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

$$j = \frac{I}{S}. \tag{13.1}$$

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:

$$I = \frac{U}{R}. \tag{13.2}$$

The current ***I*** is measured in amperes, the voltage ***U*** in volts and the resistance ***R*** in ohms (W).

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 **ρ** is called specific resistance or electrical resistivity of the material.
The unit of **ρ** is Ohm·m (**Ω 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 **σ**: $\sigma = \frac{1}{\rho}$.

The unit of conductivity **σ** is siemens [S] = [Ω^{-1} m^{-1}].

Thus, Ohm's Law at a point can be obtained as:

$$j = \sigma E. \qquad (13.4)$$

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 $\boldsymbol{n = n_+ + n_-}$ in which a current ***I*** is flowing. This constitutes an average drift velocity $\boldsymbol{\upsilon_+}$, $\boldsymbol{\upsilon_-}$ of each charge carrier.

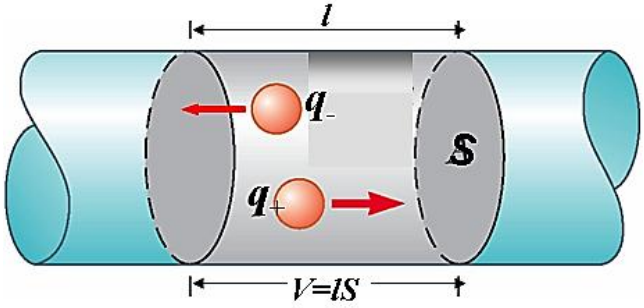

Fig. 13.1. The selected volume of the electrolyte

Each charge carrier (positive $\boldsymbol{q+}$ or negative $\boldsymbol{q-}$ ion) moves on average a distance ***l***: $l_+ = \upsilon_+ t = \mu_+ E t$ and $l_- = \upsilon_- t = \mu_- E t$,
where mobility is velocity of the charge carrier per electrical field strength.

The total charge $\boldsymbol{Q = Q_+ + Q_-}$ transferred during time ***t*** through the cross-sectional area ***S*** is:

$$Q = Q_+ + Q_- = q_+ n_+ S l_+ + q_- n_- S l_- = (q_+ n_+ \mu_+ + q_- n_- \mu_-) S t E. \qquad (13.5)$$

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 **σ** 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 α is the coefficient of the dissociation.

The equation for electrolyte conductivity **σ** can be written as:

$$\sigma = qn\alpha(\mu_+ + \mu_-). \quad (13.8)$$

Thus, the conductivity **σ** depends on the value of the ion charge ***q***, concentration ***n***, coefficient of the dissociation ***α*** and mobility of the ions **μ**.

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.

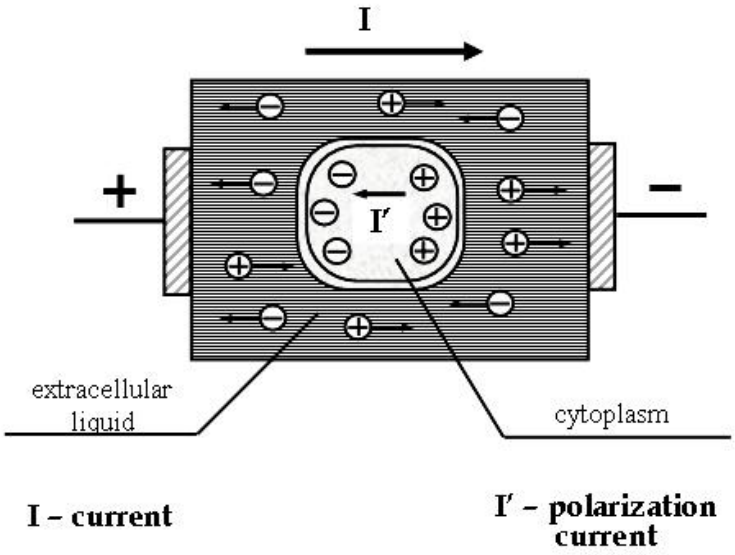

Fig. 13.2. The movement of ions in extracellular liguid and cytoplasm. ***I*** is the principal current; ***I'*** is the interstitial polarization current

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 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 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 trasdermally 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 appearence?
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:

$$U = U_m \sin\omega t; \quad I = I_m \sin(\omega t + \varphi), \tag{14.1}$$

where $\boldsymbol{U_m}$ is the amplitude value of voltage; $\boldsymbol{I_m}$ is the amplitude value of current; $\boldsymbol{\omega = 2\pi n = 2\pi/T}$; $\boldsymbol{\omega}$ is angular frequency (radians/sec); n is the frequency (measured in Hertz, 1/sec); $\boldsymbol{T}$ is the period; $\boldsymbol{\varphi}$ is the phase difference between current and voltage (radians).

