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The High-frequency Radio-wave Surgery Method: Physics of Processes and Medical Application

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The results of the analysis of the physical basis and clinical application of high frequency monopolar and bipolar electronic devices in surgery are presented in the paper. The efficiency of high-frequency radio-wave method in the treatment of benign skin tumors was evaluated. The radio-wave method includes a set of effects on the biological tissue to dissect them (electrotomy), purposeful destruction, stop bleeding and mechanical fixation (coagulation), and local removal of biotissues (ablation). The device operates in the frequency range 1.76-3.50 MHz and provides: discrete output power control in all operating modes; light indication of supply voltage of the power supply network and output power level; sound frequency-tone alarms. It is shown that most of the high-frequency energy in monopolar systems is concentrated and converted to heat near the active electrode. It indicates 89 % efficiency of the radio wave methods used for the cutaneous neoplasms removal. The advantages of the method of high-frequency radio-wave surgery for the treatment of neoplasms of the skin are proved: the operation is performed practically bloodless, there is no risk of atrophic and hypertrophic scarring, the risk of infection of the patient is reduced, the improvement of reparative processes due to the temperature effect and reliability, and reduced postoperative period.

Keywords: Radio-wave surgery, High-frequency current, Monopolar and bipolar modes, Skin neoplasms.

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1. INTRODUCTION

At the modern stage of the medicine development, a number of new surgical methods are applied that are performed using high-intensity laser radiation, focused ultrasound, high frequency current [1, 2]. Contactless methods of high-frequency surgical influences using electrodes have been developed for the dissection and coagulation of biological tissues, as well as the methods which used an electrically conductive ionized inert gas stream (argon-plasma coagulation) or an electrically conductive fluid (cholecoil technology). Endoscopic and laparoscopic methods of radiosurgery are firmly included in the practice of surgery [3, 4].

The influence of radio frequency (RF) waves on biological tissues results in a number of physical processes: *tissue ablation* is an effect used to dissect or remove tissues based on their thermal evaporation; *coagulation* is an effect that provides hemostasis to control bleeding during operations; *reduction of collagen* – the influence of high temperatures causes instant changes in the structure of proteins, heating allows to change the forms of tissue for medical purposes; *tissue hyperthermia* – the process of heating tissue to temperatures higher than physiological ones – is a method of treatment of skin, in which the action of subnecrotic temperatures is used to stimulate natural physiological processes in order to change the appearance of the skin and reduce the amount of subcutaneous adipose tissue. Such heating does not produce an instant coagulation effect, but can stimulate collagen production.

The mechanism of the radio-wave interaction with the biological tissue is that the high-energy radio wave leaving the generator through the active electrode is sent to a neutral electrode ("antenna"), meets the resistance of the cells and instantly warms them up. The intracellular fluid boils and breaks the cell membrane. When boiling, small vapor bubbles are formed, which move the tissues in front of the radio wave. We note the characteristic feature of the radio wave. During surgery, the active electrode remains cold because it does not cause significant burns to surrounding tissues and promotes rapid wound healing with less scarring.

In the frequency range 200 kHz-400 MHz, RF energy can be safely used to process tissues to create the desired thermal effect. RF energy can be delivered in continuous mode, high frequency pulsation mode and pulse mode (see Fig. 1).

The pulse mode is ideally suited when there is a need to heat small sections of tissue, with limited thermal conductivity of surrounding tissues, which is analogous to the principle of using short pulses in laser exposure (see, for example, [2]). Pulse mode is effective for fractional ablation of the skin and is characterized by a pulse duration that does not exceed the time of thermal relaxation of the treated area.

The purpose of this paper was to analyze the physical basis, to describe the clinical application of monopolar and bipolar electronic systems in high-frequency RF surgery, to evaluate the effectiveness of radio wave surgery in the treatment of benign skin tumors.

