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Evaluation of optimum modes and conditions of contact ultrasonic treatment of wound surface and creation of tools for its implementation

V.N. Khmelev[1], R.N. Golykh[1], A.V. Shalunov[1], V.V. Pedder[2], V.A. Nesterov[1], R.S. Dorovskikh[1]

[1] *Biysk Technological Institute (branch) of Altai State Technical University named after I.I. Polzunov, Russia*
[2] *Scientific production enterprise "Metromed" Ltd, Russia*

ABSTRACT: *The paper presents results of researches on evaluation of optimum modes and conditions of contact ultrasound influence on wound surface to remove (extract) pathological contents (infectant) (separation between liquid and solid phases). In order to optimize modes and conditions of process model of converse ultrasonic capillary effect was proposed. It considers capillary-porous system "solid-liquid" as a whole, but takes into account effects and phenomena inside separate capillary. Among effects and influencing factors it should be underlined following factors: change of dielectric constant leading to changes of disjoining pressure and consequently to the origin of converse ultrasonic capillary effect; bending and radial deformation of the capillary; formation of cavitation fog preventing extraction of wound content. The model allows to determine determine extraction rate depending on amplitude of ultrasonic vibrations, area of radiating surface of the waveguide radiator, amount of drainage canals in it and physical properties of wound content. It was obtained, that for the most widely spread in surgical practice types of wound content (viscosity of no more than 110 mPa·s) vibration amplitude of the radiator of the waveguide-tool should not exceed 39…90 µm at the insonification of the nidus of infection and radiating surface of the radiator of the waveguide-tool should contain no less than 12 draining canals per unit area in 20 cm^2. Evaluated optimum modes and conditions let develop and make ultrasonic waveguide-tools for implementation of extraction process. Designed waveguide-tools are recommended to use in specialized medical surgery and conservative therapy devices.*

Keywords - *Ultrasonic, extraction, biological tissue, wound infection, converse ultrasonic capillary effect*

I. INTRODUCTION

Wound infection developing at 35-45% of patients of the surgical hospitals and even more number of oncological patients is not only clinical problem, but also general biological problem [1, 2]. Most of the patients have post-operative wound complications accompanied by syndrome of endogenous toxicosis [3]. At the syndrome of endogenous toxicosis endotoxins are accumulated that leads to the death of cells. The analysis of syndrome of endogenous toxicosis appearance shows, that it is possible to suppress it by the application of the methods of therapeutic action on different stages of pathological development of the disease locally influencing on endotoxins substrates in the nidus of wound infection.

One of the most promising approaches to local remove of wound content including endotoxins is the possibility of use of ultrasonic energy.

It is known that at the application of mechanical vibrations of ultrasonic frequency on the biological tissue – natural capillary-porous system "liquid-solid" - remove of pathological content can be realized due to the appearance of converse ultrasonic capillary effect [3]. The action of converse ultrasonic capillary effect causes mass transfer of pores and capillaries content of the biological tissue to surface of the wound.

However at present converse ultrasonic capillary effect is not widely used in medicine, as there is no scientific data on the modes (ultrasonic vibration amplitude) and the conditions of ultrasonic action (the area of insonified wound surface, number of drainage channels of the waveguide-tool), at which the most productivity (rate) of the extraction can be provided. To determine optimum modes and conditions required for practical realization of the converse capillary effect it is necessary to carry out complex theoretical studies of mass transfer process in the capillary-porous system "liquid-solid" allowing analyze characteristic properties of converse capillary effect action and its power characteristics.

II. Problem Statement

Until present most researches of liquid medium flow in the capillaries under the action of ultrasonic action considered direct ultrasonic capillary effect discovered and studied by Konovalov E.G., Kitaygorodskiy U.A., Prokhorenko P.P., Dezhkunov N.V., Rozin U.P. and others [4–7]. The main point of the effect is the acceleration of the process, which is opposite to the extraction – penetration of liquid to the capillary cavity under the action of ultrasonic vibrations.

At that very few studies are devoted to the investigation of converse ultrasonic capillary effect observed at the size of the capillaries of less than 10^{-5} m [3, 8], which are specific for the biological tissues. However existing theoretical descriptions do not allow explaining the mechanism of the converse capillary effect [3, 8, 9] and determining interaction of extraction rate of pathological content with the modes and conditions of ultrasonic action in order to develop means of the practical realization of the process.

Thus, final aim of the paper is to design means (waveguide-tools) for ultrasonic extraction of pathological content from the biological tissues due to theoretical determination of optimum modes and conditions of the action.

Implementation of developed waveguide-tools in the surgery and conservative therapy by their use as a part of medical apparatuses lets realize contact ultrasonic action on the nidus of wound infection at stationary and ambulance patients. Proposed method of influence makes possible to stop the development of the syndrome of endogenous toxicosis due to ultrasonic capillary extraction of the endotoxins from the smallest pores of the biological tissue (up to 20 nanometers and less) and improves clinical symptoms independently of the illness stage.

To achieve stated objective it is necessary to solve following particular tasks:

– development of physical-mathematical model and determination of optimum modes and conditions of the realization of mass transfer process in the capillary-porous system "liquid-solid" at the interaction of insonified biological tissues with the transducer – the waveguide-tool having one or several drain holes on the radiating surface;

– definition of optimum vibration amplitude, the area of radiating surface of the wave-guide-tool and the number of the drainage channels in it to provide maximum productivity of extraction on the base of the developed model analysis;

– development of the procedure of engineering calculations of the waveguide-tools on the base of carried out theoretical studies;

– construction of the waveguide-tool samples calculated with the use of proposed procedure and study of their functional possibilities.

