SOME APPLICATIONS OF FLUID'S FLOW LAWS IN MEDICINE

Sh.Sh. AMIROV[1,2,3], A.I. HASANOVA[1], N.A. MAMMADOVA[1]

[1]Department of Medical and Biological Physics, Azerbaijan Medical University, 167 S.Vurgun str., Az-1022, Baku, Azerbaijan

[2]Faculty of Physics, Baku State University, 23 Z.Khalilov str., Az-1148, Baku, Azerbaijan

[3]Department of Physics and Electronics, Khazar University, 41 Mahsati str., Az-1096, Baku, Azerbaijan

**Corresponding author: e-mail: phys_med@mail.ru*

In the paper some applications of the laws of fluid flow to human blood vessels are studied. The movement of the physiological solution in the syringe was considered and an expression for the syringe equation was obtained by applying the above laws. An ideality and reality properties of liquids are reviewed and newtonian as well as non-newtonian liquids are analyzed. The variation of viscosity in large vessels and capillaries and its indicator of various pathological states have been studied. Also, the pressure distribution in the veins was considered depending on the value of the hydraulic resistance.

Keywords: Average pressure, blood vessels, Pouseuilli's law, hydroulic resistance, continuity equation.
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1. INTRODUCTION

The role of the laws of physics at various stages of development of medical and biological sciences has been reflected in a number of research works. It is not accidental that the opposite opinion is true, that is, researchers working in those scientific fields have made great contributions to the development of physics itself. A number of doctors and physiologists, such as Yung Thomas, Poiseuilli Jean Louis Marie, Mayer Julius Robert, Helmholz German Ludwig Ferdinand, Darsonal Jacques Arsen etc., succeeded in studying certain physical phenomena. Poiseuille, a French physics and physiologist, studied fluid flow and internal friction in thin cylindrical tubes and first applied a mercury manometer to study blood pressure [1]. Germany doctor Mayer is among the first researchers to discover the law of energy storage and conversion.

A number of macroprocesses in the human body are physical processes by nature. For example, the blood circulation, which is a complex physiological process, is related to the laws of fluid flow [2,3,4,5,6,7], the propagation of elastic oscillations in blood vessels is related to oscillations and waves, the work of the heart is related to mechanics, the generation of biopotentials is related to the electric field, etc. is related.

2. DISCUSSIONS

The study of fluid flow is directly related to biology and medicine. The main reason for studying the flow of liquid by the French doctor L.M.Poiseuille, one of the famous scientists in this field of science, was his interest in the flow of blood in the human body. If frictional forces are not taken into account, the movement of imcompressible fluid is expressed by Bernoulli's equation [2]. This equation states that the sum of the static, hydrostatic and dynamic pressures in a fluid-flowing pump remains constant.

$$P+\rho gh+\frac{1}{2}\rho\upsilon^2=const. \qquad (1)$$

where $p-$ is the pressure in a static fluid, $\rho-$ is the density of the fluid, $\upsilon-$ is the velocity of the fluid at an arbitrary point and $h-$ is the height of the fluid particles above a certain reference level. The first term of the equation is the potential energy density (in other 1words, the potential energy per unit volume), which is achieved by the presence of pressure in the liquid. Second and thirs terms of equation are the hydrostatic and dynamic pressures per unit volume which are determined by the potential and kinetic energies of fluid particles. Bernouilli's equation is a mathematical expression of the law of conservation energy for the fluid particles. When there no frictional forces sum of those terms remains constant independently how the flow varies, since they express the energy. From the analysis of above equation it follows, that because of imcompressibility of the fluid, the volume flowing across cross-sectional area per unit time is equal. If we assume the motion of fluid [3] in the pipe of cross-sections A_1 and A_2, then we obtain equation of flow continuity from the law of mass conservation (Fig.1):

$$A_1\upsilon_1=A_2\upsilon_2 \qquad (2)$$

As can be seen , if the condition $A_1\succ A_2$ takes place, $\upsilon_2\succ\upsilon_1$ is provided or vice versa.

Since total mass of blood remains constant in the human body, the volume of blood flowing across vessels with both larger (aorta and arteriums with larger radius and A_1) and narrow (capillaries with smaller radius and cross-section A_2) per unit time is the same everywhere.

