Physical Principles of the Vacuum Aspiration for Prostatitis Treatment

Andrei Yu. Kulinich, Irina V. Golovacheva, and Mikhail Ye. Zhuravlev

***Abstract*—**Vacuum aspiration is an effective method of prostatitis therapy. Bacterial prostatitis leads to duct obstruction. The plug consists of dense acini epithelium and secretions. Vacuum aspiration procedure results in the destruction of the plug. The fact of the destruction has been verified by the analysis of the substance obtained during the procedure. This method is used in a few medical institutions. Meanwhile, the physical principles of the procedure have never been investigated. We analyze plausible physical mechanisms of purification of prostatic acini and ducts by means of transurethral vacuum aspiration. A mechanical model is offered to describe the process of plug destruction during vacuum aspiration procedure. The majority of medical practitioners believe that the plug is extracted as a whole during such procedure. However, our theoretical research demonstrates that the sucking of a plug as a whole, previously viewed as the most likely mechanism, is not consistent with the experimental data.

***Keywords*—**vacuum aspiration, physical model, prostatitis, plugged acini.

I. Introduction

VACUUM aspiration [1,2] is a method widely used in various branches of medicine, such as otorhinolaryngology, urology, general and gynecology surgery.

In vascular and heart surgery, the vacuum aspirators are applied to remove the thrombi [3,4]. Also, vacuum aspirators occupy a prominent place among the tissue sample devices (See, e.g., [5]). In pregnancy termination, the vacuum aspiration is the most common method [6].

Vacuum aspiration is based on the suction of liquid or solid fraction from a cavity by means of generated negative pressure. The negative pressure can remain constant during a certain time interval. Also, it can oscillate between atmospheric pressure and some negative (reduced) value of pressure. The choice of the value of negative pressure depends on the specific aim of the procedure.

In fact, medical practitioners have a rather vague idea of how vacuum aspiration devices perform. Yet, advanced medical equipment requires detailed understanding of the physical processes which underlie such therapeutic procedures. Therefore, an adequate model of such physical processes appears to be indispensable. Such model would be also indispensable for the analysis of collected clinical data.

In the present article, we analyze feasible physical mechanisms of purification of prostatic acini and ducts by means of transurethral vacuum aspiration. Though the most common treatment is with anti-biotics and anti-inflammatory medicaments [7], the preliminary physiotherapy can also be very useful. In particular, vacuum aspiration applied at the first stage of the treatment makes subsequent antibacterial medication much more efficient. In particular, such method allows doctors to shorten treatment period as well as reduce the dosage of anti-bacterial drugs due to a much more efficient transportation of the latter to the acini and ducts previously drained by vacuum aspiration. A detailed explanation of physical processes underlying vacuum aspiration of secretions from plugged acini and ducts is, undoubtedly, valuable for further development of this method – considering the fact that prostatitis affects at least 40% of men aged 35-50 years.

The paper is organized as follows. Section II offers the description of the device used for the treatment of bacterial prostatitis by vacuum aspiration. The method [8,9] was developed by A. R. Guskov and his collaborators at the Central Aviation Scientific-Research Hospital (Moscow, Russia). At present, it is used in a few medical institutions. In Section III we discuss two radically different physical mechanisms underlying the performance of the device, offering the mathematical analysis of one of them. The final section summarizes the conclusions concerning the actual physical processes involved in the discussed mechanisms.

II. Vacuum Aspiration for the Treatment of Prostatitis

In this section, we briefly describe general principles of vacuum aspiration as applied to the treatment of prostatitis. Fig. 1 presents the scheme of the prostate which consists of stroma and glands (acini). Acini drain into urethra by means of prostatic acini. The scheme below shows only several healthy and plugged acini, whereas the total number of acini is about forty and their size is significantly smaller compared to the size of the prostate. Bacterial prostatitis leads to duct obstruction. The plug consists of dense acini epithelium and secretions. It occludes the passage connecting the acinus to the urethra. Vacuum aspiration procedure results in the destruction of the plug. The fact of the destruction is verified

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by the analysis of the substance obtained during the procedure.

