Modeling of Contact Ultrasonic Extraction of Wound Contents and Development of Means for Its Realization

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Abstract: - The paper presents results of researches about evaluation of optimum modes and conditions of contact ultrasound influence on wound surface to remove (extract) pathological contents (infectant). In order to optimize modes and conditions of process, physical and mathematical model of converse ultrasonic capillary effect was proposed. The model allows to determine extraction rate depending on infectant physical properties, vibrations amplitude and structural characteristics of the radiator. Evaluated optimum modes and conditions allow to develop and to make ultrasonic waveguide-tools for implementation of extraction process. Made waveguide-tools were recommended to use in specialized medical surgery and conservative therapy devices.

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

1. INTRODUCTION

In 35-45 % of cases the patients of surgical hospitals and oncological patients have wound infection that further leads to post-operation wound complications, which are accompanied by the syndrome of endogenous intoxication [1]. At the syndrome of endogenous intoxication, the endotoxins are accumulated resulting in death of the organism cells. One of the most promising approaches to the local removal of wound contents including endotoxins is the possibility to use the energy of ultrasound.

The extraction of wound contents under the action of ultrasonic vibrations is realized due to the appearance of "converse" ultrasonic capillary effect [2]. The action of "converse" ultrasonic capillary effect causes mass transfer of pores and capillaries contents of biological tissues to the wound surface. The studies of the converse ultrasonic capillary effect existing at present time, which are observed at the sizes of the capillaries of less than 10^{-5} m typical for the biological tissues do not allow to explain the mechanism [2] and find out the interaction of extraction rate of pathological contents with the modes and conditions of ultrasonic action for further development of means of the process practical realization.

To determine optimum modes and conditions of ultrasonic action it is necessary to carry out theoretical analysis of the process of the ultrasonic extraction of wound contents. Further it is presented developed physical-mathematical model of the mass transfer process in the biological tissue.

2. THE MODEL OF THE MASS TRANSFER PROCESS IN THE BIOLOGICAL TISSUE

Presented physical-mathematical model of the mass transfer process in the capillary-porous system “liquid-solid” allows to take into account effects and phenomena leading to the extraction and in turn to determine optimum modes and conditions of the extraction (such as the amplitude of ultrasonic vibrations, the area of insonified wound surface and the number of drain channels of the tool waveguide).

Theoretically considered mass transfer process in the biological tissue – capillary-porous system “liquid-solid” – can be schematically presented in a following way (Figure 1).

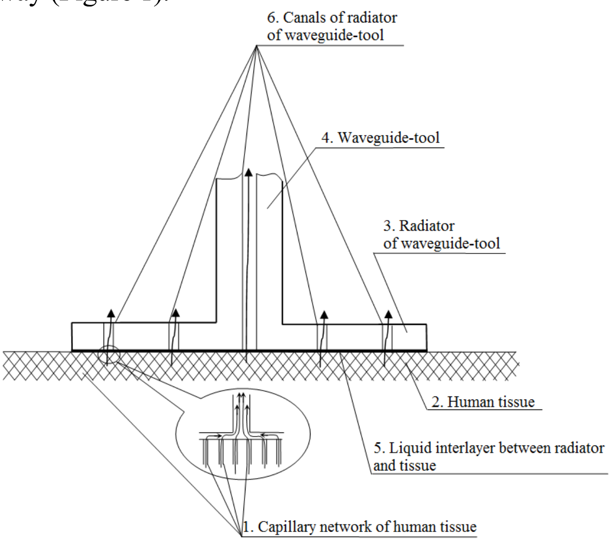


Figure1. Diagram of the mass transfer process in the biological tissue at the contact ultrasonic action

According to the given diagram first of all wound contents are transferred from the capillary network 1 to the gap between the radiator 3 of the waveguide-tool 4 and the biological tissue 2 forming the layer of liquid medium (infectant) 5. Then wound contents are moved to the drain channels 6 of the radiator 3 of the waveguide-tool 4 and they arrive to the technological cavity of the ultrasonic extractor, which realizes the drainage of the infection nidus. 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 phenomenon and also by gapping of the radiator 3 of the waveguide-tool 4 to the wound surface, where there is wound effluent at their interface.