Averaged over the period magnitudes of alternating currents and voltages ($\boldsymbol{I_{eff}}$ and $\boldsymbol{U_{eff}}$) determine their effect and are called effective values of an AC. $\boldsymbol{I_{eff}}$ and $\boldsymbol{U_{eff}}$ are related to the amplitude values of AC ($\boldsymbol{U_m}$ and $\boldsymbol{I_m}$) by the following expressions:

$$U_{eff} = \frac{U_m}{\sqrt{2}}; \quad I_{eff} = \frac{I_m}{\sqrt{2}}. \tag{14.2}$$

The average power ***P*** of an AC circuit is also called the true power of the circuit and is given by:

$$P = I_{eff}U_{eff}\cos\varphi;\ P = \frac{1}{2}I_m U_m \cos\varphi, \qquad (14.3)$$

where cosφ is the power factor. The average power ***P*** depends strongly on the phase difference **φ** 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).

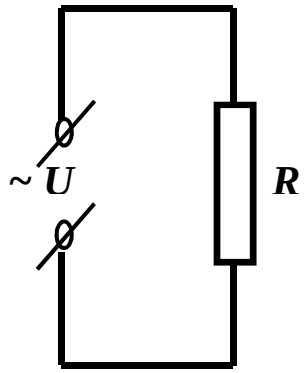

Fig. 14.1. AC circuit with a resistor

The instantaneous value of the applied voltage ***U*** is:

$$U = U_m \sin\omega t. \qquad (14.4)$$

The current ***I*** through the circuit at the instant t:

$$I = \frac{U}{R} = \frac{U_m}{R}\sin\omega t = I_m \sin\omega t. \qquad (14.5)$$

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 cosφ = 1)** is maximal:

$$P_R = I_{eff}U_{eff} = \frac{1}{2}I_m U_m.$$

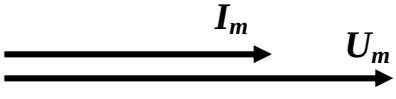

Fig. 14.2. The phasor diagram of AC circuit with a resistor representing the phase relationship between the current and the voltage

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.

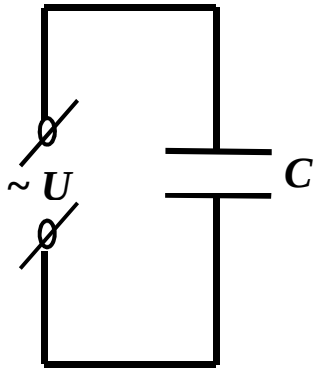

Fig. 14.3. AC circuit with a capacitor

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:

$$I = \frac{dq}{dt} = CU_m \omega \cdot \cos \omega t = I_m \sin\left(\omega t + \frac{\pi}{2}\right), \qquad (14.6)$$

where $I_m = C\omega U_m$.

$$X_C = \frac{U_m}{I_m} = \frac{1}{\omega C} \qquad (14.7)$$

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.

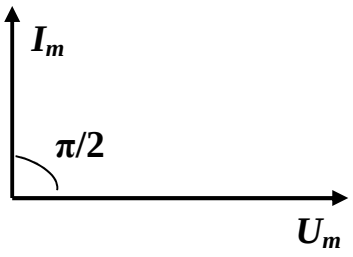

Fig. 14.4. The phasor diagram of AC circuit with a capacitor representing the phase relationship between the current and the voltage

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 $R = 0$.

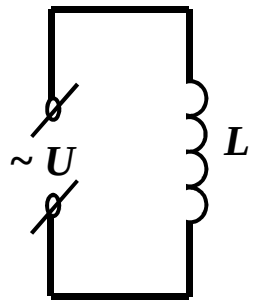

Fig. 14.5. AC circuit with a inductor

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:

$$I = -\frac{U_m}{\omega L} \cdot \cos \omega t = I_m \sin(\omega t - \frac{\pi}{2}). \qquad (14.8)$$

$$X_L = \omega L \qquad (14.9)$$

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 π/2 and average power $\boldsymbol{P_L = 0}$ **(φ = –π/2, cosφ = 0)**. This fact is presented graphically in fig. 14.6.

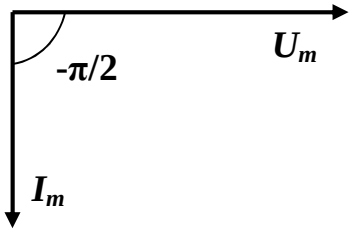

Fig. 14.6. The phasor diagram of AC circuit with a inductor representing the phase relationship between the current and the voltage

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).