At Central *Aviation* Scientific-Research *Hospital,* at the medical center “SANOS” and other institutions which borrowed this method for the treatment of prostatitis, there are used the machines providing the pressure oscillating between 1 atm (10.1 N/cm^2) and 0.5 atm (5.05 N/cm^2) at frequency $\omega = 20$ Hz. These parameters have been determined as the most efficient ones over the course of many clinical experiments.

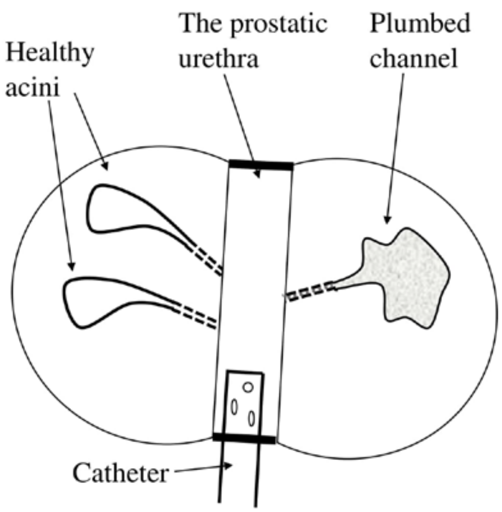

Fig. 1 The scheme of the urethra. Healthy and plugged acini are shown.

The aim of the present research is to clarify the physical mechanism of the plug destruction during the vacuum aspiration procedure. In our opinion, two radically different mechanisms may account for the effect. The first one accounts for the suction of the plug as a whole, whereas the second - for the progressive fragmentation of the plug by the oscillating pressure. In the latter case, the plug is destroyed gradually, since only the layer facing the urethra is exposed to the destruction. In the following section, we analyze the first model and prove that the hypothesis of the suction of the plug as a whole contradicts experimental data.

III. Analysis of the Model of Suction

We use the following simple model to describe the suction of the plug as a whole. In our model, the duct is represented as a cylindrical tube, and the plug - as a solid cylinder which is held in the tube by the friction forces. The device which is used in the above-mentioned institutions generates the oscillations of pressure at frequency ω according to the following law:

$$P(t) = p_0(1-\cos(\omega t)) \tag{1}$$

where p_0 is the amplitude of pressure oscillations, t is the time.

Second Newton’s law determines the motion of the plug:

$$m(t)\ddot{x}(t) = -\pi R_0^2 p_0(1-\cos(\omega t)) + 2\pi k R_0 x(t)\theta(-\dot{x}(t)) - \gamma\dot{x}(t) \tag{2}$$

where $x(t)$ is the position of the inner side of the plug at time t, $m(t)$ - plug mass at time t, R_0 - is the radius of the duct, k - the coefficient of friction between the wall of the duct and the side of the plug, γ is the coefficient of viscous friction. Since the applied pressure is never positive, the plug can move only in one direction. Heaviside step function $\theta(\dot{x}(t))$ in the right-hand side of the equation provides for the force of friction only when the plug is moving. The mass of the plug decreases over time since its extruded segment must be easily destroyed by the oscillating pressure. The plug being pressed out into the urethra experiences small viscous friction since the urethra is filled with gaseous medium rather than with a liquid one.

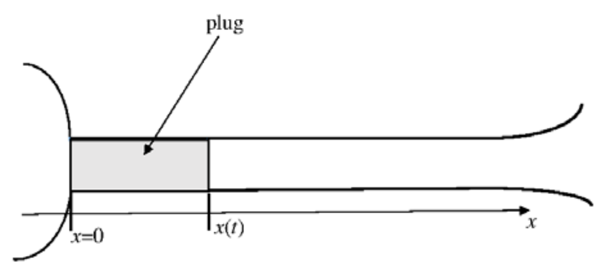

Fig. 2 Scheme of the affected acinus with the plug.

