic function:

$$E(t) = K \left\{ a_0 + \sum_{m=1}^n a_m \cos(m\omega_0 + \phi_m) \right\} = K\varepsilon(t), \quad (17.7)$$

that is, the output will be  $K$  times as the input signal. The amplifier satisfying these conditions ( $K = \text{const}$ ) can be considered as an ideal amplifier.

No practical operational (so called real) amplifier is ideal. In fact the gain depends on frequency and amplitude of input signal  $K = K(n, a_m) \neq \text{const}$  that leads to the frequency and amplitude distortion of the amplified signal.

Gain dependence on frequency is called frequency characteristic of the amplifier. For ideal amplifier frequency characteristic is a line parallel to axis of abscissas and the gain is independent on signal frequency:  $K = \text{const}$ .

For a real amplifier gain is constant only in a certain range of frequencies (fig. 17.6). The range of frequencies within which the gain  $K$  is greater or equal to  $0,7K_{\max}$  is called frequency bandwidth. If the frequency spectrum of the amplified signal completely falls into the bandwidth, frequency distortions of an output signal are negligible and the amplifier can be used for medical diagnostic.

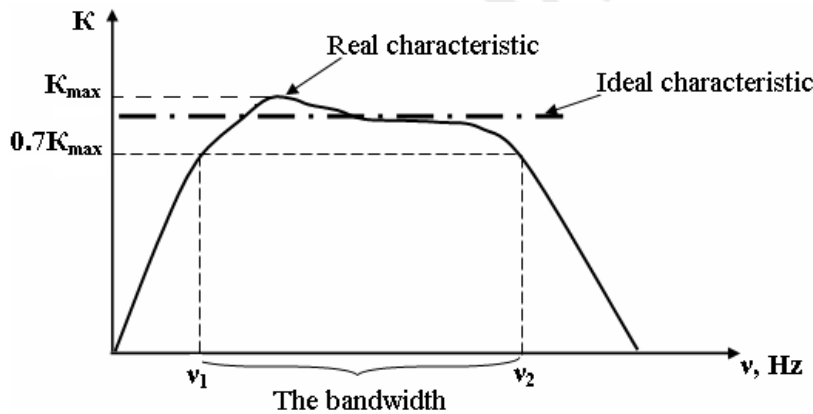


Fig. 17.6. Frequency characteristic of the amplifier. The bandwidth includes frequencies from  $\nu_1$  to  $\nu_2$  where the gain changes within the range from  $0,7K_{\max}$  to  $K_{\max}$

Another important characteristic of an amplifier is its amplitude characteristic. Amplifier amplitude characteristic is the dependence of the output signal amplitude (i. e. voltage, current, power) on the input signal amplitude. For an ideal amplifier, this dependence is always linear because the gain is constant and independent from the input signal amplitude:  $U_{out} = KU_{in}$ . For a real amplifier, this dependence is linear only in a certain range of input voltages, namely, at  $U_{in1} \leq U_{in} \leq U_{in2}$  (fig. 17.7).

Only within this range, the gain is constant and amplitude distortion are absent. Therefore, input voltage range between  $U_{in1}$  and  $U_{in2}$ , within which the amplitude characteristic is linear, is called the dynamic range  $D$  of amplifier and is expressed in decibels (dB). For voltage amplifier dynamic range  $D$  is:

$$D = 20 \lg \frac{U_{in2}}{U_{in1}}. \quad (17.8)$$

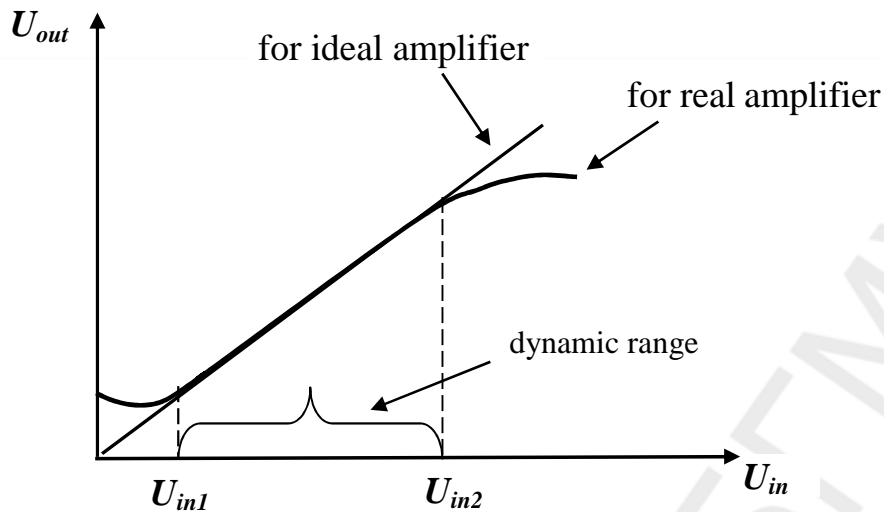


Fig. 17.7. Amplitude characteristic of amplifier

To amplify the signal without distortion by using a real amplifier it is necessary to comply with two conditions:

- the frequency spectrum of the amplified signal should completely be within the bandwidth;
- amplitude range of amplified signal should completely be within the amplifier dynamic range  $D$ .

The table 17.1 shows the ranges of amplitudes and frequencies covered by several of the common biopotential signals.

Table 17.1

**The ranges of amplitudes and frequencies covered by ECG, EEG and EMG biosignals**

Electrogram	Electrocardiogram ECG	Electroencephalogram EEG	Electromyogram EMG
Frequencies range, $Hz$	0,5– 400	1–1000	1–10000
Amplitude range, $mV$	0,1–5	0,01–0,5	0,1–50

#### 17.4. DIFFERENTIAL AMPLIFIER

A differential amplifier is a type of electronic amplifier that multiplies the difference between two inputs by some constant factor  $K$ . The differential amplifier feature is the presence of two inputs (a non-inverting input terminal and an inverting input terminal) and one common output. The gains for these inputs are equal in magnitude but opposite in sign:

$$U_{out1} = -KU_{in1}; \quad U_{out2} = +KU_{in2}. \quad (17.9)$$

The output voltage  $U_{out}$  is proportional to the difference between the voltages  $U_{in2}$  and  $U_{in1}$  appearing at the two input terminals:

$$U_{out} = U_{out2} + U_{out1} = K(U_{in2} - U_{in1}). \quad (17.10)$$

The measurement of ECG signal provides an excellent example to demonstrate the need for using a differential amplifier. The magnitude of



the ECG signal on the body surface is very small: often less than 1 mV. On the other hand, due to the surrounding power supply lines, there is a strong 50 Hz noise signal on the body surface, and the magnitude of this noise is usually 1000 times larger than that of the ECG signal. To eliminate the noises mentioned above, differential amplifier can use as shown in fig. 17.8.

Fig. 17.8 shows that three electrodes, two of them (on the right and left arms) picking up the ECG signal and the third (on the right leg) providing the reference potential, connect the subject to the amplifier. The large 50 Hz noise ( $U_{noise}$ ) in both  $U_{in2} = \varphi_2 - \varphi_0 + U_{noise}$  and  $U_{in1} = \varphi_1 - \varphi_0 + U_{noise}$  (which is called the common mode signal) will be cancelled out, and the ECG signal — the voltage drop between left leg and right arm (which is called the differential signal) is amplified:

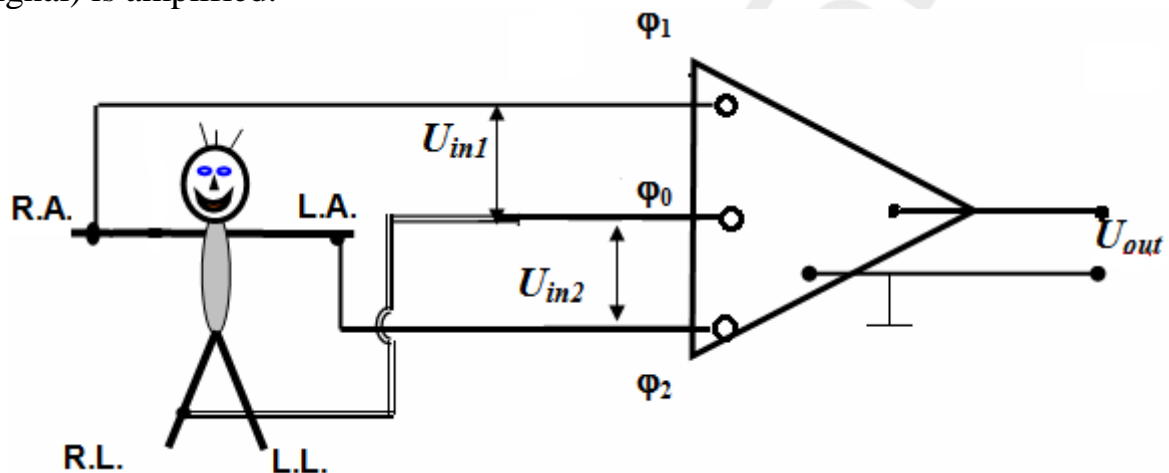


Fig. 17.8. Driven-right-leg circuit for minimizing common-mode interference

$$U_{out} = K(\varphi_1 - \varphi_0 + U_{noise} - \varphi_2 + \varphi_0 - U_{noise}) = K(\varphi_1 - \varphi_2). \quad (17.11)$$

Strong rejection of the common mode signal is one of the most important characteristics of a good biopotential amplifier.

### Questions:

1. Describe the main sensor characteristics. What is the difference between passive sensors and active ones?
2. What is a thermocouple? Describe temperature measurement by thermocouple.
3. Explain dependence of conductor electric resistance on temperature. Give the graph.
4. What is the difference between resistance temperature detectors and thermistors?
5. Describe purpose and constitution of biopotential amplifier.
6. What is a harmonic spectrum of the periodic signal? What is harmonic spectrum determined by? Specify amplitude and frequency parameters for ECG, EEG and electromiogram.
7. Give real amplifier frequency characteristic and amplitude one. How to determine a frequency bandwidth and amplifier dynamic range?
8. How is it possible to amplify the signal without distortion by using a real amplifier?
9. Describe the differential amplifier construction.

## Chapter 18. ELECTROMAGNETIC WAVES. LIGHT POLARIZATION

### 18.1. ELECTROMAGNETIC EQUATION. THE ELECTROMAGNETIC SPECTRUM OF RADIATION

A controversy over the nature of light existed for centuries. In the seventeenth century, Sir Isaac Newton explained many properties of light with a particle model. In the early nineteenth century, Thomas Young performed some interference experiments that could be explained only by assuming that light is a wave. By the end of the nineteenth century, nearly all known properties of light, including many of its interactions with matter, could be explained by assuming that light consists of an electromagnetic wave. By an electromagnetic wave, we mean that light can be produced by accelerating an electric charge. According to Maxwell's theory a varying electric field sets up a magnetic one which, generally speaking, is also varying. This varying magnetic field sets up an electric field, and so on. Thus, if one use oscillating charges to produce a varying (alternating) electro magnetic field, then in the space surrounding the charges a sequence of mutual transformations of an electric and a magnetic field propagating from point to point will appear. This process will be periodic in both time and space and, consequently, will be a wave. Thus light can be represented as a transverse electromagnetic wave made up of mutually perpendicular, fluctuating electric and magnetic fields with the same amplitude and frequency.

This sinusoidally varying electric and magnetic field can be written as:

$$E = E_0 \sin \omega(t - \frac{x}{u}), \quad B = B_0 \sin \omega(t - \frac{x}{u}), \quad (18.1)$$

where  $E_0$  and  $B_0$  are the amplitude values of the electric field strength and the magnetic induction respectively;  $\omega = 2\pi\nu$  is the angular frequency;  $t$  is a time;  $\nu$  is the velocity;  $x$  is the coordinate.

If the wave is sinusoidal, then the period  $T$ , frequency  $\nu$ , and wavelength  $\lambda$ , are related by  $\nu = 1/T$ ,  $\lambda = c/\nu$ . The velocity of electromagnetic waves is determined by formula:

$$u = \frac{1}{\sqrt{\varepsilon\varepsilon_0\mu\mu_0}}, \quad (18.2)$$

where  $\varepsilon$  is a permittivity;  $\varepsilon_0 = 8,85 \cdot 10^{-12}$  F/m;  $\mu$  is a permeability;  $\mu_0 = 1,43 \cdot 10^{-7}$  Gn/m.

In a vacuum (i. e. when  $\varepsilon = \mu = 1$ ), the velocity of electromagnetic waves  $c = \frac{1}{\sqrt{\varepsilon_0\mu_0}} = 2,98 \cdot 10^8$  m·s<sup>-1</sup> is maximum. Light travels in a vacuum with a velocity  $c \approx 3 \cdot 10^8$  m s<sup>-1</sup> (to an accuracy of 0,07 %). When light travels through matter, its speed is less than this and is given by  $v = c/n$ , where  $n$  is the index of refraction of the substance. The value of the index of refraction is determined as

$n = \frac{c}{u} = \sqrt{\epsilon\mu}$  and depends on both the composition of the substance and the wavelength of the light.

The orderly distribution of electromagnetic waves according to their wavelength or frequency is called the electromagnetic spectrum. Electromagnetic spectrum covers a wide range of wavelengths or frequencies. The whole electromagnetic spectrum has been classified into different parts in order of increasing wavelength and type of excitation. The electromagnetic spectrum includes radio waves, infrared, visible, and ultraviolet light, X-rays; and gamma rays. All of these are fundamentally similar in that they move at  $300\,000\text{ km s}^{-1}$  the speed of light. The only difference between them is their wavelength (or frequency), which is directly related to the amount of energy the waves carry. The shorter the wavelength of the radiation, the higher the energy.

On one end of the spectrum are radio waves with wavelengths billions of times longer than those of visible light. On the other end of the spectrum are gamma rays. These have wavelengths millions of times smaller than those of visible light. The following are the basic categories of the electromagnetic spectrum, from longest to shortest wavelength:

**Radio waves** are used to transmit radio and television signals. Radio waves have wavelengths ( $\lambda > 10^{-3}\text{ m}$ ) that range from less than a centimeter to tens or even hundreds of meters;

**Infrared (IR)** is the region of the electromagnetic spectrum that extends from the visible region to about one millimeter (in wavelength  $10^{-3}\text{ m} > \lambda > 0,76 \cdot 10^{-6}\text{ m}$ ). Infrared waves include thermal radiation. Infrared radiation can be measured using electronic detectors and has applications in medicine;

**Visible light:** the rainbow of colors is known as visible light is the portion of the electromagnetic spectrum with wavelengths between 400 to 760 nanometers ( $760\text{ nm} > \lambda > 400\text{ nm}$ ). It is the part of the electromagnetic spectrum that we see, and coincides with the wavelength of greatest intensity of sunlight;

**Ultraviolet (UV)** radiation has a range of wavelengths  $400\text{ nm} > \lambda > 80\text{ nm}$ . A small dose of ultraviolet radiation is beneficial to humans, but larger doses cause skin cancer and cataracts. UV is used to destroy the bacteria and for sterilizing surgical instruments;

**X-rays** are high energy waves which have great penetrating power and are used extensively in medical applications (as a diagnostic tool) and in inspecting welds. The wavelength range is  $80\text{ nm} > \lambda > 10^{-5}\text{ nm}$ ;

**Gamma rays** have wavelengths of less than  $\lambda < 10^{-5}\text{ nm}$ . They are more penetrating than X-rays. Gamma rays are generated by radioactive atoms and in nuclear explosions, and are used in many medical applications (for example, for treatment of cancer).

Light was discovered to have both particle properties and electromagnetic wave properties at the same time. A traveling of light can be described by

a wave with wavelength  $\lambda = c/\nu$ . As light moves from one medium into another where it travels with a different speed, the frequency remains the same. The wavelength changes as the speed changes. According to the quantum theory light may at times exhibit properties like those of particles in their interaction with matter. Each particle of light or photon has energy  $E$ . The energy of each photon (a «particle» concept) is related to its frequency (a «wave» concept) by

$$E = h\nu = h \frac{c}{\lambda}. \quad (18.3)$$

The proportionality constant  $h$  is called Planck's constant. It has the numerical value  $h = 6,63 \cdot 10^{-34} \text{ J s} = 4,14 \cdot 10^{-15} \text{ eV s}$ . The electron volt (eV) is a unit of energy.  $1 \text{ eV} = 1,6 \cdot 10^{-19} \text{ J}$ . It is the energy acquired by an electron that moves through a potential difference of 1 V. We use the number « $h$  stroke» or « $h$  bar»:  $\hbar = h/2\pi = 1,05 \cdot 10^{-34} \text{ J}\cdot\text{s} = 0,66 \cdot 10^{-15} \text{ eV}\cdot\text{s}$ . In terms of the angular frequency  $\omega = 2\pi\nu$ ,

$$E = \hbar \omega. \quad (18.4)$$

It should be noticed the shorter the wavelength of the radiation, the higher the energy and the more harmful for biological objects.

## 18.2. POLARIZATION OF LIGHT

Light can be represented as a transverse electromagnetic wave made up of mutually perpendicular, fluctuating electric and magnetic fields. Fig. 18.1 shows the sinusoidally varying electric field in the  $xy$  plane, the sinusoidally varying magnetic field in the  $xz$  plane and the propagation of the wave with a velocity  $v$  in the  $x$  direction. The fig. 18.1 presents the electric field (denoted by  $E$ ) in the  $xy$  plane, the magnetic field (denoted by  $B$ ) in the  $xz$  plane and the propagation of the wave in the  $x$  direction.

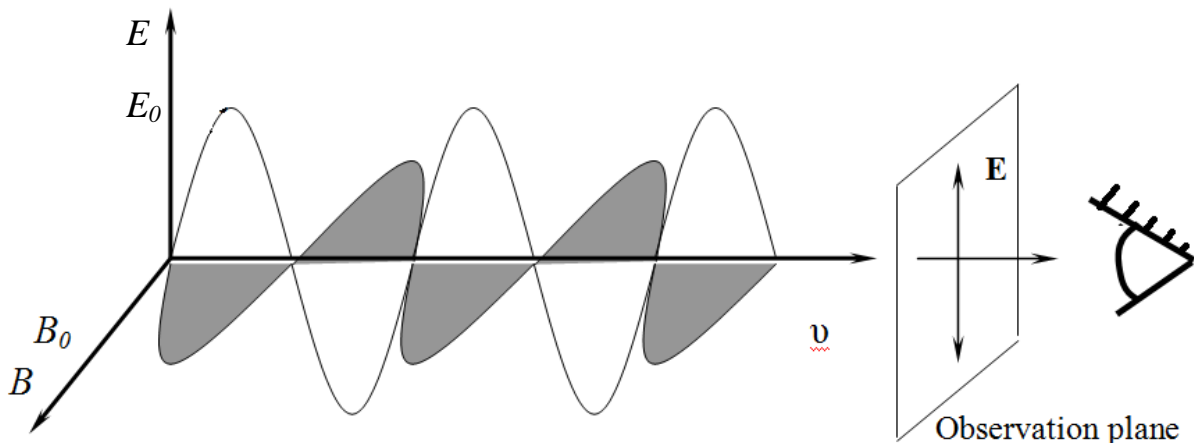


Fig. 18.1. Electromagnetic wave

Conventionally, when considering polarization, the electric field vector  $E$  is described and the magnetic field  $B$  is ignored since it is perpendicular to the electric field and proportional to it. Historically, the orientation of

a polarized electromagnetic wave has been defined in the optical regime by the orientation of the electric vector, and in the radio regime, by the orientation of the magnetic vector. Vector  $E$  is called light vector. At the point of intersection, the electric field is measured and shown as a vector in the observation plane, which is perpendicular to light of propagation. In other words, the length and direction of the vector represents the strength and the direction of the electric field measured at the starting point of the vector. Don't interpret these fig. 18.1 as showing waves located in space. The plane in which the light vector oscillates will be called the plane of oscillations.

The shape traced out in an observation plane by the electric vector  $E$  as such a plane wave passes over it is a description of the **polarization state**. If the vector of the electric field (measured at a fixed point of space) oscillates along a straight line then the waves are called plane-polarized or linearly polarized waves. In this case the tip of the vector  $E$  traces out a single line in the plane as illustrated in fig. 18.2.

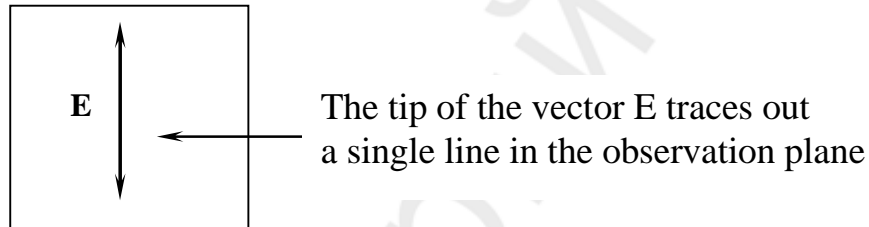


Fig. 18.2. Plane-polarized or linearly polarized light

At any fixed point in space that is in the line of the propagation of this wave, the electric field vector rotates in a circle while its length remains constant. Such waves are called circularly polarized waves. In this special case the electric vector traces out a circle in the observation plane which is perpendicular to light of propagation, so this special case is called circular polarization. Circular polarization may be referred to as right ( $R$ ) or left ( $L$ ), depending on the direction in which the electric field vector rotates (fig. 18.3). Circular polarization is a limiting case of the more general condition of elliptical polarization.

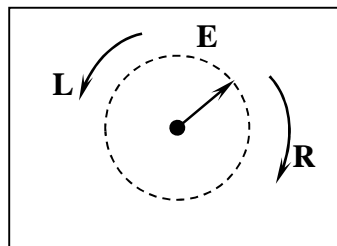


Fig. 18.3. Circularly polarized light

**Elliptical polarization** is the polarization wave such that the tip of the electric field vector  $E$  describes an ellipse in an observation plane. The magnitude of the electric field vector varies as it rotates (fig. 18.4).

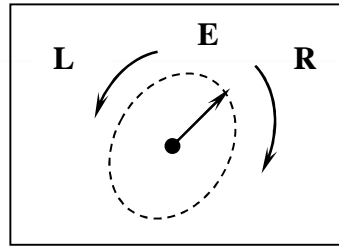


Fig. 18.4. Elliptically polarized light

Most light sources contain waves in which the electric fields are oriented (oscillated) in all possible directions and this light is referred to as «unpolarized» (natural). Thus unpolarized light is a linear superposition of linearly polarized waves. Light emitted by the sun, by a lamp in the classroom, or by a candle flame is unpolarized light. Such light waves are created by electric charges which vibrate in a variety of directions, thus creating an electromagnetic wave which vibrates in a variety of directions. This concept of unpolarized light is rather difficult to visualize. In general, fig. 18.5 is to picture unpolarized light as a wave which has a multitude of vibrations.

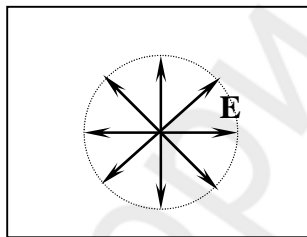


Fig. 18.5. Unpolarized light

Partly polarized light can be considered as a mixture of natural (unpolarized) and plane-polarized light (fig. 18.6). The expression

$$P = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \quad (18.5)$$

is known as the degree of polarization. For plane-polarized light  $I_{\min} = 0$ , and  $P = 1$ . For natural light,  $I_{\min} = I_{\max}$  and  $P = 0$ . For partly polarized light,  $P < 1$ .

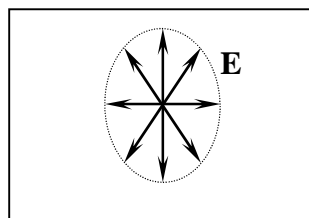


Fig. 18.6. Partly polarized light

It is possible to transform unpolarized light into polarized light. The process of transforming unpolarized light into polarized light is known as **polarization**. There are a variety of methods of polarizing light.

### 18.3. POLARIZATION BY REFLECTION

When unpolarized light is incident on a boundary between two dielectric surfaces, for example on an air-glass boundary, then the reflected and transmitted components are partially plane polarized. Light with the perpendicular oscillations to the plane of incidence (is said to be s-polarized) predominate in the reflected ray (in fig. 18.7 these oscillations are denoted by points), and oscillations parallel to the plane of incidence (p-polarized light) predominate in the refracted ray (they are depicted in the fig. 18.7 by double-headed arrows). The degree of polarization depends on tint angle of incidence.

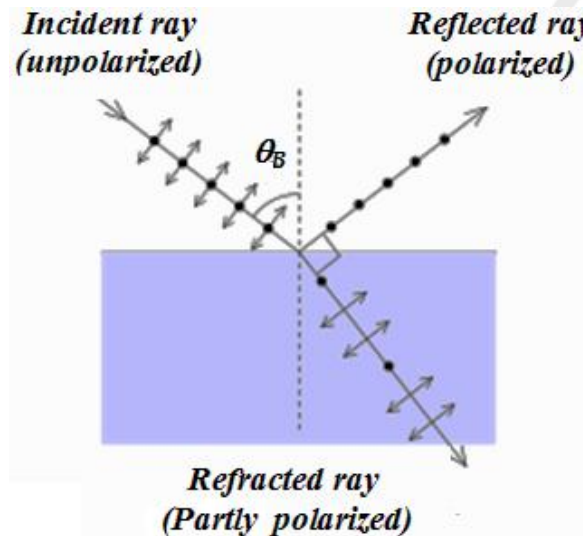


Fig. 18.7. Polarization by reflection

At one particular angle of incidence, however, light with one particular polarization cannot be reflected. This angle of incidence is Brewster's angle  $\theta_B$ :

$$\operatorname{tg} \theta_B = \frac{n_2}{n_1}, \quad (18.6)$$

where  $n_1$  and  $n_2$  are the refractive indices of two media.

This equation is known as Brewster's law. Note that, since p-polarized light is refracted (i. e. transmitted), any light reflected from the interface at this angle must be s-polarized.

A simple polarizer can be made by tilting a stack of glass plates at Brewster's angle to the beam (fig. 18.8). For visible light in air and typical glass, Brewster's angle is about  $57^\circ$ . Some of the s-polarized light is reflected from each surface of each plate. For a stack of plates, each reflection depletes the incident beam of s-polarized light, leaving a greater fraction of p-polarized light in the transmitted beam at each stage. After one interface the refracted beam will be partially polarized, having lost some of its s-polarized component. If the stack contains many plates, then the refracted beam will have a high degree of polarization, since at each interface the same fraction of the remaining

*s*-polarization is lost. This pile-of-plates polarization mechanism is used in many polarizing beam splitters, where many layers of dielectric thin film are laid onto the interior prism angle of the beam splitter.

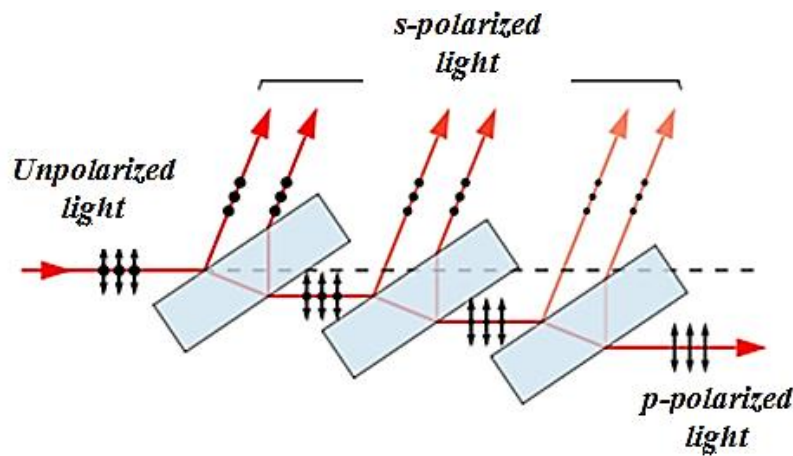


Fig. 18.8. A stack of plates at Brewster's angle to a beam reflects off a fraction of the *s*-polarized light at each surface, leaving a *p*-polarized beam. Full polarization at Brewster's angle requires many more plates than shown

#### 18.4. OPTICAL ANISOTROPY

Isotropic media is a media in which light behaves the same way no matter which direction it is traveling. Anisotropic media, that is, media in which light behaves differently depending on which direction the light is propagating. The behavior of a light ray that propagates through an anisotropic material is dependent on its polarization. An anisotropy crystal, such as calcite, will divide an entering ray of monochromatic light into two rays having orthogonal polarizations. The rays will usually propagate in different directions and have different propagation speeds. One of the rays is called an ordinary and designated by the symbol *o*-ray. Its propagation speed ( $u_o = \frac{c}{n_o}$ ) is constant in different directions. For the other ray, called an extraordinary ray and designated by *e*-ray, propagation speed ( $u_e = \frac{c}{n_e}$ ) is various in different directions.

However, there are one or two directions such that any light in that direction in the crystal has the same speed, regardless of its state of polarization. This direction is called the optic axis. The crystals have two optic axes are said to be biaxial, which have one optic axes is called uniaxial ones.

It must be borne in mind that an optical axis is not a straight line passing through a point of a crystal, but a definite direction in the crystal. Any straight line parallel to the given direction is an optical axis of the crystal.

A plane passing through an optical axis is called a principal plane of the crystal. Customarily, the principal plane passing through the light ray is used.



Investigation of the ordinary and extraordinary rays shows that they are both completely polarized in mutually perpendicular directions. The plane of oscillations of the ordinary ray is perpendicular to a principal plane of the crystal. In the extraordinary ray, the oscillations of the light vector occur in a plane coinciding with a principal plane.

### 18.5. POLARIZATION IN DOUBLE REFRACTION

Many crystals are anisotropic to light and exhibit properties such as birefringence. When a light ray normally incident on a birefringent crystalline surface it will be divided into two rays (ordinary and extraordinary) at the boundary according to the refraction law because  $n_o \neq n_e$  (fig. 18.9).

$$\sin \beta_o = \frac{\sin \alpha}{n_o}; \quad \sin \beta_e = \frac{\sin \alpha}{n_e}. \quad (18.7)$$

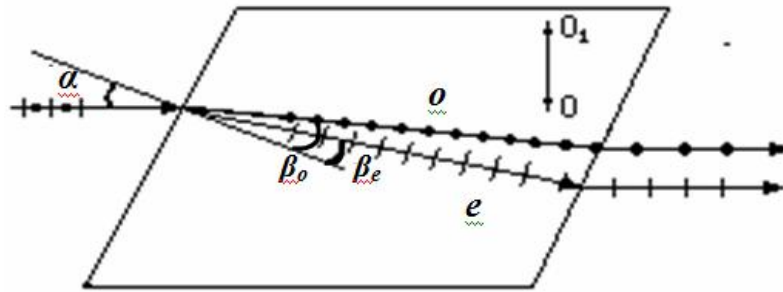


Fig. 18.9. Double refraction phenomenon

The index of refraction for the extraordinary ray  $n_e$  is a continuous function of direction. The index of refraction for the ordinary ray  $n_o$  is independent of direction. The two indices of refraction are equal only in the direction of an optic axis. The extraordinary ray will deviate from the incident direction while the ordinary ray will not. The ordinary ray index  $n_o$  and the most extreme extraordinary ray index  $n_e$  are together known as the principal indices of refraction of the material. Birefringent crystals are used in many polarization devices. In some devices the difference in the refractive index is used to separate the rays and eliminate one of the polarization states, as in the Nicol prism.

### 18.6. THE NICOL PRISM

The Nicol prism is an optical device used to generate a beam of polarized light. It was the first type of polarizing prism to be invented, in 1828 by William Nicol. It consists of a rhombohedral crystal of calcite (Iceland spar) that has been cut at a  $68^\circ$  angle, split diagonally, and then joined again using Canada balsam (fig. 18.10).

Unpolarized light enters one end of the crystal and is split into two polarized rays by birefringence. One of these rays (the **ordinary** or **o-ray**) experiences a refractive index of  $n_o = 1,658$  and at the balsam layer (refractive

index  $n_b = 1,55$ ) undergoes total internal reflection at the interface since  $n_o > n_b$ , and is reflected to the side of the prism. Then ordinary ray is absorbed by black mounting material in the prism housing. The other ray (the *extraordinary* or *e-ray*) experiences a lower refractive index ( $n_e = 1,486$ ), is not reflected at the interface, and leaves through the second half of the prism as plane polarized light.

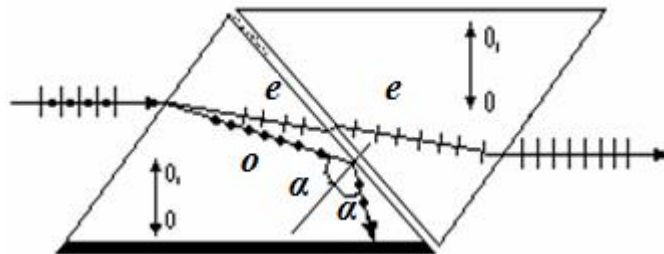


Fig. 18.10. The Nicol polarizing prism

### 18.7. PHENOMENON OF DICHROISM

In some crystals, one of the rays (ordinary or extraordinary) is absorbed to a greater extent than the other as illustrated in fig. 18.11.