2. PHYSICAL ASPECTS OF THE RADIO-WAVE SURGERY METHOD

The radio-wave method involves a set of effects on the biological tissues for their dissection, purposeful destruction, bleeding arrest, and mechanical fixation or local removal of the tissue.

The biotissue coagulation is carried out as a result of local heating of the biotissue with high frequency current to a temperature above 60 °C. This results in irreversible

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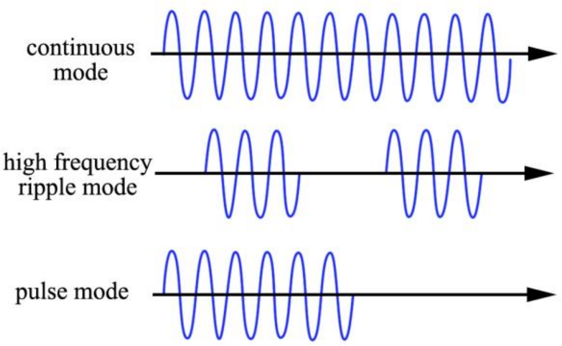


Fig. 1 – Standard wave forms

clotting (denaturation) of the tissues of proteins, which leads to the coagulation of small blood and lymphatic vessels to ensure hemostasis. In addition to hemostasis, electrocoagulation is used for the mechanical connection of biotissues fragments: "welding" of medium and large vessels, alveoli exfoliated during pathological processes of biotissues; for necrotization of different tumors and in many other cases.

Biotissue dissection is also due to the heat released into the tissue, but only at a higher current density than is the case when coagulation. High current power leads to intense local heat release, under the action of which intercellular and intracellular fluid instantly boils and tears up the tissue near the cutting electrode surface [3, 4]. The heat generated by the passage of current through the biotissue coagulates the protein and provides coagulation of the surfaces.

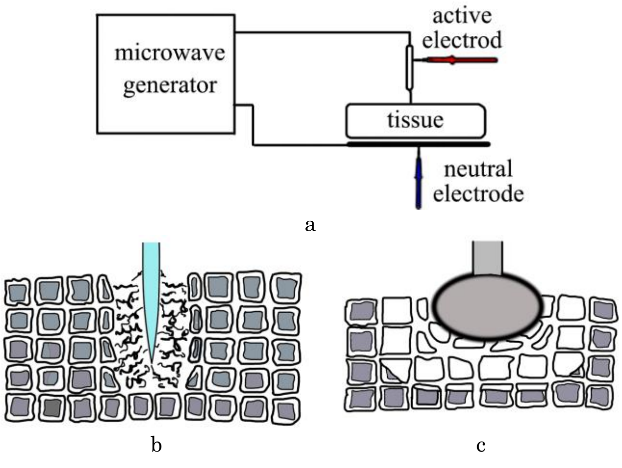


Fig. 2 – Circuit of monopolar effect on tissue (a) in modes of cutting (b) and coagulation (c)

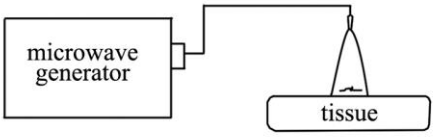


Fig. 3 – Circuit for bipolar mode

There are two main methods of high-frequency surgical exposure: monopolar (Fig. 2) and bipolar (Fig. 3) (see, for example, [5-8]). When monopolar exposure, a high-frequency current from an active electrode spreads over the patient's body and enters the neutral electrode. The active electrode has a small area of the working surface and therefore directly from this electrode the high-frequency current has the highest density causing heating of the tissue.

Monopolar effect is used for coagulation and dissection for biological tissues. In monopolar RF systems, an active electrode is used, and a neutral one in the form of a plate for grounding with a large contact surface is located outside the treated area. In such an electrode configuration, a high density of RF current occurs near the active electrode, and the RF current diverges towards the neutral electrode.