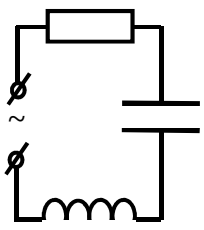

Fig. 14.7. The series LCR circuit

The expression

$$Z = \frac{U_m}{I_m} = \sqrt{R^2 + (X_C - X_L)^2} = \sqrt{R^2 + (\frac{1}{\omega C} - \omega L)^2} \qquad (14.10)$$

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

$$I_m = \frac{U_m}{Z} = \frac{U_m}{\sqrt{R^2 + (\omega L - \frac{1}{\omega C})^2}}. \qquad (14.11)$$

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. $\boldsymbol{I}$ is in phase with $\boldsymbol{U}$. 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 $Z = R$.

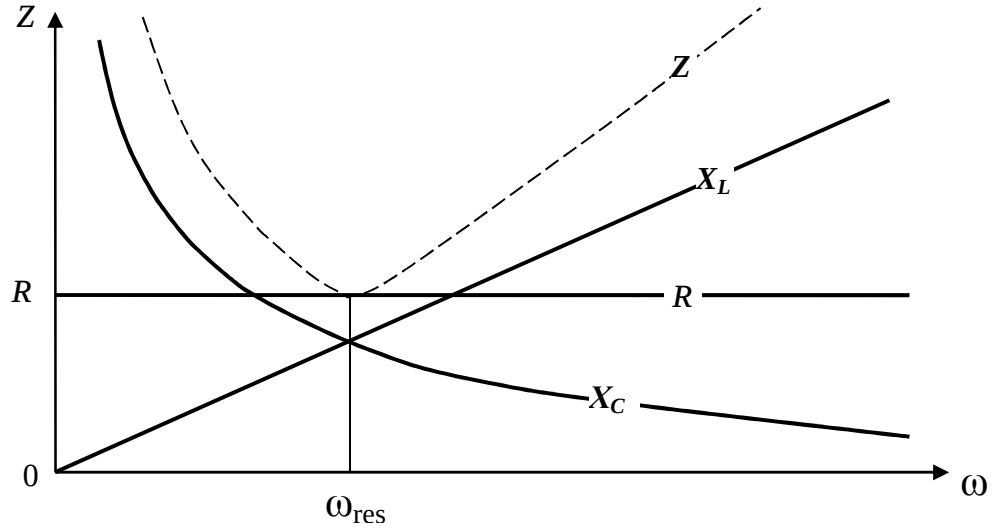

Fig. 14.8. Dependence of ohmic resistance *R*, inductive reactance X_L, and the capacitive reactance X_C and impedance *Z* on current frequency

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 Na^+ (~140 mM) and 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 K^+, protein- and HPO_4^{2-} + 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.

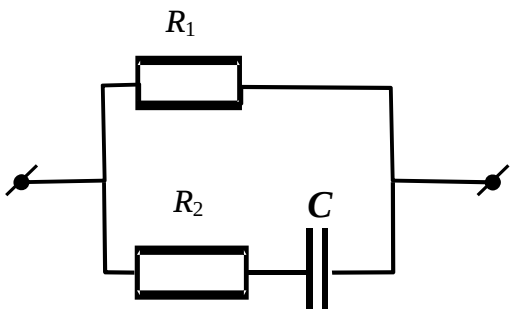

Fig. 14.9. The equivalent circuit of living tissue

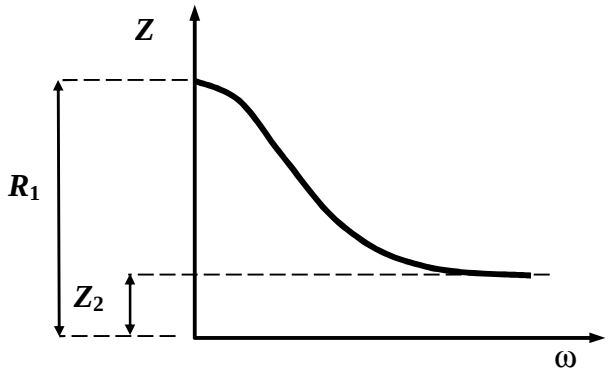

Fig. 14.10. A typical dependence of living tissue impedance on the current frequency

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 trough R_1. At high frequencies (> 1 MHz) the membrane capacitance is no impediment to the current and it flows indiscriminately trough the extra and intracellular media.