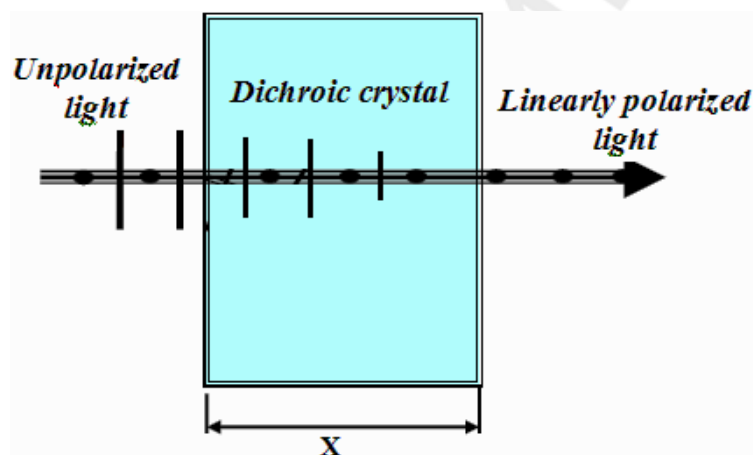


Fig. 18.11. Phenomenon of dichroism

That is one in which light rays having different polarizations are absorbed by different amounts. This phenomenon is called dichroism. This circumstance has been taken advantage of for manufacturing a polarizing device called a polaroid. A crystal of tourmaline (a mineral of a complex composition) displays very great dichroism in visible rays. An ordinary ray is virtually completely absorbed in it over a distance of 1 mm. However, this crystal is seldom used as a polarizer, since the dichroic effect is strongly wavelength dependent and the crystal appears coloured. In crystals of herapathite (iodoquinine sulphate), one of the rays is absorbed over a path of about 0,1 mm. Herapathite is a celluloid film into which a great number of identically oriented minute crystals of iodoquinine sulphate have been introduced. Polaroid filters absorb one component of polarization while transmitting the perpendicular

components. The intensity of transmitted light depends on the relative orientation between the polarization direction of the incoming light and the polarization axis of the polarizer and is described quantitatively by Malus intensity Law.

### 18.8. POLARIZED LIGHT TRANSITION THROUGH A POLARIZER. MALUS'S LAW

Plane-polarized light can be obtained from originally unpolarized light with the aid of devices called polarizers. These devices freely transmit oscillations parallel to the plane which we shall call the polarization plane and completely or partly retain the oscillations perpendicular to this plane.

Assume that plane-polarized light of amplitude  $E_0$  and intensity  $I_0$  falls on a polarizer (fig. 18.12).

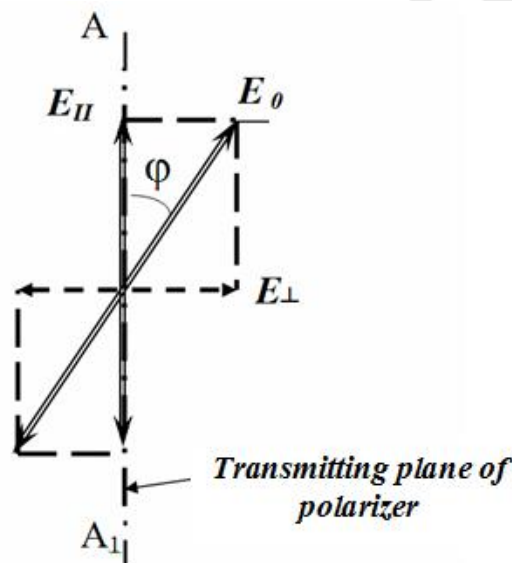


Fig. 18.12. An amplitude  $E_0$  obliquely to the transmitting plane of polarizer is resolved into vector components parallel and perpendicular to that plane

An oscillation of amplitude  $E_0$  occurring in a plane making the angle  $\phi$  with the transmitting polarizer plane can be resolved into two oscillations having the amplitudes  $E_{\parallel} = E_0 \cos\phi$  and  $E_{\perp} = E_0 \sin\phi$  (fig. 18.12). The first, oscillation will pass through the device, the second will be retained. The intensity of the transmitted wave is proportional to  $E_{\parallel}^2 = E_0^2 \cos^2\phi$ , i. e. is  $I \cdot \cos^2\phi$ , where  $I$  is the intensity of the oscillation of amplitude  $E$ . Consequently, an oscillation parallel to the plane of the polarizer carries along a fraction of the intensity equal to  $\cos^2\phi$ .

Assume that plane-polarized light of amplitude  $E_0$  and intensity  $I_0$  incidents on a polarizer. The component of the oscillation having the amplitude  $E = E_0 \cos\phi$ , where  $\phi$  is the angle between the plane of oscillations of the incident light and the plane of the polarizer, will pass through the device. Hence, the intensity of the transmitted light  $I$  is determined by the expression:

$$I = I_0 \cos^2\phi, \quad (18.8)$$

where  $I_0$  is the initial intensity, and  $\phi$  is the angle between the light's initial plane of polarization and the axis of the polarizer (is the angle between the transmission axes of the polarized beam and the polarizer). This relation (18.8) is known as Malus's Law. It was first formulated by the French physicist Etienne Malus.

When unpolarized light is incident on an ideal polarizer, the intensity of the transmitted light is one-half that of the incident light. This can be explained if we resolve the electric fields of the incident waves into components parallel and perpendicular to the polarizing axis. Because the incident light is a random mixture of all states of polarization, these components will, on average, be equal (all the values of  $\phi$  are equally probable). Since the polarizer transmits only the component parallel to the axis of polarization, one-half of the incident intensity is transmitted. When the polarizer is rotated about the direction of a natural ray, the intensity of the transmitted light remains the same.

If two polarizers are placed one after another (the second polarizer is generally called an analyzer), the mutual angle between their polarizing axes gives the value of  $\phi$  in Malus' Law. If the two axes are orthogonal  $\phi = 90^\circ$ , the polarizers are crossed and in theory no light is transmitted (fig. 18.13), though again practically speaking no polarizer is perfect and the transmission is not exactly zero. The maximum intensity equal to  $\frac{I_0}{2}$  obtained at  $\phi = 0$  (the polarizers axes are parallel).

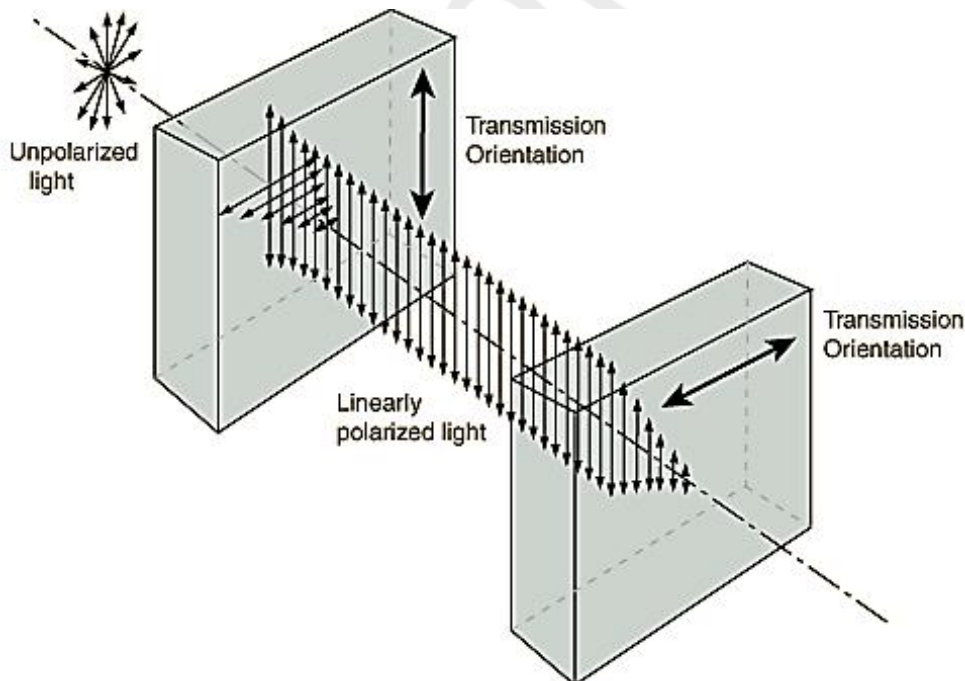


Fig. 18.13. The crossed polarizers

If a transparent object is placed between the crossed polarizers, any polarization effects present in the sample (such as birefringence) will be shown

as increases in transmission. This effect is used in polarimetry to measure the optical activity of a sample.

### 18.9. OPTICAL ACTIVITY

An optical activity is the rotation of linearly polarized light as it travels through certain materials (fig. 18.14). Some substances known as optically active ones have the ability of causing rotation of the plane of polarization of plane-polarized light passing through them. Such substances include crystalline bodies (for example, quartz, cinnabar), pure liquid (turpentine, nicotine), and solutions of optically active substances in inactive solvents (aqueous solutions of sugar, tartaric acid).

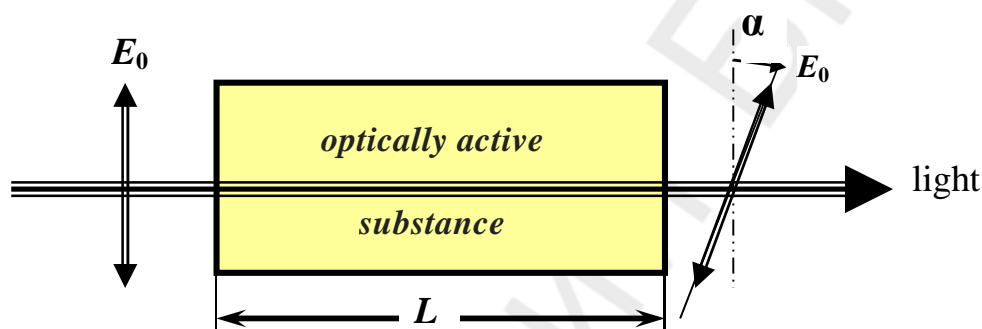


Fig. 18.14. A rotation of linearly polarized light as it travels through optically active substance

Crystalline substances rotate the plane of polarization to the greatest extent when the light propagates along the optical axis of crystal. The angle of rotation  $\alpha$  is proportional to the path  $L$  traveled by a ray in the crystal:

$$\alpha = \alpha_0 L, \quad (18.9)$$

The coefficient  $\alpha_0$  is called the rotation constant. It depends on the wavelength (dispersion of the ability to rotate).

In solutions, the angle of rotation of the plane of polarization proportional to the path  $L$  of the light in the solution and to the concentration of the active substance  $c$ :

$$\alpha = \alpha_0 c L, \quad (18.10)$$

Here  $\alpha_0$  is a quantity called the specific rotational constant.

Depending on the direction of rotation of the polarization plane optically active substances are divided into right-hand and left-hand ones. There exist right-hand and left-hand quartz, right-hand and left-hand sugar, etc. If we place an optically active substance (a crystal of quartz, a transparent tray with a sugar solution, etc.) between two crossed polarizers, then the field of vision becomes bright. To get darkness again, one of the polarizers has to be rotated through the angle  $\alpha$  determined by expression (18.9) or (18.10). When a solution is used, we can determine its concentration  $c$  by equation (18.10) if we know the specific rotational constant  $\alpha_0$  of the given substance and the length  $L$  and have

measured the angle of rotation  $\alpha$ . This way of determining the concentration is used in the production of various substances; in particular in the sugar industry (the corresponding instrument is called a saccharimeter). It is used in the sugar industry to measure syrup concentration, in optics to manipulate polarization, in chemistry to characterize substances in solution, and is being developed as a method to measure blood sugar concentration in diabetic people.

**Questions:**

1. What is an electromagnetic wave? Explain relationship between electric field strength amplitude and magnetic induction one. What does absolute refractive index characterize?
2. Specify the electromagnetic spectrum main ranges.
3. What polarization types are known? What is the degree of polarization?
4. How does polarization change by reflection from dielectric? Write Brewster's Law.
5. What is the double refraction phenomenon? Describe properties of ordinary wave and extraordinary one.
6. Explain the Nicol prism construction and a light propagation through it.
7. Explain phenomenon of dichroism. What are the polarizers?
8. Write Malus's Law.
9. What is the optical activity? How to determine a concentration of optically active substance by polarizer?

## Chapter 19. THERMAL RADIATION

Bodies can emit electromagnetic waves at the expense of various kinds of energy. The most widespread is thermal radiation, i. e. the emission of electromagnetic waves at the expense of the internal energy of bodies. Thermal radiation occurs at any temperature, but at low temperatures practically only long (infrared) electromagnetic waves are emitted.

### 19.1. BASIC CHARACTERISTICS OF THERMAL RADIATION

We'll characterize the intensity of thermal radiation by the magnitude of *the energy flux* measured in watts (W) and use the symbol  $\Phi$ . *The energy flux*  $\Phi$  is the total rate of emitted energy.  $\Phi$  can be written in the form:

$$\Phi = \frac{E}{t}, \quad (19.1)$$

where  $E$  is the radiation energy,  $t$  is the time.

The second important characteristic is *the radiant emittance*. *The radiant emittance* of the body is the energy flux emitted by unit surface area of a radiating body in all directions. We'll use the symbol  $R$  to designate this quantity. The radiant emittance has units of  $\text{Wm}^{-2}$  and can be written in the form:

$$R = \frac{\Phi}{S}, \quad (19.2)$$

where  $\Phi$  is the energy flux,  $S$  is a surface area.

Radiation consists of waves having different wavelengths  $\lambda$ . Let  $dR_\lambda$  be the energy flux emitted by unit surface area of a body on wavelength  $\lambda$  within the wavelength interval  $d\lambda$ . When the interval  $d\lambda$  is small, the flux  $dR_\lambda$  will be proportional to  $d\lambda$ :

$$dR_\lambda = r_\lambda d\lambda. \quad (19.3)$$

The  $r_\lambda$  is called *the emissivity* of a body and  $r_\lambda$  is the spectral radiance of the body. The emissivity  $r_\lambda$  has units of  $\text{Wm}^{-3}$ . Like the radiant emittance  $R$ , the emissivity  $r_\lambda$  depends greatly on the temperature of a body. Thus,  $r_\lambda$  is a function of the wavelength and temperature.

The radiant emittance  $R$  and the emissivity  $r_\lambda$  are related by the formula:

$$R_T = \int_0^\infty dR_T = \int_0^\infty r_{\lambda T} d\lambda \quad (19.4)$$

(to stress that the radiant emittance  $R$  and the emissivity  $r_\lambda$  depend on the temperature, we have provided them with the subscript  $T$ ).

Assume that the flux of radiant energy  $d\Phi_\lambda$  due to electromagnetic waves whose wavelength  $\lambda$  is within the interval from  $\lambda$  to  $\lambda + d\lambda$  falls on an elementary area of a body's surface. A part of this flux  $d\Phi_\lambda(\text{abs})$  will be absorbed by the body. The dimensionless quantity

$$\alpha_{\lambda T} = \frac{d\Phi_\lambda(\text{abs})}{d\Phi_\lambda} \quad (19.5)$$

is called the *absorptivity* of a body. The absorptivity of a body is a function of the wavelength and temperature.

By definition,  $\alpha_{\lambda T}$  cannot be greater than unity. There are three kinds of the bodies with a different absorptivity: a blackbody, the gray bodies and the all other bodies (fig. 19.1):

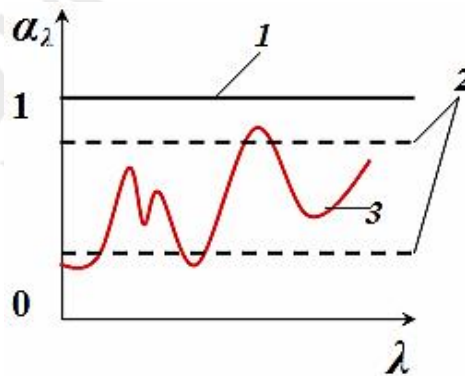


Fig. 19.1. Dependence of the absorptivity  $\alpha_\lambda$  on wavelength  $\lambda$ :

1 — is a blackbody; 2 — is the gray bodies; 3 — is the all other bodies

1. A blackbody completely absorbs the radiation of all wavelengths falling on it,  $\alpha_{\lambda T} \equiv 1$  at the all wavelengths.

2. The gray bodies have the same absorptivity at the all wavelengths too, but it is smaller of the unity:  $\alpha_{\lambda T} \equiv \alpha_T = \text{const} < 1$ .

3. The absorptivity of the all other bodies is not constant and depends on wavelength  $\alpha_{\lambda T} = f(\lambda)$ .

Blackbodies do not exist in nature. Carbon black and platinum black have an absorptivity  $\alpha_{\lambda T}$  close to unity only within a limited range of wavelengths. It is difficult if not impossible to make a surface that is completely absorbing; the absorption can be improved by making a completely enclosed cavity provided with a small hole, as in fig. 19.2. The radiation penetrating in the cavity through the hole will undergo multifold reflections, part of the energy is absorbed upon each reflection and as a result virtually the entire radiation of any frequency is absorbed by such a cavity.

The radiation entering the hole in the cavity bounce from the walls many times before chancing to pass out through the hole again, and they therefore have a greater chance of being absorbed.

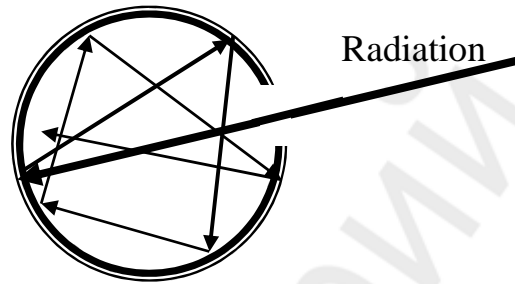


Fig. 19.2. The model of a blackbody

Such a hole in a cavity is a better approximation to a blackbody than is the absorbing material lining the cavity.

The blackbody radiant emittance  $R_b$  and its emissivity  $\epsilon_\lambda$  are related by the formula:

$$R_b = \int_0^{\infty} dR_b = \int_0^{\infty} \epsilon_\lambda d\lambda. \quad (19.6)$$

Much work was done on the properties of blackbody or thermal or cavity radiation in the late 1800s and early 1900s. While some properties could be explained by classical physics, others could not. The description of the function  $\epsilon_\lambda(\lambda, T)$  by Planck is one of the foundations of quantum mechanics. Max Planck has made an assumption absolutely alien to classical notions, namely, to assume that electromagnetic radiation is emitted in the form of separate portion of energy (quanta) whose magnitude is proportional to the frequency of radiation:

$$E = h\nu, \quad (19.7)$$

where the constant of proportionality  $h$  was subsequently named Planck's constant. Moreover Planck has obtained formula for the function  $\epsilon_\lambda(\lambda, T)$ :

$$\epsilon_\lambda = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}. \quad (19.8)$$



We'll not discuss the history of these developments, but will simply summarize the properties of the blackbody radiation function that are important.

Let's consider the main thermal radiation laws that have been opened.

## 19.2. THERMAL RADIATION LAWS

### Kirchhoff Law

There is a definite relation between the emissivity and absorptivity of any body. We can convince ourselves that this is true by considering the following experiment. Assume that several bodies are confined in an enclosure maintained at a constant temperature  $T$  (fig. 19.3).

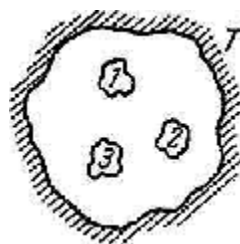


Fig. 19.3. Several bodies are confined in an enclosure maintained at a constant temperature  $T$

The cavity inside the enclosure is evacuated so that the bodies can exchange energy with one another and with the enclosure only by emitting and absorbing electromagnetic waves. Experiments show that such a system will arrive at a state of thermal equilibrium after a certain time elapses — all the bodies will acquire the same temperature  $T$  equal to that of the enclosure. In this state, a body having a greater emissivity  $r_{\lambda T}$  loses more energy from unit surface area in unit time than a body whose emissivity  $r_{\lambda T}$  is lower. Since the temperature (and, consequently, the energy) of the bodies does not change, then the body emitting more energy must absorb more, i. e. have a greater  $a_{\lambda T}$ . Thus, the greater the emissivity  $r_{\lambda T}$  of a body, the greater is its absorptivity  $a_{\lambda T}$ . Hence follows the relation

$$\left( \frac{r_{\lambda}}{a_{\lambda}} \right)_1 = \left( \frac{r_{\lambda}}{a_{\lambda}} \right)_2 = \dots = \frac{\varepsilon_{\lambda}}{1} = \varepsilon_{\lambda}, \quad (19.9)$$

where the subscripts 1, 2 etc. relate to different bodies. This relation expresses the following law established by the German physicist Gustav Kirchhoff: at the stage of thermal equilibrium the ratio of the emissivity and the absorptivity does not depend on the nature of a body, it is the same (universal) function of the wavelength (frequency) and temperature for all bodies and equals the emissivity  $\varepsilon_{\lambda}$  of a blackbody.

The quantities  $r_{\lambda T}$  and  $a_{\lambda T}$  can vary exceedingly greatly for different bodies. Their ratio, however, is identical for all bodies and equals the emissivity  $\varepsilon_{\lambda}$  of a blackbody. This signifies that a body which absorbs certain rays to a greater extent will emit these rays to a greater extent too.

### Stefan–Boltzmann Law

For a long time, attempts to obtain the form of the function  $\epsilon_\lambda(\lambda, T)$  theoretically did not provide a general solution of the problem. In 1879 the Austrian physicist Joseph Stefan analysing experimental data, arrived at the conclusion that the radiant emittance  $R$  of any gray body is proportional to the fourth power of the absolute temperature. But subsequent more accurate measurements, however, showed that his conclusions were erroneous. In 1884 the Austrian physicist Ludwig Boltzmann, on the basis of thermodynamic considerations, obtained theoretically the following value for the radiant emittance  $R_b$  of a blackbody:

$$R_b = \sigma T^4, \quad (19.10)$$

where  $\sigma$  is a constant quantity, and  $T$  is the absolute temperature.

Relation (19.10) between the radiant emittance of a blackbody and its absolute temperature was named the **Stefan–Boltzmann Law**. The constant  $\sigma$  is called the **Stefan–Boltzmann constant**. Its experimental value is  $\sigma = 5,67 \cdot 10^{-8} \text{ W} \cdot \text{m}^{-2} \text{ K}^{-4}$ .

The temperature dependence of the gray body radiant emittance is similar:

$$R_g = \alpha \cdot \sigma T^4, \quad (19.11)$$

where  $\alpha$  is the gray body absorptivity.

### Wien's Displacement Law

At first the wavelength dependence of the black body emissivity has been established experimentally. The value of  $\epsilon_\lambda$  is plotted for several different temperatures in fig. 19.4.

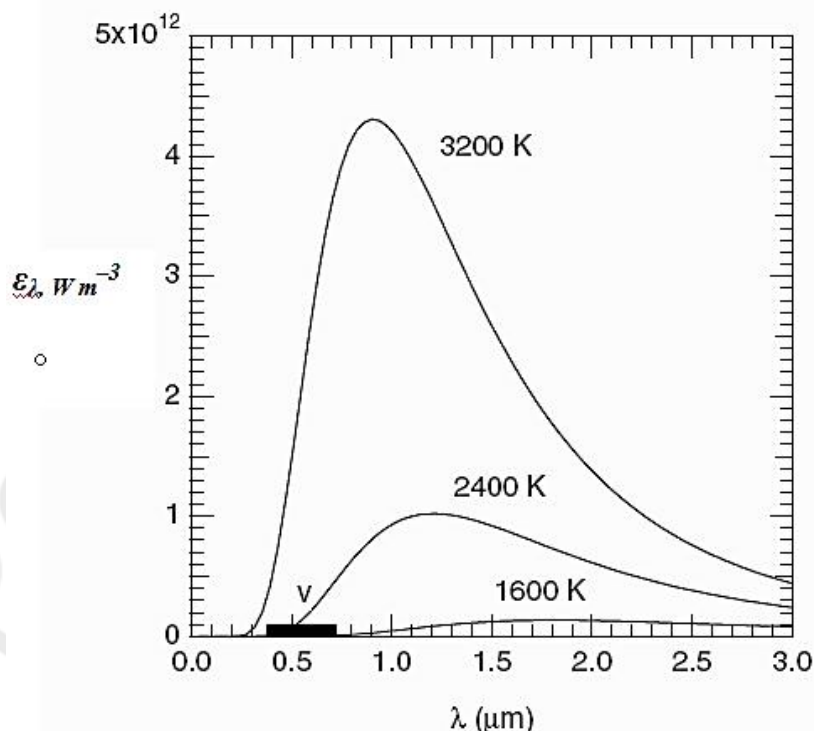


Fig. 19.4. The blackbody radiation function for several temperatures. The visible spectrum is marked by  $\nu$

In 1893 the German physicist Wilhelm Wien has established the relation between the wavelength  $\lambda_{\max}$  corresponding to the maximum of the black body emissivity function  $\epsilon_{\lambda}(\lambda, T)$  and the temperature, that is known as Wien's displacement Law:

$$\lambda_{\max} = \frac{b}{T}, \quad (19.12)$$

where the experimental value of the Wien's constant  $b$  is:  $b = 2900 \mu\text{m}\cdot\text{K}$ . Wien's displacement law is severe true only for the black and gray bodies.

This relationship is useful for the determining the temperatures of any hot radiant objects whose temperature is far above that of its surroundings. Thus, when the temperature of a blackbody increases, the overall radiated energy increases and the peak of the radiation curve moves to shorter wavelengths (fig. 19.4). The value of  $\epsilon_{\lambda}$  is plotted for several different temperatures in fig. 19.4. As the blackbody become hotter, the spectrum shifts toward shorter wavelengths.

### 19.3. HEAT TRANSFER MECHANISMS IN COOLING THE HUMAN BODY

Fig. 19.5 gives a simplified model of the process by which the human body gives off heat.

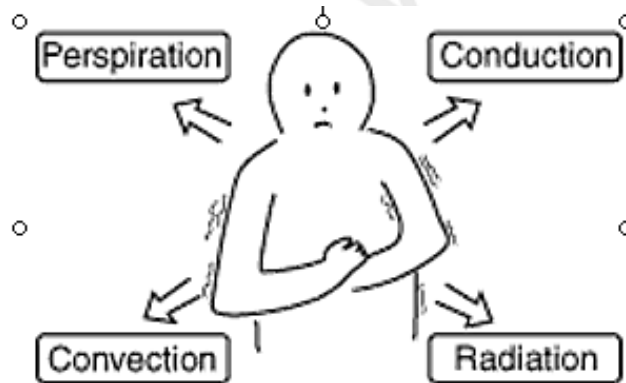


Fig. 19.5. A simplified model of the process by which the human body gives off heat

Even when inactive, an adult male must lose heat at a rate of about 90 watts as a result of his basal metabolism. One implication of the model is that radiation is the most important heat transfer mechanism at ordinary room temperatures and is  $\sim 50\%$  from total heat transfer mechanism. When the body temperature is above ambient temperature the net radiation loss rate takes the form:

$$P = \alpha_{gb}\sigma \cdot S(T_b^4 - T_s^4), \quad (19.1.)$$

where  $P$  is net radiated power,  $S$  is the area of the human body (a typical body area according to physiology texts is equal  $1,5\text{--}2 \text{ m}^2$ ) and  $\alpha_{gb}$  is the absorptivity of the skin (human skin is a near blackbody radiator in the infrared,  $\alpha_{gb} = 0,97$ ),  $\sigma = 5,67 \cdot 10^{-8} \text{ W}\cdot\text{m}^{-2}\text{K}^{-4}$  is Stefan-Boltzmann constant. This model indicates that an unclothed person at rest in a room temperature of  $23^\circ\text{Celsius}$  ( $T_s$ ) would

be uncomfortably cool. The skin temperature of 34 °C ( $T_b$ ) is a typical skin temperature taken from physiology texts, compared to the normal core body temperature of 37 °C. In this case the temperatures must be in Kelvins and in this case  $P = 133$  Watts. This suggests that radiation alone is more than adequate for body under these conditions.

As one of the basic heat transfer mechanisms, convection involves the transport of energy by means of the motion of the heat transfer medium, in this case the air surrounding the body.

Another basic heat transfer mechanism is heat conduction. In estimating the effect of convection on the cooling of the body, it is lumped in with conduction. Together, they are not generally adequate for cooling.

This becomes a problem when the ambient temperature is above body temperature, because all three standard heat transfer mechanisms work against this heat loss by transferring heat into the body. Since there must be a net outward heat transfer, the only mechanisms left under those conditions are the evaporation of perspiration from the skin and the evaporative cooling from exhaled moisture.

#### **19.4. INFRARED RADIATION FROM THE HUMAN BODY**

The principle of infrared thermography is based on the physical phenomenon that any body of a temperature above absolute zero ( $-273,15$  °C) emits electromagnetic radiation. There is clear correlation between the surface of a body and the intensity and spectral composition of its emitted radiation. By determining its radiation intensity the temperature of an object can thereby be determined in a non-contact way. Researches on thermal processes developed inside the human body and on the quantity of heat emitted by the body in its environment allowed obtaining important information about the equilibrium between the human body and its environment and about the body's biological activity and state of health. Methods like thermography and thermovision, involving measuring human body's temperature, are presently used at present as medical diagnose methods for diseases even in their early stages of development. A very accurate piece of information about the thermal processes that are developing inside the human body can be obtained from direct measurements of the heat emitted by the body's surface using thermal flux sensors of a thermoelectric type. Thermoelectric effects occurring in anisotrope and inhomogeneous media are involved in functioning of this type of sensors that can detect heat fluxes up to  $10^{-8}$  W/cm<sup>2</sup>. Thermographic cameras detect radiation in the infrared range of the electromagnetic spectrum (roughly 0,9–14 μm) and produce images of that radiation. Since infrared radiation is emitted by all objects based on their temperatures, according to the black body radiation law, thermography makes it possible to «see» one's environment with or without visible illumination.

The human body radiates energy in the infrared, and this is a significant source of energy loss. Infrared radiation has been used for over 40 years to image the body, but the value of the technique is still a matter of debate. According to Wien's displacement law we can estimate the wavelength  $\lambda_{\max}$  corresponding to the human body maximum emissivity considering the temperature of skin is  $T = 34\text{ }^{\circ}\text{C} = 273 + 34 = 307\text{ K}$ :

$$\lambda_{\max} = \frac{b}{T} = \frac{2900\text{ }\mu\text{mK}}{307\text{ K}} = 9,5\text{ }\mu\text{m}. \quad (19.14)$$

In the infrared region in which the human body radiates, the skin is very nearly a blackbody. Measurements of the absorptivity of human skin have shown that for  $5\text{ }\mu\text{m} < \lambda \leq 25\text{ }\mu\text{m}$ ,  $\alpha_{\lambda T} = 0,98 \pm 0,01$ . This value was found for white, black, and burned skin.

Two types of infrared imaging are used.

1. In near infrared photography the subject is illuminated by an external source with wavelengths from 0,8 to 25  $\mu\text{m}$ . The difference in absorption between oxygenated and nonoxygenated hemoglobin allows one to view veins lying within 2 or 3 mm of the skin. Either infrared film or a solid-state camera can detect the reflected radiation. Thermal imaging detects thermal radiation from the skin surface.

2. Significant emission from human skin occurs in the range 4–30  $\mu\text{m}$ , with a peak at 9  $\mu\text{m}$  (fig. 19.6). The detectors typically respond to wavelengths below 6–12  $\mu\text{m}$ .

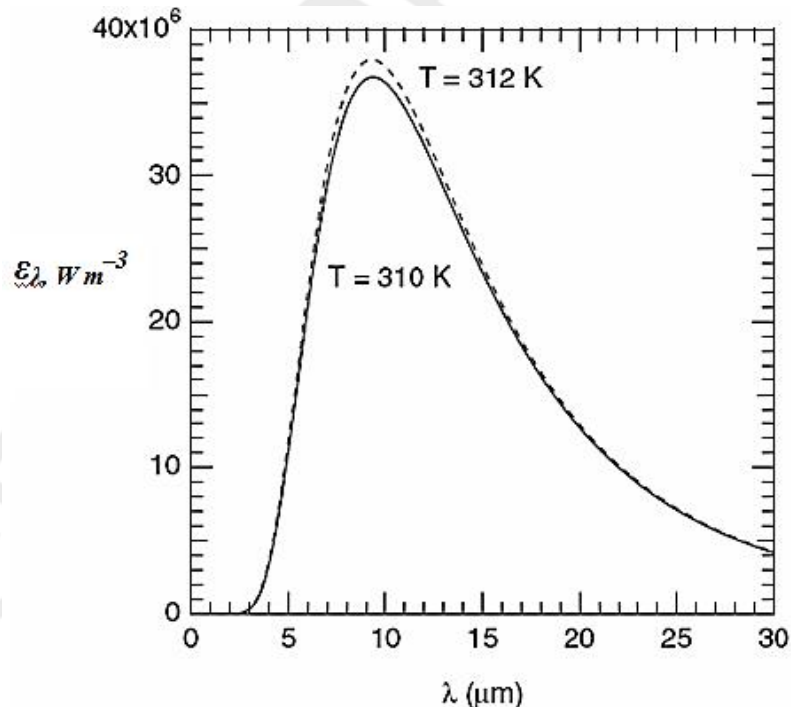


Fig. 19.6. The blackbody radiation function  $\epsilon_{\lambda}(\lambda, T)$  for  $T = 310\text{ K}$  and  $T = 312\text{ K}$

Thermography began about 1957 with a report that skin temperature over a breast cancer was slightly elevated. There was great hope that thermography

would provide an inexpensive way to screen for breast cancer, but there have been too many technical problems. Normal breasts have more variability in vascular patterns than was first realized, so that differences of temperature at corresponding points in each breast are not an accurate diagnostic criterion.