According to Ohm's law in the differential form and determination of the electric field, we obtain:

$$\frac{1}{r^2}\cdot\frac{\partial}{\partial r}\left(r^2\cdot\frac{\partial\varphi}{\partial r}\right)=0,$$

where φ is the electric field potential. The solution of this equation provides the distribution of the RF current density between the electrodes:

$$j=\frac{\sigma U r_0 R}{r^2\left(R-r_0\right)}, \quad (1)$$

where σ is the electrical conductivity of tissue; U is the voltage between the electrodes; r is the radius of the smaller electrode; R is the larger electrode radius.

Analyzing ratio (1), we can draw the following conclusions. First, the heat generated by the RF current near the active electrode is independent of the size, shape, or location of the neutral electrode, when the electrode is much larger than the size of active electrode and is located at a distance exceeding the active electrode size. Secondly, the heating decreases significantly as the distance from the electrode increases. Most RF energy in monopolar systems is converted to heat near the active electrode. The heating range can be set as the radius of the active electrode. Third, the RF current is centered on the RF electrode and diverges rapidly towards the neutral electrode.

Monopolar devices are most commonly used for tissue removal. The results of treatment using monopolar electronic systems depend on the density of the RF energy (power) and the size of the active electrode. In cutting tools, a needle-type electrode is used to focus the electric current over a small area.

The method of bipolar radiosurgery is that both outputs of the generator are connected to two equivalent active electrodes, structurally combined in a surgical instrument (Fig. 3), such as pincers for coagulation. The distance between these electrodes during surgery is the order of the linear size of their working surfaces. Therefore, the current propagates in a relatively small amount of tissue, mainly between the electrodes.

Systems, in which the active electrode through the instrument channel is fed directly to the operated tissues, are successfully used for the coagulation and dissection of biotissues. The most commonly used are loop electrodes, biopsy probes, perforation catheters.

Thermal power (P), which is released from the tissue under the electric current influence for a time period (t), is described by Joule's law:

$$P = \frac{j^2}{\sigma} = j^2 \cdot \rho \, .$$

The power increases as a quadratic function of the RF current density and changes directly in proportion to the tissue resistivity (resistivity of dry skin is $\rho = 10^5$ Ohm·m). The higher the electrical conductivity of the biotissue, the greater the heating of the tissue in the presence of a constant voltage between the electrodes. As the biotissue warms, its electrical conductivity increases.

3. EXPERIMENTAL EQUIPMENT

The electronic device EXBA-350M/120B "NADIYA" (Ukraine) is intended for coagulation and cutting of soft tissues and blood vessels of the organism by high-frequency current in microsurgery, neurosurgery, cosmetology. It is operated in specially equipped premises at an ambient temperature of 10 to 35 °C and a relative humidity of 80 %.

Device EXBA-350M/120B "NADIYA" is a high-frequency current source. The RF voltage is applied to the active and passive (monopolar) electrodes or to the bipolar pincers (electrode) and fed to the tissue of the operated patient. The electrosurgical effect of cutting and coagulation is based on providing a sufficiently high degree of heating of biological tissues by a narrow RF current at the point of contact of the active electrode or between the bipolar pincers ends.

The operation principle of the EXBA-350M/120B "NADIYA" is the peculiarities of the action of high-frequency radio waves on biotissues: electric current is converted into high-frequency radio waves, which are sent to tissue through the electrode in the form of a thin wire. The short-wave energy concentrated at the end of the electrode leads to the instantaneous destruction of cellular structures by "evaporation" of tissue; the cells disintegrate due to the release of their own energy. Evaporation of tissues results in a coagulation effect, whereby a dry operating field is formed.

The device provides: discrete output power control in all operating modes; light indication of power supply voltage, operating mode, output power level; sound frequency-tone alarms, which differs in different operation modes. The device is controlled by the buttons on the front of the unit and the foot pedal.

The device generates three types of waves in the frequency interval 1.76-3.50 MHz.

