JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. 11 No 3, 03008(4pp) (2019)
ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том 11 № 3, 03008(4cc) (2019)

Effect of Ultrasound Radiation on Biological Tissues: Physical Bases and Technological Principles

I.M. Lukavenko, V.V. Andryushchenko, O.V. Yazykov

Sumy State University, 2, Rimsky- Korsakov St., 40007 Sumy, Ukraine

(Received 09 March 2019; revised manuscript received 20 June 2019; published online 25 June 2019)

The paper presents the modern methods based on the effects of various types of radiation on biological tissues. Ultrasonic, as well as laser, radiation is widely used in medicine for therapeutic purposes, in the diagnosis and in surgical practice. The authors analyzed the physical foundations and technological principles of ultrasonic medical instruments, including ultrasonic scalpels. The concentration of an ultrasonic beam with an intensity of hundreds W/cm^2 in a small area is achieved by focusing the vibrational energy. The use of ultrasonic waves in surgery is based on two principles: the application of the properties of intense ultrasonic waves to penetrate into the depths of living tissues without damaging them and the effect on the object of a special surgical instrument that emits ultrasonic oscillations at a frequency from 20 to 70 kHz. It has been shown that the «Harmonic» ultrasonic scalpel can produce three types of effects: cavitation, co-infection/coagulation and intersection. Cavitation is caused by the gas bubble formation at body temperature due to rapid changes in the volume of tissues and intracellular fluids under the vibration influence. Coagulation is due to the fact that under the action of pressure and ultrasound in tissues there is protein fragmentation, which causes adhesion of collagen molecules at a low temperature from 37 °C to 63 °C. Coagulation is the process of protein denaturation at temperatures up to 150 °C. For high-frequency vibration, there is a rapid over-stretching of tissues that are easily intersected by a surgical instrument. It has been established that at the operating frequency of the «Harmonic» ultrasonic scalpel of 55 kHz, the influence on soft tissues occurs at a constant velocity $V \cong 0.85$ mm/s.

Keywords: Ultrasonic radiation, Magnetostriction and piezostriction effects, Ultrasonic scalpel, Biological tissues, Electroacoustic transducer.

DOI: 10.21272/jnep.11(3).03008 PACS numbers: 42.55.Wd, 42.62.Be

1. INTRODUCTION

The methods based on the effect of different types of radiation (for example, laser and ultrasonic) on biological tissues are becoming more widely used in modern surgery. The biological effects of laser and ultrasonic radiation are varied. On the wavelength scale of radiation, lasers occupy an optical range from 10 μm to 100 nm [1], ultrasonic waves occupy a frequency range from 20 kHz to 100 MHz.

In medicine, there are three main areas of application of radiation: for diagnosis, therapy and surgery. For each specific type of application of lasers in medicine, the decisive role is played by the parameters of laser radiation. For surgery, where virtually a mechanical cutting tool is replaced with a non-contact and less traumatic laser tool, powerful lasers are needed. If the tissue is treated in the ablation mode (see, for example, [2-4]), i.e. in the pulsed mode with pulse durations less than the thermal conductivity time, it is necessary to use ultraviolet lasers (excimer – 193 nm, 248 nm, 308 nm), which work on the photochemical mechanism of tissue destruction, which does not lead to temperature increase and thermal destruction of the fabric.

As for ultrasound, it is also like laser radiation, it is successfully used in medicine for therapeutic purposes in therapy, in the diagnosis of various diseases and in surgical practice. Using ultrasonic sterile liquids, it is possible to wash and disinfect surgical instruments, perform dispersion and inhalation by ultrasonic scalpels. In diagnostic studies, medical technology uses ultrasonic vibrations of the high-frequency range (up to 20 MHz) of low intensity (0.01-0.08 W/cm^2), ensuring the practical absence of any harmful effect on the objects under study.

The aim of this work was to analyze the physical basis and constructive-technological principles of the ultrasonic scalpel and determine the incision depth from the ultrasound exposure time on soft tissues.

