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HYDRODYNAMICS OF NEW GENERATION CARDIAC VALVE PROSTHESES

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Abstract. The article demonstrates the results of the experimental investigation of the hydrodynamic and kinematic characteristics of bileaflet cardiac valve prostheses of new generation. At present cardiac valve prostheses (CVP) are used in cardiac surgery for replacement of diseased natural valves. The article also presents the results of study of ROSCARDICS (Russia) and BUTTERFLY (Germany), the new generation bileaflet valves. The study of hydrodynamics of valves was conducted by means of the photochromic visualization method (visualization of flow). The method is based on activation of color tracers in the originally colourless photochromic solution by pulse laser radiation. The carried out investigation has shown that the valves of a new generation have better hydrodynamic characteristics as compared with the best models of CVP, widely used in clinical practice.

Key words: photochromic flow visualization method, artificial heart valves

Background

Cardiac valve prostheses are used in cardiac surgery for replacement of diseased natural valves. Implantation of cardiac valve prostheses (CVPs) is one of effective ways used for treatment of diseased cardiac valves. CVP implantation recovers the pump function of the heart and also improves general hydrodynamics [1-4]. Over the past 10-15 years the world cardiac centers have been using ST. JUDE (USA) and CARBOMEDICS (USA) bileaflet valves [1-3]. Implantation of these valves gives good clinical results but their characteristics considerably differ comparing with natural valves. One of the trends of improving the characteristics of CVP is improving hydrodynamics of the valve. The full opening of leaflets leads to creation of an orifice for blood flow. Widening a blood flow orifice at the moment of the full opening of leaflets improves the hydrodynamic characteristics of CVP. In this case a valve has a smaller pressure drop and, as a result - smaller loads on the heart, it gives smaller hemolysis of blood. All these factors influence long-term results in patients with implanted CVPs, especially, in cases when two-three CVPs have been implanted. Therefore, the search of valve models with better hydrodynamic and kinematic characteristics, lower murmur and hemolysis levels is an urgent task.

ROSCARDICS (Russia) belongs to a new generation type of bileaflets, such as ST. JUDE Medical (Masters) (USA) and CARBOMEDICS (USA), widely used in cardiac surgery. ROSCARDICS CVP is a valve with a low profile of velocity, having two locking elements and increased reliability.

The semicircular turning leaflets located inside the ring open and close the effective orifice of the valve. Titanium (the material of the ring) and carbon (the material to construct the leaflets) have unique biocompatibility, high mechanical properties and durability.

Unlike such bileaflet valves as ST. JUDE and CARBOMEDICS, ROSCARDICS has a large effective orifice flow area at the moment of the maximum flow through the valve. At the present moment the development of the valve has been completed and it is being tested clinically. The article includes the findings of the study of the valve hydrodynamics under conditions of a model physiological flow.

Another new generation bileaflet valve which is dramatically different from ST. JUDE, CARBOMEDICS and ROSCARDICS is BUTTERFLY (Germany). BUTTERFLY valve is still in the stage of development and the technology of this valve is more complex, than that of modern bileaflet CVPs. The key difference of the valve consists of the fact that it has two bileaflets, located on one axis misaligned comparatively to the axis of symmetry of the lifting ring of the valve. Such arrangement of leaflets provides a larger orifice area at the moment of full opening, compared with ST. JUDE, CARBOMEDICS and ROSCARDICS bileaflet valves.

Experimental method

During the research of the CVP hydrodynamics the photochromic visualization method was used, as it has obvious advantages over other methods of investigation of hydrodynamic flows behind the valve. The flow behind the valve is non-steady and has complex spatial distribution, therefore, the photochromic visualization method of study of CVP hydrodynamics, used in the course of the research, underwent a number of essential changes [5-6]. The photochromic visualization method photochromic visualization is based on the activation of color tracers in an originally colorless photochromic solution using pulse laser radiation during 10^{-6} to 10^{-9} seconds.

Development of the photochromic visualization method at the Institute for Problems of Mechanics, the Russian Academy of Sciences begun in 1985 [5-6]. The improvements made to the photochromic flow tracer helped to develop visualization systems with several tracers. Consequent investigations allowed using water solutions as a model fluid.

Color tracers in the photochromic solution were produced by using the radiation of the second harmonic of ruby lasers at the wavelength of λ = 347 nm. The equipment used for the experiment included two ruby lasers with the second harmonic optic generators.

