Analysis of the hydrodynamic causes of thrombosis and hemolysis in the centrifugal pump of the artificial blood supply system

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Abstract. The article is devoted to the analysis of the hydrodynamic causes of complications of the use of centrifugal pumps in artificial circulation systems. In the treatment of cardiovascular diseases, rotary pumps began to be used: centrifugal, axial and disk. Of the three types of rotary pumps, centrifugal pumps have the highest power density due to the use of centrifugal force. Statistics show that the greatest blood damage in the form of thrombosis and hemolysis is observed in these pumps. The article concludes that the main hydrodynamic cause of thrombosis and hemolysis is the force field formed by the centrifugal force of inertia, which generates vortex and separation zones. When passing through these zones, red blood cells experience intense hydrodynamic effects in the form of local accelerations and impacts against the walls of the channels, which leads to their deformation, and then to the destruction of some red blood cells. On the one hand, thanks to this force, the intensity of energy conversion in a centrifugal pump becomes higher compared to other types of pumps. On the other hand, a large unevenness of speed and pressure occurs in the channels, which has a traumatic effect on red blood cells. Hydrodynamic solutions to weaken the force field that injures red blood cells will inevitably be accompanied by a decrease in the intensity of energy conversion and the benefits of using this type of pump.

1 Introduction

The disadvantage of the functioning of artificial circulatory systems (ACS) is thrombosis and hemolysis, which consists in the destruction of the membrane of red blood cells, which are the carrier of oxygen to the cells of the body. The transfer of oxygen is carried out using a complex red protein contained in the cytoplasm of red blood cells - hemoglobin. An erythrocyte in the form of a biconcave disk with a diameter of 7 to 10 microns freely passes through the vascular system to the cells of the body, delivering oxygen to them and taking away carbon dioxide. In a natural physiological mode, hemolysis of red blood cells in a living organism occurs in approximately 120 days.

Statistics on thrombosis and hemolysis in ACS with rotary pumps indicate that the greatest blood damage is recorded in centrifugal pumps (CP) [1, 2]. Those. CPs have two

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conflicting properties: better weight and dimensional parameters and worse hemocompatibility. This indicates the relevance of analysis in 2 directions:

- assessment of the energy reasons for the advantages of using centrifugal pumps compared to other types of pumps;
- analysis of hydrodynamic causes of mechanical hemolysis in the impeller of a centrifugal pump.

1.1 Types of rotary pumps for artificial circulation systems

The principle of operation of rotary pumps differs significantly from the mechanism of operation of the natural heart. Based on its operating principle, the heart can be classified as a volumetric pump. It does not have a rotor with an impeller, and the conversion of mechanical energy into pressure occurs by compression - reducing the volume of the working cavity (right and left ventricles of the heart) with subsequent pushing of blood through a check valve into the atrium. The pump design, similar to a natural heart, is large and has a bulky power supply system.

An alternative to displacement pumps has become rotary pumps, their speed is high, and therefore small-sized designs [3, 4]. In particular, such pumps have long been used in space systems [5]. They are part of low-power energy systems for thermal regulation and life activity and ensure fluid circulation in a closed circuit of the system. For example, on board the Mir orbital stations and the ACS, dozens of small-sized centrifugal pumps were installed in various circuits of life support and thermal control systems.

The parameters of space system pumps have energy parameters similar to ACS pumps. Therefore, the first mechanical ACS pump, commissioned by Dr. M. DeBakey, was developed by specialists in the aerospace industry [6].

Figure 1 shows a general view of the flow cavity of 3 types of rotary pumps used in space and medicine. These are axial, centrifugal and disc pumps [7-9]. From an energy point of view, they belong to rotary machines, because The rotor torque generated by the electric drive is used as the initial energy. In pumps, the mechanical energy of rotation of the rotor is converted into hydraulic energy of the pumped liquid. Rotary pumps differ from each other in the way they convert mechanical energy into hydraulic energy. In particular, in axial and centrifugal pumps, thanks to the profiling of the inter-blade channels of the impeller, a pressure drop is formed in the radial and circumferential directions. This provides increased flow swirl. At the outlet of the pump, the velocity is converted to static pressure. In disc pumps there are no blades and the conversion of mechanical into hydraulic flow energy is carried out due to disc friction.