2. REASONS OF PRACTICAL USE OF ULTRASONIC DEVICES

2.1 Physical Basis of Ultrasound Medical Instruments

A new range of experimental and clinical medicine – ultrasound surgery – has been developed. The ultrasound used in surgery is based on two principles. The first principle uses the property of ultrasonic waves to affect objects while simultaneously penetrating deep into living tissues without damaging them. The concentration of an ultrasonic beam with an intensity of hundreds W/cm^2 in a small area is achieved by focusing the vibrational energy. As a result, cells that are in the zone of greatest concentration are subjected to thermal destruction (ultrasonic ablation), while the surrounding tissues remain intact.

In some cases, the principle of focused ultrasound can be indispensable, allowing to avoid performing complex surgical operations [5]. In another case, the use of ultrasound is based on the principle of impacting an object with a special surgical instrument, which is indicated by low-frequency ultrasound oscillations from 22 to 60 kHz (ultrasonic dissection). The shape of the working part of the ultrasonic instrument depends on its purpose.

Ultrasonic instruments are equipped with electroacoustic transducers, which use one of two ways of converting the energy of electrical oscillations into mechanical: magnetostriction and piezoelectric effects (see Fig. 1).

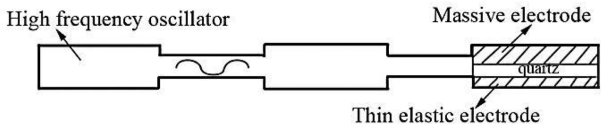

Fig. 1 – To explain the physical operating principles of ultrasonic surgical instruments

The amplitudes of mechanical displacements obtained by single-wave usually do not exceed 4-6 μm and, as a rule, are not sufficient for effective work on biological tissues, therefore, additional core concentrators are used that can amplify the amplitude of oscillations of an acoustic transducer several dozen times. Moreover, various elements of ultrasonic medical instruments can make longitudinal, torsional, bending vibrations, and sometimes more complex forms of vibrations.

Usually, for the transmission of ultrasonic energy from the acoustic transducer to a biological object, this type of oscillation is chosen, at the use of which the working process is most simply realized. However, it is necessary to take into account the specific features associated with the distribution and application of one or another type of oscillations. So, the propagation speeds of longitudinal c_1, torsional c_2 and bending c_b oscillations in concentrators are different:

$$c_1 = \sqrt{\frac{E}{\rho}};\ c_2 = \sqrt{\frac{G}{\rho}};\ c_b = \sqrt{C_1}\sqrt{r_x\omega},$$

where E and G are the 1st and 2nd kind elastic modules, respectively; ω is the circular frequency; r_x is the inertia radius of the hub cross section.

The consequence of differences in the sound speeds is the difference in the resonant lengths of the single-half-wave concentrators of different types of oscillations. For example, longitudinal vibration concentrators are 1.5-1.7 times longer than similar torsional vibration concentrators. Depending on the type of biological tissue (soft, bone, cartilaginous) and the type of work with this tissue (connection, separation, processing), concentrators are performed with the corresponding working endings (scalpels, knives, shoulder blades, etc.).

For most ultrasonic medical instruments, the region of the most rational frequencies, defined as taking into account the impact on the biological environment, lies in the range of 20-70 kHz. Ultrasonic medical instruments operate at frequencies: 22 kHz ± 7 %, 44 kHz ± 7 %, 55 kHz ± 7 % 66 kHz ± 7 % (base frequencies) and 26.5 kHz ± 7 % (additional frequency).

2.2 Constructive Features

Waveguide concentrators are used to transfer ultrasonic energy from the transducer to the object. They transform small amplitude oscillations that occur on their larger input end area (at the junction with the transducer) into larger amplitude oscillations, which are concentrated on a small area of the output end.

A typical ultrasonic medical instrument consists of an electro-acoustic transducer (magnetic or piezostrictive), a waveguide hub and a set of replaceable hub tools. A diagram of a medical instrument with a magnetostrictive transducer is shown in Fig. 2.