The flow structure behind artificial heart valves was studied under steady flow conditions in the course of a special series of experiments. The results of the experiments showed that the photochromic visualization method could be used for analyzing the structure and degree of homogeneity located behind cardiac valve prostheses. This, in turn, helps to obtain information, which can successfully be used for comparison and development of cardiac valve prostheses [1-6]. In the next series of experiments, the flow structure behind cardiac valve prostheses was studied under conditions of pulsating flow [6]. The measurements were made on a special hydrodynamic model shown schematically in [5-6]. The fluid velocity measurements were carried out in two cross-sections at distances of between 13 and 26 mm. from the ring valve. Pump frequency was 60 beats/min. Stroke volume was fixed at 70 ml. Systolic duration was 400 ms. and 600 ms., respectively, during all measurements.

During the investigations of hydrodynamics of the cardiac valve prostheses by means of photochromic visualization, a model photochromic physiological liquid was used. The composition of this liquid was very complex. The makeup of this composition included: (1) glycerin; (2) distilled water; (3) salt; (4) an interface activity substance; (5) a photochromic substance; and (6) a blood substitute (Rheopolyglucinum). The addition of a blood substitute to the photochromic solution was made as the first step. The result of this addition was that the life-time of the photochromical solution was increased from three to thirty days. This result was achieved due to the special effects of the blood substitute, which prevented mixing the aggregate solutions. During this experiments the photochromic solutions with the kinematic viscosity of $\nu = 0.03\,\text{sm}^2/\text{s}$ and with the maximal viscosity of $\nu = 0.1\,\text{sm}^2/\text{s}$ were used.

The model physiological photochromic solution with the viscosity of $\nu = 0.03\,\text{sm}^2/\text{s}$ has the following proportions: glycerin (31.6 %); distilled water (62.7 %); photochromic substance (0.002 %); salt (0.8 %); surface activity substance (0.85 %); blood substitute (4.048 %).

This solution was utilized only for the opening and closing phases of the valve.

The remaining model of physiological photochromic solution with the viscosity of $\nu = 0.1\,\text{sm}^2/\text{s}$ was utilized to investigate the fluid dynamics of the valves and to determine the opening and closing times of the valves. This solution was composed of the following proportions: glycerin (59.6 %); distilled water (35.4 %); photochromic substance (0.002 %); salt (0.74 %); surface activity substance (0.57 %); blood substitute (3.688 %).

During our experiments, laminar flow could be observed in front of the valve. This was due to the fact that the photochromic solution used for investigation of the hydrodynamics of the cardiac valve prostheses was quite viscous. As a result, turbulent flow was a direct result of the valve performance. This is very important because when we investigated the fluid dynamics of the valves, the inspection was conducted in a non-flexible tube.

To test hydrodynamics of ROSCARDICS and BUTTERFLY, the aortal position was chosen. The aortal position is most difficult to investigate because it forms a more complicated velocity area than that of the mitral one.

Utilizing a high-speed camera, photographs of both ROSCARDICS and BUTTERFLY valves during their complete working cycle were taken. This investigation includes results taken from kinematic studies of each valve during the abovementioned working cycle. Each valve has specific characteristics related directly to their opening and closing phases.

Study results

"ROSCARDICS"

ROSCARDICS is a bileaflet valve with a low profile of velocity, which has two leaflets-closing elements. Figure 1A illustrates the cross-sections of ROSCARDICSC bileaflet valve and the arrangement of axes, with the leaflets completely open. As for the coordinate system shown in Fig. 1A the flow features behind the valve were investigated at various cross-sections. In Fig. 1A it is possible to see the bloodstream going between the leaflets creating a central flow and a flow between the walls and the leaflets. Appearance of a flow between the leaflets in the form of a jet has allowed classifying the valve as valve with a central flow. Disk CVPs, which are also widely applied for implantation, do not have a central flow [1, 6].

The investigated valves were installed on a hydrodynamic bench simulating physiological flow through valves [2-3, 6]. On such a bench it was possible to change a number of cycles of the valve, flow rate of the fluid simulating blood, pressure in front of the valve.