Following sections are devoted to the solution of stated tasks.

III. The Model of Mass Transfer Process in the Biological Tissue

To solve the first of stated tasks it is necessary to formulate the model of the mass transfer process in the capillary-porous system "liquid-solid" allowing determine optimum modes and conditions of extraction according to ultrasonic vibration amplitude, area of simultaneously insonified wound surface and number of the drainage channels of the waveguide-tool.

The model should take into account effects and phenomena leading to the extraction of pathological content from a single pore or a capillary, and also it allows analyzing extraction efficiency from the capillary-porous system in a whole.

Theoretically considered mass transfer process in the biological tissue (capillary-porous system "liquid-solid") can be presented in a following way (Fig. 1).

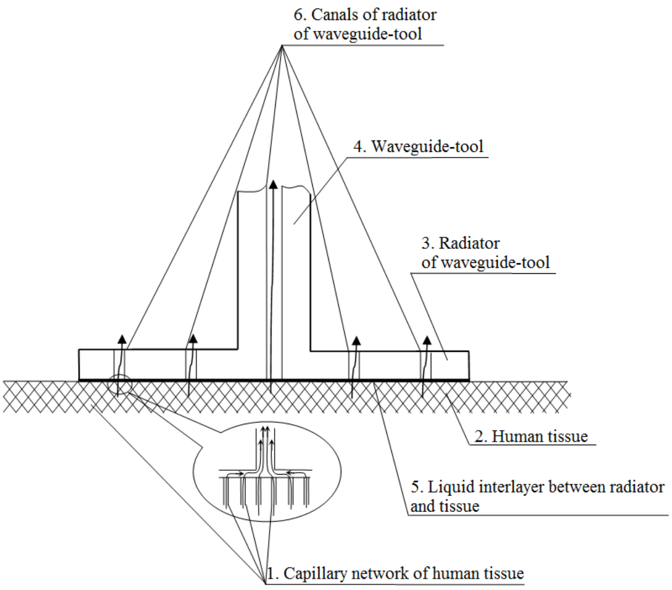


Fig.1. Diagram of mass transfer process in the biological tissue at the contact ultrasonic action

According to the diagram mass transfer of wound content initially occurs from the capillary network 1 to the gap between the radiator 3 of the waveguide-tool 4 and biological tissue 2 generating a layer of liquid medium (infectant) 5. Further wound content is transferred to the drainage channels 6 of the radiator 3 of the waveguide-tool 4, and then it comes to the technological chamber of the ultrasonic extractor, which realizes draining of nidus of infection. The presence of intermediate layer of liquid medium 5 between the wound surface and the radiator 3 of the waveguide-tool 4 is caused by wetting effect and also by untight fit of the radiator 3 of the waveguide-tool 4 to the wound surface, where there is wound effluent in the interface.

To determine optimum modes and conditions of the action providing the realization of the process with maximum efficiency the flow of wound content is described by Navier-Stokes equations (1-4) with the boundary conditions (5-6) on the surface of the biological tissue:

$$\frac{\partial u}{\partial r}+\frac{u}{r}+\frac{\partial v}{\partial z}=0 \qquad (1)$$

$$\rho\left(u\frac{\partial u}{\partial r}+v\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial r}+\eta\left(\frac{1}{r}\frac{\partial u}{\partial r}-\frac{u}{r^2}+\frac{\partial^2 u}{\partial r^2}+\frac{\partial^2 u}{\partial z^2}\right) \qquad (2)$$

$$\rho\left(u\frac{\partial v}{\partial r}+v\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial z}+\eta\left(\frac{1}{r}\frac{\partial v}{\partial r}+\frac{\partial^2 v}{\partial r^2}+\frac{\partial^2 v}{\partial z^2}\right) \qquad (3)$$

$$\rho\left(\left\langle u_1\frac{\partial v_1}{\partial r}+v\frac{\partial v_1}{\partial z}\right\rangle+\frac{1}{4}\left\langle U_{us}^*\frac{\partial V_{us}}{\partial r}+U_{us}\frac{\partial V_{us}^*}{\partial r}+\frac{\partial}{\partial z}\left(V_{us}V_{us}^*\right)\right\rangle\right)=\frac{F-F_B}{lS_c}+2\eta\frac{\partial^2}{\partial z^2}\langle v_1\rangle-\frac{\partial^2}{\partial z^2}\langle p_1\rangle \qquad (4)$$

$$u=\langle u_1\rangle=\frac{G_{sp}}{\rho} \qquad (5)$$

$$p=\langle p_1\rangle \qquad (6)$$

where u and v are the radial and axial components of rate of movement of pathological content in the channels of the radiator of the waveguide-tool, respectively, m/s; p is the static pressure in liquid, m/s; ρ is the density of liquid, kg/m^3; η is the viscosity of liquid, Pa·s, u_1 and v_1 are the radial and axial rate of stationary liquid movement in a single capillary of the biological tissue, respectively, m/s; U_{us} and V_{us} is the complex amplitude of the radial and axial vibrational speed of the capillary wall, respectively, m/s; F is the force magnitude acting on liquid in a single capillary, N; F_B is the Bjerknes force acting on the cavitation fog in the intermediate layer and defined according to the papers [10–12], N; S_c is the capillary cross-section area, m^2; l is the length of the capillary, m; <> is the averaging sign of the capillary cross-section area.