Advantages of thermography are: it shows a visual picture so that can help compare temperatures over a large area; it is capable of catching moving targets in real time; measurement in areas inaccessible or hazardous for other methods; it is a non-destructive test method. There are some limitations and disadvantages of thermography: quality cameras are expensive and are easily damaged; images can be hard to interpret accurately even with experience; accurate temperature measurements are very hard to make because of emissivities; most cameras have  $\pm 2\%$  or worse accuracy (not as accurate as contact); ability to only measure surface body areas. IR detector allows to determine temperature of internal organs with accuracy up to  $0,1-0,2\text{ }^{\circ}\text{C}$ .

Thermography has also been proposed to detect and to diagnose various circulatory problems. Clinical applications of thermography are phlebology — vein thrombosis, vascular cancer, ischemy of the limbs. Spectron thermography for use also include: adjunctive diagnostic screening for the detection of the breast cancer, neuromusculoskeletal disorders, extracranial cerebral and facial vascular disease, thyroid gland abnormalities, and various other neoplastic, metabolic and inflammatory conditions.

**Questions:**

1. What basic characteristics of thermal radiation are known? Specify relationship between the characteristics.
2. What is an absorptivity of a body? Which three kinds of the bodies with a different absorptivity are known?
3. Write thermal radiation laws: Kirchhoff Law, Stefan–Boltzmann Law, Wien’s Displacement Law.
4. Describe human body infrared radiation, its spectrum and peak emission wavelength.
5. Explain heat transfer mechanisms in cooling the human body.
6. Describe thermography fundamentals. Explain advantages of this method.

## **Chapter 20. OPTICAL SPECTRA OF ATOMS AND MOLECULES**

### **20.1. LIGHT ABSORPTION**

When light travels through a medium, it interacts with the medium. The important interactions are absorption and scattering. Absorption is a transfer of energy from the electromagnetic wave to the atoms or molecules of the medium resulting in decreasing of incident light intensity (fig. 20.1).

The lose of energy depends on the path length of light in the medium, properties of the material and on the light wavelength. The absorption is described by the empirical expression called Bouguer’s Law of absorption. Bouguer described how intensity changes with distance in an absorbing

medium. For solids for a parallel beam of light passing through a homogeneous absorbing material (fig. 20.2) the lose of light intensity —  $\Delta I$  is proportional to the path length through the material  $\Delta x$  and the initial light intensity  $I$ :

$$\Delta I = -kI\Delta x \text{ or } dI = -kIdx, \quad (20.1)$$

where the coefficient of proportionality  $k$  is called as the coefficient of light absorption or the linear decay constant. The distance  $x$  light traveled through the medium is called the path length. The solution of the differential equation (20.1) is the function  $I = I(x)$ . To obtain the general solution of the equation (20.1) it is necessary to separate the variables first. Variable  $I$  should be on the left side, and variable  $x$  — on the right side:

$$\frac{dI}{I} = -kdx.$$

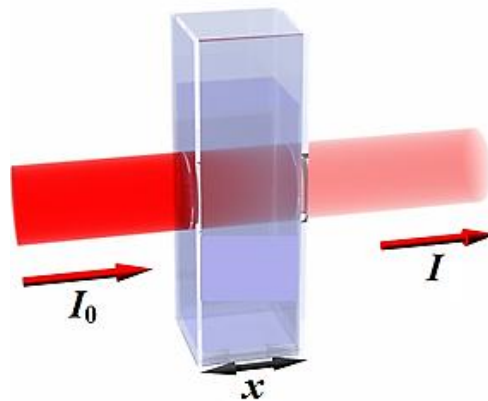


Fig. 20.1. Diagram of absorption of a beam of light as it travels through a cuvette of width  $x$ .  $I$  is the transmitted light,  $I_0$  is the incident light

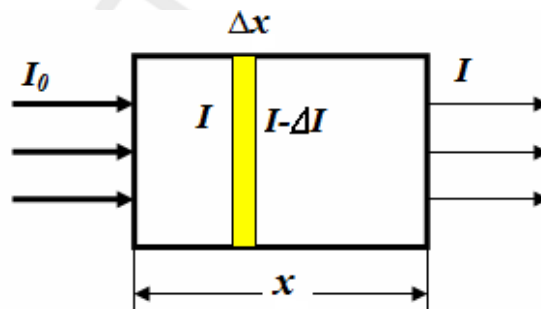


Fig. 20.2. Light passing through a uniform absorbing medium

Then it is necessary to integrate left and right sides:

$$\int \frac{dI}{I} = -k \int dx$$

$$\ln I = -kx + \ln C$$

$$I = Ce^{-kx}$$

Taking into account the initial conditions: if the medium is absent  $x = 0$ , the light intensity passed through the absorbing medium  $I$  will be the same as

the intensity of incident light  $I = I_0$ , one can receive constant  $C = I_0$  and find a particular solution of the equation (20.1):

$$I = I_0 e^{-kx}, \quad (20.2)$$

where  $I$  is intensity of transmitted light;  $I_0$  is intensity of incident light;  $k$  is the linear decay constant;  $x$  is path length of the light absorbing sample.

The equation (20.1) is the **Bouguer's Law of absorption**. When light passes through a uniform absorbing medium with the linear decay constant  $k$  its intensity  $I_0$  decreases exponentially with increase in medium thickness (fig. 20.3).

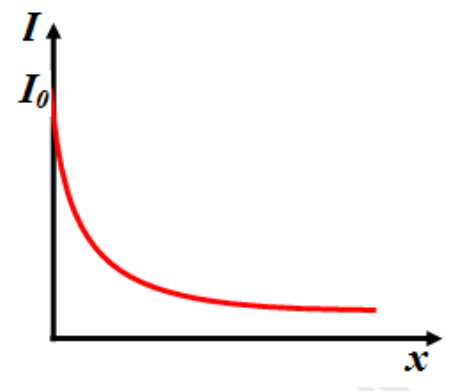


Fig. 20.3. Dependence of the transmitted light intensity on the absorbing medium thickness

$k$  is a characteristic of the medium and depends on wave length  $\lambda$ . The unit of the linear decay constant  $k$  is  $\text{m}^{-1}$ .  $k$  is the path length over which the intensity  $I$  is attenuated to  $1/e$ . The dependence of  $k(\lambda)$  or  $k(\nu)$  is individual for each substance and determines its absorption spectrum.

Beer found that linear decay constant  $k$  for a solution of an absorbing substance is linearly related to its concentration  $C$  by a constant  $\alpha$ , a characteristic of the absorbing substance:

$$k = \alpha C, \quad (20.3)$$

where  $\alpha$  is molar extinction coefficient depending on the  $k$  and wave length  $\lambda$ .

Beer's Law is valid at low concentrations, but breaks down at higher concentrations. Bouguer's and Beer's Laws are combined to describe the attenuation of light by a solution (fig. 20.4). Substituting equation (20.3) in equation (20.2) the Lambert–Beer–Bouguer Law can be obtained.

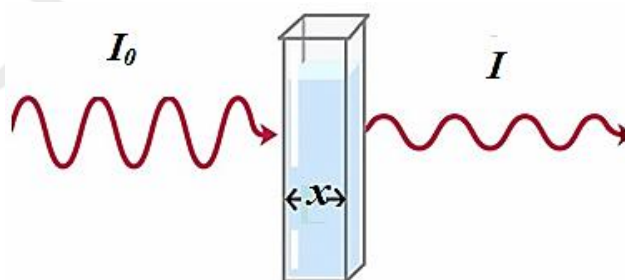


Fig. 20.4. The attenuation of light by a solution



This **Lambert–Beer–Bouguer Law** states that the amount of light absorbed by a solution  $I$  is an exponential function of the concentration  $C$  of the absorbing substance present and of the length of the path  $x$  of the light through the sample:

$$I = I_0 e^{-\alpha Cx}. \quad (20.4)$$

Typical units are:  $[k] = \text{cm}^{-1}$ ;  $[C] = \text{M}$  or (moles/liter);  $[\alpha] = \text{M}^{-1}\text{cm}^{-1}$ .

Let's introduce two characteristics of light absorbance by substance: transmittance  $T$  and optical density  $D$ .

$T$  is called the transmittance and defined as the ratio of the intensity of transmitted light  $I$  to intensity of incident light  $I_0$ :

$$T = \frac{I}{I_0} = \frac{I_0 e^{-\alpha Cx}}{I_0} = e^{-\alpha Cx}. \quad (20.5)$$

Transmittance  $T$  is a measure of the light that passes through the sample.  $T$  is expressed in percent (%). 100 % transmittance means no light is absorbed by the solution so that incident light is 100 % transmitted.  $T$  exponentially depends on the concentration  $C$  of the colored solution (fig. 20.5).

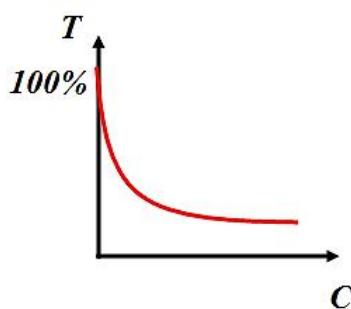


Fig. 20.5. Dependence of the transmittance  $T$  on the concentration  $C$  of the solution

Optical density  $D$  is the logarithmic ratio of intensity of incident light  $I_0$  to that of transmitted light  $I$ .  $D$  can be defined as the base-ten logarithm of the reciprocal of the transmittance:

$$D = \lg \frac{I_0}{I} = \lg \frac{1}{T} = -\lg T = k_1 x = \alpha_1 Cx, \quad (20.6)$$

where  $k_1 = k \lg e = 0,43k$ ,  $\alpha_1 = \alpha \lg e = 0,43\alpha$ .

Optical density  $D$  represents the amount of light absorbed by the sample.  $D$  is directly proportional to concentration  $C$  of the colored solution (fig. 20.6).

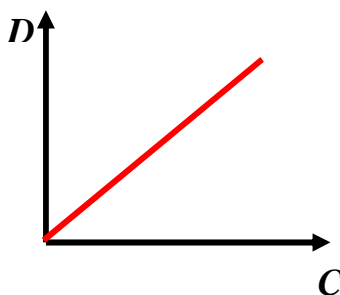


Fig. 20.6. Dependence of the optical density  $D$  on the concentration  $C$  of the solution

$D$  depends on wavelength  $\lambda$  of incident light. Moreover  $D(\lambda) \sim k(\lambda) \sim \alpha(\lambda)$  determine the substance absorption spectrum.  $D$  has not unit (numerical number only).

Colorimetry is the method of definition of the colored solution concentration  $C$ . Colorimetry is based on the Lambert–Beer–Bouguer Law. The colorimeter is used to quantitatively measure and record the light absorption ( $D$ ) and transmission ( $T$ ) of a colored solution at a specific wavelength (fig. 20.7).

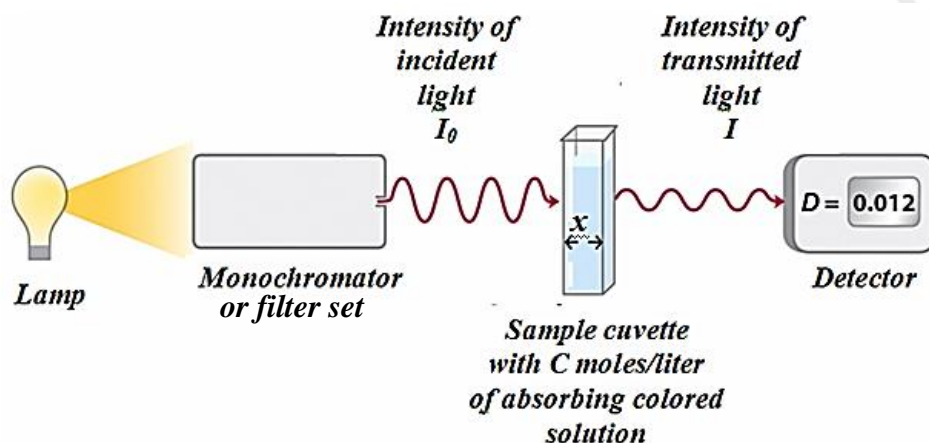


Fig. 20.7. Basic design of the colorimeter

Schematic diagram of a single-beam colorimeter is shown in fig. 20.8.

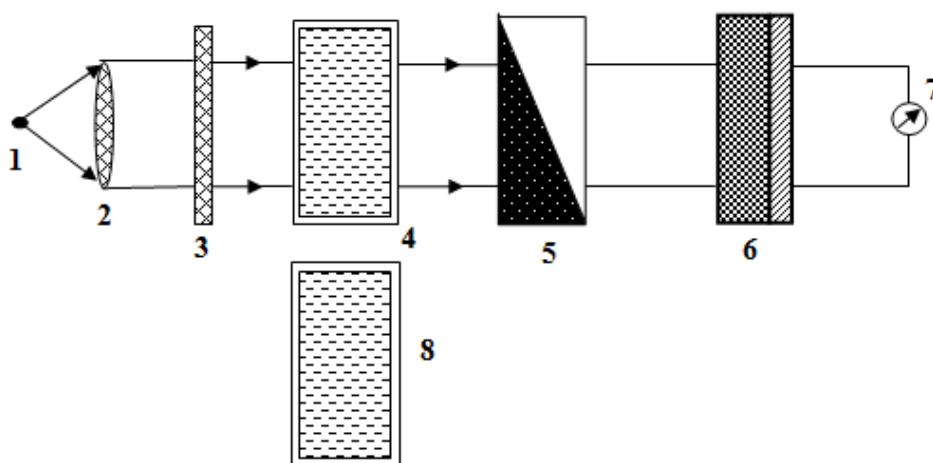


Fig. 20.8. Schematic diagram of a single-beam colorimeter:

1 — source of light (visible light has a range of wavelength of 400–760 nm); 2 — lens (for creating parallel beam of light); 3 — wavelength selector (Coloured filter) is used to remove all but a narrow band (specific wavelength) of visible radiation; 4 — a sample cell (light is passed (transmitted) through the sample contained within a little glass (plastic) cuvette. A solution containing an absorbing material (4) is compared to a reference solution (8) of the same solvent and non-absorbing materials. The transmittance of the reference solution is set to 100 % (Abs = 0), then the relative transmittance of the solution is measured; 6 — photoelectric cell (light that penetrates hits the photoelectric cell. The current developed by the photoelectric cell is translated into percent transmission or absorbance through a detector; 7 — detector (records transmittance  $T$  and optical density  $D$ )

A colorimeter measures the intensity of light passing through a colored solution compared to the intensity of light passing into a reference solution of the same solvent. A detector measures the transmittance  $T$  (% of light passing through) of the solution. This is mathematically converted to optical density  $D$  ( $D = -\lg T$ ) (absorbance). The optical density  $D$  is directly proportional to the solution concentration  $C$ . Higher optical density (absorbance)  $D$  means a higher concentration  $C$  and a more intense colour. By measuring the light absorbed one can determine the concentration of a solution  $C$ .

Colorimetry is used to measure haemoglobin content of blood, glucose in blood, cholesterol.

## 20.2. LIGHT SCATTERING

Any material whose refractive index is different from that of the surrounding medium (optically inhomogeneous) scatters light. Scattering is the process by which particles suspended in a medium of a different index of refraction diffuse a portion of the incident radiation in all directions (fig. 20.9).

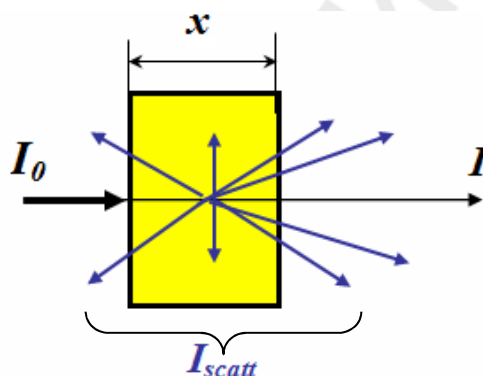


Fig. 20.9. Light scattering

Difference between scattering and absorption is:

- both scattering and absorption remove flux from an incident wave;
- during scattering process flux is not lost from the incident beam but is redistributed over the total solid angle centered around the scatterer and it does not change the internal energy states of the molecules;
- absorption changes the internal energy states of the molecules;
- absorption is spectrally selective, scattering is not;
- scattering depends on the ratio of particle size to wavelength of light.

When light passes through a scattering medium its intensity  $I$  decreases exponentially with increase in medium thickness  $x$ .

$$I = I_0 e^{-\sigma x}, \quad (20.7)$$

where  $\sigma$  is scattering coefficient.  $\sigma$  is a characteristic of the medium and depends on  $\lambda$ ;  $[\sigma] = \text{M}^{-1}$ .  $I_0$  is intensity of the incident light.

When light passes through a medium which is absorbing and scattering simultaneously, its intensity  $I$  decreases exponentially with increase in medium thickness  $x$ :

$$I = I_0 e^{-(\sigma + k)x}, \quad (20.8)$$

where  $I$  is intensity of the transmitted light;  $I_0$  is intensity of the incident light;  $\sigma$  is the scattering coefficient;  $k$  is the linear decay constant;  $x$  is path length of the medium.

Lord Rayleigh was the first to deal with scattering of light by air molecules. The strength of scattering depends on the wavelength of the light and also the size of the particle which cause scattering. When a light penetrates into a medium composed of particles whose sizes are much smaller than the wavelength of the incident light ( $d < 0,2\lambda$ ) the scattered intensity on both forward and backward directions are equal (fig. 20.10), the scattering process is elastic and is called Rayleigh scattering. In this scattering process, the energy (and therefore the wavelength) of the incident light is conserved and only its direction is changed. The scattering phase function, or phase function, gives the angular distribution of light intensity scattered by a particle at a given wavelength (fig. 20.11). For the Rayleigh scattering the scattering function is given by  $I_{scatt}/I_0 = (1 + \cos^2 j)$ .

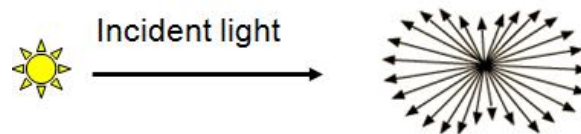


Fig. 20.10. For Rayleigh scattering the scattered intensity on both forward and backward directions are equal

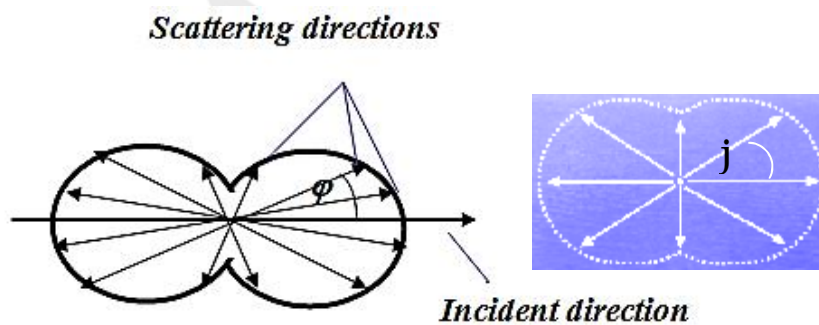


Fig. 20.11. Scattering angle function in case of Rayleigh scattering

The intensity of the scattered light is inversely proportional to the fourth power of the wavelength. This is known as **Rayleigh scattering Law**:

$$I_{scatt} \sim \frac{1}{\lambda^4}. \quad (20.9)$$

Hence, the shorter wavelengths are scattered much more than the longer wavelengths. The blue appearance of sky is due to scattering of sunlight by

the atmosphere. According to Rayleigh's scattering Law, blue light is scattered to a greater extent than red light. This scattered radiation causes the sky to appear blue. At sunrise and sunset the rays from the sun have to travel a larger part of the atmosphere than at noon. Therefore most of the blue light is scattered away and only the red light which is least scattered reaches the observer. Hence, sun appears reddish at sunrise and sunset.

When light passes through a colloidal solution it is scattered by the particles of solution. When a light penetrates into a medium composed of particles whose sizes are comparable to wavelength of radiation (aerosols, water vapour)  $d > 0,2\lambda$  the scattered intensity is more in the forward direction relative to the backward direction (fig. 20.12). The scattering of light by the colloidal particles is called Tyndal scattering.



Fig. 20.12. For Tyndal scattering the scattered intensity is more in the forward direction relative to the backward direction

In case of Tyndal scattering the intensity of the scattered light is inversely proportional to the second power of the wavelength:

$$I_{scatt} \sim \frac{1}{\lambda^2}. \quad (20.10)$$

For Tyndal scattering the longer wavelengths scattered more than shorter wavelengths.

When scatterers are large ( $d \gg \lambda$ ) the dependence of intensity  $I_{scatt}$  on  $\lambda$  practically disappears and angular distribution of scattered intensity becomes more complex. Clouds are white as all wavelengths are scattered equally.

### 20.3. TYPES OF SPECTRUM

Atomic spectroscopy is the determination of elemental composition of a given sample and also the relative concentration of the several composition compounds by its absorption or emission spectrums. An absorption spectrum occurs when light passes through a cold, dilute gas and gas atoms absorb light at characteristic frequencies. This gives rise to dark lines (absence of light) in the spectrum (fig. 20.13). An element's emission spectrum is the relative intensity of electromagnetic radiation of each frequency it emits when it is excited (fig. 20.14).

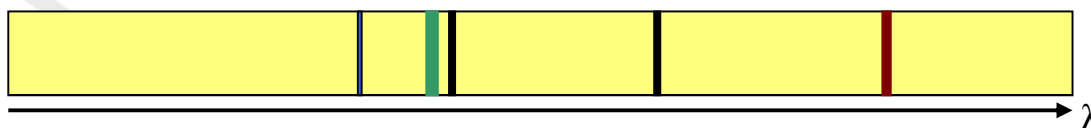


Fig. 20.13. An absorption spectrum

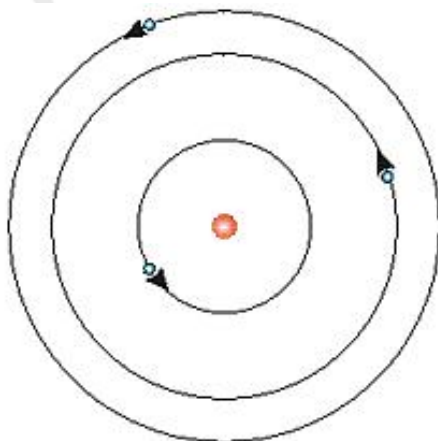


*Fig. 20.14.* An emission spectrum

Each element emits a characteristic set of discrete wavelengths according to its electronic energy structure, by observing these wavelengths the sample elemental composition can be determined. With the use of emission spectroscopy in the late 19<sup>th</sup> century, it was found that the radiation from hydrogen, as well as other atoms, was emitted at specific quantized frequencies. It was the effort to explain this radiation that led to the first successful quantum theory of atomic structure, developed by Niels Bohr.

#### **20.4. BOHR'S THEORY OF THE HYDROGEN ATOM**

The simplest system that can emit or absorb light is an isolated atom. In the early part of the 20<sup>th</sup> century, experiments by Ernest Rutherford and others had established that atoms consisted of a diffuse cloud of negatively charged electrons surrounding a small, dense, positively charged nucleus. The planetary model of the atom still had shortcomings. Firstly, a moving electric charge emits electromagnetic waves; according to classical electromagnetism, an orbiting charge would steadily lose energy and spiral towards the nucleus, colliding with it in a tiny fraction of a second ( $10^{-9}$  s). Secondly, the model did not explain why excited atoms emit light only in certain spectrum. Quantum theory revolutionized physics at the beginning of the 20<sup>th</sup> century when Max Planck and then Albert Einstein postulated that light energy is emitted or absorbed in fixed amounts known as quanta. In 1913 Niels Bohr used this idea in his model of the atom, in which the electrons could only orbit the nucleus in particular circular orbits with fixed angular momentum and energy (fig. 20.15). They were not allowed to spiral into the nucleus, because they could not lose energy in a continuous manner; they could only make quantum leaps between fixed energy levels.



*Fig. 20.15.* The Bohr atom model

Bohr's theory of the hydrogenic (one-electron) atom is based on the following postulates:

1. The electron revolves in circular orbits around the nucleus which are restricted by the quantization of angular momentum i. e. they revolve in orbits where the angular momentum of electron is an integral multiple of  $h/2\pi$ , where  $h$  is Planck's constant.

$$mvr = \frac{nh}{2\pi}, \quad (20.11)$$

where  $n = 1, 2, 3 \dots$  — is the principal quantum number,  $m$  is the mass of the electron,  $v$  is the electron velocity, and  $r$  is the orbit radius.

2. The energy of the atom has a definite value in a stationary orbit:  $E_1, E_2, E_3 \dots E_n$  (fig. 20.16). These orbits are called stationary states. In these orbits of special radius electron does not radiate energy as expected from Maxwell's laws. This is called as Bohr's quantization rule.

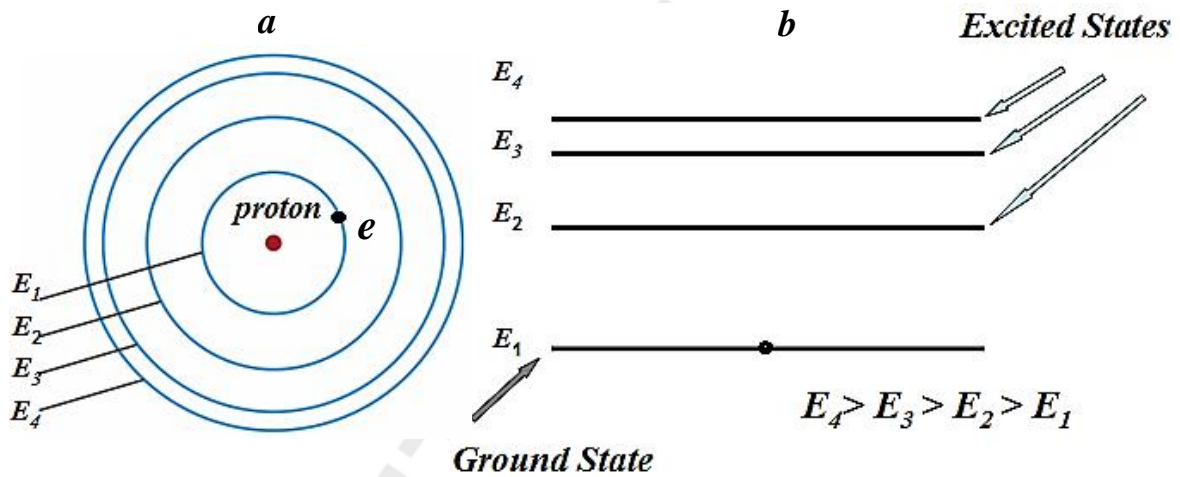


Fig. 20.16. The Bohr atom (a). Energy level diagram (b)

3. The electron can jump from one stationary orbit to another. If it jumps from an orbit of higher energy  $E_2$  to an orbit of lower energy  $E_1$  (fig. 20.17), it emits a photon. The energy of the photon is:

$$h\nu = E_2 - E_1. \quad (20.12)$$

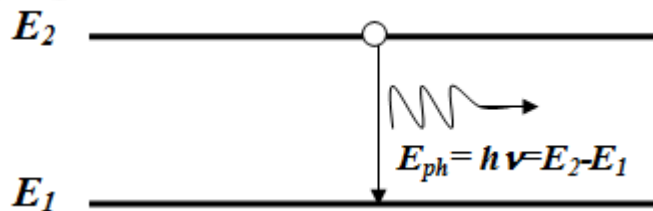


Fig. 20.17. Emission of photon

The electron can absorb energy from some source and jump from a lower energy level to a higher energy level and then emits energy jumping from a higher energy level to a lower energy level as shown in the following fig. 20.18.

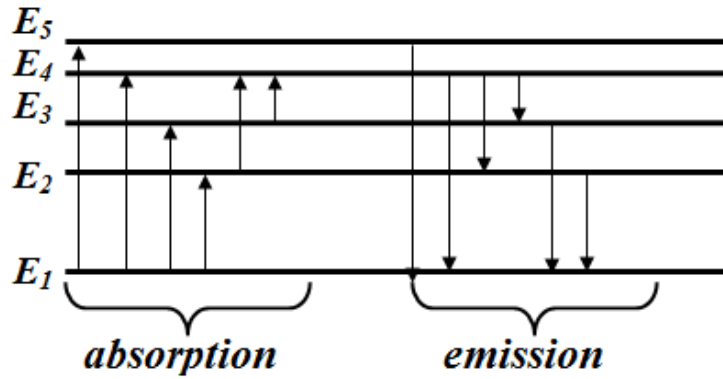


Fig. 20.18. The various ways of how an electron can absorb energy from some source and jump from a lower energy level to a higher energy level and then emits energy jumping from a higher energy level to a lower energy level

Thus from the Bohr model of the atom follows that electrons exist only in the certain energy levels within an atom. The electron energy in these levels has well defined values and electrons jumping between them must absorb or emit the energy equal to the difference between them. In optical spectroscopy, the energy absorbed by electron to move it to a higher energy level and/or the energy emitted as the electron moves to a lower energy level is in the form of a photon (a particle of light). Because this energy is well-defined, an atom's identity can be found by the energy of this transition. The wavelength of the emitted light can be related to its energy  $hn = \frac{hc}{\lambda} = \Delta E$ . It is usually easier to measure the wavelength of light than to directly measure its energy.

## 20.5. ENERGY STATES OF A HYDROGEN ATOM

The above postulates can be used to calculate allowed energies of the atom for different allowed orbits of the electron. The theory developed should be applicable to hydrogen atoms and ions having just one electron. Thus, within the Bohr atom framework, it is valid for  $\text{He}^+$ ,  $\text{Li}^{++}$ ,  $\text{Be}^{3+}$  etc. Let us consider the case of an ion with the charge of nucleus being  $Ze$  and an electron moving with a constant speed  $v$  along a circle of radius  $r$  with the center at the nucleus. The force acting on the electron is that due to Coulomb attraction and is equal to

$$F = \frac{Ze^2}{4\pi\epsilon_0 r^2}. \quad (20.13)$$

The acceleration of the electron is towards the center and has a magnitude  $\frac{u^2}{r}$ . If  $m$  is the mass of the electron, from Newton's law  $F = ma$ , we obtain

$$\frac{Ze^2}{4\pi\epsilon_0 r^2} = \frac{mu^2}{r}. \quad (20.14)$$



Using Bohr's angular momentum quantization rule (20.11) for the value  $n$ , the principal quantum number, we obtain both the velocity  $v$  and the radius  $r$  as:

$$u = \frac{Ze^2}{2\varepsilon_0hn}, \quad r = \frac{\varepsilon_0h^2n^2}{m\pi Ze^2}. \quad (20.15)$$

It is seen that the allowed radii are proportional to  $n^2$ . For each value of  $n = 1, 2, 3, \dots$ , we have an allowed orbit. For  $n = 1$ , we have the first orbit (smallest radius), for  $n = 2$ , we have the second orbit and so on.

The kinetic energy of the electron in the  $n_{th}$  orbit is

$$E_k = \frac{mu^2}{2} = \frac{mZ^2e^4}{8\varepsilon_0^2h^2n^2}. \quad (20.16)$$

The potential energy of the atom is

$$E_p = -e\phi = -\frac{Ze^2}{4\pi\varepsilon_0r} = -\frac{mZ^2e^4}{4\varepsilon_0^2h^2n^2}. \quad (20.17)$$

We have taken the potential energy to be zero when the nucleus and the electron are widely separated. The total energy of the atom is

$$E = E_p + E_k = -\frac{mZ^2e^4}{8\varepsilon_0^2h^2n^2} < 0. \quad (20.18)$$

Equations (20.16) to (20.18) give various parameters of the atom when the electron is in the  $n_{th}$  orbit. The atom is also said to be in the  $n_{th}$  energy state in this case.

From equation (20.15) the radius of the smallest circle allowed to the electron is ( $n = 1$ )

$$r_1 = \frac{\varepsilon_0h^2}{m\pi Ze^2}. \quad (20.19)$$

For hydrogen atom  $Z = 1$  and substituting the values of other constants we get  $r_1 = 0,0529$  nm. This length is called the Bohr radius and is a convenient unit for measuring lengths in atomic physics. It is generally denoted by the symbol  $a_0$ . The second allowed radius is  $4a_0$  and the third allowed radius is  $9a_0$  and so on. In general, the radius of the  $n_{th}$  orbit is

$$r_n = n^2a_0. \quad (20.20)$$

From equation (20.18) the total energy of the atom in the state  $n = 1$  is

$$E_1 = -\frac{mZ^2e^2}{8\varepsilon_0^2h^2} < 0. \quad (20.21)$$

For hydrogen atom  $Z = 1$  and substituting the values of the constants  $E_1 = -13,6$  eV. Note that the energy is negative and hence a larger magnitude means lower energy. The zero of energy corresponds to the state where the electron and the nucleus are widely separated. This is the energy when the electron revolves in the smallest allowed orbit  $r = a_0 = 0,053$  nm. We also

see from equation (20.18) that energy of an electron is proportional to  $\frac{1}{n^2}$ .