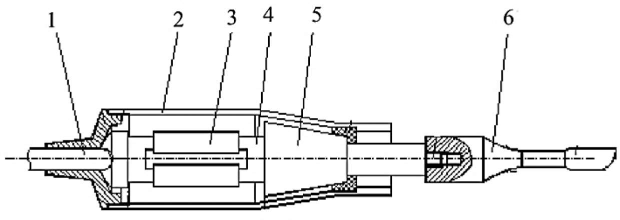

Fig. 2 – Ultrasonic instrument with a magnetostrictive transducer: 1 – power supply cord; 2 – case; 3 – winding; 4 – magnetostrictor; 5 – matching element; 6 – hub tool

In medical ultrasonic instruments, concentrators of exponential, conical and step forms are used. The hubs, made in the form of a round rod with an exponential change in cross section, are bodies whose cross-sectional area in the direction of propagation of elastic oscillations changes according to the exponential law:

$$S_2 = S_1 e^{-\alpha x},\ S_2 = S_1 e^{-\alpha x},$$

where S_1 is the hub area at the base of the transducer; S_2 is the hub area at distance x from the transducer; $\alpha = \frac{2\ln k}{l}$ is the exponential rate. The increase in amplitude is directly proportional to the ratio of the initial S_1 and the final S_2 sections of the concentrator.

Amplification coefficient in the case of circular cross-section is $k = \sqrt{\frac{S_1}{S_2}} = \frac{D_1}{D_2}$. Hub length is $l = \frac{nc}{2f}\sqrt{1+\left(\frac{\ln k}{\pi n}\right)^2}$, where $n = \frac{2l}{\lambda}$.

Then the diameters of the concentrators are related by the ratio:

$$D_2 = D_1 e^{-\frac{\alpha}{2}x}.$$

Determination of the full geometric dimensions of the hub is performed graphically.

3. EFFECTS OF FOCUSED ULTRASOUND ON BIOLOGICAL TISSUES

The intensity of the ultrasound emitted by the piezotransducers usually does not exceed 10 W/cm^2, so if in a certain limited volume it is required to obtain ultrasound of higher intensities, it is focused using concave-surface radiators, ultrasonic lenses or systems consisting of several separate emitters controlled by a computer and arranged so that the ultrasonic beams emitted by them intersect at the right place in space. Most often, a ceramic emitter is used, which is a part of a sphere and focuses ultrasonic energy in the region of the center of curvature of the radiating surface (Fig. 3).

The focal area is an ellipsoid of rotation, elongated in the direction of propagation of ultrasonic waves. The diameter of the focal spot depends on the frequency of ultrasound and decreases with its increase. Theoretically, in a medium that does not absorb ultrasound, no more than 84 % of the energy from the emitter passes through the focal area [6]. Obviously, in tissues whose absorption coefficient is always non-zero, this value is even smaller.

The exact shape of the area of tissue destruction depends on its structure and properties. In a homogeneous fabric, the focus of destruction resembles an ellipsoid. The characteristics of ultrasound in the focal area can be easily estimated, knowing the dimensions and radius of curvature of the ceramic transducer, as well as the frequency of the ultrasound and its intensity at the radiating surface [6, 7]. So, the radius of the focal area is determined by the formula

$$r_0 = 0.61\frac{\lambda F}{R},$$

where F is the distance from the focal area to the radiator; R is the radiator curvature radius; λ is the ultrasonic wavelength.

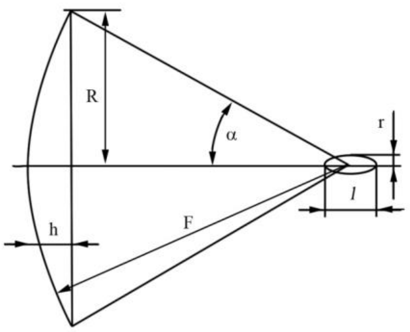

Fig. 3 – Geometric characteristics of a spherical radiator and focused ultrasonic zero: R is the radiator radius; F is the focal length; h is the depth; α is the disclosure angle; r and I are the radius and length of the focal area, respectively

The length of the focal area is calculated by the formula $l = \dfrac{2\lambda}{1-\cos\alpha}$, where α is the radiator opening angle. The intensity in the focal area can be calculated by the ratio $I_f = \dfrac{4\pi^2 h^2}{\lambda^2}\cdot\cos\dfrac{2\alpha}{2}$.

Converging in focus, the ultrasonic waves then diverge again. In this case, the sign of the curvature of the wave front is reversed. In the focal region itself, the wave can be considered practically planar and used to calculate the known relations for a plane wave. The focal area of the emitter is combined with the area that must be destroyed.