To determine optimum modes and conditions of the ultrasonic action providing realization of the process with maximum efficiency the flow of wound contents in the single capillar is described by Navier-Stokes equations (1-3) with the boundary conditions (4-5) on the surface of the biological tissue:

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

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

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

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

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

where u and v are the radial and axial components of the motion speed of the pathological contents 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 speed of the stationary liquid motion in the single capillary of the biological tissue, respectively, m/s; U_{us} and V_{us} are the complex amplitude of the radial and axial vibration speed of the capillary wall, respectively, m/s; F is the magnitude of the force acting upon liquid in the single capillary, N; F_B is the Bjerknes force acting upon the cavitation cloud in the intermediate layer and it is defined according to the papers [3-5], N; S_c is the cross-sectional area of the capillary, m^2; l is the length of the capillary, m;

G_{sp} is the specific productivity of wound content extraction, kg/(m^2·s); <> is the sign of averaging over the cross-sectional area of the capillary.

The solution of the system of equations allows calculating cumulative extraction rate depending on the modes and conditions of the action on the base of the expression (6):

$$G = N\frac{\pi d^2}{4}\langle V\rangle\rho\,; \qquad (6)$$

where N is the number of the drain channels in the radiator of the waveguide-tool; d is the diameter of the single channel, m; $\langle V\rangle$ is the averaged extraction rate of pathological contents over the cross-section of the single drain channel, m/s; ρ is the density of the wound contents, kg/m^3.

Further the expression for the force acting upon liquid in a single capillary is presented, which has a following form:

$$F = \frac{\pi d^2 c_2^2 V_0^2}{2}\times \left[\left(\frac{\partial h}{\partial \Pi}\left[\frac{1}{\varepsilon_{l0}^2}-\frac{\ln\varepsilon_{l0}}{\varepsilon_{l0}^2}\right]\frac{A_0}{A_1+p_0}\right)^2\times \left(6\pi\, k\, q_e n_0^2 N_A\, h^2 z\rho_2\right)^2\times \left(\frac{\rho_2(\omega z_0)^2}{4R^2}+\frac{\sigma\cos\theta}{R^3}\right)+\frac{\sigma\cos\theta}{R}\left(\frac{4\nu}{\omega^2}\right)^2\right]; \qquad (7)$$

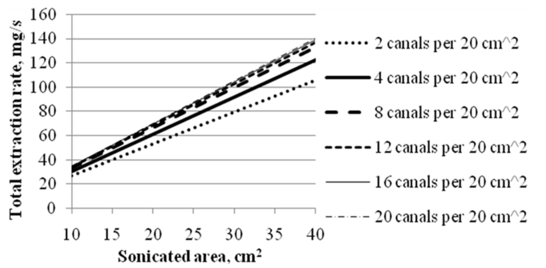
where z is the valence of ions in the polymolecular thin layer; F is the Faraday number, which is equal to 96485.33(85) coulomb/mol; k is the electrostatic constant, which is equal to $9\cdot10^9$ J·m/coulomb^2; q_e is the atomic charge, $1.6\cdot10^{19}$ coulomb; ε_{l0} is the dielectric constant of liquid in the capillary; N_A is Avogadro number being equal $6.02\cdot10^{23}$ mol^{-1}; n_0 is the concentration of ions at the boundary of the polymolecular thin layer of liquid and the internal cavity of the capillary, mol/m^3; h is the thickness of the polymolecular thin layer, m; Π is the disjoining pressure in the thin layer, Pa; d is the diameter of the capillary, m; c_2 is the speed of sound in the wound contents, m/s; V_0 is the amplitude of the vibration speed of the wound contents, m/s; ρ_2 is the density of the wound contents, kg/m^3; A_0 (nondimensional) and A_1 (Pa) are the constant factors determining the dependence of dielectric constant of liquid phase on pressure [6, 7]; σ is the surface tension of the wound contents, N/m; θ is the wetting angle between the boundary of the meniscus and the capillary wall; ω is the circular frequency of the ultrasonic vibrations, s^{-1}; z_0 is the length of the capillary, m; ν is Poisson ratio of the biological tissue.

The substitution of the expression (7) to system of Navier-Stokes equations (1–5) allows defining cumulative extraction rate (flow rate) of the pathological contents, which is necessary for revealing of optimum modes and conditions of the ultrasonic action.