The impedance Z for this circuit is determined by:

$$Z = \frac{R_1\sqrt{R_2^2 + X_c^2}}{\sqrt{(R_1 + R_2)^2 + X_c^2}}. \qquad (14.12)$$

At very high frequencies $X_C = \frac{1}{\omega C} \to 0$ the expression for the impedance is:

$$Z_2 = \frac{R_1 R_2}{R_1 + R_2} \qquad (14.13)$$

At medium and high frequencies the impedance Z can be written as:

$$Z = \sqrt{R_2^2 + \left(\frac{1}{\omega C}\right)^2}. \qquad (14.14)$$

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):

$$K = \frac{Z_L\ (\nu = 10^3\,\text{Hz})}{Z_H\ (\nu = 10^6\,\text{Hz})} > 1. \qquad (14.15)$$

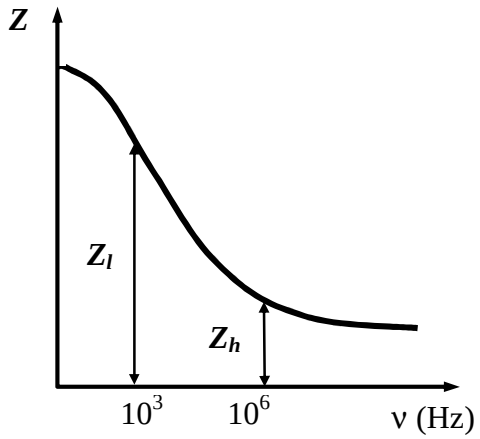

Fig. 14.11. The determination of tissue viability

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. Elecrtostimulation 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 elecrtostimulation 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 elecrtostimulation 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 ($\boldsymbol{I_0}$): is the maximal magnitude of a pulse parameter, such as the voltage, current; [mA].

Pulse duration ($\boldsymbol{t_u}$): is the period of time during which a pulse is present; [ms].

Interpulse interval ($\boldsymbol{t_0}$): is the time between the end of one pulse and the beginning of the next pulse in a series, or other words $\boldsymbol{t_0}$ is the period of time between pulses during which there is no current flow; [ms].

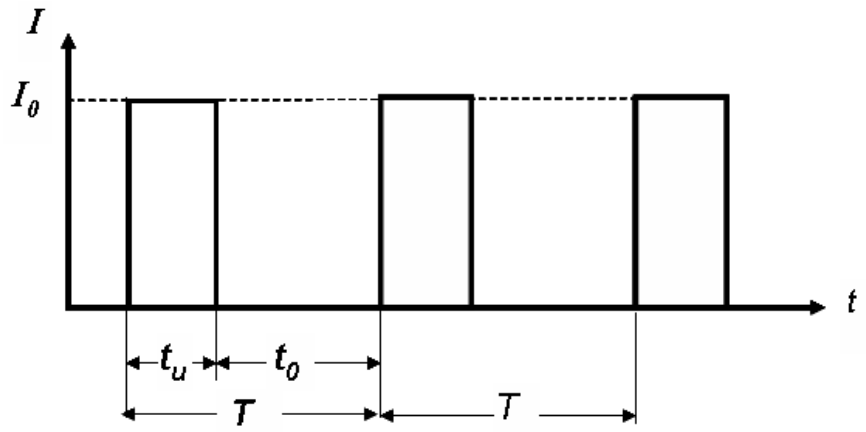

Fig. 15.1. The rectangular form pulse current and its parameters

Period (***T***): the period is equal to the pulse duration plus the interpulse interval; [ms]:

$$\boldsymbol{T = t_u + t_0.} \tag{15.1}$$

Pulse repetition frequency or frequency *n* is the number of pulses per time unit (e. g. seconds) [Hz]:

$$n = \frac{1}{T}. \tag{15.2}$$

The fill factor ***k*** is defined as the ratio of the pulse duration ($\boldsymbol{t_u}$) 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:

$$k = \frac{t_u}{T}. \tag{15.3}$$

The duty cycle ***Q*** shows how many times pulse period is more than a pulse duration:

$$Q = \frac{T}{t_u} = \frac{t_u + t_0}{t_u} = 1 + \frac{t_0}{t_u}. \tag{15.4}$$

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 $\boldsymbol{0{,}1\ I_0}$ and $\boldsymbol{0{,}9\ I_0}$.

Pulse rise time ($\boldsymbol{t_{rt}}$): is the period of time during which a pulse rises from ten percent of its amplitude value ($\boldsymbol{0{,}1 \cdot I_0}$) to 90 percent of its amplitude value ($\boldsymbol{0{,}9 \cdot I_0}$).

Pulse fall time ($\boldsymbol{t_{ft}}$): is the period of time during which a pulse falls from ninety percent of its amplitude value ($\boldsymbol{0{,}9 \cdot I_0}$) to ten percent of its amplitude value ($\boldsymbol{0{,}1 \cdot I_0}$).

Pulse peak time ($\boldsymbol{t_{pt}}$): is the period of time during which a pulse $\boldsymbol{I \geq 0{,}9 I_0}$.