4. METHODOLOGY AND RESEARCH RESULTS

Ultrasonic scalpel «Harmonic Ethicon-Surgery» (Germany) is capable of producing three types of exposure: cavitation, co-infection/coagulation and intersection. Cavitation is caused by the formation of gas bubbles at body temperature due to rapid changes in the volume of tissues and intracellular fluids under the influence of vibration. Under the influence of pressure and ultrasound in the tissues, fragmentation of proteins occurs, which causes adhesion of collagen molecules at low temperatures. Thus, coagulation is achieved at a temperature from 37 to 63 °C. With local exposure to energy for a long time, the rise in temperature leads to denaturation of proteins – coagulation, at a maximum temperature of 150 °C. With high-frequency vibration, due to the tension, pressure, or combined action of these two factors, there is a rapid overstrain of tissues that are easily intersected by an acute blade or tip of the instrument.

The electric energy generated by a controlled microcontroller by a high-frequency generator, by means of a piezoelectric system located in the handle, is converted into mechanical energy. The blade or tip of the tool fluctuates along the axis with a constant frequency of 55 kHz. The displacement in length can be from 25 to 100 μm and is regulated by 5 levels by changing the power of the generator. The structural scheme of the ultrasound scalpel is shown in Fig. 4.

Fig. 5 shows the dependence of the cut depth of soft tissues by the ultrasound scalpel «Harmonic Ethicon-Surgery». It is found that at operating frequency $f = 55\cdot 10^3$ Hz the effect on the soft tissues of the abdominal cavity occurs at a constant rate $V \cong 0.85$ mm/s.

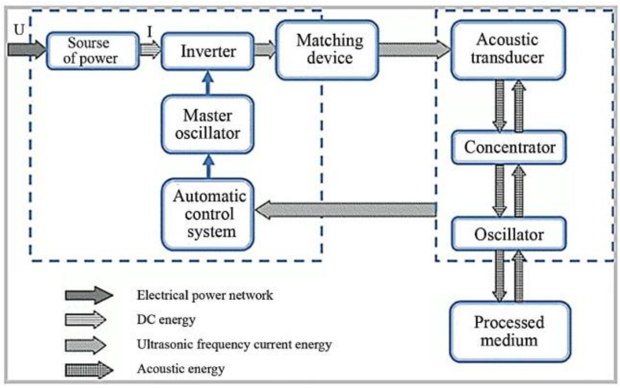

Fig. 4 – The structural scheme of the ultrasonic scalpel

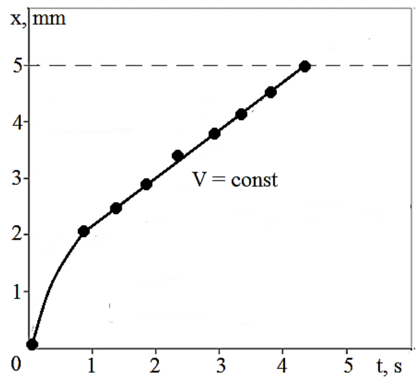

Fig. 5 – Dependence of the cut depth versus the exposure time on soft biological tissue by ultrasonic waves

Ultrasound leads to the destruction of the solid structure of soft tissues and allows to obtain a bloodless cut (the damaged edge of the tissue closes under the influence of an ultrasonic wave), which is very important for many surgical operations.

5. CONCLUSIONS

1. In the work, the analysis of physical bases and constructive and technological principles of ultrasonic medical instruments, including ultrasonic scalpels, was carried out. The ultrasound used in surgery is based on two principles: the use of the properties of intense ultrasonic waves to penetrate into the depths of living tissues without their treatment and exposure to the object by a special surgical instrument, which is reported by ultrasonic oscillations from 20 to 70 kHz.

2. It is shown that the «Harmonic Ethicon-Surgery» ultrasonic scalpel is capable of producing three types of effects: cavitation, co-infection/coagulation and intersection. Cavitation is caused by the formation of gas bubbles at body temperature due to rapid changes in the volume of tissues and intracellular fluids under the influence of vibration. Co-infection is due to the fact that under the action of pressure and ultrasound in the tissues there is a fragmentation of proteins, which causes the adhesion of collagen molecules at a low temperature from 37 to 63 °C. With local energy exposure over an extended period of time, a rise in temperature leads to denaturation of proteins – coagulation, at a temperature of 150 °C. With high-frequency vibration due to tension, pressure, or simultaneous action of these two factors, there is a rapid over-tension of fabrics that intersect with the tool blade.