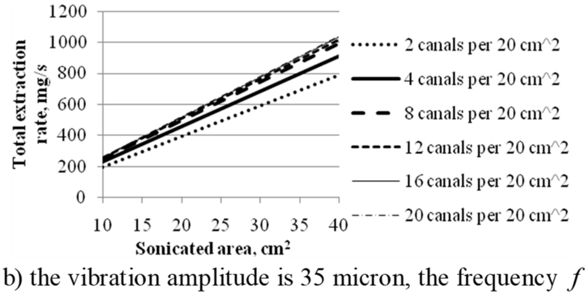
3. THE RESULTS OF CALCULATIONS OF EXTRACTION RATE OF THE WOUND CONTENTS FROM THE BIOLOGICAL TISSUE

To determine optimum modes and conditions of the ultrasonic action the calculations of cumulative extraction rate depending on the amplitude of ultrasonic vibrations, area of insonified wound surface and number of the drain channels were carried out.

Further there are dependences of the cumulative extraction rate on the conditions, mode of the action and physical properties of the pathological contents to be extracted (Figures 2-4) (the diameter of the pores of the model biological tissue is 10^{-7} m). The conditions are the area of insonified surface of the biological tissue and the number of the drain channels in the radiator (Figures 2), the mode is the vibration amplitude of the radiator (Figures 3-4).



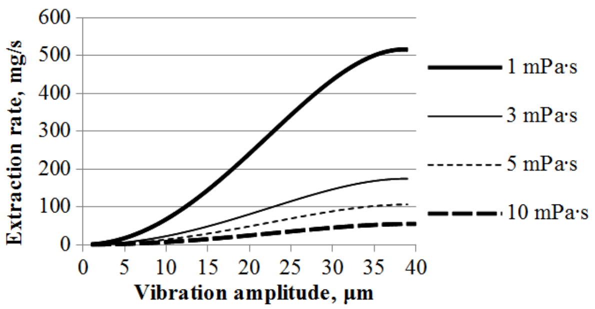
a) the viscosity is 1 mPa·s, the surface tension is 72 N/m; the vibration amplitude is 10 micron, the frequency f is 23.85 kHz



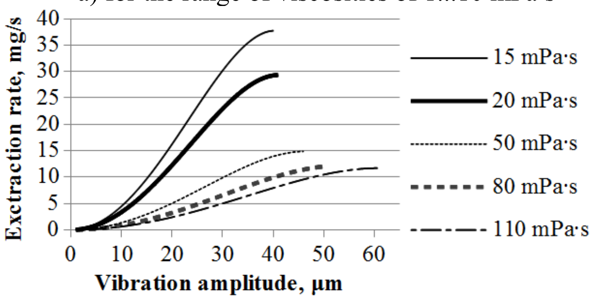
b) the vibration amplitude is 35 micron, the frequency f is 23.85 kHz

Figure 2. Dependences of the extraction rate of the wound contents, which are close to water in the physical properties, on the area of radiating surface of the waveguide-tool at different numbers of the channels in it

Given dependences of the specific extraction rate (Figure 2) allow concluding, that the action by the waveguide-tool containing no less than 12 channels on the radiating surface with the area of 20 cm^2 is the most preferable. It is caused by the fact, that in this case the extraction rate exceeds 95% of maximum possible one. The use of less number of the channels leads to the decrease of the extraction rate up to 20%. The maximum number of the channels is chosen according to the conditions that they do not influence on the distribution of the vibration amplitudes and the cyclic strength of the waveguide-tool.

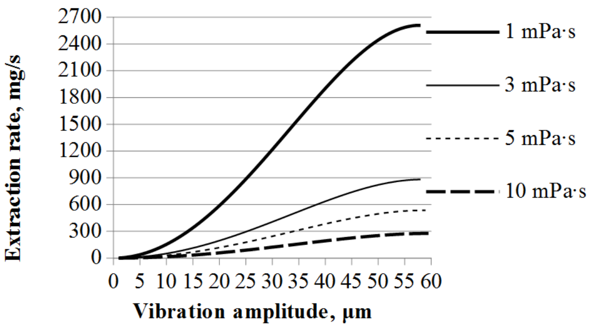


a) for the range of viscosities of 1...10 mPa·s

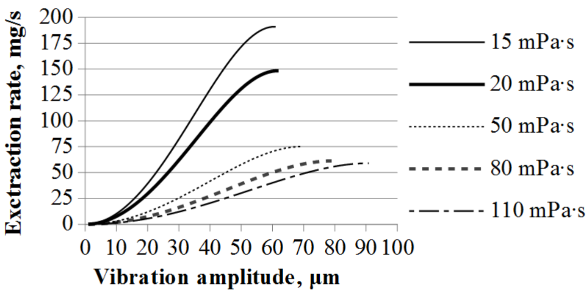


b) for the range of viscosities of 15...110 mPa·s

Figure 3. Dependences of the extraction rate on the vibration amplitude of the radiator of the waveguide-tool at different viscosities of the wound contents (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