Thus,

$$E_n = \frac{E_1}{n^2} = \frac{-13,6}{n^2} (eV) \quad (20.22)$$

The energy in the state  $n = 2$  is  $E_2 = E_1/4 = -3,4$  eV. In the state  $n = 3$  it is  $E_1/9 = -1,5$  eV etc. The lowest energy corresponds to the smallest circle. The state of atom with the lowest energy is called is ground state. The higher energy states are called excited states. Thus the energy of a hydrogen atom in the ground state is  $-13,6$  eV and in the first excited state is  $-3,4$  eV. Positive energy states correspond to the ionization atom where the electron is no longer bound. The hydrogen atom energy levels determined by formula (20.22) are shown schematically in fig. 20.19.

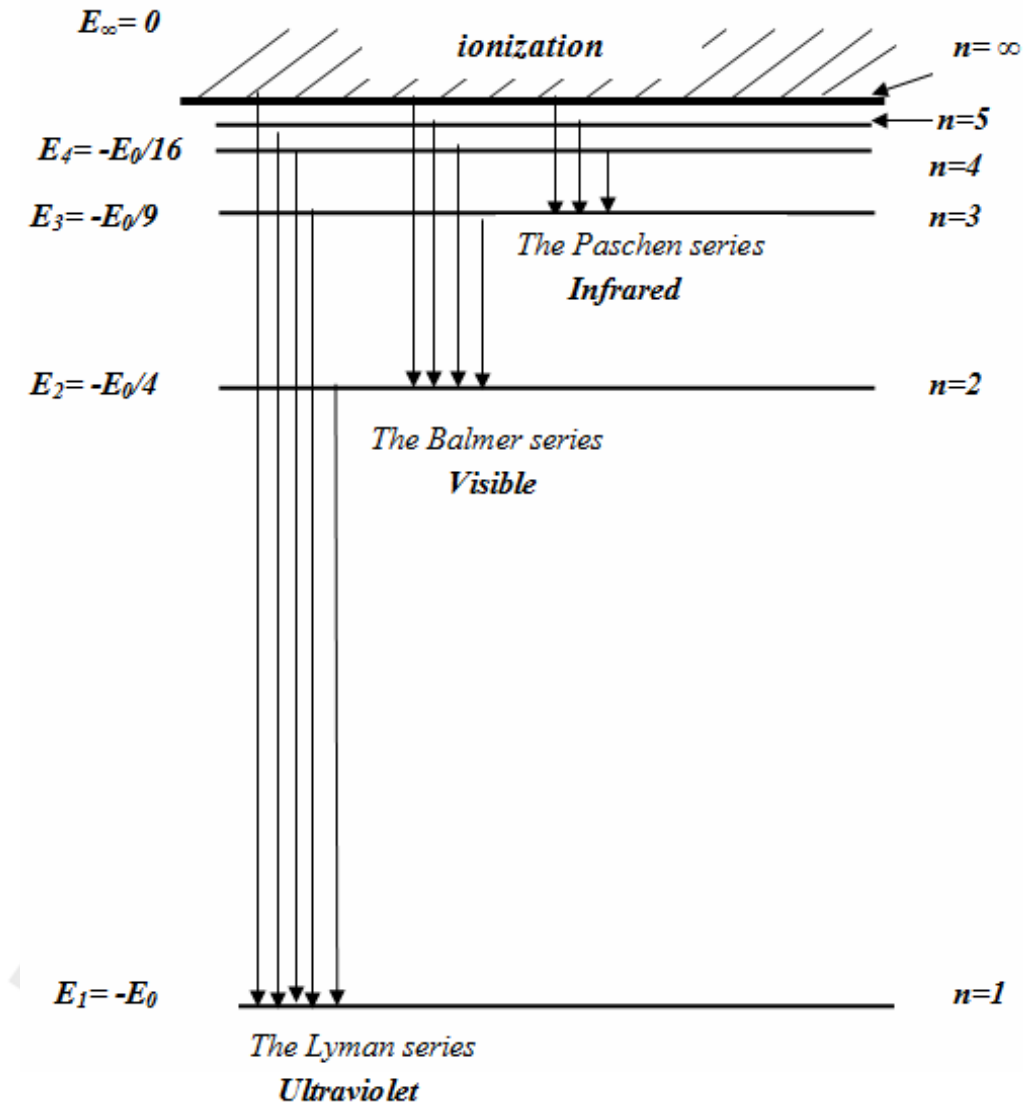


Fig. 20.19. Hydrogen energy diagram illustrating Lyman, Balmer and Paschen series formation

The radiation of atoms that do not interact with one another consists of separate spectral lines. The emission spectrum of atoms is accordingly called a line spectrum. The atomic spectra show the energy structure of atoms therefore the studying of these spectra served as a key to cognition of the structure of atoms. It was noted first of all that the lines in the spectra of atoms are arranged not chaotically, but are combined into groups or, as they are called, series of lines.

This is revealed most clearly in the spectrum of the simplest atom — hydrogen. When a hydrogen atom ( $Z = 1$ ) passes from the state  $k$  to the state  $n$ , a photon is emitted:  $h\nu = E_k - E_n$ .

The frequencies of all the hydrogen atom spectrum lines can be represented by a single formula:

$$\nu = \frac{E_k - E_n}{h} = \frac{E_0}{h} \left( \frac{1}{n^2} - \frac{1}{k^2} \right) \quad (20.23)$$

where  $n = 1, 2, 3, 4, \dots$ ;  $k = n+1, n+2, n+3, \dots$ . We have arrived at the generalized Balmer formula.

The group of spectral lines that corresponds to transitions from any higher energy levels to certain low level forms spectral series. There are some spectral series in hydrogen emission spectrum.

1. **The Lyman series** is the series of transitions and resulting emission lines of the hydrogen atom as an electron goes from any excited energy levels  $k \geq 2$  to the ground one  $n = 1$  (where  $n$  and  $k$  are the principal quantum numbers of the states). The lines of the Lyman series are located in the ultraviolet range of the spectrum. The frequencies of the Lyman series are obtained from formula (14.3.11) if  $n = 1$  and  $k = 2, 3, 4, 5, \dots$

$$\nu = \frac{E_0}{h} \left( 1 - \frac{1}{k^2} \right), \quad (20.24)$$

where  $k = 2, 3, 4, 5, \dots$

2. **The Balmer series** is characterized by the electron transitions from  $k \geq 3$  to  $n = 2$ , where  $n$  and  $k$  are the principal quantum numbers of the states. The spectral lines associated with this series are located in the visible part of the electromagnetic spectrum. The frequencies of the Balmer series can be represented in the form:

$$\nu = \frac{E_k - E_2}{h} = \frac{E_0}{h} \left( \frac{1}{4} - \frac{1}{k^2} \right), \quad (20.25)$$

where  $k = 3, 4, 5, 6, \dots$

3. **The Paschen series** is the emission lines corresponding to an electron transitions from  $k \geq 4$  to  $n = 3$ . The lines of the Paschen series are located in the near infrared range of the spectrum. The frequencies of the Paschen series are given by formula:

$$\nu = \frac{E_0}{h} \left( \frac{1}{9} - \frac{1}{k^2} \right), \quad (20.26)$$

where  $k = 4, 5, 6, 7, \dots$

## 20.6. MOLECULAR SPECTRUM

The internal energy of a molecule  $E_{mol}$  includes the electronic energy  $E_{el}$ , the vibrational energy of nuclei  $E_{vib}$ , and the rotational energy of the whole molecule  $E_{rot}$ :

$$E_{mol} = E_{el} + E_{vib} + E_{rot}. \quad (20.27)$$

The every type of the internal molecule energy is quantized. In a molecular system every electronic state includes some vibrational levels and a lot of rotational ones as shown in fig. 20.20. Thus, the rotational motion of molecule is quantized and described by the rotational quantum number  $j$  also giving a ladder of unequally spaced energy levels. Separations of rotational energy levels correspond to the microwave region of the electromagnetic spectrum. The vibration motion of nuclei is also quantized and described by vibrational quantum number  $\nu$ .

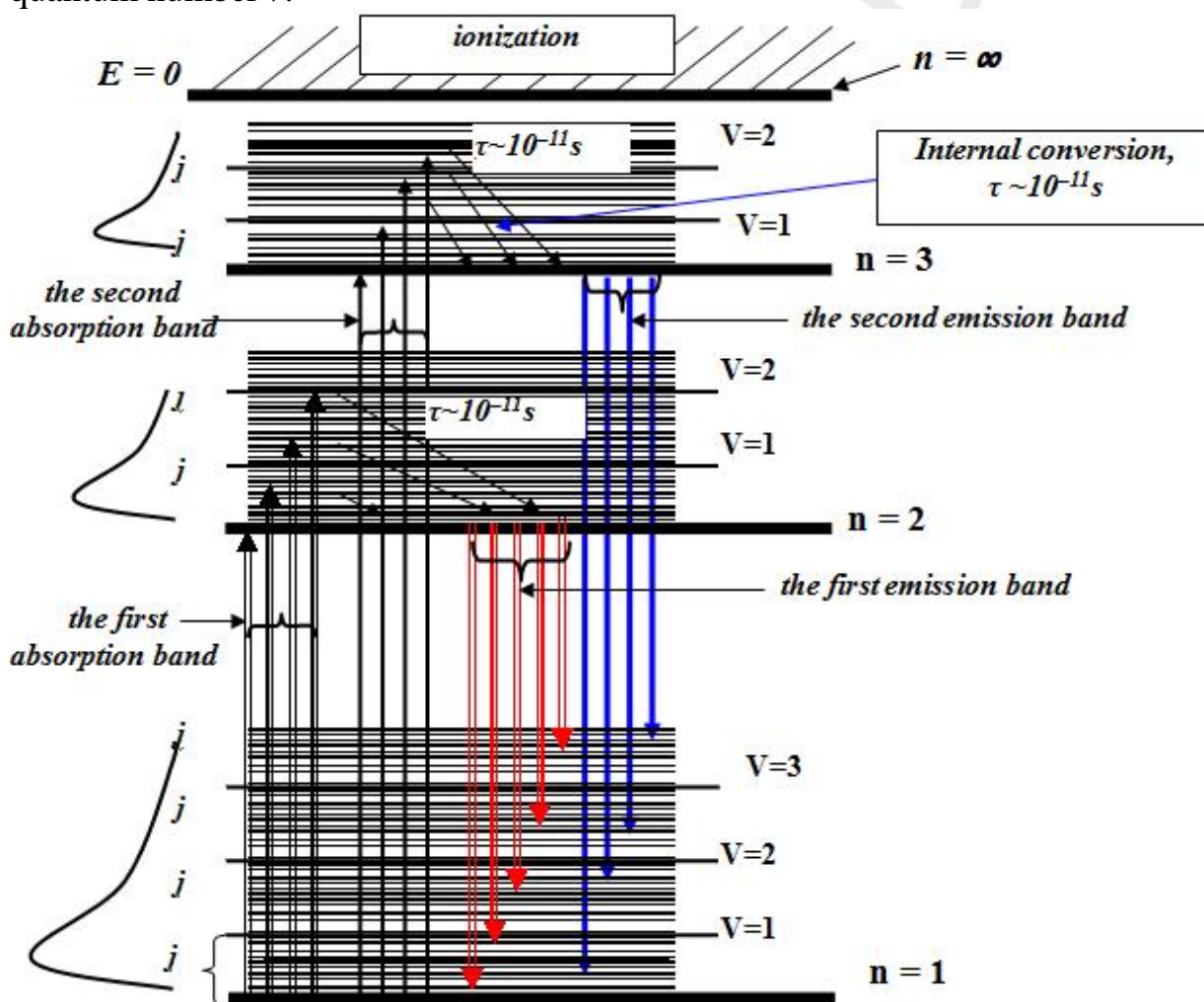


Fig. 20.20. Molecular energy diagram illustrating an absorption and emission band appearance

Vibration and rotational energy levels are very closely spaced while the energy spacing of electronic levels are much larger:

$$E_{el} \gg E_{vib} \gg E_{rot}.$$

Absorption of a photon results in a change of the electronic energy accompanied by changes in the vibrational and rotational energies. If the molecule is initially at level  $E_1$  ( $n = 1$ ), if this is the ground state, the molecule will remain in this state unless got excited. When an radiation of frequency  $\nu$  is incident on the species, there is a finite probability that the molecule will absorb the incident energy and jump from its ground electronic state to one of the various vibrational-rotational states in excited electronic level  $E_2$  ( $n = 2$ ) or  $E_3$  ( $n = 3$ ). In this case the absorption lines are caused by a transition between closed located quantized energy states. They are composed of more than one wavelength of light and this spectral line is broadening. Collisions with other molecules cause the excited molecule to lose vibrational energy until it reaches the lowest vibration state of the excited electronic state. So molecule in  $\tau \sim 10^{-11} - 10^{-12}$  seconds turns from the higher vibrational-rotational state of electronic level  $E_2$  ( $n = 2$ ) to the lowest vibrational-rotational state of the excited electronic state  $E_2$  ( $n = 2$ ), losing energy by non-radiative means, such as transfer of energy as heat to another molecules. This phenomenon is called internal conversion. After that a molecule falls back down to the any vibrational-rotational energy levels of the ground electronic state  $E_1$  ( $n = 1$ ) and leaves the excite state. Energy is emitted, the wavelength of which refers to the discrete lines of the emission spectrum Note however that the emission extends over a range of frequencies, thus spectral lines are broadening. Wavelength band appears in emission spectrum. The emitted photon due to the internal conversion has less frequency  $\nu$  than the absorbed photon; this frequency difference is known as the Stokes shift. That is why emitted light always has a longer wavelength than the absorbed light due to the internal conversion.

Molecules have various states referred to energy levels. If the frequency of the radiation matches the vibrational frequency ( $h\nu = E_{v,2} - E_{v,1}$ ) of the molecule then radiation will be absorbed, causing a change in the amplitude of molecular vibration. The energy of a vibrational mode depends on molecular structure and environment. Infrared spectroscopy is the measurement of the wavelength and intensity of the absorption of mid-infrared light by a sample. Mid-infrared is energetic enough to excite molecular vibrations to higher vibrational-rotational energy levels.

The wavelength of infrared absorption bands is characteristic of specific types of chemical bonds, and infrared spectroscopy finds its greatest utility for identification of organic and organometallic molecules. Infrared and microwave probes are used extensively in the laboratory. Since the vibrational and rotational levels depend on the masses, separations, and forces between the various atoms bound in a molecule, it is not surprising that spectroscopy can be used to identify specific bonds. This is a useful technique in chemistry.

Biological applications are difficult because the absorption coefficients are large; thin samples must be used, particularly in an aqueous environment.

## 20.7. THE SPECTRAL DEVICES

The devices which measure the interaction between light and materials as a function of wavelength are spectrometer and spectrograph. A spectrometer is used in spectroscopy for producing spectral lines and measuring their wavelengths and intensities. Spectrometer is a term that is applied to instruments that operate over a very wide range of wavelengths, from gamma rays and X-rays into the far infrared. If the region of interest is restricted to near the visible spectrum, the study is called spectrophotometry.

Early spectroscopes were simply a prism with graduations marking wavelengths of light. Modern spectroscopes, such as monochromators, generally use a diffraction grating, a movable slit, and some kind of photodetector, all automated and controlled by a computer.

When a material is heated to incandescence it emits light that is characteristic of the atomic makeup of the material. Particular light frequencies give rise to sharply defined bands on the scale which can be thought of as fingerprints.

In the original spectroscopy design in the early 19th century, light entered a slit and a collimating lens transformed the light into a thin beam of parallel rays. The light was then passed through a prism that refracted the beam into a spectrum because different wavelengths were refracted different amounts due to dispersion. This image was then viewed through a tube with a scale that was transposed upon the spectral image, enabling its direct measurement (fig. 20.21).

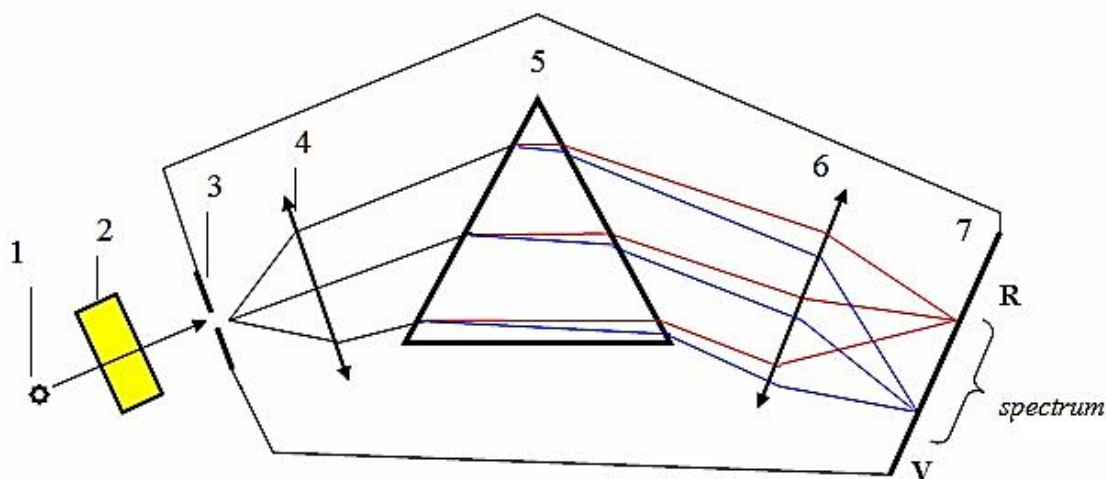


Fig. 20.21. Prism spectrometer schematic:

1 — a light source; 2 — a substance under investigation; 3 — a slit; 4 — a collimating lens;  
5 — a prism; 6 — a camera lens; 7 — a camera lens focal plane

With the development of photographic film, the more accurate spectrograph was created. It was based on the same principle as the spectroscopy, but it had

a camera in place of the viewing tube. In recent years the electronic circuits built around the photomultiplier tube have replaced the camera, allowing real-time spectrographic analysis with far greater accuracy. Arrays of photosensors are also used in place of film in spectrographic systems. Such spectral analysis, or spectroscopy, has become an important scientific tool for analyzing the composition of material in physical and analytical chemistry for the identification of substances through the spectrum emitted from or absorbed by them.

## 20.8. LUMINESCENCE

Luminescence is light produced using energy sources other than heat. Sometimes luminescence is called «cold light», because it can occur at room temperature and cooler temperatures. To produce luminescence, energy is absorbed by an electron of an atom or molecule, causing it to become excited, but unstable. When the electron returns to a lower energy state the energy is released in the form of a photon (light). The energy of the photon  $h\nu$  determines its wavelength or color ( $\lambda = \frac{c}{\nu}$ ).

There are different manners of atom and molecule exciting and the following kinds of luminescence are known:

1. **Photoluminescence** is a process in which a substance absorbs photons (electromagnetic radiation, usually ultraviolet or visible range) and then emits photons. This can be described as an excitation to a higher energy state and then a return to a lower energy state accompanied by the emission of a photon (luminescence).

2. **Cathodoluminescence** is an optical phenomenon where the atomic excitation is produced by a beam of electrons which is generated by an electron gun (e. g. cathode ray tube) and then impacts on a luminescent material, causing the material to emit visible light.

3. **Electroluminescence** is an optical phenomenon where a material emits light in response to an electric current passed through it, or to a strong electric field.

4. **Chemiluminescence** is the emission of light due to excitation in the result of a chemical reaction:  $A + B \rightarrow AB^* \rightarrow AB + h\nu$ .

5. **Bioluminescence** is chemiluminescence which takes place in numerous living organisms. For example, the American firefly is a widely studied case of bioluminescence. The firefly reaction has the highest known quantum efficiency ~ 88 %.

6. **Roentgenluminescence** is the optical luminescence produced by X-rays.

7. **Radioluminescence** is the phenomenon by which luminescence is produced in a material by the bombardment of ionizing radiation such as alpha and beta particles.

The main characteristics of luminescence are:

**Luminescence spectrum** is a dependence of luminescence intensity  $I_{lum}$  on luminescence wavelength  $\lambda$ .

**Exciting radiation spectrum** is a dependence of photoluminescence intensity  $I_{lum}$  on exciting radiation wavelength  $\lambda$ .

**The luminescence quantum yield**  $\gamma$  gives the efficiency of the luminescence process. It is defined as the ratio of the number of photons emitted to the number of photons absorbed:

$$\gamma = \frac{n_{emitted}}{n_{absorbed}}. \quad (20.28)$$

The maximum luminescence quantum yield is 1,0 (100 %); every photon absorbed results in a photon emitted. Compounds with quantum yields of 0,10 are still considered quite luminescent.

**The delay time**  $\tau$  is the time during that the intensity of the luminescence decreases in  $e = 2,7$  times.

After the radiation causing luminescence has stopped the intensity of the luminescence decays exponentially (fig. 20.22) with time and is described by the formula:

$$I_{lum} = I_0 e^{-t/\tau}, \quad (20.29)$$

where  $I_0$  is the intensity of the stationary luminescence;  $t$  is the time;  $\tau$  is the delay time during that the intensity of the luminescence decreases in  $e = 2,7$  times.

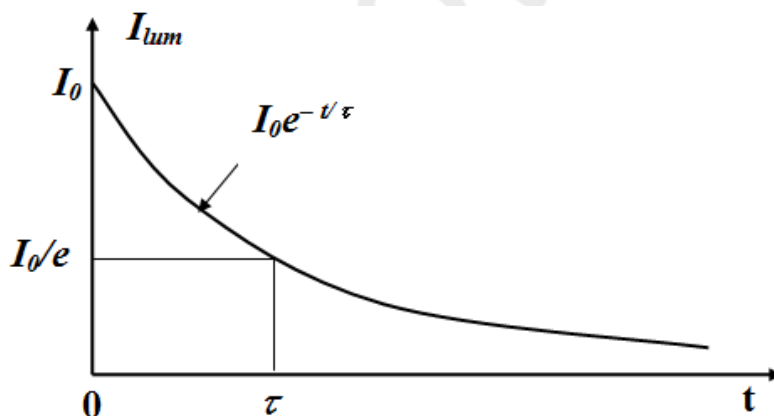


Fig. 20.22. The luminescence intensity decay with time

There are two principal varieties of luminescence: **fluorescence** and **phosphorescence**, distinguished by the delay time. If the luminescence decays in very short time ( $\sim 10^{-9}$ – $10^{-7}$  s) it is known as **fluorescence** (in this case  $\tau < 10^{-7}$  s). If  $\tau > 10^{-4}$  s, then it is known as **phosphorescence** ( $\tau > 10^{-4}$  s). Fluorescence appearances if the electron selection rules are satisfied, the transition is fairly rapid (typically  $10^{-8}$  s). Sometimes the electron becomes trapped in a state where it cannot decay according to the electronic selection



rules. It may then have a lifetime up to several seconds before decaying and in this case phosphorescence occurs.

Fluorescence spectroscopy is primarily concerned with electronic and vibrational states. Tryptophan is an important intrinsic fluorescent probe (amino acid), which can be used to estimate the nature of microenvironment of the tryptophan. When performing experiments with denaturants, surfactants or other amphiphilic molecules, the microenvironment of the tryptophan might change. For example, if a protein containing a single tryptophan in its «hydrophobic» core is denatured with increasing temperature, a red-shift emission spectrum will appear. This is due to the exposure of the tryptophan to an aqueous environment as opposed to a hydrophobic protein interior. In contrast, the addition of a surfactant to a protein which contains a tryptophan which is exposed to the aqueous solvent will cause a blue shifted emission spectrum if the tryptophan is embedded in the surfactant vesicle or micelle. Proteins that lack tryptophan may be coupled to a fluorophore. At 295 nm, the tryptophan emission spectrum is dominant over the weaker tyrosine and phenylalanine fluorescence.

There are several laws that deal with molecular luminescence:

1. **The Stokes Law:** the wavelength of the luminescence light is always greater than that of the exciting radiation (fig. 20.23).

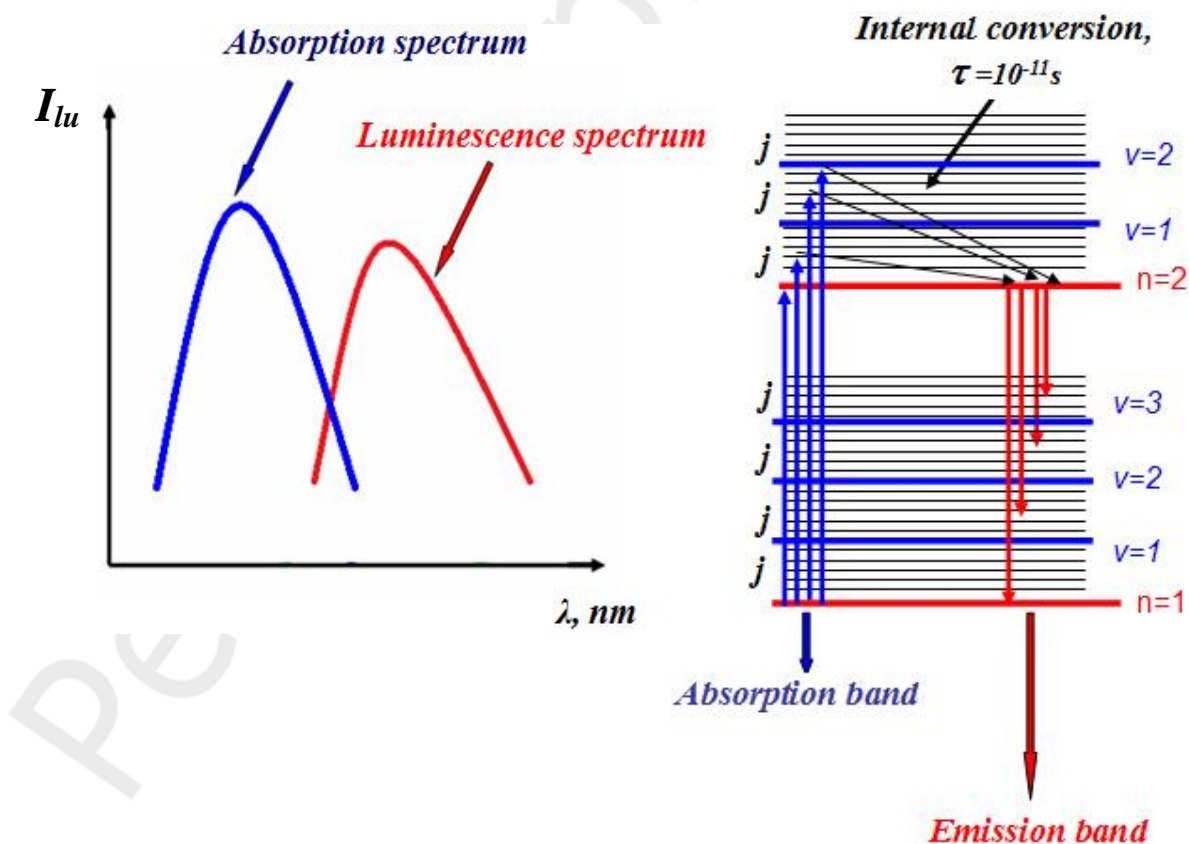


Fig. 20.23. The Stokes Law is explained by internal conversion in molecules

2. **The Kasha–Vavilov Law:** luminescence spectrum and the quantum yield of luminescence are independent of the wavelength of exciting radiation.

Both of these laws are explained by internal conversion in molecules.

**Questions:**

1. What is the light absorption? Describe fundamental laws of the light absorption. What is the light absorption spectrum?
2. Write Lambert-Beer-Bouguer Law. What does molar extinction coefficient depend on?
3. What are transmittance and optical density? Describe their dependence on the wavelength and solution concentration.
4. What is the light scattering? Explain differences between Tyndal scattering and Rayleigh scattering. Write Rayleigh scattering Law.
5. What do Bohr's postulates describe? Specify these postulates.
6. Explain appearance of emission spectra and absorption one.
7. Give the energy states of a hydrogen atom. Explain spectral lines formation for a hydrogen atom.
8. Explain molecular spectrum formation. Give molecular spectrum classification.
9. What is a luminescence? Which kinds of luminescence are known?
10. Write a formula for luminescence intensity decay with time.
11. Explain the Stokes Law and the Kasha–Vavilov one.

## **Chapter 21. STIMULATED EMISSION. LASER**

Light Amplification by Stimulated Emission of Radiation, commonly referred to as «Laser» describes a wide range of devices. The lasers can function as oscillators (sources of light) and as amplifiers. Lasers have revolutionized various fields of science and technology, and are being used in a wide range of applications in medicine, communications, defense, measurement, and as a precise light source in many scientific investigations.

### **21.1. PROCESSES OF ABSORPTION AND EMISSION IN ATOMIC SYSTEM**

The principle of operation remains the same though there is a wide range of lasers. Laser action occurs in three stages: population inversion creation, spontaneous emission, and stimulated emission. We must begin with an account of how light (photon) can interact with individual atoms within an amplifying medium («atoms» will be used to include molecules and ions). Energy levels associated with molecules, atoms and nuclei are in general discrete, quantized energy levels and transitions between those levels typically involve the absorption or emission of photons. Electron energy levels have been used as the example here, but quantized energy levels for molecular vibration and rotation also exist. Transitions between vibrational quantum states typically occur in the infrared and transitions between rotational quantum states are typically in the microwave region of the electromagnetic spectrum.

Atoms consist of a positively charged core (nucleus) which is surrounded by negatively charged electrons. According to the quantum mechanical

description of an atom, the energy of an atomic electron can have only certain values and these are represented by energy levels  $E_1 < E_2 < E_3 \dots$ . The electrons can be thought of as orbiting the nucleus, those with the largest energy orbiting at greater distances from the nuclear core. There are many energy levels that an electron within an atom can occupy, but here we will consider only two. Also, we will consider only the electrons in the outer orbits of the atom as these can most easily be raised to higher unfilled energy states.

A photon of light is absorbed by an atom in which one of the outer electrons is initially in a low energy state. The energy of the atom is raised to the upper energy level, and remains in this excited state for a period of time that is typically less than  $10^{-7}$  second. It then spontaneously returns to the lower state, with the emission of a photon of light. Absorption is referred to as a resonant process because the energy of the absorbed photon must be equal to the difference in energy between the levels. This means that only photons of a particular frequency (or wavelength) will be absorbed. Similarly, the photon emitted will have energy equal to the difference in energy between the two energy levels. These common processes of absorption and spontaneous emission cannot give rise to the amplification of light. Spontaneous emissions are random and isotropic in nature. The best that can be achieved is that for every photon absorbed, another is emitted. The above processes are represented in fig. 21.1, where  $E_1$  is the ground-state or lower energy level and  $E_2$  is the excited-state or higher energy level. The particle of the material, which undergoes the process of excitation, might be an atom, molecule, or ion depending on the laser material.

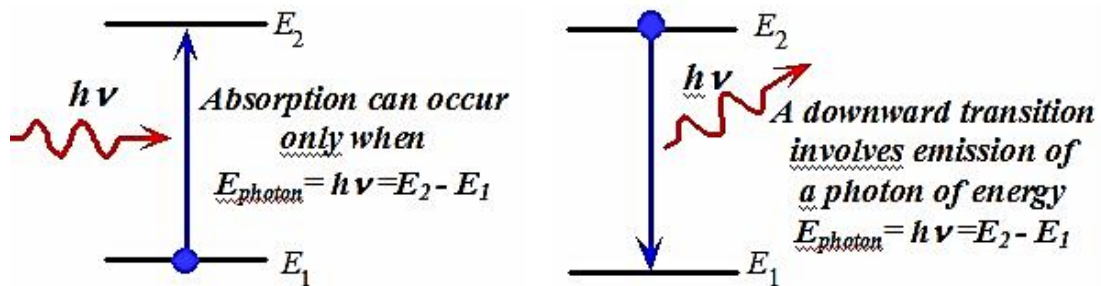


Fig. 21.1. The processes of absorption and spontaneous emission

Above it was stated that an atom in a high energy, or excited, state can return to the lower state spontaneously. However, if a photon of light interacts with the excited atom, it can stimulate a return to the lower state (fig. 21.2). One photon interacting with an excited atom results in two photons being emitted.

Furthermore, the two emitted photons are said to be in phase, i. e. thinking of them as waves, the crest of the wave associated with one photon occurs at the same time as on the wave associated with the other. This feature ensures that there is a fixed phase relationship between light radiated from different atoms in the amplifying medium and results in the laser beam produced having the property of coherence.

The energy of the incoming photon of light must match the difference in energy between the two energy levels

$$E_{\text{photon}} = h\nu = E_2 - E_1$$

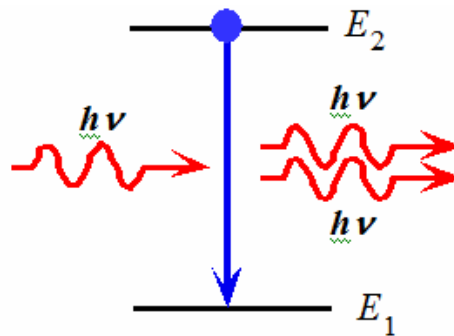


Fig. 21.2. A process of stimulated emission

Stimulated emission has very important properties. The direction of its propagation exactly coincides with the direction of propagation of the stimulating radiation, i. e. of the external radiation producing a transition. The same relates to the frequency, phase, and polarization of the stimulated emission and stimulating radiation. Consequently, the stimulated emission and the radiation stimulating it are strictly coherent. This feature of stimulated emission underlies the action of light amplifiers and generators known as lasers. Stimulated emission is the process that can give rise to the amplification of light. As with absorption, it is a resonant process; the energy of the incoming photon of light must match the difference in energy between the two energy levels. Furthermore, if we consider a photon of light interacting with a single atom, stimulated emission is just as likely as absorption; which process occurs depends upon whether the atom is initially in the lower or the upper energy level. However, under most conditions, stimulated emission does not occur to a significant extent. The reason is that, under most conditions, that is, under conditions of thermal equilibrium, there will be far more atoms in the lower energy level, than in the upper level  $n_1 > n_2$ , so that absorption will be much more common than stimulated emission. If stimulated emission is to predominate, we must have more atoms in the higher energy state than in the lower one. This unusual condition is referred to as a population inversion and it is necessary to create a population inversion for laser action to occur. When the number of particles in the excited state is greater than the number of particles in the ground state  $n_2 > n_1$ , the material is in a state of «Population Inversion» (fig. 21.3).