Numerical solution of the system of equations (1-6) by finite element method allows find velocity distribution in the capillary network of insonified biological tissue and in the channels of the waveguide-tool. Obtained distribution lets calculate total extraction velocity depending on the modes and the conditions of action on the base of the expression (7):

$$G=N\frac{\pi d^2}{4}\langle V\rangle\rho \qquad (7)$$

where N is the number of drainage channels in the radiator of the waveguide-tool; d is the diameter of the single channel, m; $\langle V \rangle$ is the average extraction velocity of pathological content along the cross-section of the single drainage canal, m/s; ρ is the density of wound content, kg/m^3.

However to determine distribution of liquid phase flow velocities total force F (see equation (4)) acting on the volume of liquid in the single capillary (Fig. 2) and leading to its ultrasonic extraction remains unknown.

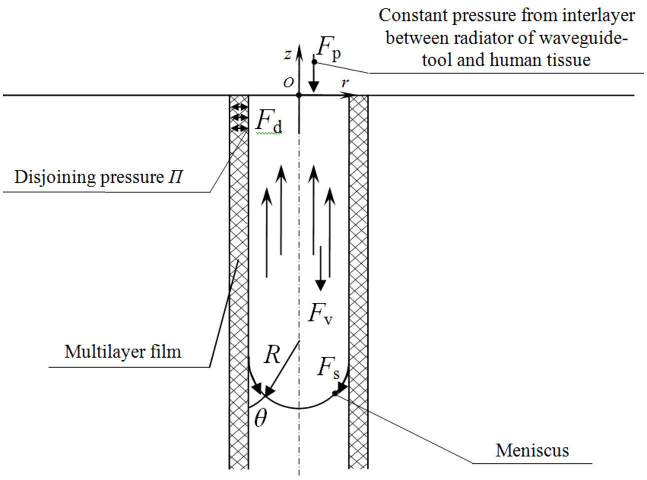


Fig. 2. Diagram mass transfer process in a single capillary

This force balances additional pressure F_p occurring on the surface of the biological tissue (Fig. 3) due to hydraulic resistance of the drainage channels and viscous friction force F_v in liquid phase. Liquid moves uniformly. According to the hypothesis [6, 10], force F is the increment sum of disjoining pressure in the multilayer film ΔF_d on the walls of the capillary [3, 8] and surface tension forces ΔF_s [3] caused by meniscus curvature ($F = \Delta F_d + \Delta F_s$).

Obtained equation for force acting on liquid in the single capillary can be expressed in a following way:

$$F = \frac{\pi d^2 c_2^2 V_0^2}{2} \times$$
$$\times \left[\left(\frac{\partial h}{\partial \Pi} \left[\frac{1}{\varepsilon_{l0}^2} - \frac{\ln \varepsilon_{l0}}{\varepsilon_{l0}^2} \right] \frac{A_0}{A_1 + p_0} \right)^2 \times \left(6\pi\, k\, q_e n_0^2 N_A\, h^2 z \rho_2 F\right)^2 \times \left(\frac{\rho_2 (\omega z_0)^2}{4R^2} + \frac{\sigma \cos\theta}{R^3} \right) + \frac{\sigma \cos\theta}{R} \left(\frac{4\nu}{\omega^2} \right)^2 \right] \tag{8}$$

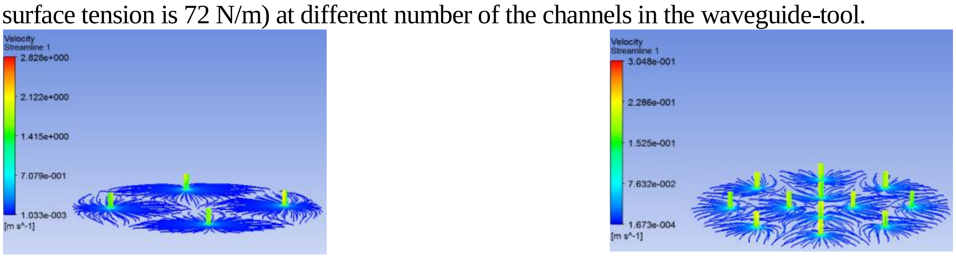
where z is the ion valence in the multilayer film; F is the Faraday constant equals to 96485.33(85) C/mol; k is the electrostatic constant equals to $9{\cdot}10^9$ $J{\cdot}m/C^2$; q_e is the ion charge $1.6{\cdot}10^{19}$ C; ε_{l0} is the liquid dielectric constant in the capillary; N_A is the Avogadro's number equals to $6.02{\cdot}10^{23}$ $mole^{-1}$; n_0 is the ion concentration at the boundary between multilayer liquid film and internal cavity of the capillary, mol/m^3; h is the thickness of the multilayer film, m; Π is the disjoining pressure in the film, Pa; d is the diameter of the capillary, m; c_2 is the velocity of sound in wound content, m/s; V_0 is the amplitude of vibrational velocity of wound content, m/s; ρ_2 is the density of wound content, kg/m^3; A_0 (dimensionless) and A_1 (Pa) are the constant coefficients defining dependence of dielectric constant of liquid phase on pressure [9]; σ is the surface tension of wound content, N/m; θ is the wetting angle between the meniscus boundary and capillary wall; ω is the circular frequency of ultrasonic vibrations, s^{-1}; z_0 is the length of the capillary, m; ν is the Poisson constant of the biological tissue.