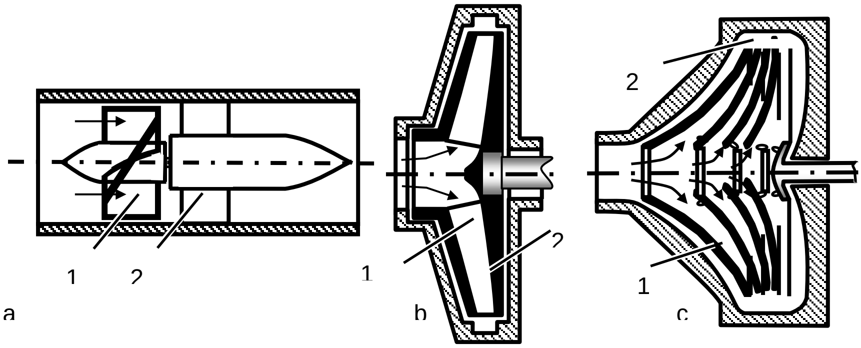

Fig. 1, Rotary pumps: a - axial pump; b - centrifugal pump; c - disc pump

1 - impeller; 2 - outlet device

1.2 Advantages of centrifugal pumps

Of the three types of rotary pumps, the most intensive energy conversion occurs in the central pump. Thanks to the centrifugal force, which throws the liquid from the center to the periphery, the speed of the pumped flow further increases. As a result, the size of the CP decreases. In Figure 2 shows a diagram of a centrifugal pump integrated into the flow part of the artificial circulation system [10].

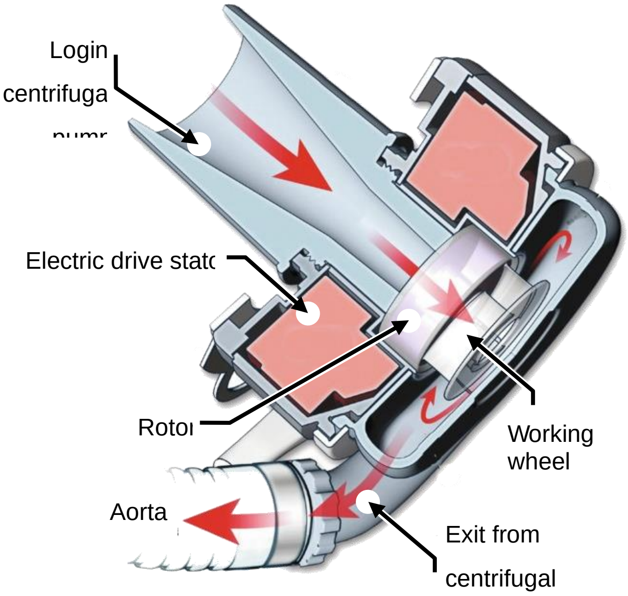

Fig. 2, Centrifugal pump in the artificial circulation system

2 Hydrodynamics of flow in centrifugal pumps

The works of Russian scientists are devoted to the application of ACS: Demikhov V.P., Shumakov D.V., Bockeria L.A., Gauthier S.V., Itkin G.P. and others [11, 12].

The works of most authors provide statistics on complications and unfavorable outcomes of the use of ACS, anticoagulant therapy regimens, and options for blood clots getting from the pump into the vessels, but do not study the hydrodynamic causes of pump thrombosis [13-15].

2.1 Models of flow in a centrifugal pump

Common theoretical models of flow in CPs are based on the principle of continuous flow. As an example of such an approach, we can point out Euler's jet theory, which is based on the assumption that the flow in the inter-blade channels of the CP impeller is uniform. The disadvantage of the theory is that flow uniformity can only be ensured with an infinite number of blades of zero thickness. Correction for the reality of the process and the transition from the pressure with an infinite number of blades, denoted $N_{t\infty}$ (the index “t∞” is generally accepted and means: “t” - theoretical, “∞” - an infinite number of blades) to the actual pressure N is carried out using empirical hydraulic parameter k_z [9].