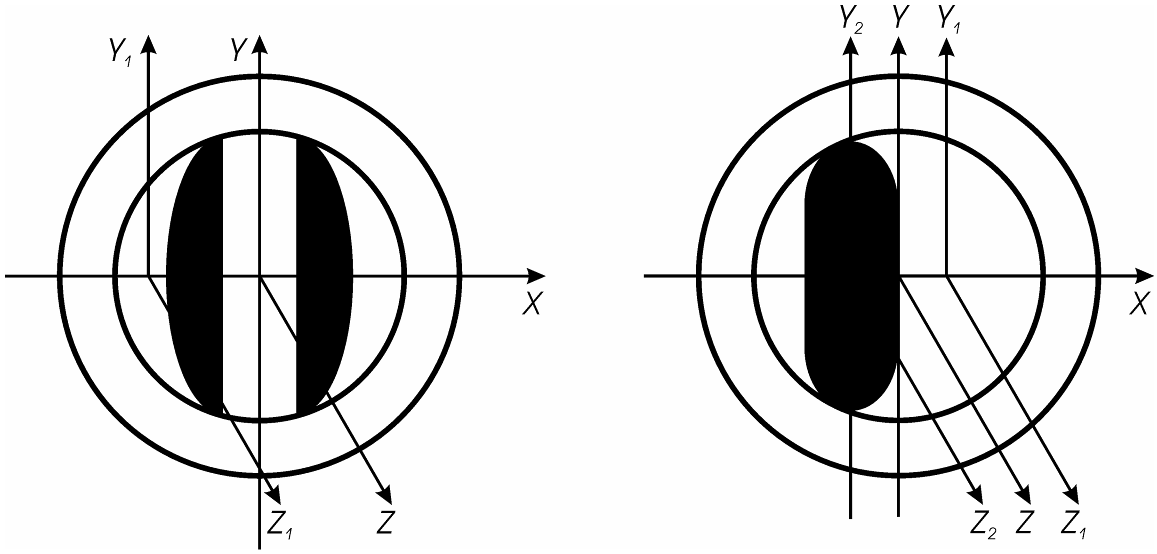

Fig. 1. The cross-sections of ROSCARDICS and BUTTERFLY bileaflet valves.

The analysis of movement of a tracer in a flow obtained by a high-speed camera demonstrates various phases of opening and closing of the valve. The use of a high-speed camera allowed determining kinematic characteristics of the valve. The kinematic characteristics include also the time of opening and closing of the valve and the character of motion of leaflets. It was possible to observe that both leaflets of ROSCARDICS valve in the stage of opening began to open simultaneously. However, in the stage of closing one leaflet began to close first and only after 0.02857 seconds the other one did. The results of high velocity filming and processing the obtained data allowed determining the times of opening and closing of ROSCARDICS.

Time of opening of ROSCARDICS valve was T_{open} = (0.057 $\pm$ 0.0019) s; time of closing of ROSCARDICS valve was T_{close} = (0.065 $\pm$ 0.00221) s.

Comparing the time of opening and closing of the ROSCARDICS CVP with the time indications of disk valves we can say that this valve is a fast-response valve and its parameters are close to the physiological ones.

The use of photochromic visualization method for research of hydrodynamic bileaflet CVPs under the conditions of model physiological flow allows to see the structure of a flow in one cross-section, not distributing the flow of the model [1-3, 5]. Laser radiation created color lines formed behind the valve at certain moments of a working cycle of the valve and high-speed camera registered the motion pattern of tracers in the flow. Each stage of activity was characterized by a specific flow pattern behind the valve. Therefore, several stages of operation of the valve were determined. Figure 2 shows the profiles of velocity obtained in the *X-Z* plane. From the mentioned profiles it is possible to select the following stages of activity of the valve.

The first stage: the leaflets begin to open. At the same time, a velocity profile behind the valve is slanting and velocities are slow. For this stage the condition of bloodstream behind the valve after its closing is of high importance. As after the closing the flow velocity sharply drops, the stagnation and circulating zones behind the valve are being formed which should be washed out after the beginning the opening of the valve. Areas of closed circulation should be of small size, which is possible to observe during the experiment and after the beginning leaflets motion; these areas begin to move forward. The end of this stage is characterized by formation of two peaks of a velocity profile with a slight delay, the flow