The substitution of the expression (8) in Navier-Stokes system of equations (1-6) allows defining total extraction rate (flow rate) of pathological content, which is necessary for the solution of the second task - determination of optimum modes and conditions of ultrasonic action.

IV. Results of Calculations of Extraction Rate of Wound Content from the Biological Tissue

To determine optimum modes and conditions of ultrasonic action we carried out calculations of the total extraction rate depending on amplitude of ultrasonic vibrations, area of insonified wound surface and number of drainage channels of the radiator.

Fig. 3 shows obtained pictures of wound content flow with physical properties close to water (the viscosity is 1 mPa·s; the surface tension is 72 N/m) at different number of the channels in the waveguide-tool.



a) 4 channels b) 12 channels

Fig. 3. Pictures of wound content flow at different number of the drainage channels in the radiator of the waveguide-tool of 20 cm^2

Further the dependences of extraction rate on the conditions, modes of influence and physical properties of extracted pathological content (Fig. 4–8) are presented (the diameter of the pores of biological tissue model is 10^{-7} m). As it was mentioned above, the conditions are the area of insonified surface of the biological tissue and the number of the drainage channels in the radiator (Fig. 4–5), and the mode is the vibration amplitude of the radiator (Fig. 7–9).

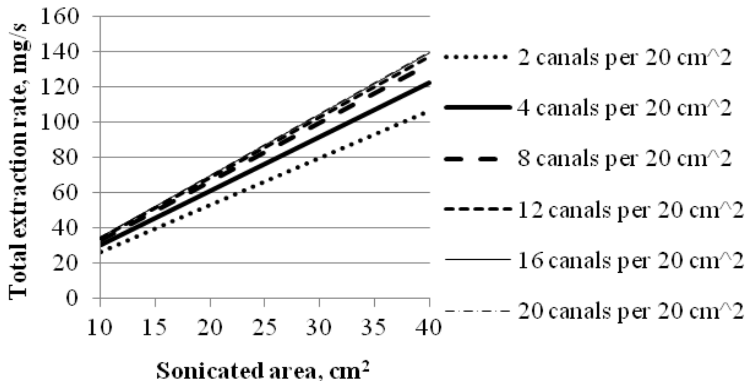


Fig. 4. Dependences of extraction rate of wound content, which physical properties are close to water (the viscosity is 1 mPa·s, the surface tension is 72 N/m) on the area of the radiating surface of the waveguide-tool at different number of the channels in it (the vibration amplitude is 10 μm, the frequency *f* is 23.85 kHz)

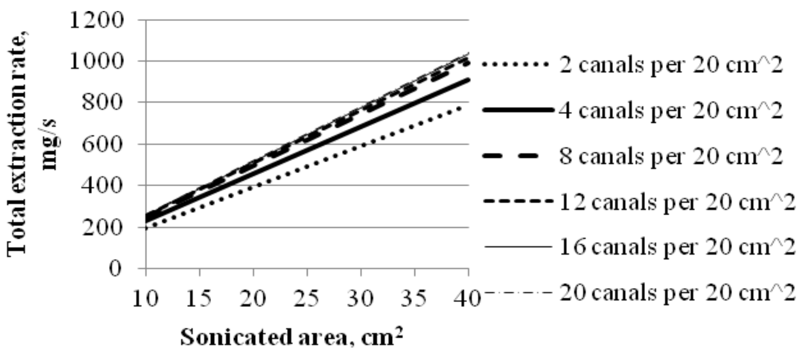
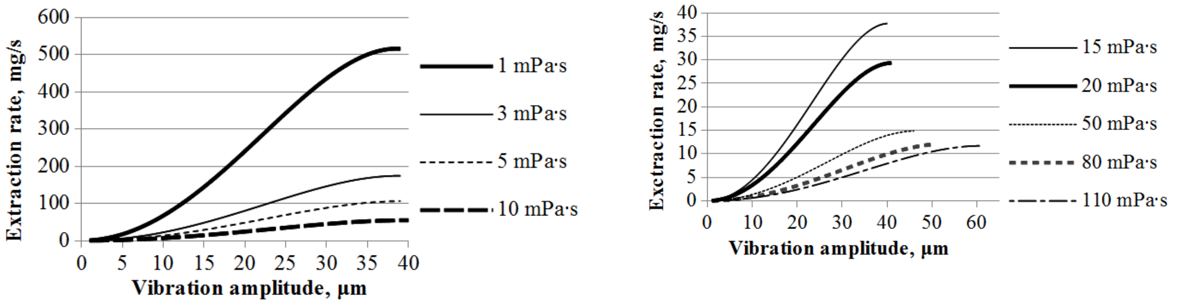


Fig. 5. Dependences of extraction rate of wound content, which physical properties are close to water on the area of the radiating surface of the waveguide-tool at different number of the channels in it (the vibration amplitude is 35 μm, the frequency *f* is 23.85 kHz)

As it follows from presented dependences (Fig. 4–5), extraction rate depends linearly on the area of the radiating surface of the waveguide-tool and at the increase of the number of drainage channels it approaches asymptotically to maximum possible value observed at hydraulic resistance of the canals, which tends to zero.