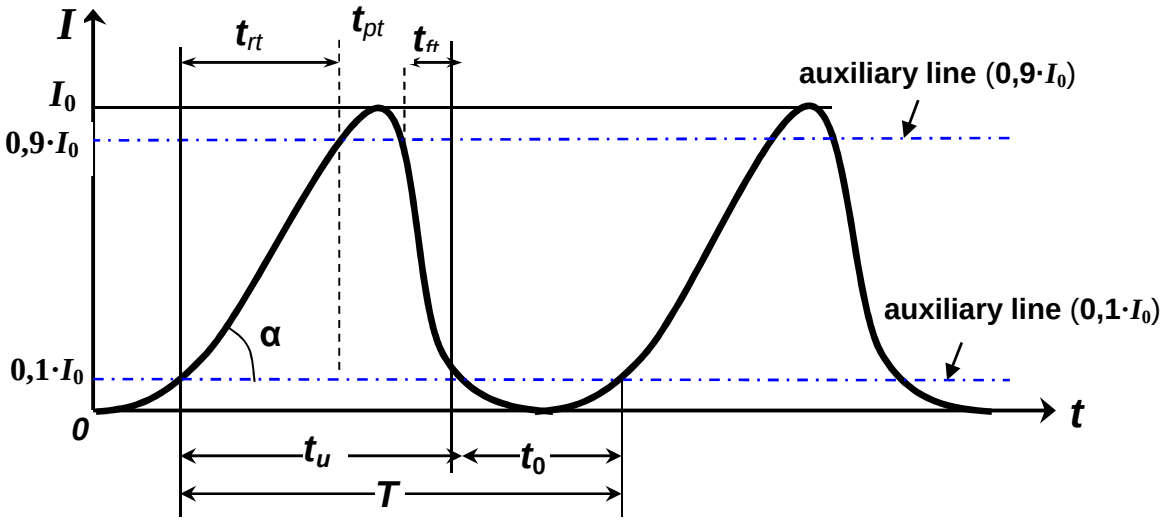

Fig. 15.2. The arbitrary pulse current and its parameters

Steepness of the pulse (***K***) determines the rate of current rise in the time from $\mathbf{0{,}1 \cdot I_0}$ to $\mathbf{0{,}9 \cdot I_0}$:

$$K = \frac{0{,}9I_0 - 0{,}1I_0}{t_{rt}} = \frac{0{,}8I_0}{t_{rt}} = \text{tg}\alpha \qquad (15.5)$$

In this case the pulse duration t_u can be obtained as a sum:

$$t_u = t_{rt} + t_{pt} + t_{ft}. \qquad (15.6)$$

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 deplorization. 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:

$$I_{thr} < I < I_{let\text{-}go}. \qquad (15.7)$$

The threshold current I_{thr} dependence on the rectangular pulse duration t_u is given by Weiss–Lapicque Law:

$$I_{thr} = \frac{a}{t_u} + b, \qquad (15.8)$$

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 $t_u \to \infty$).

– **the chronaxie** t_{chr} is that pulse duration at which the threshold value is twice that of the rheobase.

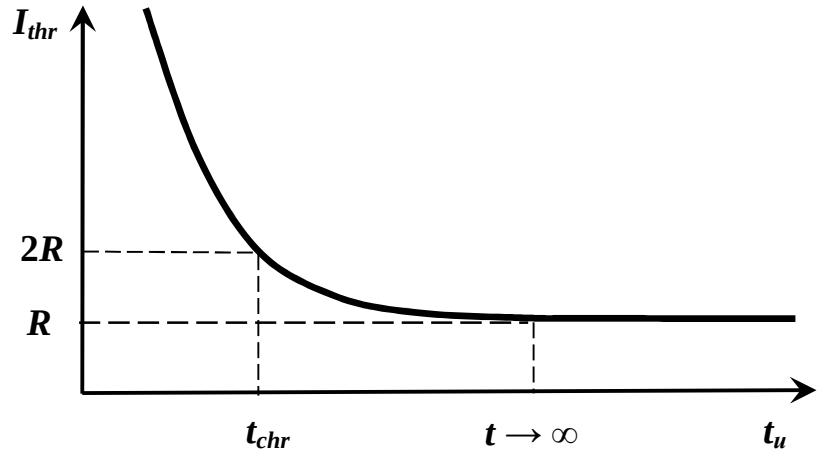

Fig. 15.3. The strength-duration curve shows the inverse relationship between the lowest stimulus current pulse required to produce a response versus its duration

Values of the constants (***a*** and ***b***) can be related to rheobase ***R*** and chronaxie t_{chr}, which are determined experimentally.