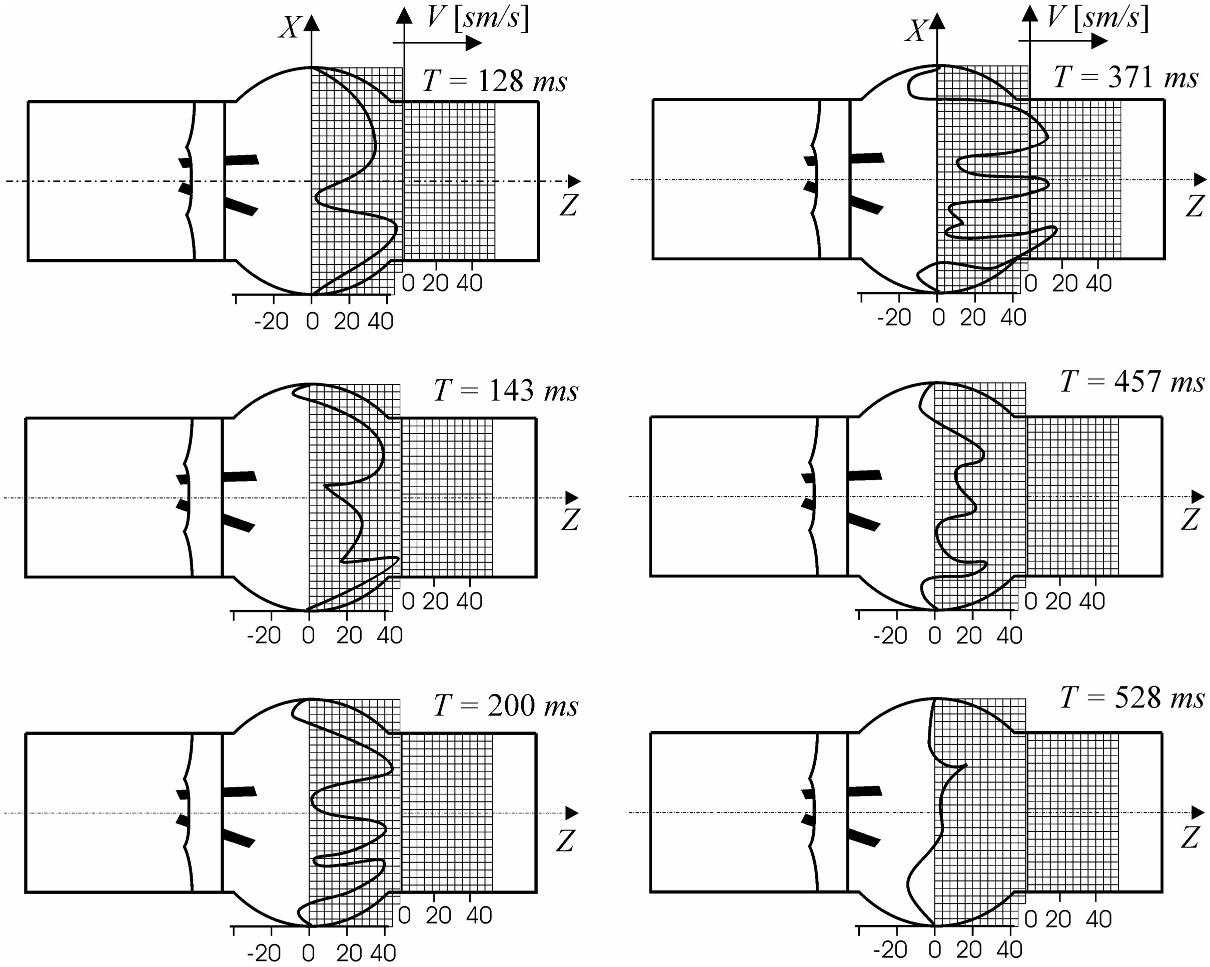

Fig. 2. The profiles of velocity behind valve ROSCARDICS in the X-Z plane.

begins passing between leaflets, as shown in Fig. 2. Thus, at this stage the flow is performed in all areas opened for an incoming flow between leaflets and also in circumferential regions.

The second stage: the leaflets are completely open, the flow through the valve accelerates. It is possible to observe formation of three areas of jet flow, but peak velocities are still insignificant. The intensity of velocity in jet flow areas increases, it is the stage of acceleration of a flow through the valve at T = 143 ms (T is the duration of one cycle of activity of the valve, in our case T = 1 sec); Fig. 2 illustrates the formation of the jet flow. The flow begins to stream between the leaflets. The flow rate through the valve is increasing all the time. Then the peak velocity between leaflets becomes equaling to the peak velocity in the outlying fields. Above the upper leaflet in the sinus field the circulating counter-clockwise flow is being formed. At T = 371 ms the velocities achieve their peaks and their values in the jet flow field become approximately identical. On the boundary line between the central area of the jet flow and the lower area of the jet flow the vortices formation is created which results in instability of the velocity profile at the outlet from the sinus. Such phenomenon is typical for all bileaflet valves.