1. "CUTTING" mode (monopolar). In this mode, the apparatus generates a fully straightened and filtered form of radio wave, which is a continuous stream of high-frequency oscillations, producing the thinnest, ideally even section. Such a wave ($j \cong 40$ mA/mm^2) provides the least transverse heating and tissue destruction. 90 % of the energy of radio waves is spent on the cut and 10 % – on coagulation. In the "CUTTING" mode, clean microscopically equal incisions are performed with a slight coagulation: cosmetic skin incisions, biopsy, autopsy abscesses, keratoma removal, skin flap formation, and removal of cosmetic defects and other manipulations of the skin and soft tissues, which do not require increased hemostasis.

2. "CUTTING/COAGULATION" mode (monopolar). A fully straightened waveform is a radio wave of weak pulsation that produces an incision with light superficial coagulation (without charring) and a "co-radiation film" on the tissue sections. Such co-ablation effectively stops bleeding and seals non-tear fibers, allowing "dry cuts" and reducing pain in the postoperative period. 50 % of the energy of radio waves is spent on the cut and 50 % – on coagulation. In this mode, the dissection of tissue occurs simultaneously with the surface coagulation. In this mode, most surgical procedures are performed on all sub-cutaneous tissues, mucous membranes and internal organs, and neoplasms are removed: fibrous polyps, papillomas, warts, nevi, fistulas, epitheliomas, cysts, etc.

3. "COAGULATION" mode (monopolar or bipolar). The partially straightened waveform is a pulsating flow of high-frequency oscillations ($j \cong 6$-10 mA/mm^2). 90 % of radio-wave energy is spent on coagulation and 10% – on the cut. Radio-wave coagulation differs from electro-coagulation by the absence of tissue charring and does not form burn scar.

4. RESULTS AND DISCUSSION

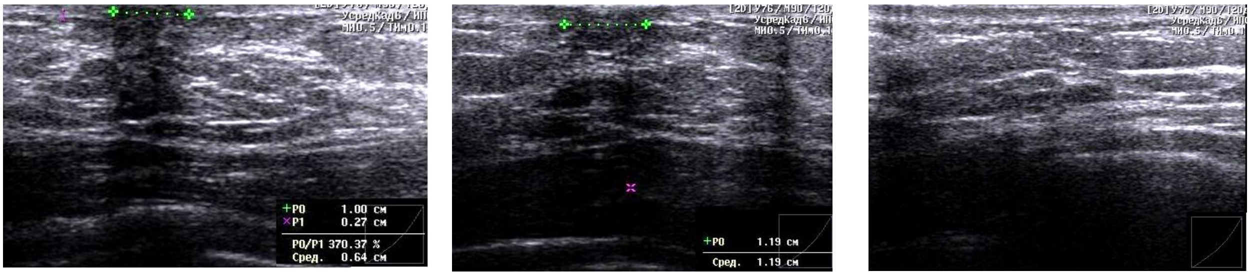
The radio-wave technique begins to be actively used in the surgical treatment of benign neoplasms of the skin, mucous membranes, mammary gland (papillomas, angiomas, polyps, nevus etc.).

There were 356 patients under observation, 58 of them (16.3 %) with scarring on the skin and 298 (83.7 %) with various forms of melanocytic nevus. Age of patients ranged from 20 to 68 years. Nevuses were localized on the skin of the face in 8 % of patients, on the skin of the trunk in 42 %, elements with multiple localization on the skin of the trunk and extremities – in 34 % of patients.

Before the treatment, all patients were subjected to clinical and laboratory researches, examination by the oncologist. Each intervention for the removal of the skin melanocytic neoplasms was ended by histological examination. All patients were followed by local infiltration anesthesia after intracutaneous testing. With a large area of removal of the postoperative defects, cosmetic sutures with atraumatic thread were superimposed.