We express the plug mass through its density ρ, so that $m(t) = \rho\pi R_0^2 x(t)$, and introduce dimensionless variables according to the formulae:

$$\varphi = \omega t, \quad P_0 = \frac{p_0}{\rho\omega^2 R_0^2}, \quad K = \frac{2k}{\omega^2\rho R_0^2}, \quad \Gamma = \frac{\gamma}{\pi\omega\rho R_0^3} \tag{3}$$

The initial Eq. (2) then transforms into the equation for the new variable $z(\varphi) \equiv x(\varphi/\omega)/R_0$:

$$z(\varphi)z_{\varphi\varphi}(\varphi) = -P_0(1-\cos\varphi) + K\,z(\varphi)\times\theta(-z_\varphi(\varphi)) - \Gamma z_\varphi(\varphi) \tag{4}$$

The choice of parameters can be made on the basis of the available experimental data. Some parameters are known, namely, $p_0 = 0.5$ atm = 50662.5 Pa, the frequency $\omega = 20$ Hz. The average value of the duct radius is $R_0 = 5\times10^{-5}$ m and the average length of the duct and, correspondingly, the initial (at $t = 0$) length of the plug is $x(0) = L = 1$ mm. The density of the duct can be estimated as $\rho \sim$ 3000 – 4000 kg/m^3.

Using these values, we obtain the following expressions for the parameters of Eq. (4):

$$P_0 = 1.70 \times 10^7 , \quad K \sim 667.0\, k , \quad \Gamma \sim 4.24 \times 10^7 \gamma \qquad (5)$$

The viscous friction is negligibly small compared to the other forces that our model takes into account. So, we neglect this term. Now there is one unknown parameter - friction coefficient k. We need to find the value of k which would provide for the procedure time.

We use modified Euler method [10] to get the numerical solution of Eq.(4). Clinical trials show that the total time of the aspiration procedure is about 90 min. It takes several sessions, each session taking approximately 15 min. This time cannot be reduced by moderate varying of the device parameters. In the dimensionless parameters (3), this time value corresponds to $\Phi_0 = 6.5 \times 10^6$.

The plug starts moving at some moment $\varphi = \varphi_0$ when the power produced by the device exceeds friction. Therefore, the condition $Kz_0 < P_0$, where $z_0 = L / R_0$, is the initial condition for the solution $z(\varphi)$. The second initial condition is zero velocity $z_\varphi(\varphi_0) = 0$. The initial value of time, φ_0, is determined by the condition

$$P_0 (1 - \cos \varphi_0) = K\, z_0 \qquad (6)$$

Now we estimate the values of the parameter *K*. We search for the value of *K* which results in the total procedure time equaling Φ_0. The friction coefficient γ for gas is so low that the corresponding term can be neglected. It is clear that the time of the suction of the plug increases as the difference $P_0 - Kz_0$ approaches zero remaining positive. Numerical calculations show that for $K = 0.99(P_0 / z_0)$ the total time of suction is as small as $\Phi = 0.05$, which is much smaller than the period of the oscillations. Correspondingly, the time of suction is less than one second. The plug starts to move at $\varphi_0 = \arccos\left(1 - K\, z_0 / P_0\right) \approx 1.5607961$. Fig. 3 displays $z(\varphi)$ for these parameters. Visible nonlinear character of the function $z(\varphi)$ is caused by the decrease of mass as the plug moves outward from the acinus channel, as well as by the decrease of the force of friction.

So, we obtained $\Phi << \Phi_0$ for reasonable parameters. To get the experimental total time Φ_0 in this model, we must use the parameters which obey the inequality $0 < \left(P_0 - (Kz_0)\right) / P_0 < 0.01$. Moreover, even small (within one percent) increase of the pressure amplitude leads to a radical decrease of the time of the suction of the plug. Meanwhile, clinical trials show that a more significant variation of the pressure does not lead to a visible decrease of the total time of aspiration procedure. This conclusion is correct for various modifications of the presented model. For instance, if we apply significant value of viscous friction term or assume that the mass of the plug did not decrease, the time of the aspiration is