The third stage is characterized by slowing down of the flow rate and closing of the valve. The velocities drop in all areas. It is possible to see in Fig. 2 at T = 457 ms. The decrease of the peak velocity in the central jet flow is due to the fact that on the boundary lines between the zones of jet flows the areas of closed circulation are formed which slow down the central jet. As it is illustrated in Fig. 2 at T = 528 ms a profile of velocity in the plane *X-Z* becomes unstable. For activity of the valve in the horizontal plane or with small slope to a vertical plane of the valve it is observed that a back flow is formed under the lower leaflet which begins to close the lower leaflet, and the velocity between the leaflets drops down to zero. Above the upper leaflet the extensive area of closed counter-clockwise circulation is formed. The valve closes.

The obtained results of flow visualization indicate that ROSCARDICS valve is a valve with a central flow. At the moment of full opening the flow through the valve goes through all three areas: between leaflets, as well as over and under the leaflets. The times of opening and closing of the valve are similar to physiological parameters and, thus, it is noted that recoil of the leaflets was not observed during the closing period. Recoil of the leaflets was observed in ST. JUDE valve. The phenomenon connected with the recoil of leaflets increases dynamic regurgitation of the valve (back flow to the ventricle at the moment of closing) and blood hemolysis. Such process of closing of the valve without recoiling of the leaflets reduces the volume of dynamic regurgitation and the level of hemolysis of blood. A weak circulating flow formed after the closing behind the valve is carried away by the flow at the beginning opening of the valve which reduces probability of a blood clot formation, especially, in the sinus. Sinuses are also washed well by the filling flow.

The article presents the findings of the investigation of the flow pattern in the *Y-Z* plane [6].

The research activities of the hydrodynamic characteristics in the *Y-Z* plane have provided the following results.

– The current in the form of a narrow jet is formed between the leaflets, the size of which amounts to 30 % of the sinus's diameter while the remaining part of the sinus's diameter is occupied by stagnation areas.
– In the outlying areas (between a wall of the pipe and a leaflet) the current has a flat profile and the peak velocity increases.

It is necessary to note that in the *Y-Z* plane between the leaflets the jet flow area is formed while in the outlying regions a stagnation area is created, as shown in Fig. 3. The jet flow area of ROSCARDICS valve is more intensive than that of ST. JUDE valve, that is, the flow volume passed between the leaflets of ROSCARDICS is higher than that of ST. JUDE.

Kinematic study of ST. JUDE valve shows that, though leaflets close simultaneously, there is recoil of leaflets after closing. After implantation this defect results in prolongation of the closing time, dynamic regurgitation and greater blood hemolysis.

"BUTTERFLY"

BUTTERFLY bileaflet valve has a more complex production process than of the one of ST. JUDE and ROSCARDICS. Valves of ST. JUDE-type have symmetrical geometric characteristics but BUTTERFLY valve has the following asymmetrical characteristics.

1. The leaflet turning axis is located non-symmetrically comparing with the symmetry axis of the ring of the valve.
2. The leaflets are located on a turning axis non-symmetrically.
3. The leaflets are of different size, weight and form.

Thus, taking into the account the fact that there are two bileaflets of different weight and size operating in the valve, it is natural that the kinematics of such valve differs from that of bileaflets valves. Although the bileaflets begin to open at the same time due to the fact that the lower bileaflet is smaller, the lower bileaflet is in the fully open position prior to the opening of the upper leaflet. However, the upper bileaflet continues its opening motion until it is fully open. At first, only the lower bileaflet begins to close. After it is completely closed, the upper bileaflet begins the process of the closure. The time period for the closure of the upper bileaflet is approximately 0.04 seconds.