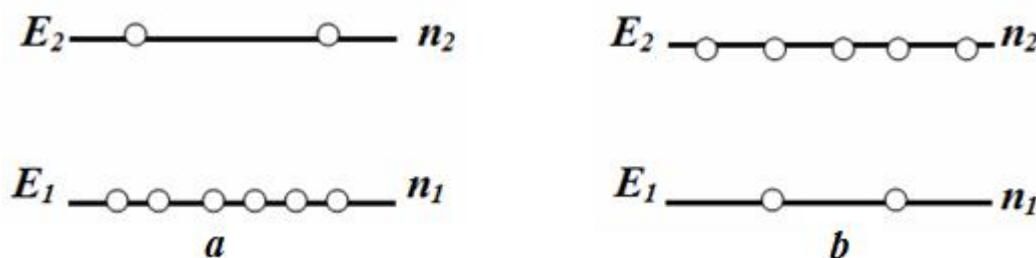


Fig. 21.3. A condition of thermal equilibrium (a) and a state of «Population Inversion» between 2 and 1 levels (b)

Population inversion is a prerequisite for laser action. Energy can be transferred into a laser medium to achieve population inversion by several mechanisms including absorption of photon, collision between electrons (or sometimes ions) and species in the active medium, collisions among atoms and molecules in the active medium, recombination of free electrons with ionized atoms, recombination of current carriers in a semiconductor, chemical reactions producing excited species, and acceleration of electrons. If during the process of stimulated emission, the population inversion is maintained by continuous pumping of energy, the laser action continues indefinitely and the result is a continuous wave laser. On the other hand, if the pumping cannot be maintained the output is a pulsed laser.

## 21.2. CONSTRUCTION OF A LASER

A laser consists of an amplifying medium (the gain medium), a source of excitation energy, and a resonator or feedback mechanism to perform the three stages of laser action. The general construction of a laser is shown in fig. 21.4.

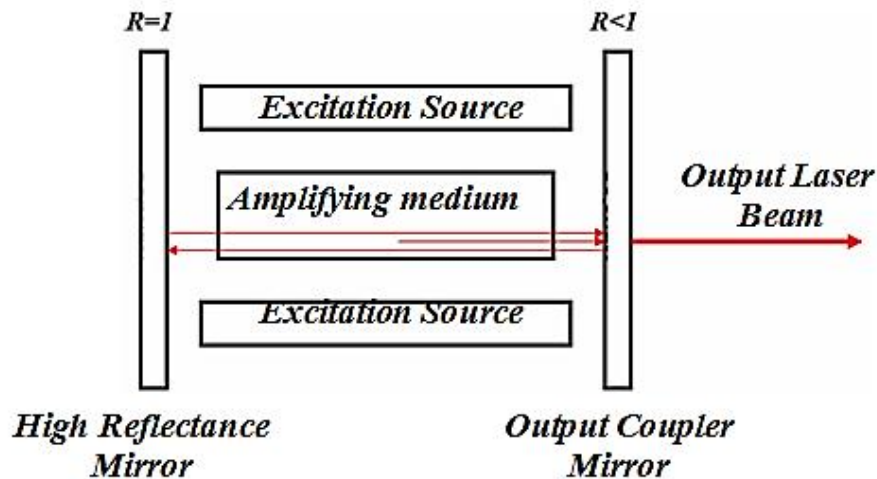


Fig. 21.4. Laser components

**Amplifying medium:** All lasers contain an energized substance that can increase the intensity of light passing through it. This substance is called the amplifying medium or, sometimes, the gain medium, and it can be a solid, a liquid or a gas. Whatever its physical form, the amplifying medium must contain atoms, molecules or ions, a high proportion of which can store energy that is subsequently released as light.

In a neodymium YAG (Nd:YAG) laser, the amplifying medium is a rod of yttrium aluminium garnate (YAG) containing ions of the lanthanide metal neodymium (Nd). In a dye laser, it is a solution of a fluorescent dye in a solvent such as methanol. In a helium-neon laser, it is a mixture of the gases helium and neon. In a laser diode, it is a thin layer of semiconductor material sandwiched between other semiconductor layers. The factor by which the intensity of

the light is increased by the amplifying medium is known as the gain. The gain is not a constant for a particular type of medium. It's magnitude depends upon the wavelength of the incoming light, the intensity of the incoming light, the length of the amplifying medium and also upon the extent to which the amplifying medium has been energized. An amplifying medium is one in which population inversion is possible (fig. 21.3).

The downward transition from the excited to the normal state is triggered by stimulated emission. The lasers are classified depending on the number of energy levels used for the excitation and the stimulated emission process. Commercial lasers are three-level and four-level systems (fig. 21.5), while the simple two-level system is not used in practice, as it is difficult to achieve population inversion in a two-level system.

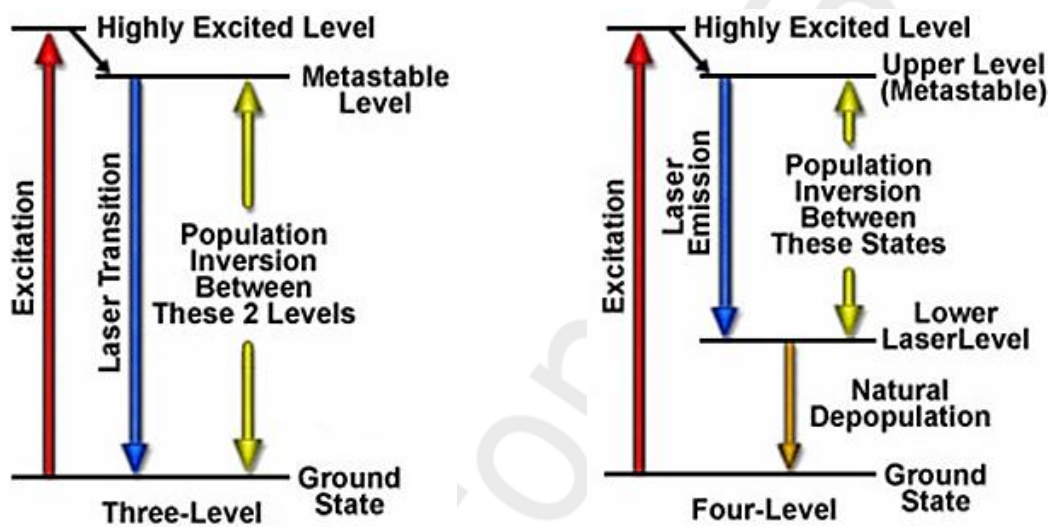


Fig. 21.5. Three-level and four-level laser energy diagrams

**Excitation Source:** Population inversion is achieved by «pumping energy» from an external source. Depending on the external source, the excitation process is called as optical pumping or electrical pumping. In electrical pumping, an AC or DC electrical discharge is used for excitation. Gas lasers and semiconductor lasers are usually excited using electrical pumping. In optical pumping, light is the source of energy and is used for most of the solid-state and dye lasers.

**Resonator:** A resonator consists a pair of parallel mirrors. The high degree of collimation arises from the fact that the cavity of the laser has very nearly parallel front and back mirrors which constrain the final laser beam to a path which is perpendicular to those mirrors. The back mirror is made almost perfectly reflecting while the front mirror reflecting is  $R < 1$ , letting out about  $(1 - R) \%$  of the beam. This  $(1 - R) \%$  is the output beam which one see. But the light has passed back and forth between the mirrors many times in order to gain intensity by the stimulated emission of more photons at the same wavelength. If the light is the slightest bit off axis, it will be lost from the beam.

### 21.3. CHARACTERISTICS OF LASER LIGHT

1. **Coherent:** different parts of the laser beam are related to each other in phase due to stimulated emission properties. These phase relationships are maintained over long enough time so that interference effects may be seen or recorded photographically. This coherence property is what makes holograms possible.

2. **Monochromatic:** laser light consists of essentially one wavelength, having its origin in stimulated emission between two of atomic or molecular energy levels.

3. **Collimated:** because of bouncing back between mirrored ends of a laser cavity, those paths which sustain amplification must pass between the mirrors many times and be very nearly perpendicular to the mirrors. As a result, laser beams are very narrow and do not spread very much.

### 21.4. THE RUBY LASER

The ruby laser takes its place in history by being the first working laser to be demonstrated. Theodore Maiman, working at Hughes Labs. in the USA, showed the first working optical laser to the world in 1960. The active medium is a cylindrical crystal of synthetic sapphire ( $\text{Al}_2\text{O}_3$ ) doped with roughly 0,05 %, by weight, of chromium ions ( $\text{Cr}^{3+}$ ).

Fig. 21.6 gives a diagram of the energy levels of the chromium ion  $\text{Cr}^{3+}$  (level  $E_3$  is a band formed by a collection of closely arranged levels).

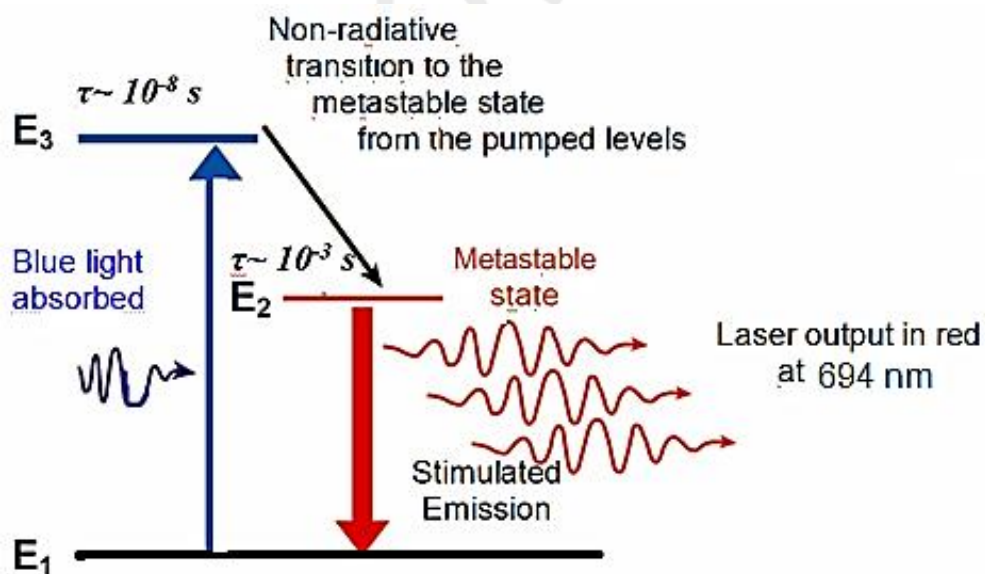


Fig. 21.6. A diagram of the energy levels of the chromium ion  $\text{Cr}^{3+}$  in the ruby laser

A xenon lamp is rolled over ruby rod and is used for pumping ions to excited state. When a flash of light falls on ruby rod, radiations are absorbed by  $\text{Cr}^{3+}$  which are pumped to  $E_3$ .

The excitation of the ions as a result of pumping is depicted by arrow from  $E_1$  to  $E_3$ . The lifetime of *level*  $E_3$  is very small ( $\sim 10^{-8}$  s). The  $\text{Cr}^{3+}$  ions after giving a part of their energy to crystal lattice pass to metastable level  $E_2$ . Most of the ions, however, will pass to metastable *level*  $E_2$ . The lifetime of *level*  $E_2$  is more larger ( $\sim 10^{-3}$  s). When the pumping power is adequate, the number of chromium ions at *level*  $E_2$  becomes greater than their number at *level*  $E_1$ . Consequently, levels  $E_1$  and  $E_2$  become inverted and the population inversion occurs.

Arrow from  $E_2$  to  $E_1$  depicts a spontaneous transition from the metastable level  $E_2$  to the ground one  $E_1$ . The emitted photon may produce stimulated emission of additional photons which, in turn, will produce stimulated emission, etc. A cascade of photons is formed as a result.

## 21.5. TYPES OF LASERS

There are many types of lasers available for research, medical, industrial, and commercial uses. Lasers are often described by the kind of lasing medium they use—solid state, gas, excimer, dye, or semiconductor:

1. Gas lasers (helium and helium-neon, HeNe, are the most common gas lasers) have an output of different spectral range.  $\text{CO}_2$  lasers emit energy in the far-infrared, 10,6 micrometers, and are used for cutting hard materials.

2. Excimer lasers (the name is derived from the terms *excited* and *dimers*) use reactive gases such as chlorine and fluorine mixed with inert gases such as argon, krypton, or xenon. When electrically stimulated, a pseudomolecule or dimer is produced and when lased, produces light in the ultraviolet range.

3. Dye lasers use complex organic dyes like rhodamine 6G in liquid solution or suspension as lasing media. They are tunable over a broad range of wavelengths.

4. Solid state lasers have lasing material distributed in a solid matrix, e. g., the ruby or neodymium-YAG (yttrium aluminum garnet) lasers. The neodymium-YAG laser emits infrared light at 1.064 micrometers.

5. Semiconductor lasers, sometimes called diode lasers, are not solid-state lasers. These electronic devices are generally very small and use low power. They may be built into larger arrays, e. g., the writing source in some laser printers or compact disk players.

Lasers are also characterized by the duration of laser emission — continuous wave or pulsed laser.

1. Continuous wave (CW) lasers operate with a stable average beam power. In most higher power systems, one is able to adjust the power. In low power gas lasers, such as HeNe, the power level is fixed by design and performance usually degrades with long term use. The direction of a CW laser can be scanned rapidly using optical scanning systems to produce the equivalent of a repetitively pulsed output at a given location.



2. Single pulsed (normal mode) lasers generally have pulse durations of a few hundred microseconds to a few milliseconds. This mode of operation is sometimes referred to as long pulse or normal mode.

3. Repetitively pulsed or scanning lasers generally involve the operation of pulsed laser performance operating at a fixed (or variable) pulse rates which may range from a few pulses per second to as high as 20,000 pulses per second.

### 21.6. LASER MEDICAL APPLICATIONS

There is a wide range of medical applications. Often these relate to the outer parts of the human body, which are easily reached with light; examples are eye surgery and vision correction (LASIK), dentistry, dermatology (e. g. photodynamic therapy of cancer), and various kinds of cosmetic treatment such as tattoo removal or hair removal. Lasers are also used for surgery (e. g. of the prostate), exploiting the possibility to cut tissues while causing only a low amount of bleeding.

Very different types of lasers are required for medical applications, depending on the wavelength, output power, pulse format, etc. In many cases, the laser wavelength is chosen so that certain substances (e. g. pigments in tattoos or caries in teeth) absorb light more strongly than surrounding tissue, so that they can be more precisely targeted. Fig. 21.7 shows ruby laser use for epidermal hyperpigmentation treatment. Medical lasers are not always used for therapy. Some of them rather assist the diagnosis e. g. via methods of laser microscopy or spectroscopy.



Fig. 21.7. Ruby laser is used for epidermal hyperpigmentation treatment

#### **Questions:**

1. What processes of absorption and emission in two-level quantum system are possible?
2. Which transitions are called spontaneous?
3. What is the stimulated emission? Specify main properties for the stimulated emission.
4. What is laser? Describe its construction and characterize main components.
5. What are the laser light main properties? Explain the main properties.
6. Give types of laser classification.
7. Specify lasers medical application area.

## Chapter 22. EYE VISION

### 22.1. EYE STRUCTURE

The eye is a very complex organ that sends a huge amount of information to the brain. It has a very specific design to capture and analyze light. In its simplest description, the eye is a spherical box, with a lens to focus the light that enters it, and cells to process the light.

The human eye is roughly spherical in shape (fig. 22.1). It is bounded by three distinct layers of tissue. The outer layer, *sclera*, is extremely tough. It is white in color except in the front. Here it forms the transparent *cornea*, which admits light into the interior of the eye and bends the light rays so that they can be brought to a focus. The surface of the cornea is kept moist and dust-free by the secretion from the tear glands.

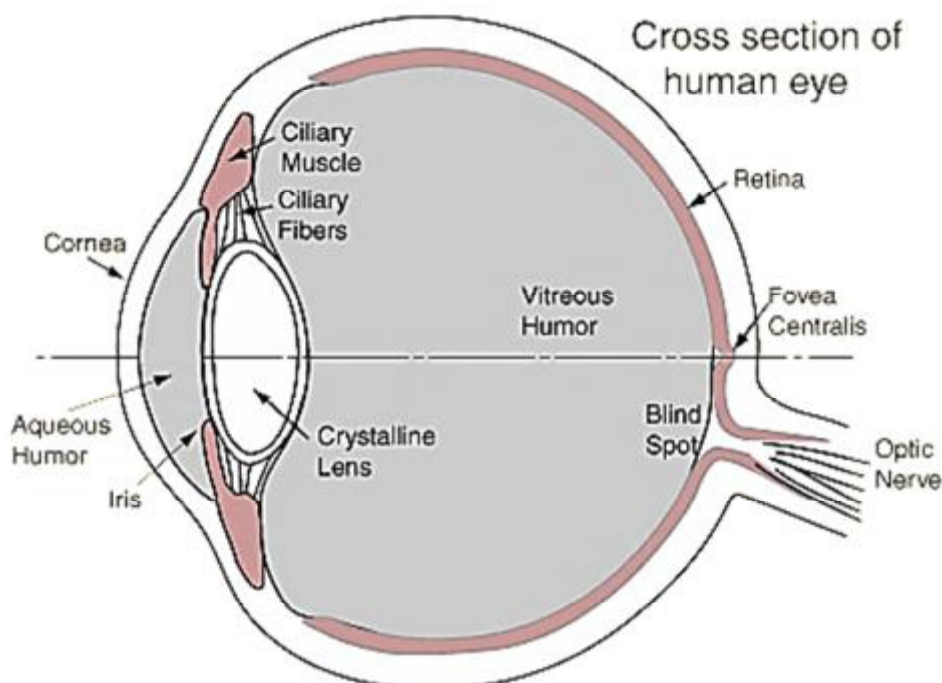


Fig. 22.1. Human eye

The middle coat of the eye, *choroid*, is deeply pigmented with melanin and well supplied with blood vessels. It serves the very useful function of stopping the reflection of stray light rays within the eye. This is the same function that is accomplished by the dull black paint within a camera.

In the front of the eye, the choroid forms the *iris*. This may be pigmented and is responsible for the color of the eye. An opening, the *pupil*, is present in the center of the iris. The size of this opening is variable and under automatic control. In dim light (or times of danger) the pupil enlarges, letting more light into the eye. In bright light, the pupil closes down. This produces clearer vision, because a smaller opening, or aperture, creates a sharper image.

Behind the pupil and iris are the crystalline *lens* and the *ciliary body*. The ciliary body contains muscles that support the lens and changes its shape. The lens is a colorless, nearly transparent double convex structure, similar to an ordinary magnifying glass. Its only function is to focus light rays onto the retina. By changing its curvature, the lens can focus on objects at different distances from it. This process is called accommodation.

The lens of the eye is bathed on one side by the *aqueous humor* and supported on the other side by the *vitreous humor*. Aqueous humor is located in the anterior chamber of the eye, the space between the lens and the cornea. It maintains the intraocular pressure and inflates the globe of the eye. The vitreous is the transparent, colorless, gelatinous mass that fills the space between the lens of the eye and the retina and occupying about 80 % of the volume of the eyeball.

The inner coat of the eye is the *retina*. It contains photoreceptors that translate light energy into electrical signals and sends them to the brain through the optic nerve. The center area of retina, called the *macula*, is used for fine central vision and color vision. The *fovea* is located in the center of the macula. It is responsible for sharp central vision, which is necessary in humans for reading, watching, driving, and any activity where visual detail is of primary importance. The *blind spot* lacks photoreceptors; it is located where the optic nerve fibers leave the eye.

## 22.2. IMAGE FORMATION BY THE EYE OPTICAL SYSTEM

The eye function is to collect light emitted or reflected by a distant object and form an image of object for presentation to the brain. The eye can see the object under study clearly if precise real optic image of this object is built on the retina. This problem is solved by an optical system of the eye. It consists mainly of the cornea and the lens, and to a lesser extent of other structures.

Most of the refraction occurs at the cornea (40–43 diopters). The cornea has an index of refraction of 1,38. The index of refraction of the cornea is significantly greater than the index of refraction of the surrounding air. This difference in optical density combined with the fact that the cornea has the shape of a converging lens is what explains the ability of the cornea to do most of the refracting of incoming light rays. The refractive index of the aqueous humor — 1,33; the crystalline lens (on average) — 1,41; and the vitreous humor — 1,34. Total refractive power  $D$  of the eye is varied from 60 to 73 diopters; the lens refractive power  $D$  is in the range 20–30 diopters.

If all the refractive surfaces of the eye are algebraically added together and then considered to be one single lens, the optics of the normal eye may be simplified and represented schematically as a «reduced eye». This is useful in simple calculations. In the reduced eye, a single refractive surface is considered to exist, with its central point 17 millimeters in front of the retina and a total refractive power of 60 diopters when the lens is accommodated for distant vision.

Eye optical system forms on the retina a *real inverted diminished* image of the distant object (fig. 22.2).

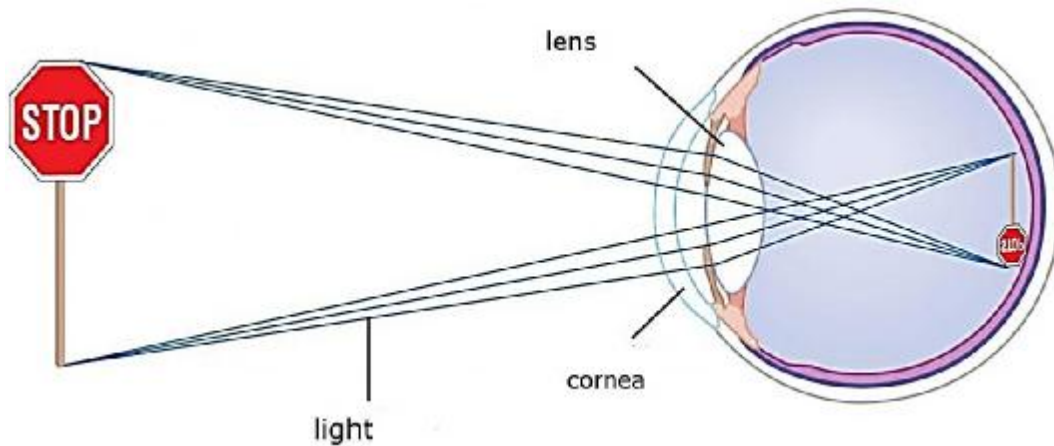


Fig. 22.2. The formation scheme of a real inverted diminished image on retina

### 22.3. ACCOMMODATION

*Accommodation* is the process by which the eye changes optical power to maintain a clear image as object distance varies.

Eye optical system makes clear image on retina, if thin-lens equation is satisfied:

$$\frac{1}{d} + \frac{1}{f} = \frac{1}{F}, \quad (22.1)$$

where  $d$  is the object to lens distance (fig. 22.3),  $f = 17 \text{ mm}$  is the image distance (lens to retina distance),  $F$  is the eye focal length.

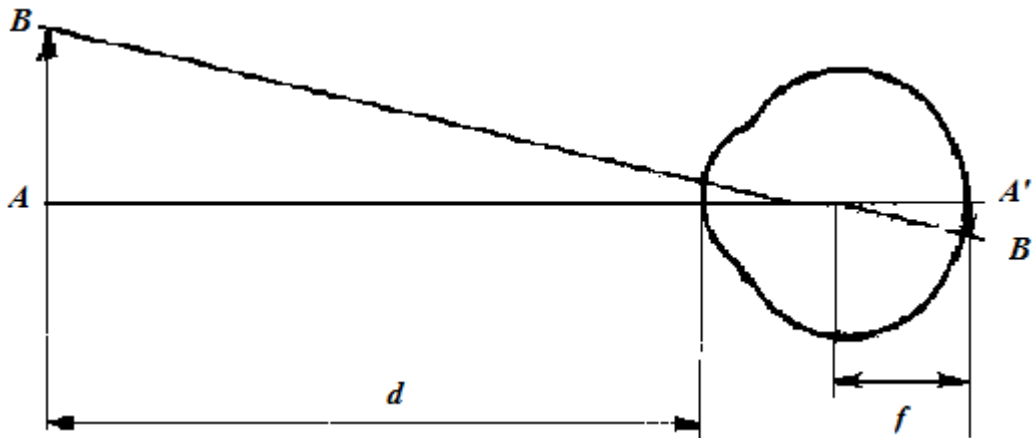


Fig. 22.3. Illustration for thin-lens equation

Light rays from distant objects ( $d \rightarrow \infty$ ) are nearly parallel and do not need as much refraction to bring them to a focus ( $f = F$ ).

Let's compare the operation of a camera and an eye. In both cases the instrument (eye or camera) must make an adjustment to put clear images on the retina or film of objects that are a variety of distances away. In a camera,

the focal length of the lens  $F$  is fixed and the image distance  $f$  is adjusted (lens to film distance is adjusted). In the eye the lens to retina distance (the image distance)  $f$  is fixed and the eye adjusts its focal length to place clear images on the retina. Eye accommodation is carried out by the lens curvature change. When the eye is relaxed, the lens has its minimum optical power for distant viewing. As the muscle tension around the ring of muscle is increased, the lens rounds out to its maximum optical power (fig. 22.4).

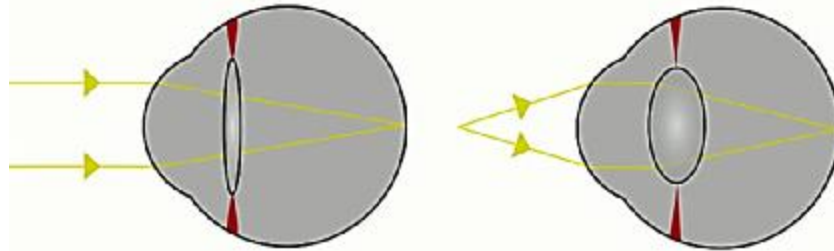


Fig. 22.4. Eye accommodation is carried out by the lens curvature change

The ability for accommodation depends on the elasticity of the eye lens and decreases with age (fig. 22.5).

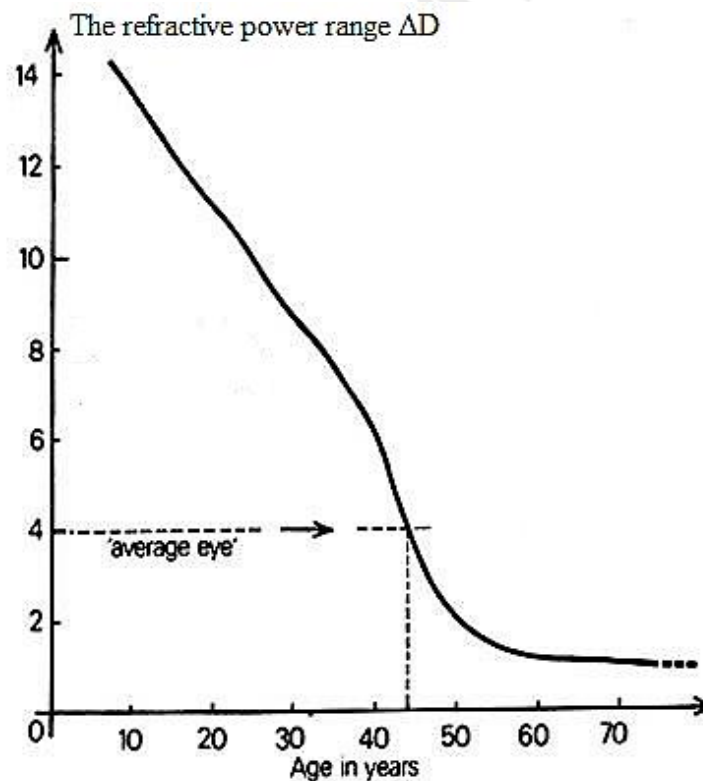


Fig. 22.5. Dependence of accommodation on the age

**Far point  $R$**  is the point at which an object must be placed along the optical axis for its image to be focused on the retina when the eye is not accommodating. For the normal eye the far point  $R$  is located at distance  $l_R \geq 20$  m from the eye. **Near point  $P$**  is the point nearest the eye at which an object is accurately focused

on the retina when the maximum degree of accommodation is employed. For the normal eye near point  $P$  at  $l_P = 10\text{--}12$  cm distance from the eye. **Range of accommodation**  $A_{PR}$  is

$$A_{PR} = \frac{1}{l_P} - \frac{1}{l_R}. \quad (22.2)$$

#### 22.4. THE EYE REFRACTION DEFECTS AND EYESIGN IMPROVEMENT

**Emmetropic eye** is a condition of the normal eye. It is achieved when the refractive power of the cornea and the axial length of the eye is balanced, and in this case rays are focused exactly on the retina, resulting in perfect vision. An eye in a state of emmetropia requires no correction.

In this case parallel light rays from distant objects are in sharp focus on the retina when the ciliary muscle is completely relaxed (fig. 22.6). This means that the emmetropic eye can see all distant objects clearly with its ciliary muscle relaxed. However, to focus objects at close range, the eye must contract its ciliary muscle and thereby provide appropriate degrees of accommodation.

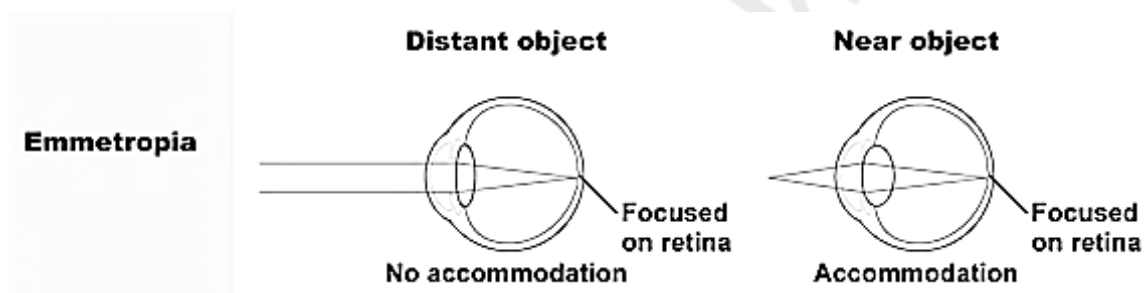


Fig. 22.6. The back focus location for normal eye

**Hyperopia**, which is also known as farsightedness, is usually due to either an eyeball that is too short or a lens system that is too weak. In this condition, parallel light rays are not bent sufficiently by the relaxed lens system to come to focus by the time they reach the retina (fig. 22.7, *a*). To overcome this abnormality, the ciliary muscle must contract to increase the strength of the lens. In old age, when the lens becomes **presbyopic**, a farsighted person is often unable to accommodate the lens sufficiently to focus even distant objects. Hyperopia can be corrected by adding refractive power using a convex lens in front of the eye (fig. 22.7, *b*).

**Myopia** (shortsightedness) is a condition of the eye where the light that comes in does not directly focus on the retina but in front of it (fig. 22.8, *a*). This is usually due to too long an eyeball. Also it can result from too much refractive power in the lens system of the eye. A myopic person has no mechanism by which to focus distant objects sharply on the retina. However, as an object moves still closer to the eye, the person can use the mechanism of

accommodation to keep the image focused clearly. A myopic person has a definite limiting *far point* for clear vision.