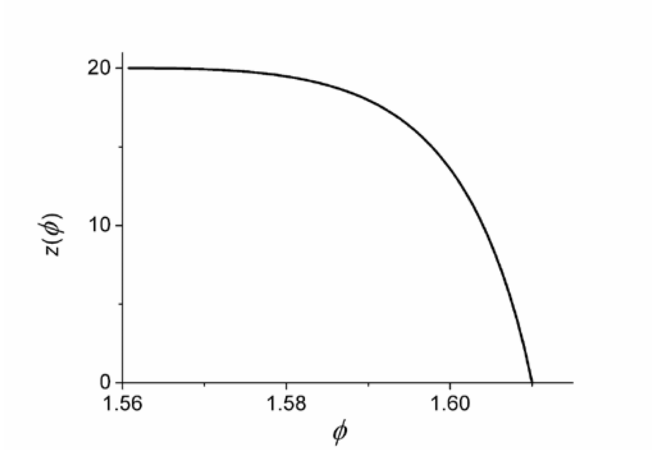

Fig. 3 The dependence of $z(\varphi)$ for the parameters of the existing devices: $P_0 = 1.689 \times 10^7$, $K = 0.99 \times P_0 / z_0$, $z_0 = 20.0$, $\Gamma = 7000.0$.

still as small as several orders comparing to Φ_0. Fig. 4 illustrates this conclusion for the model with high viscous friction, $\Gamma = 70000.0$.

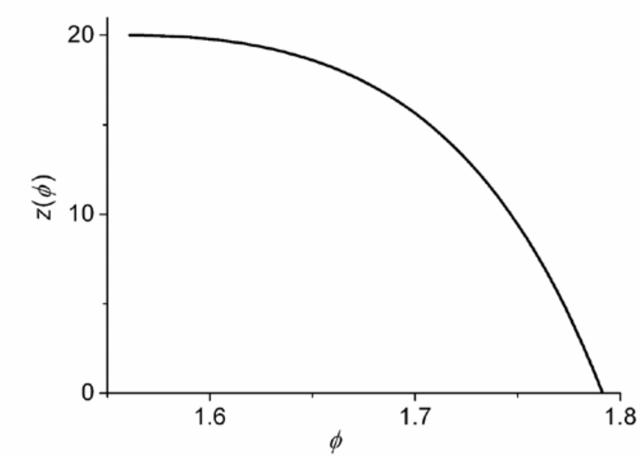

Fig. 4 Function $z(\varphi)$ for the model which takes into account viscous friction, $\Gamma = 70000.0$, while the other parameters are the same as on Fig. 3.

We note that possible modifications of the model do not lead to the plug suction dynamics that would agree with the clinical data. For instance, it seems reasonable to take into account the oscillations of friction between the wall of the duct and the side of the plug. To take this into account, we should replace the coefficient of friction (Eq. (2)) by the oscillating term of the following form

$$k \quad \to \quad k\beta\left(1-\frac{\beta-1}{\beta}\cos\omega t\right), \quad 0<\beta<1 \qquad (7)$$

Therefore, the friction coefficient harmonically changes between βk and k. This modification of the model results in moderate decrease of the procedure time.

IV. Conclusion

Our research demonstrates that the sucking of a plug as a whole cannot be the mechanism of draining the clogged acinus during vacuum aspiration procedure. The theoretical investigation of suction of a plug as a whole reveals that a small (about 1%) increase of pressure may result in a huge decrease of the time of vacuum aspiration procedure. However, such conclusion contradicts the available clinical data. In our opinion, the fragmentation of a plug by oscillating pressure must be the most probable mechanism of the recovery of inflamed acinus. In that case, the change (increase) of the oscillating pressure magnitude does not lead to the speeding up of the procedure. Detailed analysis of the latter mechanism requires a different model.

We should underscore, that we investigate the physical mechanism of draining of a prostatic acinus by means of vacuum aspiration rather than analyze medical aspects of the treatment.

As was noted in the Introduction, vacuum aspiration is widely used in different branches of medicine. The related devices are distinguished by various parameters, e.g. by the amplitude of the negative pressure and the frequency (for the devices producing the oscillating pressure). Our research, as we believe, draws attention to the fact that in various cases the physical mechanism of suction can be different.

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