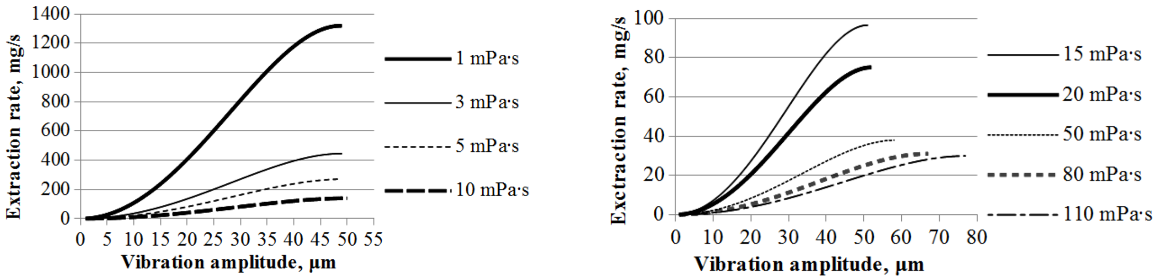
Presented dependences of specific extraction rate (Fig. 4–5) allow concluding, that the action by the waveguide-tool containing no less than 12 channels on the radiating surface of 20 cm^2 area is the most appropriate. It can be caused by the fact, that in this case extraction rate exceeds 95% of maximum possible value. The use of less channels number leads to the decrease of extraction rate up to 20%. Maximum number of the channels is selected from the condition that they do not influence on distribution of vibration amplitudes and cyclical strength of the waveguide-tool.

Further the dependences of total extraction rate on vibration amplitude of the radiator of the waveguide-tool at the frequency of f = 23.85 kHz made in the disk form with the area of 20 $см^2$ (the diameter is 50 mm) containing 12 drainage channels at different viscosities and surface tension of extracted liquid (Fig. 6–8) are shown.



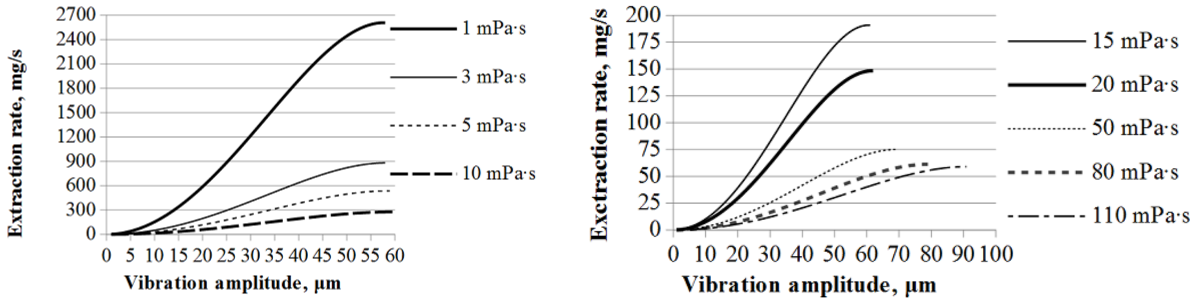
a) for the range of viscosities of 1...10 mPa·s b) for the range of viscosities of 15...110 mPa·s

Fig. 6. Dependences of extraction rate on vibration amplitude of the radiator of the waveguide-tool at different viscosities of wound content (the surface tension is 72 N/m)



a) for the range of viscosities of 1...10 mPa·s b) for the range of viscosities of 15...110 mPa·s

Fig. 7. Dependences of extraction rate on vibration amplitude of the radiator of the waveguide-tool at different viscosities of wound content (the surface tension is 45 N/m)



a) for the range of viscosities of 1...10 mPa·s b) for the range of viscosities of 15...110 mPa·s

Fig. 8. Dependences of extraction rate on vibration amplitude of the radiator of the waveguide-tool at different viscosities of wound content (the surface tension is 32 N/m)

Presented diagrams (Fig. 5–9) allows along with the conditions of action (the area of the radiator and the number of drainage channels) choose necessary vibration amplitude, at which required productivity of wound content extraction can be achieved at the application of the waveguide-tool with the 50-mm-diameter radiator.

In particular, extraction rate of wound content, which is close to water in physical properties having low viscosity of 1 mPa·s and surface tension of 72 N/m, achieves 500 mg/s at the amplitude of no more than 35 μm. At the amplitude of 12 μm the extraction rate is 100 mg/s. Whereas for wound content in the viscosity close to detritus (110 mPa·s) with the surface tension of 32 N/m the extraction rate achieves 60 mg/s.

Moreover presented dependences prove quadratic growth of extraction rate with the increase of vibration amplitude of the radiator of the waveguide-tool. However starting with some threshold value of the amplitude, which is 39 μm for liquid with the viscosity of 1 mPa·s and the surface tension of 72 N/m, the growth of the extraction rate stops due to the realization of cavitation mode [13–14]. It is caused by the action of

Bjerknes force on cavitation fog near the surface of insonified biological tissue, which prevents extraction.

These forces are known to lead to the occurrence of direct ultrasonic capillary effect [12].