131, H.Javid ave, AZ-1073, Baku
Institute of Physics
E-mail: jophphysics@gmail.com

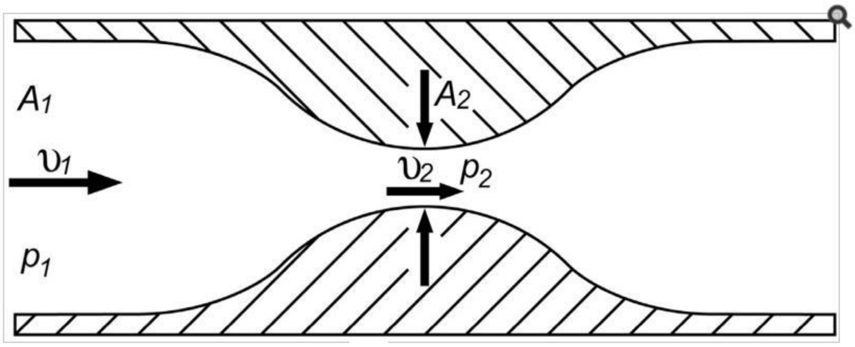

Figure 1

As it is known, a blood velocity in capillary vessels is larger smaller for several times as compared to the velocity in aorta and arteries. This is caused by the fact, that that number of capillary vessels is huge and then their total cross-sectional area is very larger than that of aorta and arteries. For the pressure relationship in two blood vessels with different cross-sections we get

$$p_2 = p_1 + \frac{\rho\upsilon_1^2}{2}\left[1-\left(\frac{A_1}{A_2}\right)^2\right] \qquad (3)$$

It is seen that we obtain negative value for pressure when second cross- sectional area is very smaller than that of first one.

We now apply simaltaneous effect of both equations of Bernouilli and continuity to the motion of physiological fluid in the syringe. Equation (1)can be rewritten for the tube whose cross-sections are at the same height relatively arbitrary reference body.

$$P_1 + \frac{1}{2}\rho\upsilon_1^2 = P_2 + \frac{1}{2}\rho\upsilon_2^2 \qquad (4)$$

A syringe has two parts with large A_1 and narrow A_2 cross sections. If we denote blood velocities in the tubes by υ_1 and υ_2 respectively, then the condition $\upsilon_1 \prec\prec \upsilon_2$ since $A_1 \succ\succ A_2$ .Then the second term in the right-hand side can be neglected and equation (4) takes the form

$$P_1 = P_2 + \frac{1}{2}\rho\upsilon_2^2 \qquad (5)$$

Since a small section of injection is opened to the atmosphere , then the effect of atmospheric pressure should taken into account in a exact calculations. In a simple calculations the pressure difference $P_1 - P_2$ in the equation (5) may be substituted by the ratio of the force exerted by our thumb F to the area A_1 In other words,

$$\frac{F}{A_1} = \frac{1}{2}\rho\upsilon_2^2 \qquad (6)$$

From this equation a speed of physioligical fluid in syringe is given by

$$\upsilon_2 = \sqrt{\frac{2F}{A_1}} \qquad (7)$$

Note, that in most references this equation is termed as syringe equation.

Atherosclerosis and blood pressure in vessels. During this disease, the walls of the arteries become thicker and the vessel narrows due to deposits accumulated on the inner wall of the vessel, which is called stenosis (Look at Fig.1). The blood speed is a function of elasticity modulus vessel's tissue and is expressed by the Moen-Kortveg formula [4, 5]:

$$\upsilon = \sqrt{\frac{Eh}{\rho\, d}} \qquad (8)$$

here E- is the Young's modulus of vessel tissue, h- refers to the thickness of the vessel's wall, $\rho -$ is the blood density, *d*- is the internal diameter of vessel.

One of the complications caused by stenosis can be explained by Bernouilli's equation. Let's suppose that the radius of the vessel has increased by 2 times. Then the area of the cross section decreases by 4 times, and this means that the speed in that section increases by the 4 times. In the narrowed part, the kinetic energy increases bya factor of $4^2 = 16$. The increase in kinetic energy is related to pressure loss. Fraction of the potential energy is converted into kinetic energy to maintain the flow at high speed. Due to the decrease in pressure in the narrowed part of the artery, the artery can be closed and the blood flow can stop due to the effect of external pressure. If such blockage occurs in the coronary artery that carries blood to the heart, the heart can stop working. A critical value for stenosis is considered to be 80%, because at this percentage the flow becomes turbulent and can cause damage to the vessel. This is explained by the fact,that the layer of sediment on the wall of the vessel can break off and block the narrowed part due to the pressure impact of a part of the blood on the wall of the vessel. If such blockage occurs in the neck artery, blood flow to some parts of the brain stops and this causes an ischemic stroke [4]. The walls of the artery have semi-elasticity. Blood spreads in pulses in elastic vessels and at this time the walls are subjected to expansion and compression (Look at Fig. 2).