Figure 4. Dependences of the extraction rate on the vibration amplitude of the radiator of the waveguide-tool at different viscosities of the wound contents (the surface tension is 32 N/m)

Further the dependences of the cumulative extraction rate on the vibration amplitude of the radiator of the waveguide-tool at the frequency of f = 23.85 kHz made in the form of the disk with the area of 20 cm^2 (the diameter is 50 mm) containing 12 drain channels at different viscosities and surface tensions of liquid to be extracted are given (Figures 3-4).

Given diagrams (Figures 3-4) allow along with the conditions of the action (the radiator area and the number of the drain channels) choosing necessary vibration amplitude, at which required productivity of the extraction of wound contents at the application of the waveguide-tool with the radiator of 50 mm diameter is achieved.

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

Moreover, presented dependences prove quadratic growth of the extraction rate with the increase of vibration amplitude of the radiator of the waveguide-tool. However, beginning with some threshold magnitude of the amplitude being 39 microns for liquid medium with the viscosity of 1 mPa·s and the surface tension of 72 N/m the rise of the extraction rate stops due to the realization of the cavitation mode [4–5]. It is caused by the action of Bjerknes forces upon the cavitation cloud near the surface of insonified biological tissue preventing extraction. The forces are known to lead to the appearance of direct ultrasonic capillary effect.

That is why; based on obtained dependences for the insonification of the biological tissue with the wound contents having viscosity in the range of 1…110 mPa·s the vibration amplitude should not exceed 39…90 micron.

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

4. DEVELOPMENT OF THE WAVEGUIDE-TOOLS FOR THE REALIZATION OF CONVERSE ULTRASONIC CAPILLARY EFFECT

The ultrasonic waveguide-tools intended for the practical realization of the ultrasonic extraction of wound contents from the biological tissue should have definite character of vibrations (longitudinal or flexural) of the waveguide tract and its working ending [8-9] and also provide required range of vibration amplitudes, which is 5–90 micron according to the results of carried out theoretical researches.

That is why the working tools can be made in the form of *the rod with the disk ending (a, b)*, *flexural vibrating disk (c, d) and longitudinal-vibrating rod with the central channel (e)* (Figure 5).

The tool of each type should have through drain holes of the small diameter (0.5…1 mm). If the tool has disk form, the holes are performed at the parts of the disk [8] vibrating with maximum amplitude in order to provide higher productivity. If the working tool is made in the form of the rod with the ending of smaller diameter (Figure 5e) it should contain one central channel with the diameter of no more than 1 mm.

a) disk diameter is 20 mm

b) disk diameter is 30 mm

c) disk diameter is 50 mm

d) disk diameter is 75 mm

e) rod waveguide-tool with the longitudinal vibrating waveguide transmission line and the central canal with inserted nozzle on the radiating end

Figure 5. Designed working tools: a, b – rod with the disk ending; c, d – flexural vibrating disk; e – rod with the central channel

According to carried out theoretical researches we calculate geometric parameters of three mentioned above types of the waveguide-tools for the insonification of the parts of the wound surfaces with the diameters of 9 mm, 20 mm, 30 mm, 50 mm and 75 mm. All developed radiators are intended for the use with the piezoelectric transducer of 23.85 kHz frequency.

It was produced one sample of each type of given working tools for further experiments. The photos of designed working tools are shown in Figure 5.

Designed tools showed high efficiency at the extraction of the wound contents from the biological tissue.

5. CONCLUSIONS

As a result of carried out theoretical and practical studies it can be concluded:

1) It was developed physical-mathematical model of the converse ultrasonic capillary effect, which allows determining optimum modes (vibration amplitude) and conditions (area and number of the drain channels of the waveguide-tool) of ultrasonic action providing maximum productivity of the extraction of the wound contents depending on its viscosity and surface tension. It is determined, that the extraction rate can achieve 500 mg/s at the vibration amplitude of the waveguide-tool not exceeding 35 microns.

2) Based on calculated range of the vibration amplitudes it was developed and designed the working tools of each type providing possibility to extract pathological contents by the help of contact ultrasonic action.

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

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