1. If $t_u \to \infty$, the threshold current I_{thr} is equal to rheobase ***R***:

$$I_{thr} \to b, \text{ it means } b = R. \quad [b] = mA$$

2. If $t_u = t_{chr}$, than $I_{thr} = 2R$, and according to Weiss–Lapicque Law:

$$2R = \frac{a}{t_{chr}} + R.$$

Thus, $a = Rt_{chr}$. $[a] = C$ (15.9)

The pulse duration t_u

The pulse duration should be $t_u \geq t \to \infty$, 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 ν_{max} = 500÷1000 Hz (T_{ref} =1 ÷2 мс);

for skeletal muscle ν_{max} = 100÷200 Hz (T_{ref} =5 ÷10 мс);

for heart muscle ν_{max} = 3,3 Hz (T_{ref} =300÷350 мс).

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 $\boldsymbol{I_{thr}}$ decreases when pulse steepness $\boldsymbol{K}$ 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 $\boldsymbol{t_u}$ **= 2–5 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 $\boldsymbol{U}$ **= 5–7 kV**, current $\boldsymbol{I}$ **~ 1 A**;

– on the heart of the nude: voltage $\boldsymbol{U}$ **=1,5–2,5 kV**, current $\boldsymbol{I}$ **~ 1 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 $\boldsymbol{t_u}$ **= 0,5–8 ms**; frequency n **= 1–1,2 Hz**; voltage $\boldsymbol{U}$ **~ 6 V**; current $\boldsymbol{I}$ **~ 1–10 mA**.

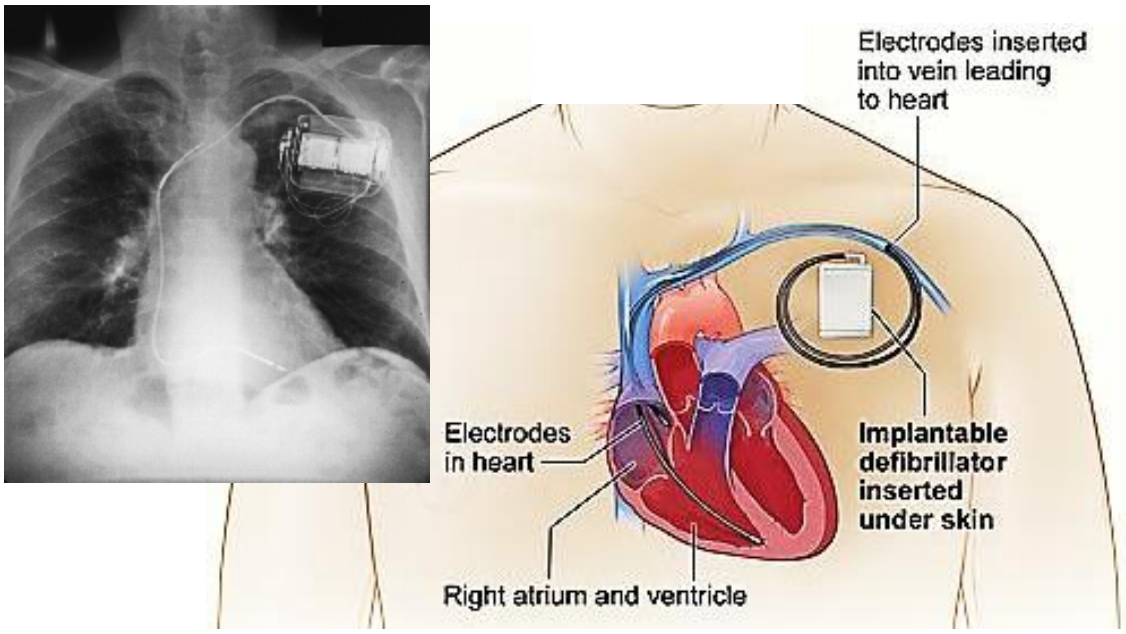

Fig. 15.4. Implantable cardioversion defibrillation

***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***:

$$Q = I^2Rt. \quad (16.1)$$

Let's ***j*** is current flux density i. e. current flowing through a unit area:

$$j = \frac{I}{S}. \tag{16.2}$$

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:

$$q = \frac{Q}{Vt}. \tag{16.3}$$

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 ν is 0,5–2,0 MHz.

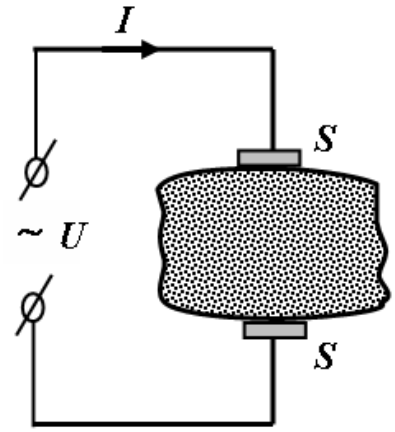

Fig. 16.1. Scheme of diathermy

In order to determine which tissues are warmed by diathermy let's write the following equation:

$$q = \frac{Q}{Vt} = \frac{I^2 Rt}{Vt} = \frac{I^2 \rho l}{SlS} = \frac{I^2 \rho}{S^2} = j^2 \rho, \tag{16.4}$$

where **ρ** 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.