3. It has been established that, at the operating frequency of 55 kHz, ultrasound acts on soft tissues with a constant speed of the order of 0.85 mm/s.

REFERENCES

1. V. Gafiychuk, I. Lubashevsky, B. Datsko, *Phys. Rev. E* **72**, 051920 (2005).
2. A.V. Yazikov, V.V. Leonov, V.V. Andryushchenko, I.M. Lukavenko, *Georgian Medical News* No 239, 11 (2015).
3. I.M. Lukavenko, V.V. Andryushchenko, V.Iu Garbuzova, A.V. Yazykov, *Georgian Medical News* No 238, 12 (2015).
4. I.M. Lukavenko, V.V. Andryushchenko, A.V. Yazykov, *J. Nano- Electron. Phys.* **10 No**6, 06031 (2018).
5. M. Peñarrocha Diago, B. Ortega Sanchez, B. Garcia Mira, E. Marti Bowen, T. von Arx, C. Gay Escoda, *Med. Oral Patol. Oral Cir. Bucal.* **13,** E143-7 (2008).
6. P.B. Rosnitskiy, P.V. Yuldashev, V.A. Khokhlova, *Acoustic. Phys.* **61** No3, 301 (2015).
7. M. Peñarrocha Diago, B. Ortega Sanchez, B. Garcia Mira, E. Marti Bowen, T. von Arx, C. Gay Escoda, *Med. Oral Patol. Oral Cir. Bucal.* **13,** E143-7 (2008).
8. T. Vercellotti. *Minerva Stomatol.* **53**, :207-14 (2004).
9. G. Eggers, J. Klein, J. Blank, S. Hassfeld, *J. Oral Maxillofac. Surg.*, **42**, 451-3 (2004).
10. A. Salami, M. Dellepiane, E. Proto, *Otol. Head Neck Surg.* **140**, 412-8 (2009).

Вплив ультразвукового випромінювання на біологічні тканини: фізичні основи і технологічні принципи

І.М. Лукавенко, В.В. Андрущенко, О.В. Язиков

Сумський державний університет, вул. Римського-Корсакова, 2, 40007 Суми, Україна

У роботі розглянуті сучасні методи, які засновані на дії різних видів випромінювання на біологічні тканини. Ультразвукове, так як і лазерне, випромінювання широко застосовується в медицині для лікувальних цілей, в діагностиці та хірургічній практиці. Авторами проведений аналіз фізичних основ і конструктивно-технологічних принципів роботи ультразвукових медичних інструментів, у тому числі ультразвукових скальпелів. Концентрація ультразвукового пучка інтенсивністю в сотні Вт/см^2 на малій ділянці досягається шляхом фокусування коливальної енергії. Використання ультразвукових хвиль в хірургії ґрунтується на двох принципах: на застосуванні властивості інтенсивних ультразвукових хвиль проникати в глибину живих тканин без їх пошкодження та на впливі на об'єкт спеціальним хірургічним інструментом, який випромінює ультразвукові коливання з частотою від 20 до 70 кГц. Показано, що ультразвуковий скальпель «Harmonic» здатний виробляти три типи впливу: кавітація, коаптації/коагуляція і перетин. Кавітація обумовлена утворенням пухирців газу при температурі тіла за рахунок швидкої зміни обсягу тканин і внутрішньоклітинних рідин під дією вібрації. Коаптація обумовлена тим фактом, що під дією тиску і ультразвуку в тканинах відбувається фрагментація білків, яка викликає адгезію молекул колагену при низькій температурі від 37 °C до 63 °C. Коагуляція – це процес денатурації білків при температурі до 150 °C. При високочастотної вібрації відбувається швидке перерозтягнення тканин, які легко перетинаються медичним інструментом. Установлено, що при робочій частоті ультразвукового скальпеля «Harmonic» 55 kHz вплив на м'які тканини відбувається з постійною швидкістю $V \cong 0.85$ мм/с.

Ключові слова: Ультразвукове випромінювання, Магнітострикційні та п'єзострикційні ефекти, Ультразвуковий скальпель, Біологічні тканини, Електроакустичний перетворювач.