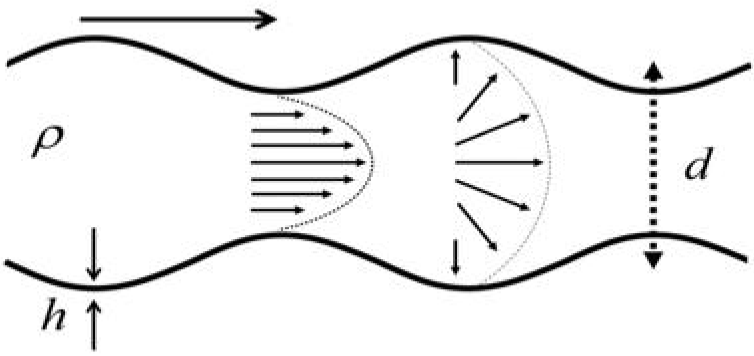

Figure 2

Newton and non-Newton fluids: Fluids have two subdivisions due to their viscosity dependent properties; Newton and non-newton fluids. For the Newton fluids the dynamic viscosity coefficient depends on the fluid's nature and its temperature. Such fluids obey the above Newton's equation and the internal frictional force is directly proportional with the velocity gradient. However, in nonnewtonian fluids, the dynamic viscosity coefficient depends on the velocity gradient in addition to the flow regime of fluid and temperature. As a real fluid a blood also possess viscosity and is a non-newtonian fluid being suspension of shape having elements in plasma. Practically, a blood plasma itself is a newton fluid. The 90% of shape having elements are erysrociytes. Main feature of erysrocytes is forming larger agregates by combination. Characteristic dimensions of erysrocytes and aggregates are in the following proportions; $d_{eryth.} \approx 8\mu m$, $d_{aggregate} \approx 10 d_{eryth.}$. Dependeng on the size ratio between erysrocytes, agrgates as well as blood vessels the internal friction does not obey to above equation (9). For aorta and arteries $d_{vessel} \succ d_{aggregate}$ and $d_{vessel} \succ d_{eryth.}$. In this case $\eta \approx 0.005 Pa \cdot \sec.$ In the small artery and arteriols $d_{vessel} \approx d_{aggregate}$ and $d_{vessel} = (5-20) d_{eryth.}$. In this case large aggregates are divided into erythrocytes and hence a friction with vessel walls is reduced. When condition of $d_{vessel} = 5 d_{eryth.}$ is fulfilled, the viscosity reaches 2/3 fraction of viscosity in the larger vessels. However in microvessels and capillaries $d_{vessel} \prec d_{eryth.}$. In this case erythrocytes undergo deformation in the capillaries of 5-6 μm diameter and the frictional area on the surface of thevessel wall increases. The viscosity values are estimated as follows: for the water $\eta_{Water} = 0.01 Poise.$, for the blood in normal case $\eta_{Blood} = (4{,}2-6)\eta_{Water}.$, in pathological state $\eta_{Blood} = (15-20)\eta_{Water}.$, during anemy $\eta_{Blood} = (2-3)\eta_{Water}.$ and viscosity of plasma $\eta_{Plasma} = 1{,}2\,\eta_{Water}.$.

Following types of blood flow are distingueshed:

1. Laminar flow. This kind of flow is regular and fluid flows with the "plates" being parallel to the direction of motion. In a laminar flow the speed of fluid changes according the parabolic law along the cross-section of a tube [6].

$$\upsilon = \upsilon_0 \left(1 - \frac{z^2}{R^2}\right) \tag{9}$$

where $R-$ is the radius of the pipe $\upsilon_0 -$ the flow speed along the axis of tube, and $Z-$ is the distance perpendicular to the direction of motion from the axis.

2.Turbulent flow. As the velocity increases the flow changes from laminar to turbulent,when the liuquid layers are mixed together and a large number of eddies of different sizes are formed in the flow stream. Small volumes of fluid move chaotically along complex trajectories. Turbulent flow is characterized by an irregular variation of the flow velocity with time at each point. The distribution of mean velocity along the pipe radius in turbulent flow differs from the parabolic distribution of laminar flow. In this case, the velocity increases faster in the parts near the walls and the distribution in the central part has less curvature. The velocity distribution in turbulent flow has a logarithmic dependence and the fluid flow regime is characterized by the Reynolds number [7].

$$\upsilon_{crit.} = \frac{\mathrm{Re}\,\eta}{\rho D} \tag{10}$$

where υ is the average velocity across the cross-section of the pipe, $D-$ is the diameter of the capillary tube. The Reynolds number Re is between 2000 and

3000 for many fluids. The movement of blood in the veins is considered laminar, except for some cases. When the blood enters the aorta from the left ventricle of the heart, the flow becomes turbulent in the branching parts of the arteries and in the places of narrowing of the vessels (when a thrombosis is formed). Because turbulent flow requires extra energy, it can cause extra strain on the heart. Noise generated during turbulent flow can be used to diagnose diseases. If we take $\mathrm{Re} = 2000$ and the diameter of the aorta as 2 cm in the above formula we get $\upsilon_{crit.} = 38cm/\mathrm{sec.}$ for the turbulent flow of blood. The flow rate of fluid is related to the radius of tube, difference in pressures, viscosity of fluid and length of tube through the Poiseuilli's formula [8]

$$Q = \frac{\pi R^4 \Delta P}{8\eta l}\Delta t \qquad (11)$$

where $\Delta P -$ is the pressure difference at the ends of tube, $\eta -$ is the dynamic viscosity, $\Delta t -$ is the time interval.