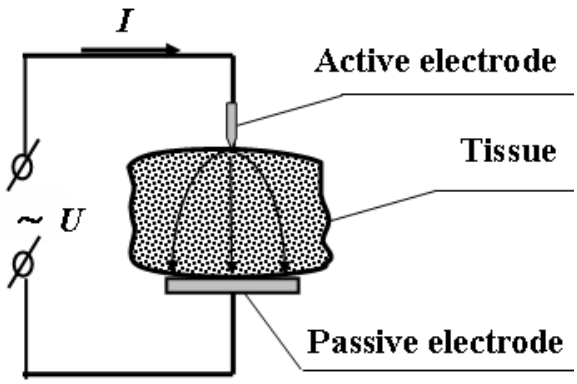

Fig. 16.2. Monopolar technique of surgical diathermy

In the case of tissue electrosection current density ***j*** is equal to ~ 40 mA/mm^2 and in the case of tissue coagulation current density ***j*** is equal to ~ 6–10 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 ν = 10–20 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 (ν = 13,56 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.

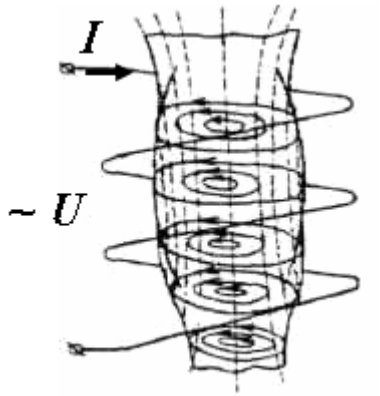

Fig. 16.3. Scheme of inductothermy

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 $\boldsymbol{\Phi}$. This current is due to the electromotive force ($\boldsymbol{\varepsilon}$) induced by the time-varying flux. The magnitude of $\boldsymbol{\varepsilon}$ depends upon the rate of the magnetic flux change $d\Phi/dt$. The direction of $\boldsymbol{\varepsilon}$ is such that the time-varying magnetic field is always opposite to that of $d\Phi/dt$. Therefore,

$$\varepsilon = -\frac{d\Phi}{dt}, \tag{16.5}$$

where $\boldsymbol{\varepsilon}$ is an electromotive force [V], $\boldsymbol{\Phi}$ is a magnetic flux [Wb], $\boldsymbol{t}$ is a time [s]. Magnetic flux $\boldsymbol{\Phi}$ can be written as $\Phi = BS$, where $\boldsymbol{B}$ is a magnetic field, $\boldsymbol{S}$ is an area.

Induced Foucault current $\boldsymbol{I}$ can be written as:

$$I = \frac{\varepsilon}{R}. \tag{16.6}$$

In order to determine which tissues are warmed by inductothermy let's write the following equation:

$$q = \frac{Q}{Vt} = \frac{\varepsilon^2 Rt}{R^2 Vt} = \frac{\varepsilon^2 t}{\frac{\rho l}{S} Slt} = \frac{\varepsilon^2}{\rho l^2}, \tag{16.7}$$

where $\boldsymbol{\rho}$ 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) (ν = 30–60 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).

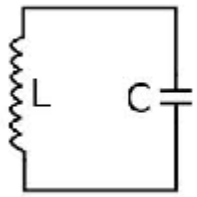

Fig. 16.4. Scheme of oscillating circuit

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: $T_{tech} = T_{ther}$ i. e. oscillation periods of technical and therapeutic circuits should be equal. C_{ther} is a variable tuning capacitor which is used to adjust the resonant frequency to the desired value.

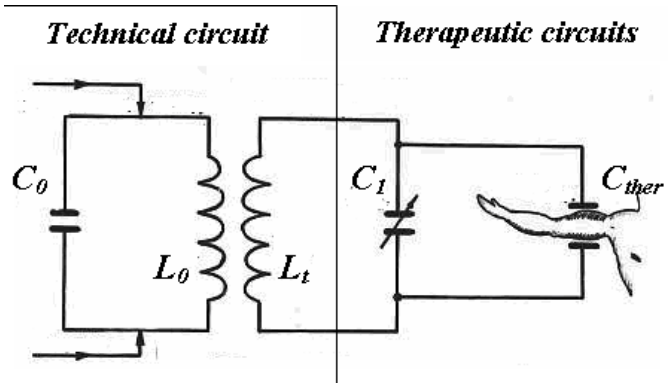

Fig. 16.5. Scheme of technical and therapeutic circuits of apparatus for UHF-therapy