An alternative to Euler’s theory could be the non-uniform, 2-zone “Jet-trace” flow model of the authors K.P. Seleznev. and Galerkin Yu.B., in which the term “Jet” refers to a high level of energy (turbulent flow regime), and “trace” to a low energy level (flow separation and not flowing regime). The disadvantage of the “Jet-trace” model is that it ignores an important feature of the hydrodynamics of small-sized CP ACS – the existence in the channels of a “thick” boundary layer, leading to an increase in tangential stresses and the formation of not a plane, but a spatial flow in the form of intense secondary flows and a paired vortex generated by them. Secondary flows are understood as flows that do not coincide in direction with the flow core. It is impossible to eliminate secondary flows from the inter-blade channel of the impeller, since their occurrence is determined by the operating principle of the pump itself.

Based on the analysis, it follows that:

1) ACS pumps are small-sized and low-flow centrifugal pumps. The Reynolds number in them in terms of relative speed is only Re=1000...10000. This leads to an increase in the relative thickness of the boundary layer;

2) studies of the hydrodynamics of flow in the central circulation do not consider the influence of the nature of the flow on hydrodynamic factors that injure the pumped blood.

Therefore, the existing models of flow in the channels of the central pump of the ACS cannot be considered as a theoretical basis for the development of new designs of centrifugal pumps of the ACS.

Optimization of the channel geometry of the CP ACS is possible only taking into account the dominant hydrodynamic features – an increase in the thickness of the boundary layer, flow separation and vortex formation. The consequence is 2 negative consequences:

- medical factor – an increase in the size of hematologically unfavorable flow zones in the total volume of the interscapular canals;
- energy factor – “slippage” of the flow, which reduces the pumping capacity of the central pump.

In addition, to optimize the geometry of channels of the CP ACS, it is irrational to use known numerical design methods because these methods apply to full-sized pumps in which the relative boundary layer is thin. To clarify the calculation algorithms and check the reliability of the results obtained with their help, i.e. Validation requires experimental data on the flow structure, which is currently not available in the literature.

2.2 Models of hemolysis

Currently, there are 2 known models of hemolysis that have a hydrodynamic origin [17]:

1. Shear stress model. As a mechanism of the traumatic process, tangential stresses in layers of liquid are considered according to the principle hemolysis is the shear stress of layers of blood relative to each other or relative to the washed surfaces. This model is acceptable for a flat laminar flow regime, which occurs only in stationary straight channels and vessels and is absent in the interblade channels of the central pump impeller.

2. Deformation model. The mechanism of hemolysis is considered to be the deformation of erythrocytes under the influence of a shock load or a difference in static pressure in the channels. The disadvantage of the model is the assumption of the ideal, i.e. theoretical rather than real distribution of static pressure in the channels of a centrifugal pump. In fact, the difference in speeds and pressures in zones of different energies is significantly greater.

Both models are united by the hypothesis that there is a uniform flow in the pump, which does not correspond to the known data on the hydrodynamics of flows in the central pump. At this time, there are no clear practical recommendations on the limits of applicability of these models, especially since they do not indicate the hydrodynamic causes of thrombosis and hemolysis in the CP ACS.

3 Vortex formation as a hydrodynamic cause of hemolysis

A simplified model of a paired vortex looks like a pair of toroidal vortices adjacent to the ends of the impeller channels, in which particles move along spiral trajectories. The real picture of vortex formation in the interblade channels turns out to be much more complicated. For example, in Fig. 3 shows a diagram of a paired vortex at the exit of the impeller (top view), consisting of two main geometrically nonequivalent secondary vortices, asymmetrically located in the channel, conventionally designated vortex A and vortex B, as well as several local vortices located in the corner sections of the channels and along the back sides of the shoulder blades.