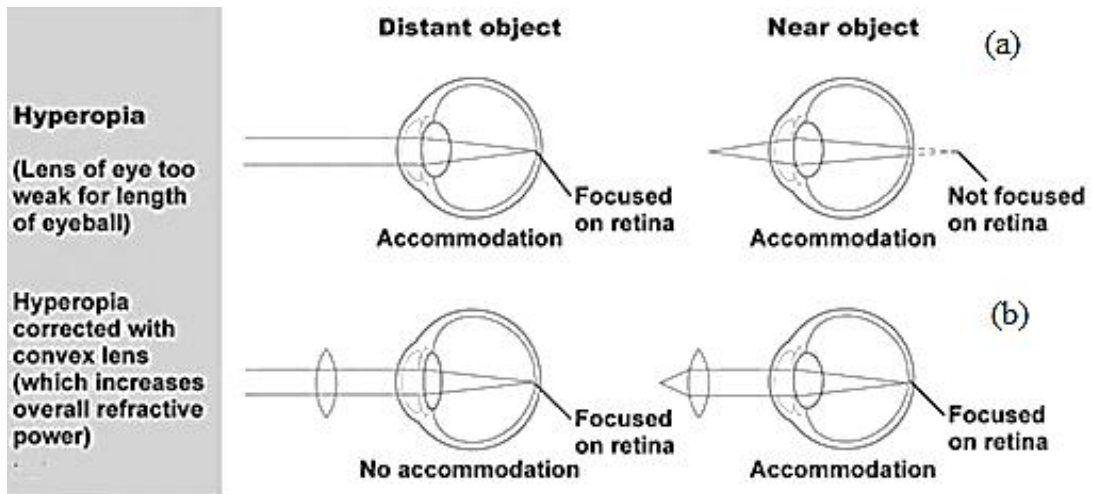


Fig. 22.7. The back focus location for far-sighted eye (a) and vision correction with a convex lens (b)

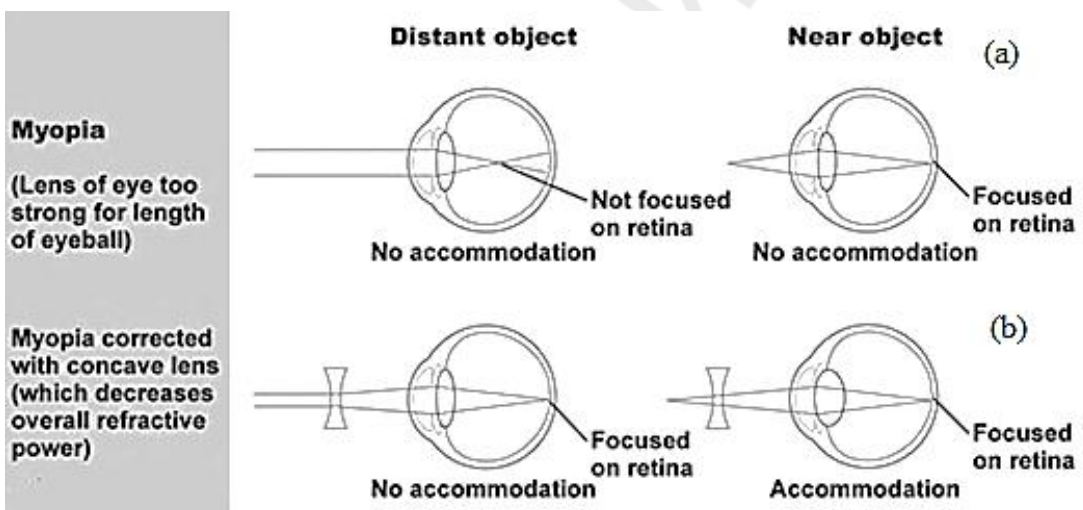


Fig. 22.8. The back focus location for short-sighted eye (a) and vision correction with a concave lens (b)

The corrective lenses have a negative optical power (i. e. are concave) which compensates for the excessive positive diopters of the myopic eye (fig. 22.8, b).

## 22.5. VISUAL ACUITY

*Visual acuity* is a quantitative measure of the ability to identify black symbols on a white background at a standardized distance as the size of the symbols is varied. Visual acuity is related with *visual angle* — the minimum angle at which resolution is just possible. It is the angle  $\phi$  under which object *AB* is seen from the optical center of the eye (fig. 22.9).

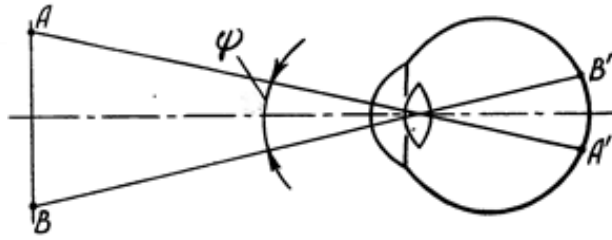


Fig. 22.9. Visual angle

The sensation of vision occurs when light is absorbed by the photosensitive rods and cones. To resolve two points, the light from each point must be focused on a different cone and the exited cones must be separated from each other by at least one cone that is not exited. The minimum distance between exited cones is  $d \approx 5 \mu\text{m}$ , so the minimum visual angle for which two luminous points (or two black points over a white background) are perceived by the eye as separate is about one angular minute:

$$\varphi_{\min} = \frac{d}{f} = \frac{5 \cdot 10^{-3} \mu\text{m}}{17 \text{ mm}} = 3 \cdot 10^{-4} \text{ rad} = 1', \quad (22.3)$$

where  $f = 17 \text{ mm}$  is the lens to retina distance.

The eye poorly recognizes the details of an object seen at an angle less than  $1'$ .

The angle  $1'$  is an angle at which a segment having a length of  $1 \text{ cm}$  is seen at a distance of  $34 \text{ m}$  from the eye. At an insufficient illumination (in twilight), the minimum angle of resolution becomes larger and may reach  $1^\circ$ .

The minimum visual angle of patient is determined using the special tables. Then *visual acuity* can be calculated as

$$\gamma = \frac{1'}{\varphi_{\min\text{patient}}}. \quad (22.4)$$

For example, if  $\varphi_{\min} = 2'$ , then the visual acuity for this patient:  $\gamma = \frac{1}{2} = 0,5$ .

By bringing an object close to the eye, one increase the angle of view, and hence make it possible to resolve finer details. However, objects cannot be brought too close to the eye since it has a limited capacity for accommodation. The most favorable distance for seeing object with a normal eye is  $d_0 = 25 \text{ cm}$ . At this distance the eye recognized details well enough without being tired. This is the *distance of normal vision*.

The eye *resolution limit* for the distance of normal vision is equal to:

$$AB = 1' \cdot d_0 = 3 \cdot 10^{-4} \text{ rad} \cdot 250 \text{ mm} = 73 \mu\text{m}. \quad (22.5)$$

## 22.6. RETINA ANATOMY AND FUNCTION

After light passes through the eye lens system and then through the vitreous humor, it enters the retina from the inside. Light passes first through several layers before it finally reaches the layer of rods and cones located on the outer



edge of the retina (fig. 22.10). This distance is a thickness of several hundred micrometers; visual acuity is decreased by this passage through such nonhomogeneous tissue. However, in the central foveal region of the retina the inside layers are pulled aside to decrease this loss of acuity.

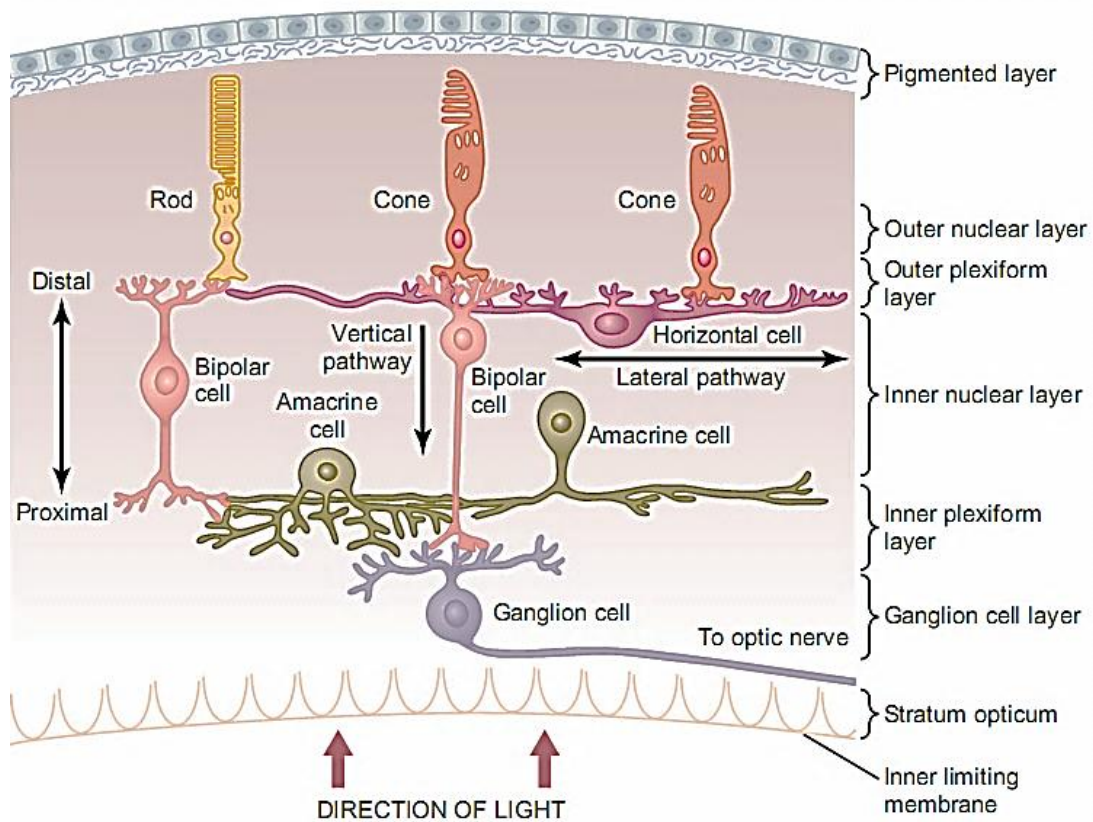


Fig. 22.10. Layers of retina

The retina contains two types of photoreceptors, termed rods and cones. (fig. 22.11). **Rods** are concentrated at the outer edges of the retina and are used in peripheral vision. There are approximately 125 million rods in the human retina. More sensitive than cones, rods are almost entirely responsible for **night vision** — vision under low illumination levels.

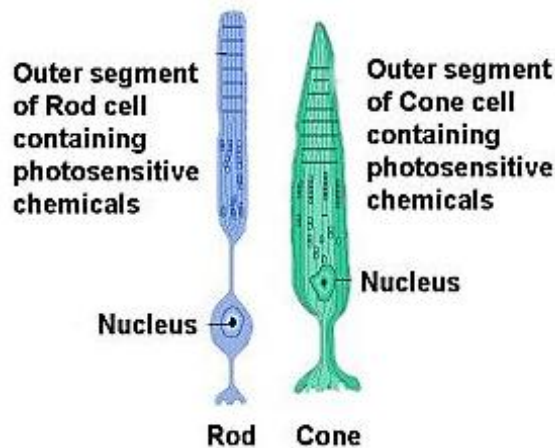


Fig. 22.11. Photoreceptors

Rods contain the light-sensitive pigment *rhodopsin* (visual purple) which undergoes a chemical reaction (the rhodopsin cycle) when exposed to visible light. Rhodopsin consists of a lipoprotein called opsin and a chromophore (a light-absorbing chemical compound called 11-cis-retinal). Rods cannot discriminate different wavelengths of light, and vision under low illumination conditions is essentially «colorblind». More than 100 rods are connected to each ganglion cell, and the brain cannot discriminate among these photoreceptors to identify the origin of an action potential transmitted along the ganglion.

*Cones* are responsible for color vision. Cone cells are densely packed in the fovea — a part of the eye, located in the center of the retina and responsible for *sharp vision*. There are approximately 6 million cones in the retina.

Cones are less sensitive to light than the rods, but allow the perception of color. They are also able to perceive finer detail and more rapid changes in images, because their response times to stimuli are faster than those of rods. Cones are maximally sensitive to light of about 550 nm, in the yellow-green region of the visible spectrum. Cones are much less sensitive than rods to light, but in the fovea there is a 1:1 correspondence between cones and ganglions, so the visual acuity is very high.

Essential components of a photoreceptor (either a rod or a cone) are the outer segment, the inner segment, the nucleus, and the synaptic body. The light-sensitive photochemical is found in the outer segment. In the case of the rods, this is *rhodopsin*; in the cones, it is one of three «color» photochemicals, usually called simply color pigments, that function almost exactly the same as rhodopsin except for differences in spectral sensitivity.

### 22.7. RHODOPSIN-RETINAL VISUAL CYCLE

When light energy is absorbed by rhodopsin, the rhodopsin begins to decompose. The cause of this is photoactivation of electrons in the rhodopsin, which instantaneously changes of the cis-form of retinal into an trans-form (fig. 22.12). This form has the same chemical structure as the cis-form but has a different physical structure — a straight molecule rather than an angulated molecule.

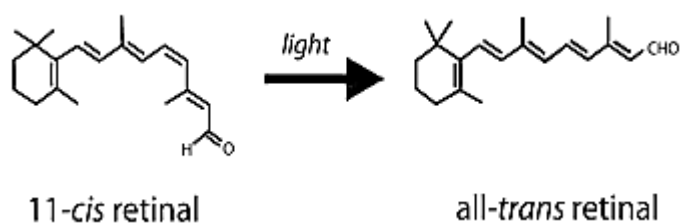


Fig. 22.12. Cis-form and trans-form of retinal

Because the three-dimensional orientation of the reactive sites of the trans-retinal, it begins to divide into opsin and a 11-cis-retinal.

This process excites electrical changes in the rods, and the rods then transmit the exciting on nerve cell and the visual image transmit into the central nervous system in the form of optic nerve action potential.

The excitation of the rod causes increased negativity of the membrane potential, which is a state of hyperpolarization. It means that there is more negativity potential than normal inside the rod membrane. This is exactly opposite to the decreased negativity (the process of «depolarization») that occurs in almost all other sensory receptors.

## 22.8. LIGHT AND DARK ADAPTATION OF EYE

Light and dark adaptation is the ability of the eye to adjust to various levels of darkness and light.

**Light adaptation** occurs when we move from the dark into bright light. Rods and cones are both stimulated and large amounts of the photopigment are broken down instantaneously, producing signals resulting in the light.

Adaption occurs in two ways:

1. By the pupil constriction, it takes about 0,3 sec.
2. By the decreasing of rhodopsin concentration in rods and iodopsin concentration in cones.

Within about one minute the cones are sufficiently excited by the bright light to take over. Visual accuracy and color vision continue to improve over the next ten minutes. During light adaptation retinal sensitivity is lost.

**Dark adaptation** is essentially the reverse of light adaptation. It occurs when going from a well light area to a dark area. Initially blackness is seen because our cones cease functioning in low intensity light. Also, all the rod pigments have been bleached out due to the bright light and the rods are initially nonfunctional.

Once in the dark, rhodopsin regenerates and the sensitivity of the retina increases over time (maximum sensitivity reaches approximately in hour). During these adaptation processes reflexive changes occur in the pupil size.

The eye is extremely sensitive to small amounts of light. For example, as few as 10 photons can generate a visual stimulus in an area of the retina where the rods are present at high concentration.

Differences in signal intensity that can just be detected by the human observer are known as **just noticeable differences (dI)**. This concept applies to any type of signal, including light that can be sensed by the observer. The smallest difference in signal that can be detected depends on the magnitude of the signal. The JND is directly proportional to the intensity of the signal:

$$dI \sim I \cdot dS$$
$$dS \sim \frac{1}{I},$$

where  $I$  is the intensity of stimulus,  $dS$  is an increment of perception, and  $k$  is a coefficient. The integral form of this expression is known as the **Weber–Fechner Law**:

$$S = k \log \frac{I}{I_0}. \quad (22.6)$$

The Weber–Fechner law is similar to the expression for the intensity of sound in decibels.

## 22.9. COLOR VISION

Different cones are sensitive to different colors of light. Let's discuss of the mechanisms by which the retina detects the different gradations of color in the visual spectrum.

All theories of color vision are based on the well-known observation that the human eye can detect almost all gradations of colors can be received when only red, green, and blue monochromatic colors are appropriately mixed in different combinations.

The spectral sensitivities of the three types of cones in humans are the same as the light absorption curves for the three types of pigment found in the cones with maximum absorption on 440, 540 and 590 nm respectively. The absorption maximum for rods corresponds to 510 nm (fig. 22.13).

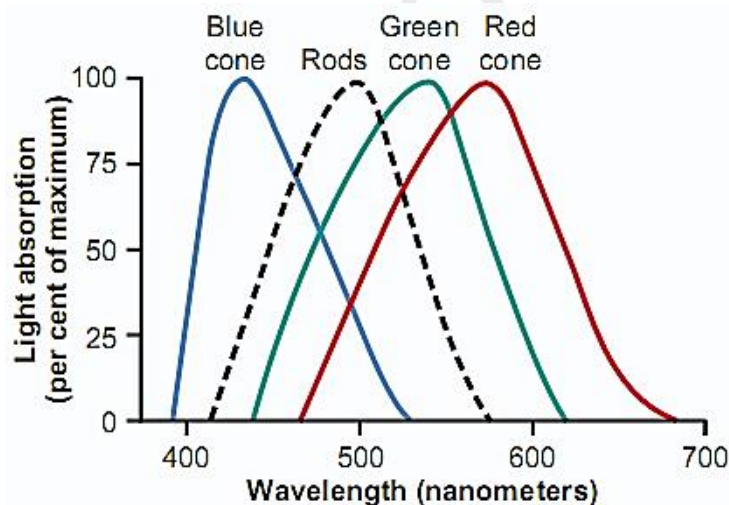


Fig. 22.13. Light absorption for cones and rods

For example, an orange monochromatic light with a wavelength of 580 nm stimulates the red cones; it stimulates the green cones to a less stimulus value, but the blue cones not at all. The nervous system interprets the ratios of stimulation of the three types of cones as the sensation of orange.

About equal stimulation of all the red, green, and blue cones gives one the sensation of seeing white. Yet there is no single wavelength of light corresponding to white; instead, white is a combination of all the wavelengths of the spectrum.

The rods are maximally sensitive to light of about 510 nm, in the blue-green region of the visible spectrum.

**Questions:**

1. Describe eye structure. What are the eye mediums optical properties?
2. Explain the eye optical system functions. Specify eye refractive power.
3. What is the eye accommodation? Describe mechanism of the accommodation. What is range of accommodation? How does it depend on age?
4. Characterize the main eye refraction defects. How are these defects corrected?
5. How is the visual acuity determined? What is the visual angle? Specify the eye resolution limit.
6. What is the eye retina construction? Describe two type photoreceptors, explain quantity and distribution of photoreceptors.
7. What are the differences between rods and cones? Describe rhodopsin-retinal visual cycle.
8. What difference between daylight vision and twilight one? Specify the light absorption spectrum for cones and rods.
9. What is the eye adaptation? Specify basic mechanisms of adaptation.

## Chapter 23. X-RAYS

X-rays are a form of electromagnetic radiation with a wavelength in the range of **80** to **10<sup>-5</sup>** nanometers. They are longer than  $\gamma$ -rays but shorter than ultraviolet rays. If X-rays have short wavelength they are called **hard** X-rays. On the other hand, the long-wave radiation is classified as **soft** X-rays. X-rays is divided into **bremstrahlung** and **characteristic** X-rays according to the mechanism of their formation.

In many languages, X-radiation is called Röntgen radiation, after Wilhelm Conrad Röntgen, who is credited as its discoverer, and who had named it X-radiation to signify an unknown type of radiation.

### 23.1. BREMSSTRAHLUNG X-RAYS

Bremstrahlung X-rays («braking radiation» or «deceleration radiation») is electromagnetic radiation produced by the deceleration of a charged particle when deflected by another charged particle, typically an electron by an atomic nucleus. The moving particle loses kinetic energy, which is converted into a heat and a photon because energy is conserved. It is characterized by a continuous distribution of radiation (continuous spectrum) which becomes more intense and shifts toward higher frequencies when the energy of the bombarding electrons is increased.

In medicine X-rays is produced in a highly evacuated glass bulb, called an **X-ray tube** (fig. 23.1). It contains two electrodes — an anode made of molybdenum, tungsten, or another heavy metal of high melting point, and a cathode. When a high voltage is applied between the electrodes, streams of electrons (cathode rays) are accelerated from the cathode to the anode and produce X rays as they strike the anode. The focusing electrode directs

the electron beam towards the anode. Some part of the electron kinetic energy turns into the energy of X-rays. The other part of this energy passes into heat so the temperature of the anode rises. Therefore anode is kept cool by means of air, water or oil cooling arrangement.

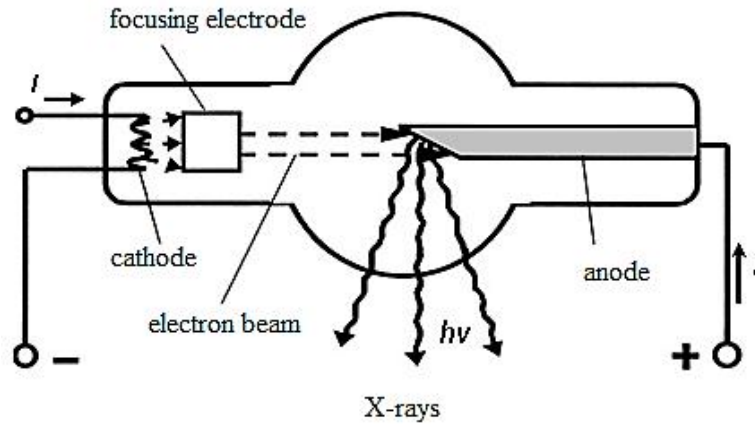


Fig. 23.1. X-Rays tube

The kinetic electron energy obtained in the electric field between the cathode and the anode can be written as:

$$\frac{mv^2}{2} = eU, \quad (23.1)$$

where  $m$  is the mass of an electron,  $v$  is the velocity,  $e$  its charge,  $U$  is the applied electrical potential difference between the cathode and the anode.

When an electron hits the target its entire kinetic energy is converted into both photon energy  $h\nu$  and heat  $Q$ :

$$eU = h\nu + Q. \quad (23.2)$$

A relation between summands in right part of this equation (23.2) is random. Therefore the different frequencies are observed in the bremsstrahlung radiation spectrum. Bremsstrahlung X-rays has a continuous spectrum in which the intensity varies smoothly with wavelength. This spectrum has a definite short wavelength  $\lambda_{\min}$  below which there is no radiation.

The **minimum wavelength**  $\lambda_{\min}$  corresponds to maximum frequency  $\nu_{\max}$ . If the magnitude of the voltage  $U$  is known the numerical value of  $\lambda_{\min}$  can be calculated. Let's assume that  $Q = 0$  (all kinetic electron energy turns into the radiation). Thus:

$$h\nu_{\max} = \frac{hc}{\lambda_{\min}} = eU \Rightarrow \lambda_{\min} = \frac{hc}{eU}. \quad (23.3)$$

where  $c$  is velocity of light.

Put the values of constants  $h$ ,  $c$  and  $e$  the minimum wavelength  $\lambda_{\min}$  can be written:

$$\lambda_{\min} (nm) = \frac{1,23}{U(kV)}. \quad (23.4)$$

The curve of bremsstrahlung X-rays spectrum for each voltage starts at a particular minimum wavelength, rises rapidly to a maximum and drops gradually but indefinitely towards the longer wavelengths (fig. 23.2). Minimum wavelength  $\lambda_{\min}$  depends on the tube voltage  $U$ . The higher voltage  $U$  the smaller value of the minimum wavelength  $\lambda_{\min}$  (23.4).

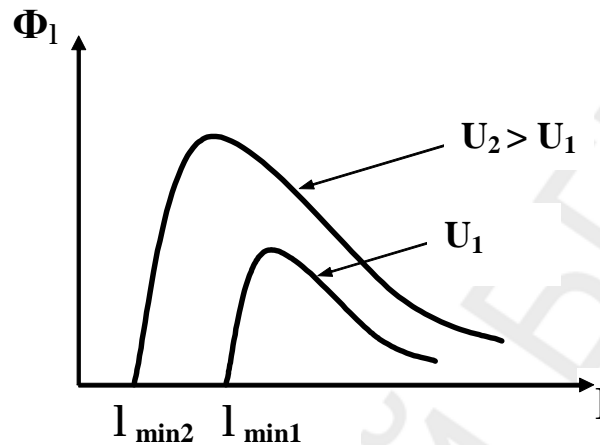


Fig. 23.2. The spectrum of the bremsstrahlung X-rays for different voltages  $U_1$  and  $U_2$  applied between cathode and anode

The spectrum of the bremsstrahlung X-rays is spectral distribution of a radiant flux, where the radiant flux  $\Phi$  is determined by the number of light quanta falling on the surface in time unite.

A total radiant flux  $\Phi$  of X-rays depends on current  $I$  and voltage  $U$  in the X-rays tube and determined by formula:

$$\Phi = k I U^2 Z, \quad (23.5)$$

where  $Z$  is the atomic number,  $k$  is the coefficient proportionality  $k = 10^{-9} (\text{V}^{-1})$ .

As can see from fig 23.3 the  $\lambda_{\min}$  is the same for different current values ( $I_1$  and  $I_2$ ) in the X-rays tube when  $U$  is constant. Therefore the radiant flux rises but the radiation hardness remains unchanged.

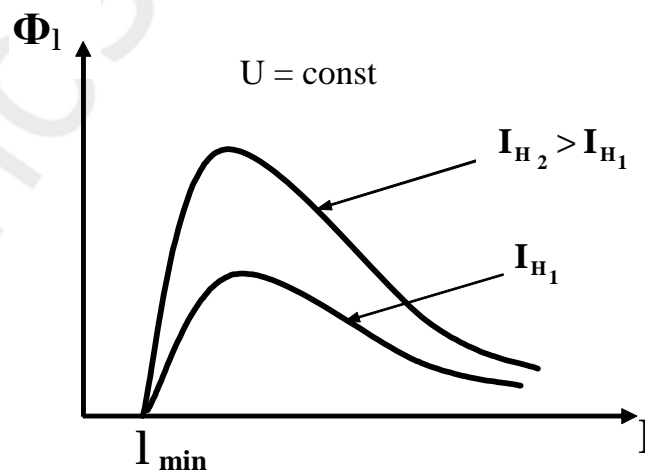


Fig. 23.3. The spectrum of the bremsstrahlung X-rays for different value of current in the X-rays tube

## 23.2. CHARACTERISTIC X-RAYS

If the bombarding electrons have sufficient energy, they can knock an electron out of an inner shell of the target metal atoms. Then electrons from higher states drop down to fill the vacancy, emitting x-ray photons with precise energies determined by the electron energy levels (fig. 23.4). These x-rays are called *characteristic x-rays*.

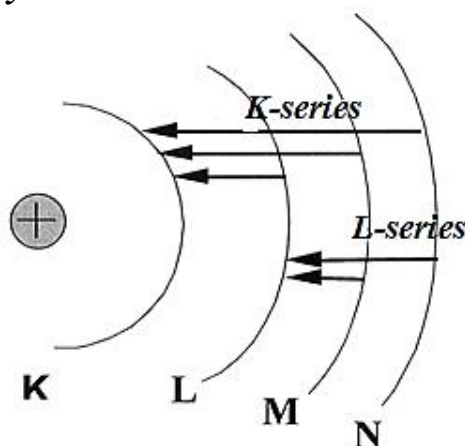


Fig. 23.4. Characteristic x-rays

This process produces an emission spectrum of X-rays at a few discrete frequencies, sometimes referred to as the spectral lines. The spectral lines generated depend on the target (anode) element used and thus are called characteristic lines. Usually these are transitions from upper shells into K shell (called K lines), into L shell (called L lines) and so on.

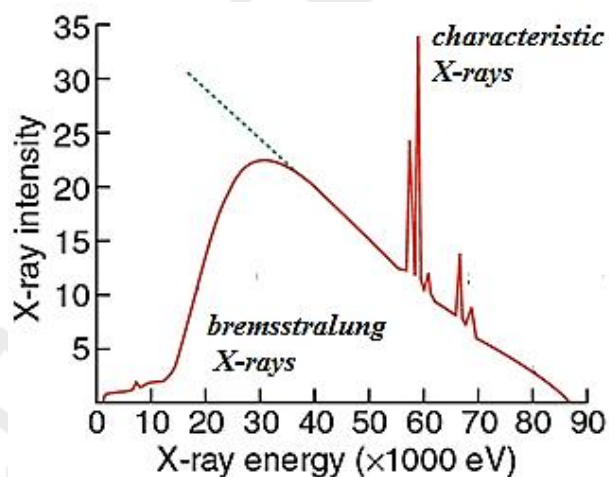


Fig. 23.5. X-rays spectrum

The frequency  $n$  of the characteristic X-rays rises as the atomic number  $Z$  increases. This relation is known as a **Moseley Law**:

$$\sqrt{\nu} = A(Z - B), \quad (23.6)$$

where  $A$  and  $B$  are constant.



### 23.3. INTERACTION BETWEEN X-RAY AND MATTER

Let's consider an interaction between quanta of X-rays and atoms and molecules of the matter. Obviously, the result of this interaction depends on the energy of the quantum. There are several different cases.

1. The quantum energy  $hn$  of X-rays is smaller than the energy of the atomic ionization  $A_i$  ( $hn < A_i$ ). Such interaction is called a **coherent scattering**. It is a process in which the photon is scattered on the entire atom. That is, the internal energy of the atom does not change. In this case the energy of the incident photon equals the energy of the scattered photon. Only soft X-ray experiences a coherent scattering (fig. 23.6, a). This is not an ionizing interaction.

2. The quantum energy  $hn$  is slightly greater than the energy of the atomic ionization  $A_i$  ( $hn \geq A_i$ ). In this case, the quantum energy  $hn$  is spent on atom ionization  $A_i$  and kinetic energy of electron  $\frac{mv^2}{2}$ :

$$hv = \frac{mv^2}{2} + A_i. \quad (23.7)$$

This phenomenon is known as a photoelectric effect or **photoeffect** (fig. 23.6, b).

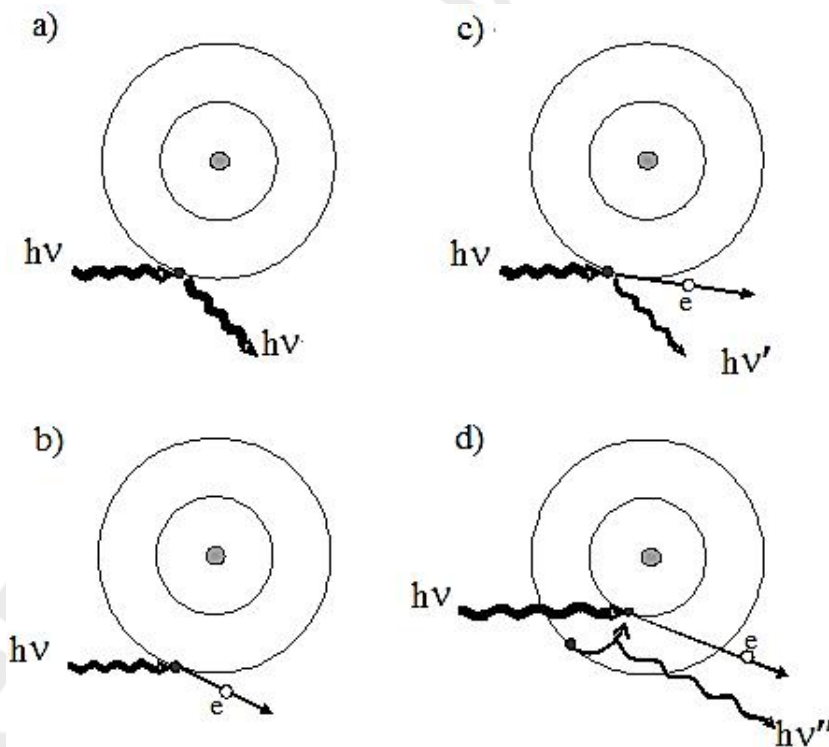


Fig. 23.6. Interaction between X-ray and matter

3. The quantum energy  $hn$  is much greater than the energy of the atomic ionization  $A_i$  ( $hn \gg A_i$ ). A photon interacts with an electron, but in contrast to the photoelectric effect, only a part of the photon energy is transferred to the electron. The photon continues on its way, but with reduced energy  $hv'$  (i. e.,

a lower frequency). This effect is called a **Compton scattering** or incoherent scattering (fig. 23.6, c). The electron is still emitted from its shell. In addition the electron obtains a kinetic energy  $E_K$ :

$$h\nu = A_i + h\nu' + E_K. \quad (23.8)$$

If the electron is ejected from interior shells then the characteristic X-ray appears.

Secondary X-rays have energy  $h\nu' > A_i$  and can produce the ionization of the matter again. Recoil electrons can also ionize adjacent atoms by means of a collision (fig. 23.6, d).

High-energy photons experience more Compton scattering than low energy photons. Unfortunately, Compton scattering is the major source of background noise in X-ray images. In addition, Compton scattering is the major source of tissue damage due to X-rays. For these reasons, this phenomenon X-rays is applied in medicine for damage cancer tumors.

### 23.4. ATTENUATION OF X-RAYS

When the X-rays pass through the matter, its intensity falls due to its absorption and scattering by the matter. The character of attenuation depends on the energy of X-rays, nature (i. e. wavelength) and thickness of matter. Let  $I_0$  be an initial intensity of X-rays incidents normally on a material and  $I$  be an intensity of the X-rays after traveling a distance  $x$  in the material (fig. 23.7). The attenuation of X-rays is described by the exponential law:

$$I = I_0 e^{-\mu x}, \quad (23.9)$$

where  $\mu = \mu_{\text{absorption}} + \mu_{\text{scattering}}$  is the **linear attenuation coefficient** of material. It depends on material density  $\rho$ .