The method of exposure to tissues is gentle, which allows the patient from the first day after surgery to perform independent care of the wound, treating the wound twice a day with an antiseptic solution with antiviral activity. The bandage is applied only for the night, except for areas in contact with clothing. The control examination by the surgeon was performed on the 2nd and 7th day after the intervention. If there was a scar, regenerating creams were administered. Epithelialization occurred within 2-3 weeks. The examination was performed 1-2 months after the operation and every year thereafter. The observation during the year allowed to establish the clinical recovery in all patients with melanocytic nevus. Sonograms are shown in Fig. 4.

The main advantage of radio-wave surgical devices is the absence of postoperative complications, low trauma and short recovery period. Unlike a scalpel, radio waves do not cause soft tissue injury. After surgery, the healing process is not accompanied by pain, and does not lead to the formation of scars. The latter is especially valuable in removing skin tumors and benign breast tumors [9, 10] and contributes to excellent cosmetic effect. In addition,



a b c

Fig. 4 – Sonograms: a – skin nevus up to 1 cm in size without invasion into the dermis deep layers, the symmetrical acoustic shadow behind the nevus; b – after removal of the nevus after 1 day, no acoustic shadow is detected, skin with a violation of architectonics due to local edema; c – complete skin regeneration after 14 days

RF waves when exposed to tissue have an antiseptic effect, which significantly prevents the penetration of infection and eliminates the inflammatory process. Compared to traditional surgery performed with a surgical scalpel, tissue integrity is restored much faster. After the procedure, a crust appears at the site of exposure, which disappears in 3-5 days on its own.

5. CONCLUSIONS

1. Physical and medical aspects of mono- and bipolar high-frequency surgery are considered. It is shown that the thermal energy generated by the RF current near the active electrode does not depend on the size, shape or location of the neutral electrode, when the electrode is much larger than the radius of active electrode.

2. It is proved that the method of high-frequency RF surgery allows to accelerate and facilitate the rehabilitation period of patients, to reduce the number of relapses and to provide low-traumatic removal of neoplasms of skin with rapid postoperative healing, which allows to achieve high cosmetic effect in surgical operations. The postoperative period proceeds without the expressed reactive phenomena from the surrounding tissues.

3. Based on the observation of patients, which were operated on melanocytic nevuses, their complete clinical recovery was established. It indicates 89 % efficiency of the radio-wave methods use for the cutaneous neoplasms removal. Exclusion criteria in the investigations were large size nevuses (11 %). Unsatisfactory cosmetic result and nevus relapse were observed in 2 % cases.

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Метод радіохвильової високочастотної хірургії: фізика процесів та медичне застосування

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У роботі представлені результати аналізу фізичних основ та клінічного застосування радіохвильових високочастотних моно- і біполярних електронних приладів в хірургії. Проведена оцінка ефективності радіохвильового метода, якпий включає в себе сукупність впливів на біотканини організму з метою їх розсічення (електротомія), цілеспрямованого руйнування, зупинки кровотеч і механічної фіксації (коагуляція) та локального видалення біотканин (абляція), при лікуванні доброякісних новоутворень шкіри. Прилад працює в частотному діапазоні 1.76-3.50 МГц і забезпечує: дискретне регулювання вихідної потужності у всіх режимах роботи; світлову індикацію подачі напруги мережі живлення та рівня вихідної потужності; звукову частотно-темброву сигналізацію. Показано, що більша частина високочастотної енергії в монополярних системах концентрується і перетворюється в тепло біля активного електрода. Установлено, що ефективність радіохвильового методу для хірургічного лікування шкірних новоутворень становить 89 %. Доведені переваги методу радіохвильової хірургії для лікування новоутворень шкіри: операція виконується практично безкровно, немає ризику атрофічного та гіпертрофічного рубцювання, змен-шується ризик інфікування пацієнта, покращуються репаративні процеси за рахунок температурного ефекту і надійного гемостазу, прискорюється загоєння післяопераційної рани та зменшується біль у післяопераційний період.

Ключові слова: Радіохвильова хірургія, Високочастотний струм, Монополярний і біполярний режими роботи, Новоутворення шкіри.