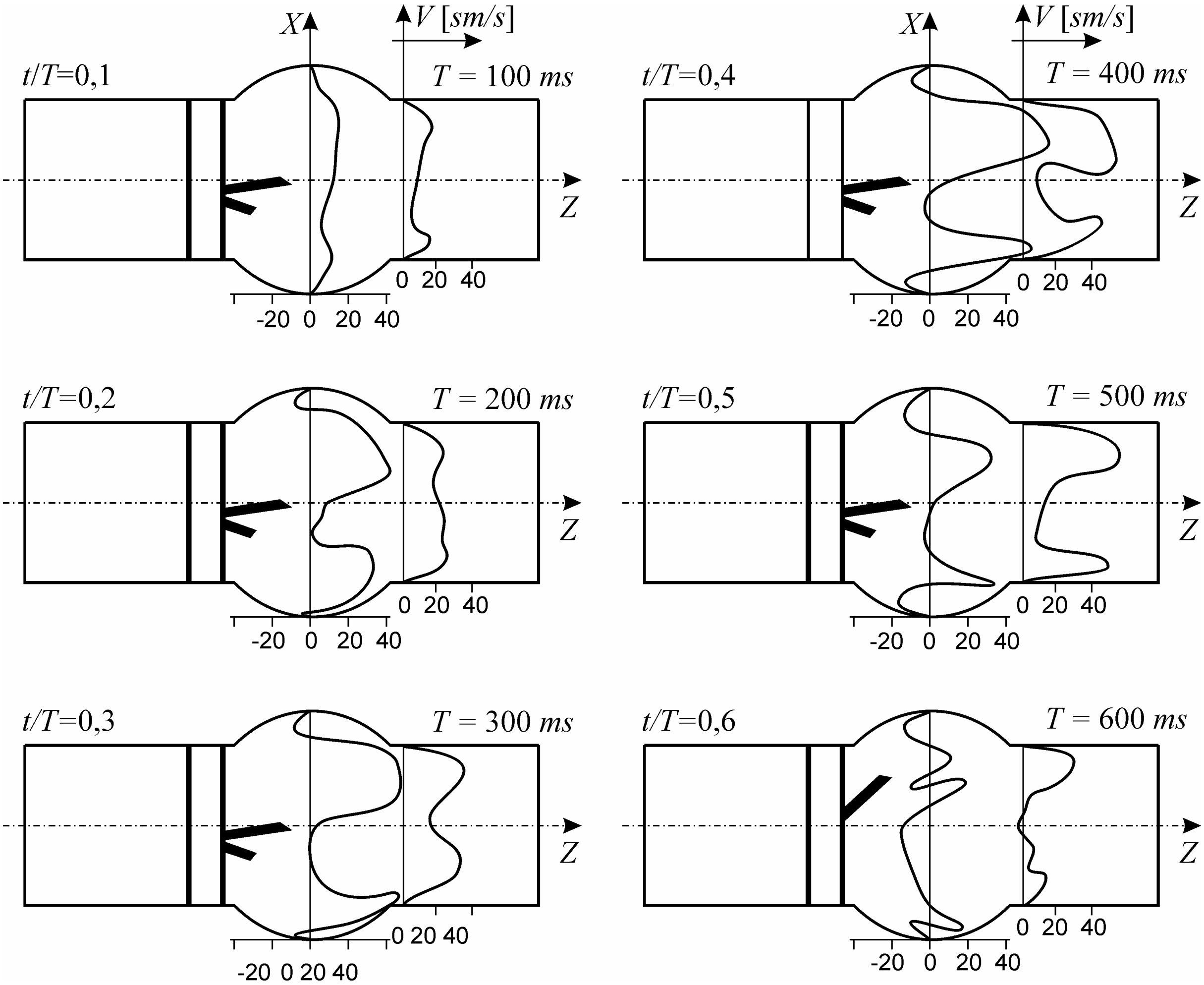

Fig. 3. The profiles of velocity behind valve BUTTERFLY in the X - Z plane.

In order to determine the influence of the kinematic viscosity of the photochromic solutions on the opening and closing times, these experiments used photochromic solutions with the kinematic viscosity of $\nu = 0.03\,\text{sm}^2/\text{s}$ and with the maximal viscosity of $\nu = 0.1\,\text{sm}^2/\text{s}$.

The kinematics viscosity of the photochromic solutions did not affect the opening and closing times.

The opening time for $\nu = 0.03\,\text{sm}^2/\text{s}$ was $t_{op} = (0.0755 \pm 0.00165)\ \text{s}$; the closing time for $\nu = 0.03\,\text{sm}^2/\text{s}$ was $t_{cl} = (0.0855 \pm 0.00243)\ \text{s}$.

The opening time for $\nu = 0.1\,\text{sm}^2/\text{s}$ was $t_{op} = (0.0707 \pm 0.00426)\ \text{s}$; the closing time for $\nu = 0.1\,\text{sm}^2/\text{s}$ was $t_{cl} = \left(0.0738 \pm 0.003167\right)\text{s}$.

While the viscosity of a model physiological solution was equal to the viscosity of blood, the times of the opening and the closing practically did not change. The use of high-speed filming during the investigation of the kinematic activity of the valve brings light on the motion of leaflets.