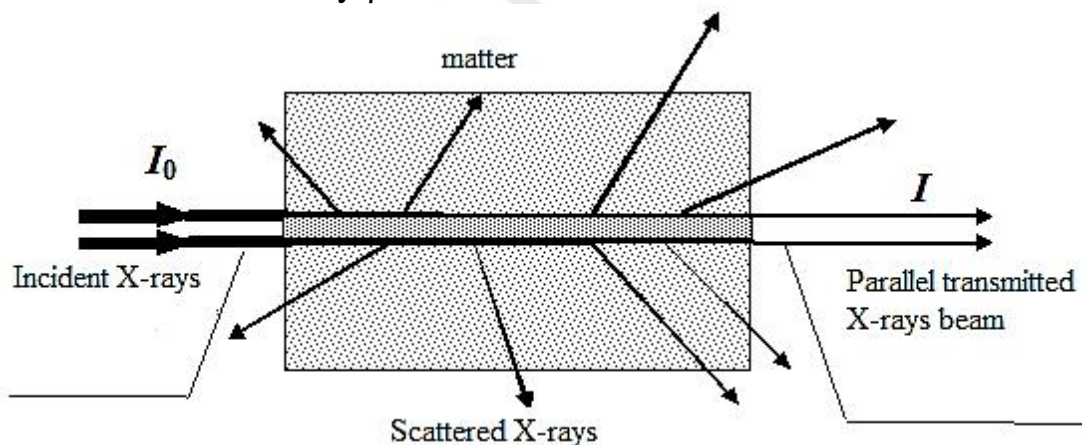


Fig. 23.7. Decrease in the intensity of X-ray through matter

A **mass attenuation** factor  $\mu_m$  is used also:  $\mu_m = \mu/\rho$ , this coefficient is independent on a density of material.

The beam of X-rays encloses quanta with different energy. They have different penetrating power. Therefore the coefficient  $\mu$  in equation (23.9) is

constant only for monoenergetic X-ray photons. For X-rays with different photon energies the effective attenuation coefficient is used.

Let's estimate the penetrating power of X-rays. In practice a half-value layer is used, which is the thickness required to attenuate the beam intensity by 50 % (fig. 23.8). One can relate the half-value layer to the linear attenuation coefficient analytically. If in equation 23.9  $x = d_{1/2}$ , then  $I = I_0/2$ :

$$\begin{aligned}
 I_0/2 &= I_0 e^{-\mu d_{1/2}} \\
 e^{+\mu d_{1/2}} &= 2 \\
 \ln e^{+\mu d_{1/2}} &= \ln 2 \\
 \mu d_{1/2} &= \ln 2 = 0,69 \\
 \text{Thus: } d_{1/2} &= \frac{\ln 2}{\mu} = \frac{0,69}{\mu}. \tag{23.10}
 \end{aligned}$$

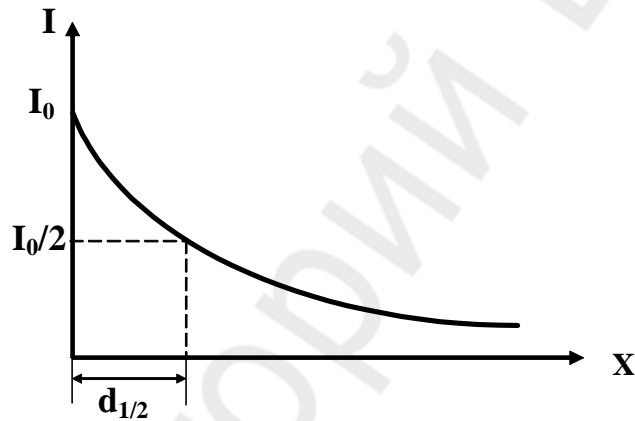


Fig. 23.8. Attenuation of X-rays passing through the matter

For example, the half-value layer for X-rays is equal 10 mm of water or 1 mm of aluminium when the applied in X-rays tube voltage  $U$  is 60 kV.

The half-value layer is a function of the energy of X-ray beam. Therefore a spectral composition of X-ray changes when the beam goes through the half-value layer. The radiation becomes harder because short rays have a big penetrating power. Soft X-rays are absorbed more strongly. This phenomenon is called «beam hardening».

### 23.5. PHYSICAL PRINCIPLES OF THE X-RAY DIAGNOSTICS

The mass attenuation coefficient  $\mu_m$  of X-rays depends on the matter composition and the wavelength:

$$\mu_m = k \lambda^3 Z^3, \tag{23.11}$$

where  $k$  is a coefficient of proportionality;  $Z$  is an atomic number of the material;  $\lambda$  is a wavelength.

From equation 23.11 one can see that the mass attenuation coefficient  $\mu_m$  is increases with the increasing of the atomic number  $Z$  and depends on the photon

energy. This is a basis of the medical X-rays diagnostics. The purpose of this diagnostic is to measure features of the internal anatomy of a patient through differences in the attenuation of X-rays passing through different parts of the body.

A simplified model of the human body consists of three different body tissues: fat, muscle, and bone. Air is also present in the lungs, sinuses and gastrointestinal tract. A **contrast agent** — a material with high  $Z$  number — may be used to accentuate the attenuation of X-rays in a particular region.

X-rays interact in fat and other soft tissues predominantly by photoelectric interactions. Low-energy X-rays are used to accentuate subtle differences in soft tissues (e. g., fat, muscles and other soft tissues) in applications such as breast imaging (mammography) where the object (the breast) provides little intrinsic contrast. When images of structures with high intrinsic contrast are desired (e. g., the chest where bone, soft tissue, and air are present), higher-energy X-rays are used. These X-rays suppress X-ray attenuation in bone which otherwise would create shadows in the image that could hide underlying soft-tissue pathology.

In comparison with muscles and bones, fat has a higher concentration of hydrogen (~ 11 %) and carbon (~ 57 %) and a lower concentration of nitrogen (~ 1 %), oxygen (30 %) and high- $Z$  trace elements (< 1 %). Hence, the effective atomic number of fat ( $Z_{\text{eff}} = 5,9$  to  $6,3$ ) is less than that of soft tissues ( $Z_{\text{eff}} = 7,4$ ) or bones ( $Z_{\text{eff}} = 11,6$  to  $13,8$ ). Because of its lower  $Z_{\text{eff}}$ , low-energy photons are attenuated less rapidly in fat than in an equal mass of soft tissues or bones.

The effective atomic number and physical density are greater for bones than for soft tissues. Hence, X-rays are attenuated more rapidly in bone than in an equal volume (not necessarily mass) of soft tissue.

There are many X-ray based procedures used in medical diagnosis, for example, fluoroscopy, mammography, X-rays computer tomography. Spiral computer tomography provides images can be displayed in three dimensions. The X-rays tomography allows receiving a layerwise image when a difference between attenuation coefficients is equal 0,1 %.

**Questions:**

1. Describe the bremsstrahlung X-rays appearance mechanism. Why does it have continuous spectrum? How to determine the minimum wavelength?

2. How to control the intensity and the hardness of radiation in the X-rays tube? Write the formula for bremsstrahlung X-rays radiant flux?

3. Compare the thermal radiation spectrum with the X-rays one. Discuss their similarity and differences.

4. Discuss the differences between the optical spectrum formation mechanisms and characteristic X-rays one.

5. Describe the interaction between X-rays and matter mechanisms. Why is the hard X-rays more harmful for an organism than the soft X-rays?

6. Write exponential law for X-rays attenuation in matter. What is the linear attenuation coefficient? Describe its relation with the half-value layer.

7. Compare the physical principles of ultrasound and X-rays one.

## Chapter 24. RADIOACTIVITY

Radioactive decay is the process in which unstable atomic nucleus (called radionuclide) emits radiation in the form of particles and electromagnetic waves. This decay results in an atom of one type, called the parent nuclide transforming to an atom of a different type, called the daughter nuclide.

### 24.1. CHARACTERISTICS OF NUCLEUS

An atom consists of a positively charged nucleus surrounded by a cloud of negatively charged electrons. Nuclei consist of positively charged *protons*, and electrically neutral *neutrons* held together by the so-called strong or nuclear force.

Let's point basic properties of the nuclear force. The nuclear force is related to a *strong interaction*. At short distances, the nuclear force is stronger than the Coulomb force; it can overcome the Coulomb repulsion of protons inside the nucleus. It is a *short-range force*, its range is limited to distances about  $10^{-15}$  meters. The nuclear force is nearly independent of whether the nucleons are neutrons or protons. This property is called *charge independence*. Every nucleon interacts with a limited number of adjacent nucleons (*property of saturation*).

The nuclear symbol is  ${}^A_Z\mathbf{X}$ . It consists of three parts: the symbol of the element  $\mathbf{X}$ , the atomic number of the element  $Z$  and the mass number of the specific isotope  $A$ .

The number of protons in the nucleus,  $Z$ , is called the *atomic number*. It determines the electric charge of nucleus and what chemical element the atom is. The number of neutrons in the nucleus is marked by  $N$ . The given element can have many different isotopes, which differ from each other by the number of neutrons contained in the nuclei. The *atomic mass number* of the nucleus can be written as:  $A = Z + N$ .

The sizes of nuclei grow through the periodic table. The nuclear radius  $R$  and the atomic mass number  $A$  are related by formula:

$$R = 1,5 \times 10^{-15} \times \sqrt[3]{A} \text{ (m)}. \quad (24.1)$$

The *nuclear charge* is equal to  $q = Ze$ . *Nuclear stability* depends on the atomic number  $Z$  and on the number of neutrons  $N$ . The light atomic nuclei contain practically as many neutrons as protons ( $N/Z = 1$ ). They are the most stable. In case  $N/Z > 1,6$  the atomic nuclei are unstable and undergo a radioactive disintegration.

The unit of energy commonly used in atomic and nuclear physics is the electron volt (eV):

$$1 \text{ eV} = 1,6 \cdot 10^{-19} \text{ C} \cdot 1\text{V} = 1,6 \cdot 10^{-19} \text{ J}.$$

Thus:

$$1 \text{ keV} = 1000 \text{ eV} = 1,6 \cdot 10^{-16} \text{ J}$$

$$1 \text{ MeV} = 10^6 \text{ eV} = 1,6 \cdot 10^{-13} \text{ J}.$$

## 24.2. MODES OF RADIOACTIVE DECAY

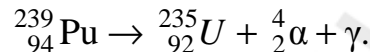
Unstable atoms undergo a radioactive decay in order to have a more stable configuration. For all types of radioactive decay conservation laws of mass number, electrical charge, total energy and impulse are performed.

**Alpha-decay** is a type of radioactive decay in which an atomic nucleus emits an alpha particle  ${}^4_2\alpha$  (a helium nucleus  ${}^4_2\text{He}$ ) and transforms into an atom with a mass number on **4** less and atomic number on **2** less.

Alpha-decay proceeds according to the following scheme:



As any type of decay,  $\alpha$ -decay can be accompanied by the emission of  $\gamma$ -rays, for example:



It often happens that the nuclei appeared as a result of radioactive transformation are also radioactive and decay. The new decay product may again be radioactive until stable nucleus is formed.

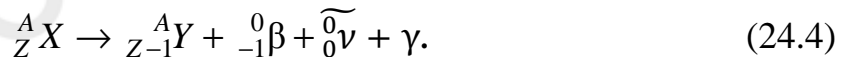
**Beta-decay** is accompanied by the interconversion between neutrons and protons inside a nucleus. There are three varieties of beta-decay:

### 1. Negative beta-decay.

In negative beta-decay an unstable nucleus ejects from itself an energetic electron  ${}^0_{-1}\beta$  and an antineutrino  ${}^0_0\bar{\nu}$  (with no rest mass), and a neutron  ${}^1_0n$  in the nucleus is converted into a proton:



Thus, negative beta decay results in a daughter nucleus, the proton number (the atomic number) of which is one more than its parent but the mass number (the total number of neutrons and protons) of which is the same  ${}^A_{Z-1}Y$ :



Neutrino  ${}^0_0\nu$  is an elementary particle that travels close to the speed of light, having no electric charge, little or no mass. It is able to pass through matter undisturbed and is thus extremely difficult to detect. The difference between neutrino  ${}^0_0\nu$  and antineutrino  ${}^0_0\bar{\nu}$  consists of the opposite direction of spins.

Energy emitted by the  $\beta$ -decay is distributed randomly between an electron and an antineutrino. Therefore the kinetic energy of emitted  $\beta$ -particles takes all possible values, from 0 to  $E_{\text{max}}$ . Thus the kinetic energy of the  $\beta$ -particles has a continuous spectrum (fig. 24.1).

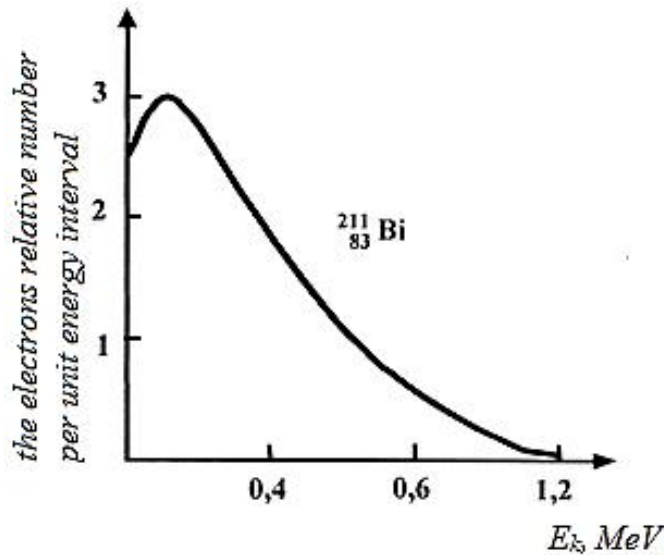
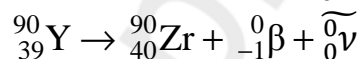
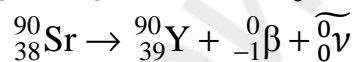
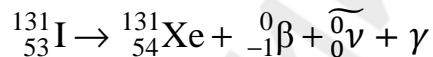
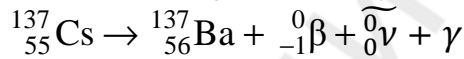


Fig. 24.1.  $\beta$ -particles kinetic energy spectrum

There are examples of the beta negative decay:



## 2. Positive beta-decay

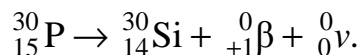
In positive beta-decay a proton  ${}_1^1p$  in the parent nucleus transforms into a neutron  ${}_1^1n$  that remains in the daughter nucleus and ejects a **positron**  ${}_{+1}^0\beta$ , which is a positive particle like an ordinary electron in mass but of opposite charge, along with a neutrino  ${}_0^0\nu$ , which has no mass:



Thus, positive beta decay produces a daughter nucleus, the atomic number of which is one less than its parent and the mass number of which is the same:



For example:



## 3. Electron capture

In **electron capture**, nucleus captures an electron located on inner atom orbit (fig. 24.2). The captured electron  ${}_{-1}^0\beta$  combines with a nuclear proton  ${}_1^1p$  to produce a neutron  ${}_0^1n$  and a neutrino  ${}_0^0\nu$ , which is ejected:



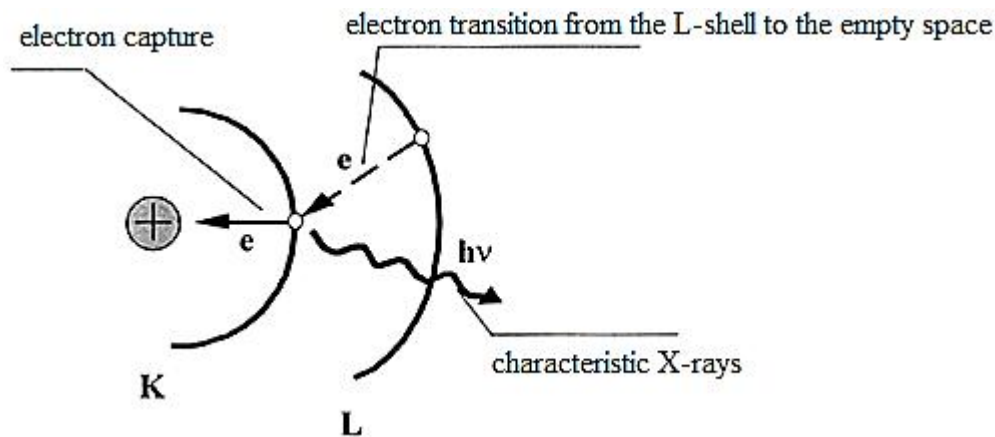
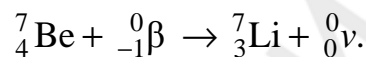


Fig. 24.2. Electron capture

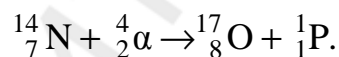
As in positron emission, the nuclear positive charge and hence the atomic number decreases by one unit, and the mass number remains the same. Electron capture is accompanied by the following electron transitions to empty spaces with characteristic X-rays producing. An example of electron capture is the transformation of beryllium  ${}^7_4\text{Be}$  into lithium  ${}^7_3\text{Li}$ :



### 24.3. NUCLEAR REACTIONS

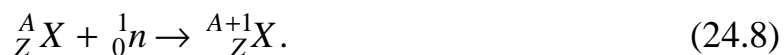
A **nuclear reaction** is a process in which two nuclei or nuclear particles collide to produce particles different from the initial particles.

The first nuclear reaction was carried by Ernest Rutherford, who bombarded nitrogen  ${}^{14}_7\text{N}$  with alpha particles  ${}^4_2\alpha$ :

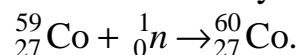


It is necessary to accelerate elementary particles up to high energy for this process. Then a charged particle can overcome the electrostatic repulsion force of nuclear protons.

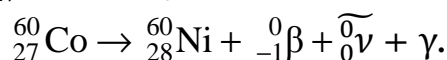
Another method of the nuclear reaction realization is **neutron activation**. A stable nucleus  ${}^A_Z\text{X}$  absorbs a neutron  ${}^1_0n$  and changes into a radionuclide  ${}^{A+1}_Z\text{X}$  of this element:



It is possible to obtain radioactive cobalt by this way:



Radioactive cobalt  ${}^{59}_{27}\text{Co}$  is subjected to electron decay:



Gamma-radiation which appears in this reaction is used in radiotherapy for the destruction of malignant tumors.



Moderated neutrons are more useful for nuclear reactions because fast neutrons can experience elastic collisions with a nucleus and scatter.

#### 24.4. RADIOACTIVE DECAY LAW

Following to the *radioactive decay Law* one can say that the number of undecayed nuclei  $N$  decreases exponentially with time  $t$ :

$$N = N_0 e^{-\lambda t}, \quad (24.9)$$

where  $\lambda$  is a constant characteristic of the given radioactive substance and known as the *decay constant*,  $N_0$  is the initial number of undecayed nuclei at the time  $t = 0$ .

The time during which a half of the initial number of nuclei  $N_0$  decays is called the *half-life*  $T$ . It is determined by the condition:

$$\frac{1}{2}N_0 = N_0 e^{-\lambda T} \Rightarrow 2 = e^{-\lambda T}.$$

Finally: 
$$T = \frac{\ln 2}{\lambda} \approx \frac{0,69}{\lambda}. \quad (24.10)$$

The half-life time can be determined from fig. 24.3:

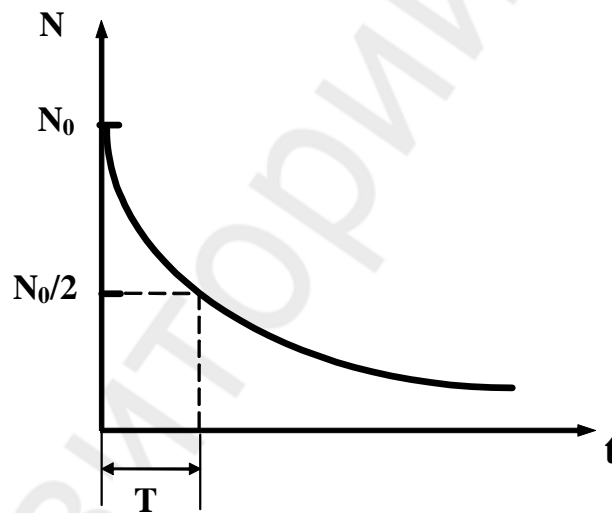


Fig. 24.3. Dependence of the number of undecayed nuclei  $N$  on time  $t$

The time during during which the number of undecayed nuclei decrease in  $e$  time is called *mean lifetime*. There is following relation between  $\tau$ ,  $\lambda$  and  $T$ :

$$\tau = \frac{1}{\lambda} = \frac{T}{0,69}. \quad (24.11)$$

#### 24.5. RADIOACTIVE SUBSTANCE ACTIVITY

The *activity* of a radioactive preparation  $A$  is defined as a number of disintegrations per unite time. On other words the *activity*  $A(t)$  is the number of radioactive transformations per second:

$$A = -\frac{dN}{dt}. \quad (24.12)$$

Let's put (24.9) in (24.12) and differentiate with respect to time:

$$A = -\frac{dN}{dt} = \lambda N = \lambda(N_0 \cdot e^{-\lambda t}) = A_0 e^{-\lambda t}. \quad (24.13)$$

Then:

$$A = \lambda N = 0,69 \frac{N}{T}. \quad (24.14)$$

The SI unit of activity  $A$  is the *becquerel* (Bq): 1 Bq = 1 transformations  $\cdot$  s<sup>-1</sup>.

Another unit of activity is the *curie* (Ci): 1 Ci = 3,7  $\cdot$  10<sup>10</sup> Bq. One curie is defined to be equal to the disintegration rate of 1 gm of <sup>226</sup>Ra, or 3,7  $\cdot$  10<sup>10</sup> disintegrations per second (d/s).

Activity  $A$  decreases with time exponentially:

$$A = A_0 e^{-\lambda t}. \quad (24.15)$$

Let's relate the activity  $A$  with radionuclide mass  $m$ . The number of undecayed nuclei  $N$  is determined as:

$$N = \frac{m}{m_N},$$

where  $m$  is a nuclei mass,  $m_N$  is one nucleus mass.

The one nucleus mass  $m_N$  can be found from following formula:

$$m_N = \frac{M}{N_A},$$

where  $M$  is an atomic mass,  $N_A$  is Avogadro constant.

$$A = \frac{0,69 \cdot N}{T} = \frac{0,69 \cdot m \cdot N_A}{TM} = \frac{0,69 \cdot 6,02 \cdot 10^{23} \cdot m}{TM} = 4,17 \cdot 10^{23} \frac{m}{TM}. \quad (24.16)$$

The activity of substance depends on its mass, thus the *unit-mass activity*  $A_m$  is used for determination of the object radiation pollution. The unit-mass activity is measured in Bq/kg or Ci/kg. It is determined as  $A_m = \frac{A}{m}$ .

The concentration of radionuclides in liquid or in gas is characterized by the *specific volume activity*  $A_v$  (unit is Bq/m<sup>3</sup>, Bq/l, Ci/l). It is determined by the formula:  $A_v = \frac{A}{V}$ .

The *specific surface activity*  $A_s$  (Bq/m<sup>2</sup>, Ci/m<sup>2</sup>) characterizes the radioactive surface pollution and is determined by the formula:  $A_s = \frac{A}{S}$ .

## 24.6. INTERACTION OF THE IONIZING RADIATION WITH THE MATTER

Ionizing radiation produces ions during the interaction with atoms in the matter. There are several types of ionizing radiation. Alpha-particles  ${}^4_2\alpha$ , beta-particles  ${}^0_{-1}\beta$ ,  ${}^0_{+1}\beta$ , neutrons  ${}^1_0n$  and protons  ${}^1_1p$  are examples of particulate

ionizing radiation. Gamma-rays and X-rays are electromagnetic ionizing radiation.

### 24.6.1. Characteristics of the radiation-matter interaction

Three important parameters associated with the passing of charged particles through matter:

**Linear specific ionization** is the total number of ion pairs  $dn$  produced per length unit  $dl$  of the path of the incident radiation:  $i = dn/dl$  (fig. 24.4). Specific ionization increases with decreasing energy of the charged particle because of the increased probability of interaction at low energies.

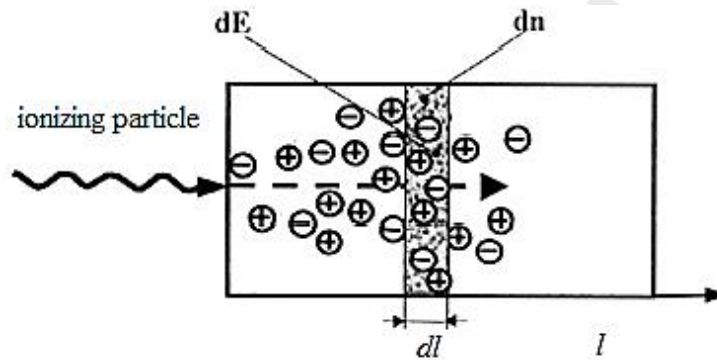


Fig. 24.4. Ion formation under ionizing radiation in the matter

**Linear energy transfer (LET)** is the amount of energy deposited per length unit of the path by the radiation:  $LET = dE/dl$ . Electromagnetic radiation and  $\beta$ -particles have low LETs. In contrast, heavy particles ( $\alpha$ -particles, neutrons and protons) lose energy very rapidly, producing many ionizations in a short distance, and thus they have high LETs.

**Mean linear range** of a charged particle is an average distance which the particle passes before its energy will be equal to the mean particles energy in this matter.

Let's consider features of the interaction with matter for different particles.

### 24.6.2. Features of the interaction of different particles with matter

**Alpha-particles**  ${}^4_2\alpha$  are easily absorbed by materials because of their charge and large mass, and can travel only a few centimeters in air and in biological tissues — 10–100  $\mu\text{m}$ . They can be absorbed by paper or the outer layers of the human skin and that is why they are not generally dangerous to life unless the source is ingested or inhaled. However, if alpha-radiation does enter the body, it is the most destructive form of ionizing radiation due to high LET. Exposure of alpha-particles produces atoms excitation, ionization, characteristics X-rays appearance, nuclear reactions.

**Beta-particles**  ${}^0_{-1}\beta$ ,  ${}^0_{+1}\beta$  have an electrical charge and mass less than alpha-particle charge. Beta particles are much more penetrating than alpha particles,

but they have smaller ionizing power. Very high energy beta particles can penetrate to a depth of about a centimeter in tissue. Eye and skin damage is possible if the source is strong. They are, however, relatively easy to deal with by shielding. Exposure of beta-particles produces ionization and bremsstrahlung X-rays appearance.

**Gamma-rays** are a form of electromagnetic radiation of the highest frequency and energy, and also the shortest wavelength (below about  $10^{-5}$  nanometer), within the electromagnetic spectrum. A high-energy gamma photon passing near a nucleus sometimes produces an electron and positron pair. Gamma-ray photons lose energy by being scattered from free electrons (Compton effect) or are completely absorbed by ejecting electrons from atoms (photoelectric effect). Thus the photoeffect and incoherent scattering (Compton effect) are the main mechanisms of interaction gamma-rays with matter. Gamma radiation frequently accompanies alpha and beta emissions. Gamma-rays have high penetrating power, they can pass tens and hundreds of meters in air and a few meters in soft tissues. Gamma-rays are much more penetrating than alpha-particles and beta- particles (fig. 24.5).

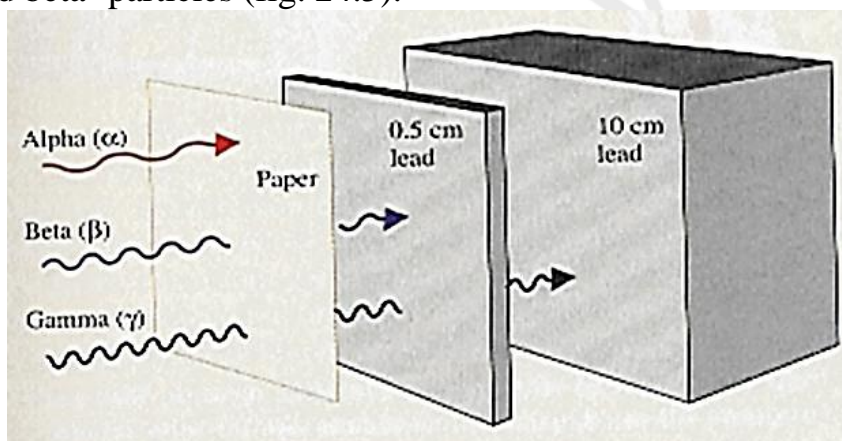


Fig. 24.5. Penetrating power of  $\alpha$ -,  $\beta$ - and  $\gamma$ -radiation

**Neutrons.** Since free neutrons are electrically neutral, they pass free through the electrical fields within atoms and so constitute a penetrating form of radiation, interacting with matter almost exclusively through collisions with atomic nuclei. The way in which neutrons interact with matter depends on their energies. Neutrons will have a low probability of interaction because of the small size of the nucleus in relation to the atom, and could thus travel considerable distances in matter.

## 24.7. PRINCIPLES OF RADIONUCLIDE DIAGNOSTICS METHODS

Radionuclide diagnostics is based on the radionuclides incorporation in biological tissue. Incorporated radionuclides are the  $\gamma$ -ray source which is registered by special detectors.

Let us specify physical properties of radiopharmaceuticals. The half-life must be short enough so that a reasonable fraction of the radioactive decays take place during the diagnostic procedure; any decays taking place later give a patient a dose that has no benefit. (This requirement can be diminished if the biological excretion is rapid.) On the other hand, the lifetime must be long enough so that the radiopharmaceutical can be prepared and delivered to a patient. For the diagnostic work, the decay scheme should minimize the amount of radiation which provides a dose to the patient but never reaches the detector. The ideal source then is a  $\gamma$  source, which means that the nucleus is in an excited state (an isomer). Such states are usually very short-lived. If the decay is a  $\beta^-$  or  $\beta^+$  decay, the product has different chemical properties from the parent and may be taken up selectively by a different organ. If it is also radioactive, it can confuse a diagnosis and give an undesirable dose to the other organ. It is necessary to remove the radioactive isotope from stable isotopes of the same element, because the chemicals are usually toxic.

Methods of the radionuclide diagnostics may be divided into two general types: gamma-scintigraphy and quantitative scintigraphy.

**Gamma scintigraphy** is a radiographic image techniques for visualizing the distribution of an injected radionuclide within the given organ as a means of studying of the anatomic structure of an organ via the introduction of an appropriate short lived gamma emitting radioisotope. The observed distribution can then be correlated with the rate and extent of drug absorption.

Different types of radionuclides tend to concentrate in different organs or tissues. So, the radionuclide used depends on which part of the body is to be scanned. For example, for scanning the thyroid gland radioactive iodine is used. Active parts of the tissue will emit more gamma-rays than less active or inactive parts. The gamma-rays which are emitted from inside the body are detected by the gamma-camera, are converted into an electrical signal, and sent to a computer. The computer builds a picture by converting the differing intensities of radioactivity emitted into different colours or shades of grey (fig. 24.6).

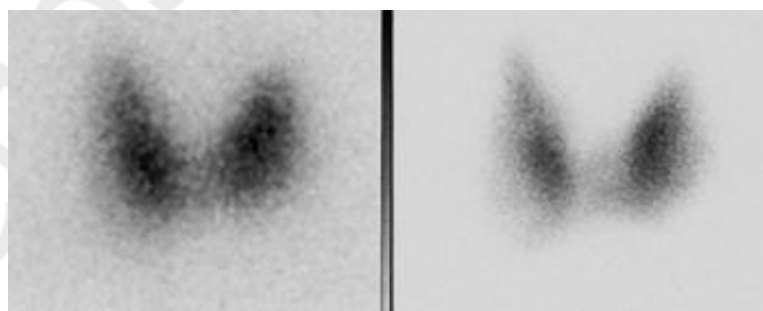


Fig. 24.6. Different types of thyroid scintigraphy

**Radiography (quantitative scintigraphy)** is a quantitative assay techniques for measuring the absorption and retention of a radionuclide within an organ as a means of studying the metabolism of the organ. It is displayed on

the dependence of gamma-ray intensity on time. This investigation allows conclude about the blood flow, work of liver, kidneys, and lungs.

Let's consider radiographic study of kidneys (fig. 24.7). The analysis data supplies detailed information about a kidney activity. It allows to find out a disturbance of an internal process (a rising branch) or an elimination process (a descending branch). One can perform this measurement for each kidney and make a comparative assessment their work.

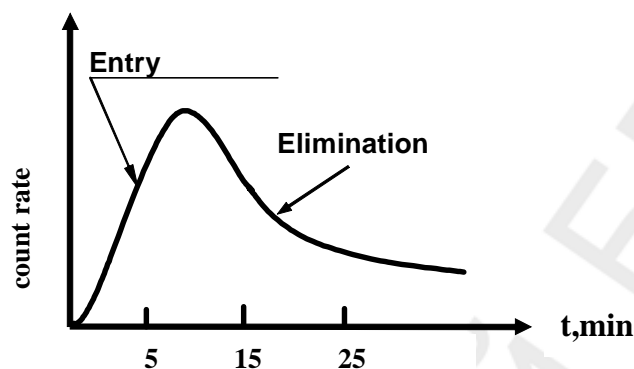


Fig. 24.7. The radiographic study of kidneys

#### 24.8. PHYSICAL BASICS OF THE RADIATION THERAPY

**Radiation therapy** makes use of ionizing radiation, deep tissue-penetrating rays which can react physically and chemically with diseased cells to destroy them. Radiation therapy is used for cancer and for blood disorders such as leukemia.

Radiation may be injected to the body by implanting radioactive substances into the tumors or by exposing the body to external sources of high-energy rays that penetrate internally. Both methods have shown good results in the treatment or arrest of cancerous growths; the type of treatment used depends largely on the size of the tumor, its location.