This fact is the evidence of necessity to limit vibration amplitude of the radiator of the waveguide-tool by the value, at which cavitation mode is realized and extraction rate is maximum. Exceeding of this value does not lead to the increase of extraction efficiency, but it can cause thermo-ultrasonic destruction of the biological tissue in the insonification area. Based on the obtained dependences vibration amplitude should not exceed 39…90 μm for insonification of the biological tissues with wound content having viscosity in the range of 1…110 mPa·s.

The dependences of extraction rate of pathological content on vibration amplitude of the radiator of the waveguide-tool with other constructions and dimensions are similar to ones shown in Fig. 7–9 and they differ from them in some adjustment coefficient *K*. The value of coefficient *K* according to carried out calculations depends on the area of the radiating surface *S* and the drainage channels on it *N* on the base of the expression (9):

$$G\left(A,\sigma,\eta,N\right)=K\,(N,S)\,G_{sp.MAX}\left(A,\sigma,\eta\right),\qquad K\,(N,S)=k\left(N\right)S. \tag{9}$$

where $G_{sp.\ MAX}$ is the maximum possible specific extraction rate (per unit area of wound surface), kg/(s·m^2); *A* is the vibration amplitude of the radiator of the waveguide-tool, m; σ and η are the surface tension (N/m) and viscosity (Pa·s) of wound content, respectively; $k(N)$ is the constant depending on the number channels per surface unit area of the waveguide-tool radiator; *S* is the radiator surface area, m^2; *N* is the number of drainage channels per unit area of the radiator, m^{-2}.

Obtained results are the base for the selection of optimum modes and conditions of ultrasonic action, which are necessary for providing required extraction productivity.

Discovered optimum modes and conditions can be used for the solution of the third stated task – development of procedure of engineering calculations of special-purpose ultrasonic waveguide-tools of various types.

V. Procedure of Engineering Calculations of the Waveguide Tools

The ultrasonic waveguide-tools intended for practical realization of ultrasonic extraction of wound content from the biological tissues should have specified character of vibrations (longitudinal or bending) of the waveguide tract and its working ending [13, 14] and also provide required range of vibration amplitudes, which is 5–90 μm according to the results of carried out theoretical studies.

That is why working tools can be made in the form of flexural-vibrating disk (a), longitudinal-vibrating rod with the central channel (b) and rod with the disk ending (c) (Fig. 9).

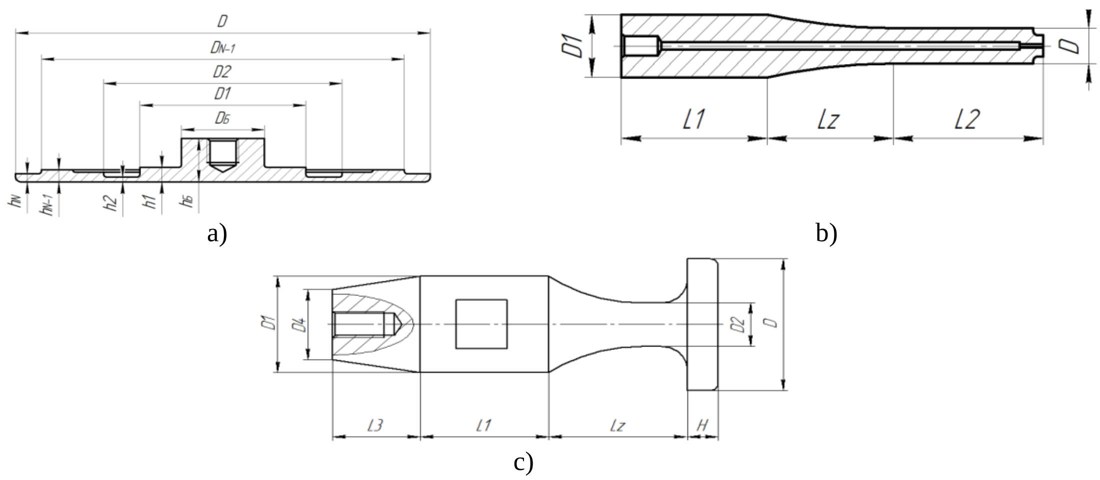


Fig. 9. Drafts of working tools of three types: a) in the form of flexural-vibrating disk; b) in the form longitudinal-vibrating rod with the central channel; c) in the form of longitudinal-vibrating rod with the disk ending

In order to make it possible to remove pathological content from the nidus of infection the tool should have through drainage holes of small diameter (0.5…1 mm).

If the working ending of the waveguide-tool is in the form of disk (Fig. 9a) [13], the holes are made on the zones of the disk vibrating with maximum amplitude to provide the highest extraction productivity (see Fig. 6-8). If the working tool is made in the form of the rod with the ending of small diameter (Fig. 9b), it should contain one central channel with the diameter of no more than 1 mm.

According to carried out theoretical studies extraction productivity depends on the number of holes and vibration amplitude in zones of holes location. At that vibration amplitudes in the different zones of the working tool, where the holes are located, are determined by the diameter (D), width and height of the thickenings ($D_1...D_{N-1}$, $h_1…h_N$) of the working tool, and also lengths of the parts of the waveguide tract (l_1, l_2, l_z, l_3). For the selection of optimum geometric parameters of the working tool, number and location of the holes in order to provide maximum efficiency of influence on wound surface we develop the procedure of engineering calculations.