The method of bloodless pressure measurement is used in clinics by the Reva-Rocki method [9]. The arteriy is not accompanied by any sound. As the pressure of the cuff surrounding the arm decreases, low tones corresponding to the maximum systolic pressure are first heard. In the subsequent decrease in pressure noises are added to the tones which are an indicator of the turbulent flow of blood in the cuffed part of the artery.

The blood flow in human vessels is resisted by the so called hydraulic resistance. Remember, now the Ohm's law for a section of circuit given by

$$U = RI$$

Here $U -$ is the difference in potentials between the ends of wire, $R -$ resistance of wire, $I -$ is the electric current or amount charge that passes across cros-sectional area of wire per unit time. If we compare the pressure difference between the ends of tube with the difference in potentials betwen the ends of wire and the volume of fluid which flows across cross-section of tube per unit time with the electrical current then we can write

$$R_{hyd.} = \frac{8\eta l}{\pi R^4} \qquad (12)$$

The quantity $R_{hyd.}$ in (12) refers to the hydraulic resistance of fluid. Then formula (11) can be rewritten by

$$\Delta P = R_{hyd.} Q \qquad (13)$$

From the last formula it can be seen, that pressure change in vessels depends on the volumetric speed of blood and the radius of vessel. Calculation the formula (11) showed that decrease in the vessel radius for 20 percent causes increase in pressure by a factor of 2. According to the formula (12) the hydraulic resistance is different in various sections of blood vessels.

$$R_{hyd.aorta} : R_{hyd.arter.} : R_{hyd.cap.} \approx 3000:500:1$$

Since the hydroulic resistance is inverse proportional to the vessel radius , then

$$R_{hyd.cap.} \succ R_{hyd.arter.} \succ R_{hyd.aorta.}$$

To calculate the hydroulic resistance in vessels it should be taken into account, that vessels are parallel at junctioning sections. Then an equivalent hydraulic resistance can be calculated through reciprocals:

$$\frac{1}{R_{hyd.equiv.}} = \frac{1}{R_{hyd.1}} + \frac{1}{R_{hyd.2}} + ... + \frac{1}{R_{hyd.N}} \qquad (14)$$

Total cross-sectional area of capillary vessels in human body is larger by a factor of 500 as compared to the cross-sectional area of aorta. Then, from the continuity equation (2) for the linear velocity of blood we get

$$\upsilon_{cap.} \approx \upsilon_{aorta}/500$$

A speed of erythrosites in capillary vessels is about $\upsilon_{cap.} \approx 1\,mm/s.$. An exchange of substance in a blood and tissues in capillary system is possible due to slow motion of erythrosites.

Distribution of average pressure in blood vessels. When the left ventricle of the heart contracts, blood pressure oscillations are observed in the aorta. Average pressure is given by

$$P_{ave.} = P_{dias.} + \frac{P_{syst.} - P_{dias.}}{3} \qquad (15)$$

where $P_{dias.}$ and $P_{syst.}$ are the pressures during diastolic and systolic periods respectively. A decrease in average pressure along the blood vessels is analyzed with the Poiseuilli's law (11). A blood is pumped from the heart with average pressure $P_{ave.}$. Since a volumetric rate Q =const. and $R_{hyd.cap.} \succ R_{hyd.arter.} \succ R_{hyd.aorta.}$ then $\Delta R_{cap.} \succ \Delta R_{arter.} \succ \Delta R_{aorta.}$.

The average pressure drop in wide vessels is about 15%, while in small vessels it is 85%. This means that most of the energy spent by the left ventricle of the heart to expel blood falls on the small vessels.

CONCLUSIONS

One can conclude, that in nonnewtonian fluids, the dynamic viscosity coefficient depends on the velocity gradient in addition to the flow regime of fluid and temperature. Hydraulic resistance in vessels increases with decrease in vessel radius. Decrease for average pressure in a wide vessels is less as compared to the narrow vessels. Hydraulic resistance is inverse proportional with the fourth power of vessel radius. Equivalent hydraulic resistance is calculated with the rule of calculation of equivalent resistance in parallel electrical wires.

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