The purpose of such radiation therapy is to destroy cancerous cells with minimal damage to normal healthy tissue or systemic involvement. Let's consider features of different rays for radiation therapy. **X-rays** are applied for the irradiation of superficial tumors. The intensity of X-ray decrease sharply as depth increases (fig. 24.8, dotted line).

**Gamma-rays** have deep penetration and cause a minimum of surface-tissue irradiation. It allows to destroy deeply located tumors. Also it decreases damage to the skin and healthy tissues. Gamma radiation from  ${}_{27}^{60}\text{Co}$  has been usually used in cancer therapy.

**Electron beams** with energy about 25 MeV produce a maximum ionization at depth of 1–3 cm. They are used for irradiation of not deeply situated tumors.

**Protons**, due to their relatively big size, scatter less easily in the tissue. The beam stays focused on the tumor shape without much lateral damage to

the surrounding tissues. All the protons of the given energy pass a certain distance; no proton penetrates beyond that distance. Furthermore, the dosage to tissue is maximum just over the last few millimeters of the particle range. This depth depends on the energy to which the particles were accelerated by the proton accelerator. Therefore it is possible to focus the cell damage due to the proton beam at the very depth in the tissues (11–14 cm) where the tumor is situated; the tissues situated before this area receive some reduced dose, and the tissues situated after the peak receive none.

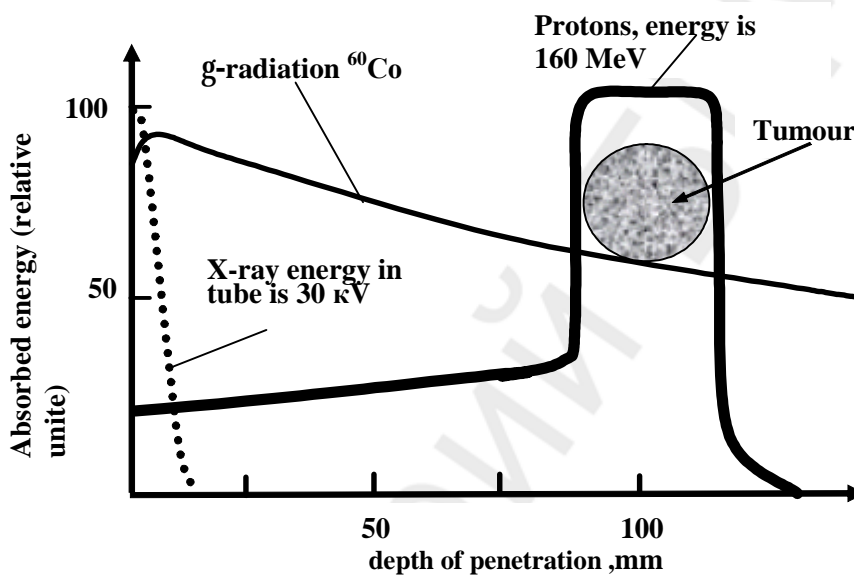


Fig. 24.8. Depth of penetration for different types of radiation

**Alpha-particles** because of small linear range in matter may be used via the contact with an organism or on introducing it inside. A radon therapy is a characteristic example of it. Radon water is used for action on the skin (radon bath), the digestive apparatus (drinking), the respiratory apparatus (inhalations).

**Questions:**

1. Specify atomic nucleus characteristics.
2. What are the basic properties of the nuclear forces?
3. Describe modes of radioactive decay.
4. Explain why some radionuclides decay is accompanied by emitting  $\gamma$ -radiation?
5. Give  $\beta$ -particles kinetic energy spectrum and explain the spectrum.
6. Derive Radioactive decay Law. What are decay constant, half-life, mean lifetime? Describe relation between them.
7. What is the activity of a radioactive substance? What are the units of activity? Give the relationship between units.
8. What is the changing of the activity with time? How does activity depend on radionuclide mass?
9. Describe the characteristics of ionizing radiation interaction with the matter. What feature for  $\alpha$ - and  $\beta$ -particles and  $\gamma$ -radiation interaction with the matter are observed?
10. Explain principles of radionuclide diagnostics methods.
11. What are the physical basics of the radiation therapy? Describe the features of the action of  $\alpha$ - and  $\beta$ -particles,  $\gamma$ -radiation, neutrons and protons on the living organism.

## Chapter 25. RADIATION DOSIMETRY

Ionizing radiations are generally characterized by their ability to excite and ionize atoms of matter with which they interact. The primary goal of radiation dosimetry is a quantitative estimation of the energy absorption in tissue and estimation of the biological effects.

### 25.1. RADIATION DOSES

#### 25.1.1. Exposure dose

*Exposure dose*  $X$  is a measure of radiation based on the ability to produce air ionization:

$$X = \frac{dQ}{dm}, \quad (25.1)$$

where  $dQ$  is a total ions charge,  $dm$  is an air mass.

If the charge  $Q$  distributes uniformly in the air mass  $m$  the exposure dose  $X$  can be written as:

$$X = \frac{Q}{m}. \quad (25.2)$$

The exposure dose is used only for air and only for X-rays or  $\gamma$ -rays and characterizes the environment ionization by electromagnetic radiation measure.

In SI the exposure dose is measured in C/kg. The off-system unit of  $X$  is roentgen (R). It is an X-ray dose or an  $\gamma$ -rays dose which action produces  $2,08 \times 10^9$  ion pairs in  $1 \text{ cm}^3$  ( $0,001293 \text{ g}$ ) of air under favorable condition.

$$1 \text{ R} = 2,58 \cdot 10^4 \text{ C/kg} \text{ or } 1 \text{ C/kg} = 3876 \text{ R}.$$

*Exposure dose rate* is determined as a derivative of the exposure dose  $X$  according to time  $t$ :

$$\dot{X} = \frac{dX}{dt}. \quad (25.3)$$

If the exposure dose rate is obtained during time  $t$  the mean exposure dose rate can be determined as:

$$\dot{X} = \frac{X}{t}. \quad (25.3a)$$

The exposure dose rate is measured in  $1 \text{ A/kg}$ .

#### 25.1.2. Absorbed dose

*Absorbed dose*  $D$  is a measure of the energy deposited in a medium by ionizing radiation per unit mass (i. e., energy per gram). Chemical and biological changes in the tissue exposed to ionizing radiation depend upon the energy absorbed in the tissue from the radiation. Absorbed dose  $D$  delivered to a small

mass  $m$  in kilograms is:

$$D = \frac{dE}{dm}$$



or

$$D = \frac{E}{m}, \quad (25.4)$$

where  $E$  is the absorbed energy in a medium from any type of ionizing radiation.

The quantity of absorbed dose described in SI units of gray. One *gray* (Gy) represents the dose corresponding to absorption of one joule of energy per kilogram of absorbing material:

$$1 \text{ Gy} = 1 \text{ J/kg.}$$

The traditional unit of the absorbed dose is *rad*:  $1 \text{ Gy} = 100 \text{ rad}$ .

Note that the absorbed dose is not a good indicator of the likely biological effect. For example, 1 Gy of alpha-radiation would be much more biologically damaging than 1 Gy of gamma-radiation.

The *absorbed dose rate* is described similarly to the exposure dose rate:

$$\dot{D} = \frac{dD}{dt}$$

or for constant dose:

$$\dot{D} = \frac{D}{t} \quad (25.5)$$

and it is measured in Gy/s, rad/s and subunits.

For external irradiation the absorbed dose is proportional to the exposure dose:

$$D = f X, \quad (25.6)$$

where  $f$  is a coefficient which depends on the irradiated material structure and photons energy.

Let us evaluate this coefficient for the air. If the exposure dose is equal to 1 R for 1 kg of air then  $2,08 \cdot 10^9$  ion pairs are generated in  $1 \text{ sm}^3$  ( $1,29 \cdot 10^{-6} \text{ kg}$ ) of air. It is necessary to spend the energy equal to  $34 \text{ eV} = 34 \cdot 1,6 \cdot 10^{-19} \text{ J}$  for one pair ions production. Then the absorbed dose  $D$  is equal to:

$$D = \frac{E}{m} = \frac{34 \cdot 1,6 \cdot 10^{-19} \cdot 2,08 \cdot 10^9}{1,29 \cdot 10^{-6}} = 88 \cdot 10^{-4} \text{ Gy} = 0,88 \text{ rad.}$$

Therefore in exposure dose of  $X = 1 \text{ R}$  the absorbed dose  $D$  will be 0,88 rad/R. Consequently coefficient for air  $f$  is equal to 0,88 rad/R for air, for water and soft tissue —  $f = 1,0 \text{ rad/R}$ . For bone tissue this coefficient  $f$  depends on photon energy and it takes on the value from 1 to 0,45 rad/R, decreasing with the quantum energy increase.

### 25.1.3. Equivalent dose

The same absorbed dose delivered by different types of radiation may result in different degrees of biological damage to body tissues. When radiation is absorbed by biological material, the energy is deposited along the tracks of charged particles in a pattern that is characteristic of the radiation type involved.

After the exposure to X-rays or gamma-rays, the ionization density would be quite low. After the exposure to neutrons, protons, or alpha-particles, the ionization along the tracks would occur much more frequently, producing a much denser pattern of ionizations. These differences in density of ionizations are the major reason that neutrons, protons, and alpha particles produce more biological effects per unit of the absorbed radiation dose than do more sparsely ionizing radiations such as X-rays, gamma-rays, or electrons.

The *relative biological effectiveness (RBE)* for the given test radiation is calculated as a ratio of absorbed dose of a reference radiation, usually X-rays 180–200 kV energy, to test radiation dose producing the same biological effect. Thus, for the same biological endpoint:

$$\text{RBE} = \frac{\text{Absorbed dose of X-rays (180–200 keV) to cause an biological effect}}{\text{Absorbe dose of comparison radiation needed to cause same effect}}. \quad (25.7)$$

For example, the 20 rad of X-rays cause the same effect as 1 rad of  $\alpha$ -particles, the RBE for  $\alpha$ -particles is 20.

In dosimetry the RBE is represented in radiobiological standarization and regulatory law by the *quality factor k*. This factor is selected for the type and energy of the radiation incident on the body, or in the case of sources within the body, emitted by the source. The value of k is  $k = 1$  for X-rays, gamma-rays and beta-particles, but it is higher for protons, neutrons  $k = 10$  for energy 0,1–10 MeV, alpha particles  $k = 20$  for energy less than 10 MeV.

The *equivalent dose* is a computed average measure of the radiation absorbed by a fixed mass of biological tissue that attempts to account for the different biological damage potential of different types of ionizing radiation. The equivalent dose is more biologically significant than the absorbed dose for assessing the health risk of radiation exposure.

The equivalent dose is calculated by multiplying absorbed dose by the appropriate quality factor:

$$H = kD, \quad (25.8)$$

where  $D$  is the absorbed dose in grays.

The SI units of the equivalent dose is Sieverts (Sv). One *sievert* is generally defined as the amount of radiation roughly equivalent in biologic effectiveness to one gray (or 100 rads) of gamma radiation:  $1 \text{ Sv} = 1 \text{ J/kg}$ . The sievert is inconveniently large for various applications, and so the millisievert (mSv), which equals to 0,001 sievert, is frequently used instead. Conventional unit, Röntgen equivalent man -*rem* is also used:  $100 \text{ rem} = 1 \text{ sievert}$ .

*Equivalent dose rate (H)* — is known as a derivative of the exposure dose according to time:

$$H = \frac{dH}{dt}. \quad (25.9)$$

If the equivalent dose doesn't depend on time, the equivalent dose rate is given as:

$$\dot{H} = \frac{H}{t}. \quad (25.9a)$$

The units of the equivalent dose rate are Sv/s, mZv/hr, rem/s etc.

#### 25.1.4. Effective equivalent dose

*Effective equivalent dose* estimates the damage of the certain equivalent dose has been delivered to some target organs. The effective equivalent dose is the sum of the products of the equivalent dose to various organs or tissues  $H_i$  and the weighting factors  $w_i$  applicable to each of the body organs or tissues that are irradiated:

$$H_{eff} = \sum_i w_i H_i. \quad (25.10)$$

The tissue *weighting factor* or coefficient of radiation risk  $w_i$  is the radiation detriment of the damage to the whole body during constant irradiation. By definition, the sum of  $w_i$  over all organs is equal to one:  $\sum_i w_i = 1$ .

For example, if human lungs are exposed to the equivalent dose 1 Sv the probability of developing radiation-induced cancer is  $P_1 = 2 \cdot 10^{-3}$ . If the whole body were to receive the equivalent dose of 1 Sv, the probability of radiation induced cancer is  $P_0 = 1,65 \cdot 10^{-2}$ . The weighting factor  $w_1$  for lungs is:

$$w = \frac{P}{P_0} = \frac{2 \cdot 10^{-3}}{1,65 \cdot 10^{-2}} \approx 0,12.$$

The table 25.1 shows  $w_i$  permissible to each target organ:

Table 25.1

Organ	$w_i$
Gonads	0,25
Breast	0,15
Red bone marrow	0,12
Lungs	0,12
Thyroid gland	0,03
Bone surfaces	0,03
Remainder	0,30

#### 25.1.5. Collective effective dose

The equivalent dose  $H$  characterizes the consequences of radiation exposure for a particular organ, while the effective equivalent dose  $H_{eff}$  — for the whole organism. To estimate radiation effects on a large group of people the collective effective dose  $S$  is used.

The *collective effective dose*  $S$  is a measure of the total amount of the individual effective doses  $H_{i\text{eff}}$  multiplied by the size of the exposed population:

$$S = \sum_i H_{i\text{eff}} N_i, \quad (25.11)$$

where  $N_i$  is the total number of individuals in the given group.

It is used to predict the magnitude of stochastic effects of radiation on the population. The collective dose is usually measured in units of *person-sieverts* or man-sieverts.

## 25.2. IONIZING RADIATION DETECTORS

The *ionizing radiation detector* is a device that is sensitive to radiation and can produce a response signal suitable for measurement or analysis. There are different detector types which are based on the effects of interaction between radiation and matter.

*Trace detectors* help to define a particle trajectory and its track length in the matter. A *Wilson cloud chamber* consists essentially of a closed container filled with a supersaturated vapor, e. g., water in the air. When ionizing radiation passes through the vapor, it leaves a trail of charged particles (ions) that serve as condensation centers for the vapor, which condenses around them. Thus the path of the radiation is indicated by tracks of tiny liquid droplets in the supersaturated vapor.

The tracks of alpha and beta particles have distinctive shapes (for example, alpha particle's track is broad and straight, while that of an electron is thinner and shows more evidence of deflection). When a vertical magnetic field is applied, positively and negatively charged particles curve in the opposite directions.

One of the disadvantages of the cloud chamber is the relatively low density of the gas, which limits the number of interactions between ionizing radiation and molecules of the gas. For this reason physicists have developed other particle detectors, notably the bubble chamber. In the *bubble chamber* (fig. 25.1) the particle track is formed in the result of boiling a superheated liquid along the particle trajectory. As charged particles move through the liquid, they knock electrons out of the atoms of the liquid, creating ions. If the liquid is close to its boiling point, the first bubbles are formed around these ions. The observable tracks can be photographed and analyzed to measure the behavior of the charged particles.

In the basic type of an ionization detector a number and characteristics of an electric beam produced in the gas by the radiation are measured. For example, *Geiger counters* are widely used to indicate the presence and intensity of nuclear radiations. When a fast-moving charged particle traverses a Geiger counter, an electrical impulse is produced and can be counted.

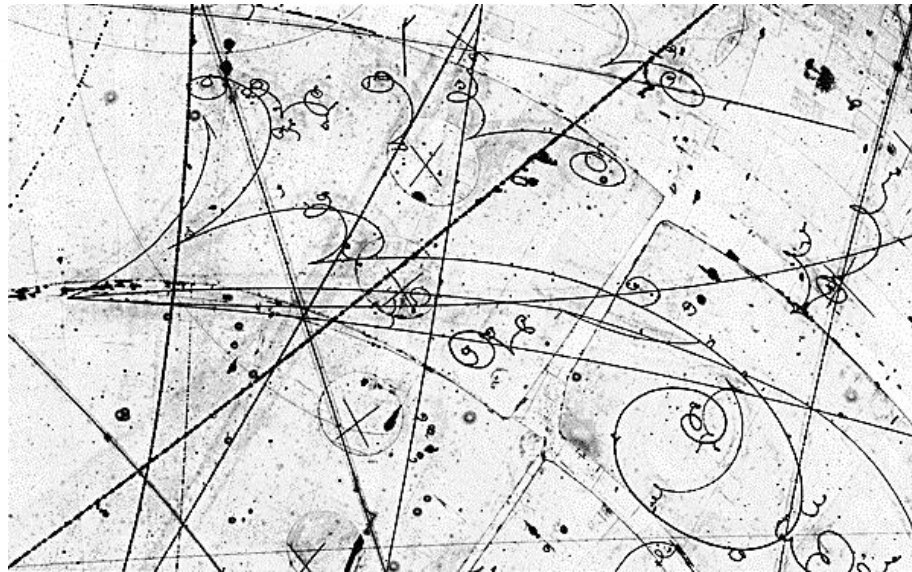


Fig. 25.1. A bubble chamber tracks of some particles

A Geiger counter consists of a gas between two electrodes (fig. 25.2). One electrode, usually cylindrical and hollow, is the cathode. The other electrode, stretched along the axis of the cylinder, is the anode. A potential of about 1000 volts is placed on the wire. As particles enter the tube, they create a large avalanche of ionization in the gas, which then discharges, creating a brief electric pulse. The tube produces the same large output pulse for virtually every charged particle that passes through the gas and so it is useful for detecting individual particles. It can therefore indicate lower levels of radiation than is possible in comparison with other types of detectors.

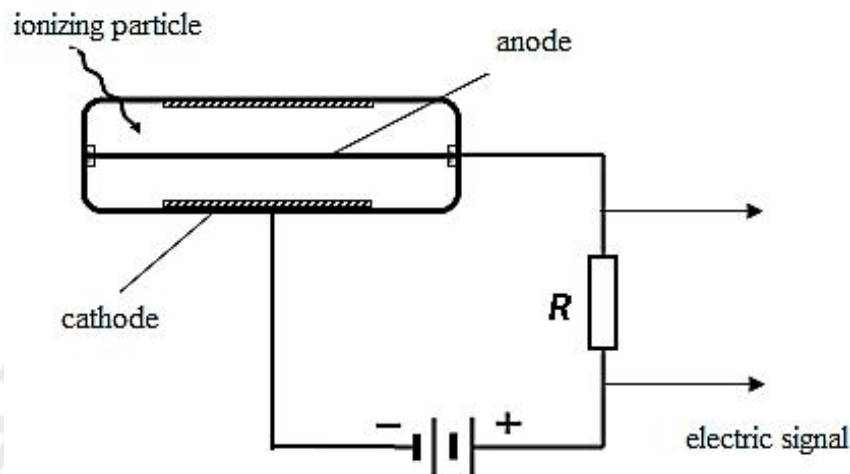


Fig. 25.2. Geiger counter

The degree of ionization per volume unit is measured by ionization detectors. X-rays and gamma-rays have a great track length in the gas they rarely cause ionization. Mainly they knock electrons out of tube wall atoms which get into gas and ionize it.

**Scintillation detector** or a scintillation counter (fig. 25.3) also measures ionizing radiation. The sensor, called a scintillator, consists of a transparent crystal, plastic, or organic liquid that fluoresces when struck by ionizing radiation. A sensitive photomultiplier measures the light from the crystal. It is attached to an electronic amplifier and other electronic equipment to count and possibly quantify the amplitude of the signals produced by the photomultiplier. In order to direct as much as possible of the light flash to the photosensitive surface, reflecting material is placed between the scintillator and the inside surface of the container.

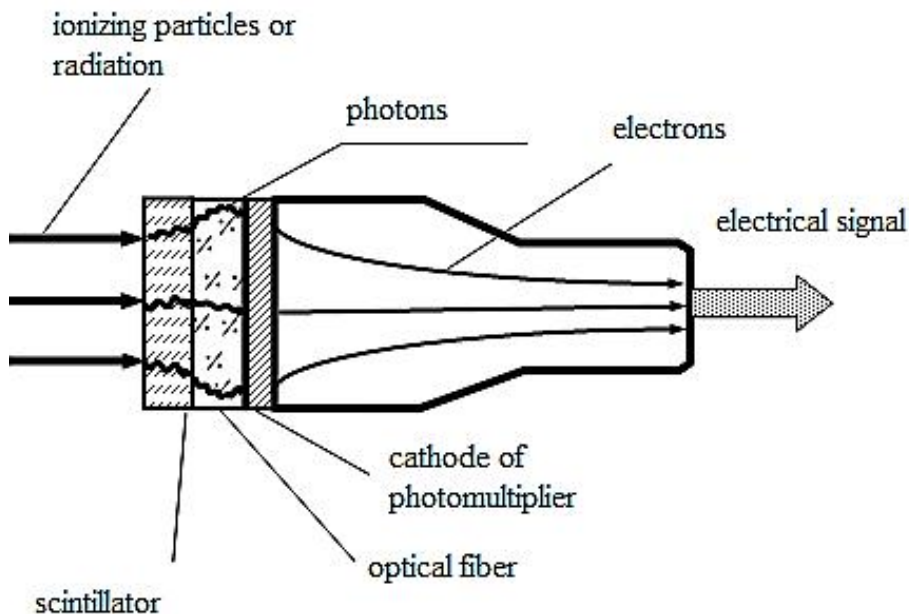


Fig. 25.3. Scintillation detector

A charged particle, moving through the scintillator, loses energy and leaves a trail of ions and excited atoms and molecules. Rapid interatomic or intermolecular transfer of electronic excitation energy follows, leading eventually to a burst of luminescence characteristic of the scintillator material. When a particle stops in the scintillator, the integral of the resulting light output, called the scintillation response, provides a measure of the particle energy, and can be calibrated by reference to particle sources of the energy. Scintillation counters may be used to detect the various types of radioactivity (alpha, beta, and gamma rays), cosmic rays, and various elementary particles.

The registration of  $\alpha$ -particles is most difficult due to their short path in matter. Alpha-radiation may be registered only from a thin surface layer so special preparation of patterns is necessary. Beta-particles have a longer path in matter so their detection is slightly simpler. The registration of  $\gamma$ -rays is the simplest due to their long path in matter. They may be registered even from a deep-seated object layer (fig. 25.4).

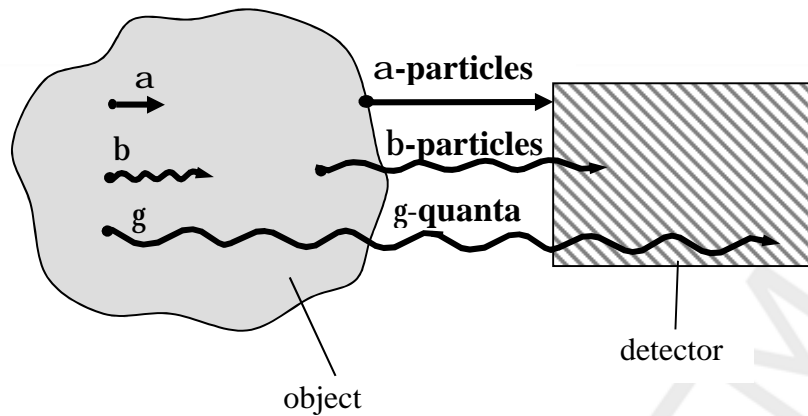


Fig. 25.4. The detection features of different particles

### 25.3. RADIATION MONITORING INSTRUMENTS

Radiation monitoring instruments are devices for the radiation doses or activity measurement. They are divided into dosimeters and radiometers.

A *dosimeter* is a device used to measure an individual's exposure to a dangerous environment, particularly when the hazard is cumulative over long intervals of time. A dosimeter consists of a detector and an electronic measuring device, which transform a detector signal into a form useful for registration.

Let us consider a dosimeter is based on ionization camera use. The ionization camera is filled with air under atmospheric or low pressure. Its active volume is  $V$ . The ionization chamber consists of two electrodes (fig. 25.5). Before using these electrodes are filled with a potential difference  $U_1$  and obtain a charge  $q_1$ .

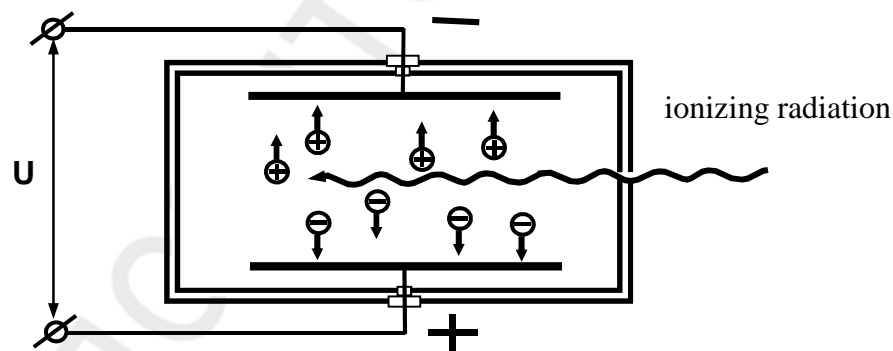


Fig. 25.5. Ionization chamber

When ionizing radiation penetrates the gas in the camera this radiation liberates electrons from the gas atoms leaving positively charged ions. The current begins to flow in a camera as soon as the electrons and ions begin to separate under the influence of the applied electric field. Therefore the potential difference decreases from the initial value  $U_1$  to  $U_2$ , and the charge decrease from  $q_1$  to  $q_2$ . Their changes are related in the following formula:

$$q_1 - q_2 = Dq = C(U_1 - U_2).$$

where  $C$  is electrocapacity.

Therefore the exposure dose is equal to:

$$X = \frac{\Delta q}{m} = \frac{C(U_1 - U_2)}{\rho \cdot V} = k(U_1 - U_2) = k \Delta U,$$

where  $V$  is a camera volume,  $m$  is air mass,  $\rho$  is the air density. Constants in this formula may be joined in coefficient  $k$  in this formula. This coefficient is determined under device calibration.

An individual radiation dosimeter is a pen-like device that measures the cumulative dose of radiation received by the device. It is usually clipped to somebody clothing to measure his actual exposure to radiation.

Exposure rate measure is based on the current determination in the detector:

$$\dot{X} = \frac{dX}{dt} = \frac{dQ}{dt \cdot m} = \frac{I}{m}.$$

Exposure rate measuring instruments are usually calibrated in mR/hr or  $\mu$ R/s.

So dosimeters help to measure the exposure dose in the air and to control  $\gamma$ -rays and X-rays background level. They can not be used to control radiation pollution degree of foodstuffs and the human organism.

A *radiometer* is a device for activity measurement. The activity is determined as the number of decay events per time unit. Therefore, radiometers count electrical pulse caused by particles hitting on the detector per time unit.

Let us consider one of the methods for determining a specific volume or mass activity. A radiometer detector and the tested specimen are placed into the lead-wall camera to minimize the influence of the natural radiation background. It is necessary to improve the measurement accuracy. At first initial background activity (without the test specimen) is measured. Let  $N_1$  be the impulse count of background activity in time  $t_1$ . Then a measuring cell is filled up with the tested product. Let a detector indicate the impulse count  $N_2$  in time  $t_2$ . Then a specific activity is calculated by the formula:

$$A_v = \frac{N_2/t_2 - N_1/t_1}{P},$$

where coefficient  $P$  take into account a specimen volume and radiometer sensitivity to different radiation types.

The determination of radioactive substance content in the human organism is a very important task. The internal irradiation radiometry is the most effective for gamma-emitting radionuclides. A special apparatus for internal the radiation dose consist of a steel protective room, a scintillation counter set, a recording system and a chair for a patient. A multichannel analyzer registers gamma-quanta and determines radionuclide type and the concentration of in the organism.



## 25.4. BACKGROUND RADIATION

*Background radiation* is the ionizing radiation emitted from a variety of natural and artificial radiation sources. Some of this radiation is man-made, such as radiation used in medical applications and some is «natural». Natural sources include cosmic rays, terrestrial, and internal. Man-made radiation includes medical X-rays, medical nuclear procedures, consumer products, industrial sources, and some miscellaneous sources of radiation. The actual background encountered by each individual varies significantly, depending upon where he lives, the food that is consumed, the radon levels in the house, and so on.

Cosmic rays have always bombarded the earth. A typical person receives 0,31 mSv per year from cosmic rays. The earth's atmosphere provides some shielding from cosmic rays. This shield is reduced at greater heights, and the cosmic ray dose is increased. Inhabitants at heights of 1600 meters receive 0,50 mSv/yr from cosmic rays, while those at the heights of 3200 meters receive 1,25 mSv. The effective equivalent dose, received by a person living at a sea level in the result of cosmic rays equals about 0,31 mSv per year.

Cosmic rays may broadly be divided into two categories, primary and secondary. The cosmic rays that arise in extrasolar astrophysical sources are primary cosmic rays; these primary cosmic rays can interact with interstellar matter to create secondary cosmic rays. The secondary cosmic rays reach the ground surface and contain all known elementary particles. The sun also emits low energy cosmic rays associated with solar flares. The exact composition of primary cosmic rays, outside the Earth's atmosphere, is dependent on which part of the energy spectrum is observed. However, in general, almost 90 % of all the incoming cosmic rays are protons, about 9 % are helium nuclei (alpha-particles) and about 1 % are electrons.

Terrestrial background originates from radioisotopes that are found everywhere in our surroundings. All elements found in nature have radioactive isotopes, many of which are also present in the environment. The exact composition of soil influences the local terrestrial background, because the minerals present determine which elements are most abundant. Terrestrial background sources are categorized as «primordial» if their half-lives are the same order of magnitude as the presumed lifetime of the earth ( $4,5 \cdot 10^9$  years). That is, these sources were present when the earth was formed and there is no way to replenish them in nature. Two isotopes of uranium,  $^{238}\text{U}$  and  $^{235}\text{U}$ , and one of thorium  $^{232}\text{Th}$ , give rise to three different decay series. In each of these series, the radioactive nuclide decays to another stable isotope of bismuth or lead. Seventeen other nuclides are primordial, but are not part of a decay series. Of these nonseries radionuclides,  $^{40}\text{K}$  and  $^{87}\text{Rb}$  make the greatest contribution to the background dose so the dose accrue 0,65 mSv per year. The mean background exposure dose rate for Belarus in normal stage is 10–12  $\mu\text{R/h}$ .

Internal background is the dose imposed by the isotopes contained in our bodies. A small percentage of the potassium in the human body is  $^{40}\text{K}$ . This radioactive nuclide emits both locally absorbed beta radiation and more penetrating gamma radiation. Similarly,  $^{14}\text{C}$ , which comprises a small percentage of the carbon atoms found in organic molecules throughout our bodies, contributes to the total dose of 1,35 mSv/yr from internal background.

Radon, as part of the  $^{238}\text{U}$  decay series, is significant because it is an alpha emitter that exists as an inert gas. Since it is inert, radon generated by decay of  $^{226}\text{Ra}$  at some depth in the soil does not bind chemically with other elements. Instead, it percolates up to the surface to escape into the atmosphere. Being heavier than most constituents of the atmosphere, it tends to remain at lower elevations. Although minable deposits of uranium ore are primarily associated with granite rock formations, uranium is found everywhere in the earth's crust. Ninety-nine percent of the uranium found in nature is  $^{238}\text{U}$ . Thus, the air we breathe anywhere on earth contains some amount of radon.

Radon itself is not particularly hazardous, when inhaled, because it does not react and in most cases is simply exhaled. A more significant concern is that two of the decay products of radon ( $^{218}\text{Po}$  and  $^{214}\text{Po}$ ), delivered to the air by decaying radon, are not inert. These products adhere to dust particles in the air, which may then be inhaled into the lung. Therefore the natural source dose is equal to 2,0 mSv per year.

Various human activities add to the annual radiation background. At first it is diagnostic radiology (0,39 mSv). Radiation received by patients in radiation therapy is not counted in man-made background, because the intention is to track radiation doses that are associated only with stochastic effects.

Various consumer products emit small amounts of radiation. Some examples include exit signs that contain  $^3\text{H}$ , a low-energy beta emitter, and smoke detectors that contain  $^{241}\text{Am}$ , an alpha emitter. Luminous dials on watches, clocks, and instruments contained  $^3\text{H}$  and  $^{147}\text{Pm}$ , both of which are low-energy beta emitters. The low-energy beta particles emitted by these substances are absorbed in the instrument components and provide negligible amounts of the radiation dose to their owners. Increasingly, liquid crystal displays and light-emitting diodes are replacing the use of radioactive materials in luminous displays. Collectively, consumer products are estimated to contribute approximately 0,1 Sv to the yearly dose from man-made background radiation.

**Questions:**

1. What is the exposure dose? What are the units of the exposure dose? Give the relationship between units.

1. What is the absorbed dose and the absorbed dose rate? What are the units of the absorbed dose?

2. Calculate a coefficient which connects on the exposure dose and the absorbed dose for the air.
3. Give a definition of the relative biological effectiveness. What does the equivalent dose mean? What are the units of the equivalent dose?
4. Write formula for the effective equivalent dose. What does this dose characterize?
5. What is the collective effective dose?
6. Why is alpha-particles registration more difficult than a gamma-rays registration?
7. What is the difference between a dosimeter and a radiometer?
8. What does a background radiation consist of?

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