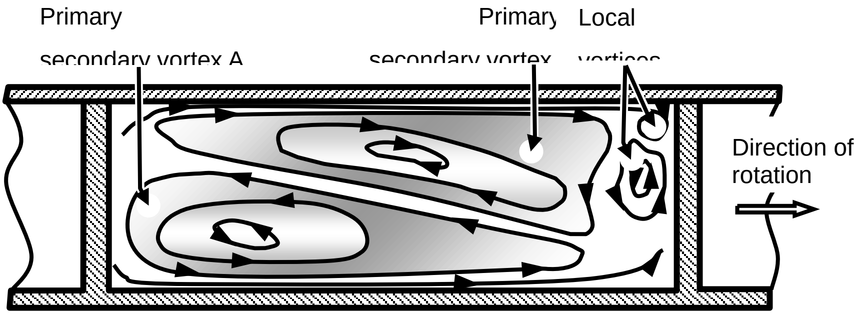

Fig. 3. Vortex system in the interblade channel of the impeller (according to data from [18])

The energy costs of the existence of a system of vortices in the interscapular channels are energy losses proportional to the level of their intensity, as well as the traumatic effect of vortices on erythrocytes, which leads to rupture of the erythrocyte membrane and the formation of blood clots.

In addition to vortex formation, an important consequence of the processes occurring in the boundary layer zone is flow separation [19]. Despite the fact that in the channels of real centrifugal wheels the flow is, as a rule, of a diffuser nature, typical schemes for their calculation, as mentioned above, are based on the principle of continuous flow in the flow part. such as Euler's jet theory.

The principle of continuous flow is an idealized scheme. Analysis of visualized flow patterns [20] showed developed separation zones, in particular, along the back side of the blades.

Flow separation is explained by the fact that due to an increase in the cross-sectional area of the impeller channels when moving from the center to the periphery, the degree of diffusivity of the channels increases, which is characterized by the coefficient $\bar{F}=F_2/F_1$, where F1 is the cross-sectional area of the channels at the inlet, F_2 – cross-sectional area of the channels at the exit from the impeller channels. In ACS centrifugal pumps, the coefficient $\bar{F}$ can reach values $\bar{F}$ =3...8. Due to large $\bar{F}$, the static pressure increases, impeding the flow and causing flow separation. Flow separation begins almost from the entrance to the channels, then transforming into an area having a triangle contour with an upper boundary shifted above the radial middle of the channels. The location of the corner vortex is along the pressure side of the blades. The zone of secondary flows is located along the perimeter of the separation zone.

Flow separation in the impeller channels occurs due to an increase in the thickness of the boundary layer along the blade profile to critical values. It has been experimentally established that in the interblade channels of the rotor blade the level of relative velocities is lower at the back side of the blades, therefore flow separation is observed primarily in this area of the interblade channels. The appearance of a separation zone along the back side of the blades of the central pump impeller is accompanied by the formation of a flow-free stagnation zone extended along the outlet section of the blades. The lack of high-speed pressure in the flowless zone contributes to the formation of blood clots.

4 Conclusion

Summarizing the above, we can come to the following conclusions.

The actual flow pattern in the inter-blade channels of the CP impeller is a complex flow, which is generated by two operational factors: low blood flow (up to 200 ml/s) and small dimensions (diameter of the inter-blade channels is less than 50 mm), which generate an increase in the relative thickness of the laminar boundary layer . The magnitude of the velocity pressure in the boundary layer to overcome the positive static pressure gradient along the interblade channels turns out to be insufficient. Moreover, the specific gravity of the mass of liquid involved in the flow not along the main trajectory of movement, from the inlet to the outlet of the impeller channels, but along the secondary trajectory, from the pressure to the back side of the blades, in small-sized central parts becomes significant. Flow separations, secondary flows and vortex formation occur. This uneven structure of the spatial flow in ACS pumps becomes the main reason that has a negative effect on the blood. Red blood cells in the interblade channels of a centrifugal pump impeller experience intense hydrodynamic influence, passing through a system of vortices, a separation zone, as well as through the force field of centrifugal and Coriolis inertia forces.

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