According to the procedure following characteristics of the waveguide-tool, which influence on extraction productivity, are defined:

1. **Resonance frequency.** It is selected lower than operating frequency of the piezoelectric transducer in 100–1000 Hz in order to provide the best matching.

2. **Radiator diameter *D*.** It is defined on the base of the requirements to ultrasonic extraction process of infectant (the size of simultaneously insonified wound surface).

3. **Thicknesses $h_1…h_N$ and diameters $D_1...D_{N-1}$** of different ring zones of the radiator**,** if it is made in the form of flexural-vibrating disk (Fig. 10a). The parameters $h_1…h_N$ and $D_1...D_{N-1}$ are selected with the use of finite element modeling in a following way, that relative amplitude difference A_n and A_{n+1} in the neighboring maximum points does not exceed $|(A_n - A_{n+1})/A_n| < 0{,}1$.

4. **Lengths of cylindrical (l_1, l_2) and exponential (l_z)** zones of the waveguide tract (Fig. 10b, c) on the base of the ratio (10) [14]:

$$l_z = \frac{c}{12\pi f}\ln\frac{D_1}{D_2}, \qquad l_1 = l_2 = \frac{c}{12\pi f}. \tag{10}$$

where c is the propagation rate of longitudinal vibrations in the material of the waveguide-tool, m/s; f is the resonance frequency of the tool, Hz; D_1 is the largest diameter of the exponential zone, m; D_2 is the smallest diameter of the exponential zone, m.

At that the ratio D_1/D_2 is selected based on the conditions, which provide necessary amplification coefficient and stiffness of the construction. For the most part of ultrasonic working tools applied in practice it is 2…4 [13, 14].

5. **Number of the drainage holes** based on the ratio (11):

$$N = \left\lfloor N_0 \frac{\pi D^2}{4S_0} \right\rfloor \tag{11}$$

where D is the diameter of the radiator, m; N_0 is specific number of holes per surface unit area of the capillary-porous sample S_0=20 cm^2 determined on the base of obtained theoretical dependences.

Using proposed procedure geometric parameters of three types of waveguide-tools for insonification of wound surface with the diameters of 9 mm, 20 mm, 30 mm, 50 mm and 75 mm were calculated. All developed radiators are intended for the application combined with the piezoelectric transducer at the frequency of 23.85 kHz.

The distributions of vibration amplitudes of designed waveguide-tools are shown in Fig. 10–12.

a) radiator of 50 mm in diameter b) radiator of 75 mm in diameter

Fig. 10. Distributions of vibration amplitude of flexural-vibrating disk radiators

According to presented distributions flexural-vibrating disk radiators of 50 and 75 mm in diameter operate on the second ring vibration mode. At that relative difference of vibration amplitude in the local maximum points is 5...10 %. It proves the fact, that proposed procedure allows design working tools providing uniformity of extraction on all insonified wound surface.

Fig. 11 shows the form of vibrations of the rod working tool with the central channel and diameter of working ending of 9 mm obtained during the calculations with the use of developed procedure.

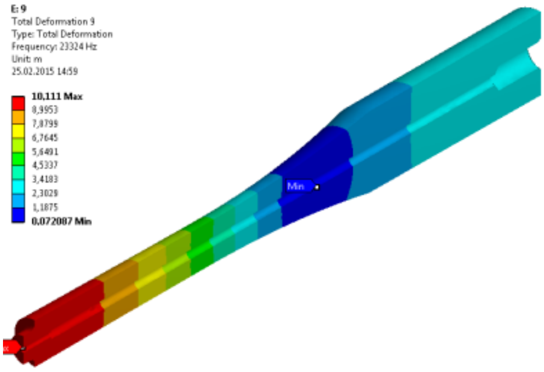
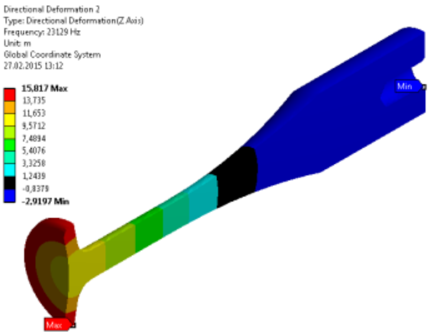


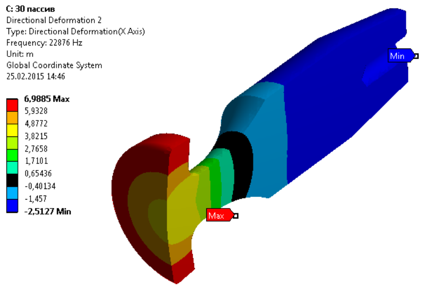
Fig. 11. Distributions of vibration amplitudes of longitudinal-vibrating tool with the central tract

According to Fig. 11 the tip of the tool vibrates uniformly. There is no any essential bend of the butt surface at the operation of the tool.

Fig. 12 shows distributions of vibration amplitudes of the working tool in the form of rod with disk ending of 20 and 30 mm in diameter.



a) 20 mm in diameter



b) 30 mm in diameter

Fig. 12. Distributions of vibration amplitude of longitudinal-vibrating disk radiators

At the analysis of the longitudinal-vibrating tools with the disk endings of 20 and 30 mm in diameter (Fig. 12) it was found out, that vibration amplitude at the edge of the disk is in 1.2…1.3 higher than in the central part. It is caused by the fact, that the construction of the disk tip is not rigid. That is why we decided to perform the holes at the periphery, which vibrates with maximum amplitude.