The specific heat ***q*** produced in conductive tissue under the UHF-therapy action can be characterized as:

$$q = \frac{Q}{Vt} = \frac{U^2 Rt}{R^2 Vt} = \frac{U^2 t}{\frac{\rho l}{S} Slt} = \frac{U^2}{\rho l^2} = \frac{E^2}{\rho}. \qquad (16.8)$$

The specific heat ***q*** produced in dielectric tissue under the UHF-therapy action can be written as:

$$q = \varepsilon\varepsilon_0 E^2 \omega \, \mathrm{tg}\delta, \qquad (16.9)$$

where **ε** is a permittivity of medium, $\boldsymbol{\varepsilon_0}$ is a permittivity of vacuum, ***E*** is electrical field strength, **ω** is frequency, **tgδ** is dielectric loss tangent.

The most significant difference between these two expressions is that the heating of electrolytes does not dependent on frequency and dielectric heating increases with an increase of the electromagnetic field frequency (fig. 16.6).

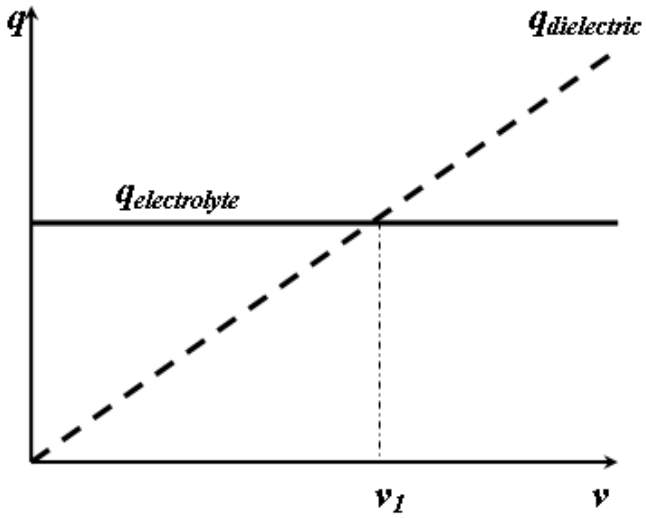

Fig. 16.6. Frequency dependence of specific heat for electrolyte and dielectric under the UHF-therapy action

At frequencies $\nu < \nu_1$ electrolyte heated more than dielectric, and at frequencies $\nu > \nu_1$ dielectric heated more effectively. At frequencies ν = 30–60 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) ν = 300–2500 MHz.

Centimeter wave therapy is a form of physical therapy in which tissues heating is based on using an electromagnetic waves with frequency ν = 2375 MHz. In this case wave length λ is equal to ~ 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 ν = 460 MHz. Length wave λ 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_2O. Deep of penetration is ~ 8–9 cm.

Hyper frequency therapy: $\nu = 3 \cdot 10^{10}–3 \cdot 10^{11}$ MHz. Length wave λ 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 (ν = 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.

$$I = \frac{U}{R} = \frac{20 \times 10^3 V}{10^7 \text{ Om}} = 20 \times 10^{-4} \text{ A}.$$

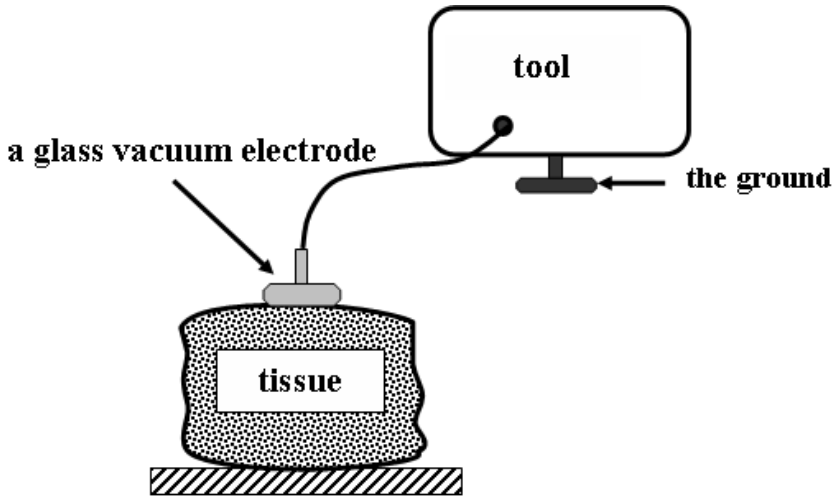

Fig. 16.7. Scheme of darsonvalisation

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?