In the process of the closing of BUTTERFLY valve the lower leaflet starts the closing first which can be seen in the film. The lower leaflet touches the ring of the valve, after that the upper leaflet begins to close. At the same time it is necessary to note that there is a large orifice at left above the upper leaflet. The valve closes softly and recoil of the leaflets has not been observed.

The analysis of development of a flow behind BUTTERFLY valve shows that during one cycle it is possible to single out three stages similar to the ones of ST. JUDE valve.

The first stage: the valve begins to open, t/T = 0.0 - 0.2.

The flow pattern behind the valve before the beginning opening presents weak circulating clockwise flow. If leaflets begin opening at t/T = 0, at t/T = 0.1 the leaflets are already open and the slanting profile directed along the flow is observed behind them.

The second stage: both leaflets are completely open and the flow begins to accelerate through the valve, reaching the maximum value at t/T = 0.4. The stage of acceleration occurs at t/T = 0.2 - 0.4.

The velocity profiles of this stage are presented in Fig. 3. At t/T = 0.3 the jet flow profile above the upper leaflet is close to parabolic and under the lower leaflet there is an area of a flow in the form of a narrow jet. A stagnation area between the leaflets is formed, the sizes of which change. The maximum stagnation zone amounts to t/T = 0.3, but at the outlet from the sinus the stagnation area disappears and it is possible to observe the profile of velocity with two peaks at the distance from walls equaling approximately 0.25 of the internal diameter of the valve. The maximum value of velocity is reached at t/T = 0.4, the sizes of the stagnation area decrease. The peak velocity in the jet flow above the upper leaflet is little higher than in the jet flow area under the lower leaflet. In the sinus area a weak back flow area is being formed.

The third stage occurs at t/T = 0.5 - 0.9, the lower leaflet is already completely closed. The intensity of velocity in the area of jet flow above the uppers leaflet in the open position is increased and the upper leaflet begins to close. The turbulence area in the sinus above the upper leaflet begins to move towards the area between the leaflet and the wall of the pipe.

The further results of research in other cross-sections of the flow using a ruler and flat color tracer were obtained earlier [6]. Creation of linear color tracers made it possible to investigate local characteristics of a flow, and its combination with a flat color tracer provides fuller information on the flow pattern behind the valve.

Figure 4A demonstrates the profiles of velocity behind the valve in the Y_1 - Z_1 plane. This plane is characterized by the fact that it is located above the top of the greater leaflet at 5 mm. During the flow acceleration stage the distribution of velocity has a parabolic profile of velocity, which remains at the outlet of the sinus. In an actual valve in a live organism such distribution of velocity is observed in all cross-sections of a healthy valve. It is necessary to note that such distribution of velocity is observed in half of cross-sections of the valve, minus the area of the sinus. In sinus a weak back flow is observed.

The character of distribution of velocity in the Y_2 - Z_2 plane is shown in Fig. 4B. This plane goes through the axis of leaflets turning, where the stagnation area is formed, the size of which in this plane is close to a minor diameter of the valve. As the flow velocity through the valve increases, the stagnation area begins to move in the opposite direction.

The analysis of photographs of flow visualization behind BUTTERFLY valve, when the filmed plane was in the $X – Z$ plane, by means of a flat color tracer allowes to see all areas of the flow. As density of a flat color tracer is considerably higher than that of a linear tracer, the mark of such tracer could be seen at a considerable distance from the valve for a long time after formation. In the obtained photographs it is visible that in the acceleration stage above the upper leaflet and under the lower leaflet the jet flow areas are formed, and the stagnation area between the leaflets widen. It is necessary to note that there is a circulating flow in a stagnation area. At the outlet of the sinus the flow leave by two jets, with a sharp boundary line between them. As the flow output through the valve increases, the stagnation area widens too. In the sinus area above the upper leaflet and under the lower leaflet it is possible to see