Further we produced one sample of developed working tools (Fig. 10–12) within the frames of solution of the fourth stated task.

The photos of produced working tools are shown in Fig. 13.

a) 20 mm in diameter

b) 30 mm in diameter

c) 50 mm in diameter

d) 75 mm in diameter

e) rod working tool with the central channel

Fig. 13. Produced working tools

On the disk flexural-vibrating working tools the holes are made within the limits of ring zone vibrating with maximum amplitude. Produced longitudinal-vibrating tool with the central channel (Fig. 13e) has a possibility to change the tip with metered orifice. It was made for carrying out studies with different diameters of the central channels due to the tip change.

Further we present the results of experiments on the determination of the parameters of produced working tools and studies of their functional possibilities in order to prove adequacy of proposed calculation procedure.

VI. Results of the Experiments

Carried out experiments include both determination of the zones, in which limits vibration amplitude is close to zero, and measurement of maximum vibration amplitude. The measurements were performed with the application of the test bench shown in Fig. 14.

The results of measurements of geometric sizes of “zero” vibration and amplitude and also proportional level of acoustic pressure in the air at the distance of 100 mm from the radiating surface for the waveguide-tools of various constructions are shown in Table 1. The measurements of amplitudes were carried out at consumed power of the electronic generator of 35…300 W, which is in proportion to the area of the radiating surface of the disk.

Fig. 14. Test bench for measurement of vibration amplitude of the radiating surface of the tools

Table 1. Characteristics of the working tool found theoretically and experimentally

Type of tool	f_T, kHz	f_M, kHz	ξ, μm	L_{SP}, dB	Diameter of the rings of vibration “zero” (theoretically), mm	Diameter of the rings of vibration “zero” (experiment), mm
Longitudinal-vibrating with the central channel	23.3	22.6	30	152	–	–
Disk D=20 mm	23.1	22.08	60	157	–	–
Disk D=30 mm	22.87	23.35	40	155	–	–
Disk D=50 mm	23.5	23.7	46	154	17; 42.8	16.4; 42.5
Disk D=75 mm	23.4	22.85	40	156	28; 62	29; 64

Symbols used in Table 1: D is the diameter of the disk ending of the working tool; f_T is the theoretically calculated value of resonance frequency; f_M is the measured value of resonance frequency; ξ is the vibration amplitude of the radiator in the maximum points; L_{SP} is the level of acoustic pressure generated by the radiator in at the distance of 100 mm from its surface.

The difference between experimental and theoretical values of the resonance frequencies of the waveguide-tools can be explained by error at their production and difference of tool material properties.

Theoretically determined parts of the surfaces of the radiating disk, on which there are vibration "zeros", and maximum amplitudes vary from the parameters obtained as a result of measurements in no more than 5% that proves adequacy of proposed procedures of calculations of the tools.

To determine functional possibilities of produced tools we carried out research on the example of the extraction process of the model of wound content (physiological solution) with simultaneous atomization. As a model of capillary-porous system we used porous foam-rubber impregnated by water.

Fig. 15 shows the photo of extraction process with simultaneous atomization at the contact of the tool of 75 mm in diameter with the porous material.

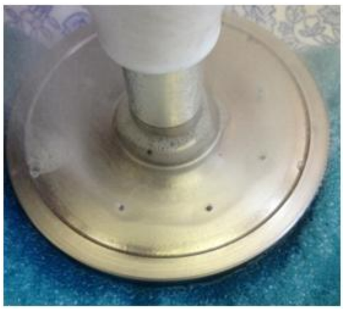


Fig. 15. Photo of moisture extraction process from the porous material

As a result of carried out experimental studies it was determined, that extracted liquid spreads on the surface of the disk radiator. Thus, it was proved principal possibility of realization of extraction of pathological content from the biological tissue, which is natural capillary-porous system.

VII. CONCLUSION

As a result of carried out studies we discovered optimum modes and conditions of ultrasonic extraction of wound content from the biological tissue and means of practical realization of the process were designed.

To achieve main goal of the paper all the tasks were solved, namely:

1. Physical-mathematical model of converse ultrasonic capillary effect allowing determine extraction rate (in mg/s) depending on vibration amplitude, radiator area, number of the channels in it and physical properties of wound content was developed.

2. Optimum modes (vibration amplitude) and conditions (area and number drainage channels of the waveguide-tool) of ultrasonic action providing maximum productivity of wound content extraction depending on its viscosity and surface tension were determined. It was stated, that extraction rate could achieve 500 mg/s at vibration amplitude of the waveguide-tool, which did not exceed 35 μm.

3. Based on the results of carried out theoretical studies the procedure of engineering calculation of three types of the waveguide-tools intended for ultrasonic action on wound surface was developed.

4. Having applied proposed procedure working tools of three types were designed and produced, experimental studies, which proved adequacy of proposed procedure and possibility of extraction of pathological content by contact ultrasonic action, were carried out.

Developed tools are recommended for the application as a part of specialized medical devices for surgery and conservative therapy.

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