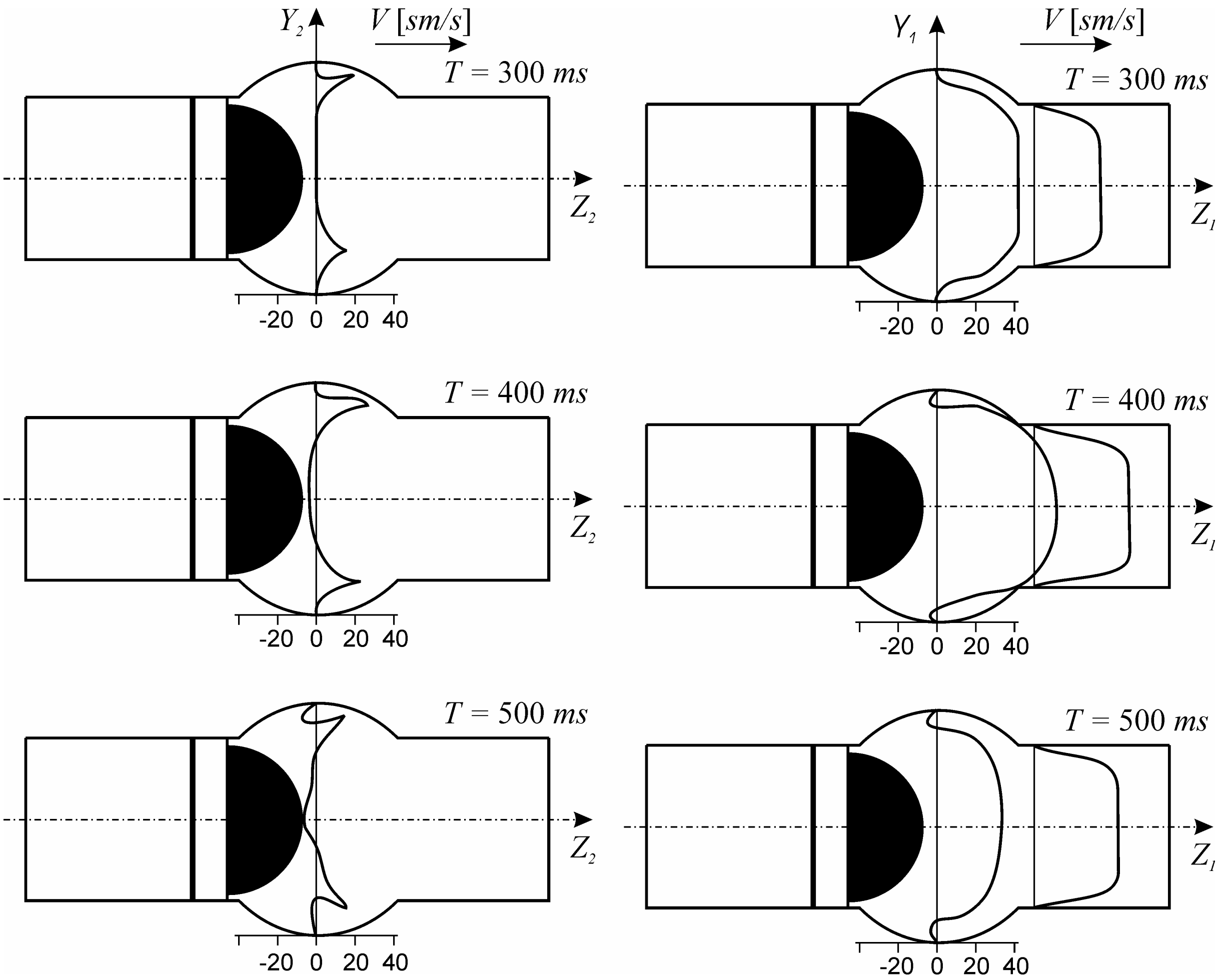

Fig. 4. The profiles of velocity behind valve BUTTERFLY in the X_2 - Z_2 and $X_1 – Z_1$ planes.

pronounced circulating areas with opposite directions of rotation. The size of the circulating area above the upper leaflet is larger than one located under the lower area. Over some time these areas move towards the main flow, increasing resistance. The main flow takes place in jet flow areas. On reaching the maximum rate of flow, the stage of slowing down at T = 500 ms begins. It does not change the flow pattern but the velocity peaks in the jet current area drop when the closing of the valve begins the lower leaflet closes first, and the slowing down area begins to move in the direction of the upper leaflet and closes it. The area of closed circulation above the upper leaflet moves into the ring section of the valve and decelerates motion of the main flow, the area of which is being narrowed down.

At T = 700 ms the valve closes. In the central part area of the back flow, which closes the upper leaflet and in the sinus area the counter clockwise closed circulation area is being formed, the size of which is considerably bigger than at the previous stage, but less intensive. It is noteworthy that the area of closed circulation does not move into the sector of the ring of the valve.

Discussion

The valves (ST. JUDE, ROSCARDICS) having space between leaflets, have three zones, in which the areas of jet flow are formed. A valve, which has a common turning leaflet axis (BUTTERFLY), has two areas of jet flow. On the boundary lines of jet flow areas, stagnation areas are formed.

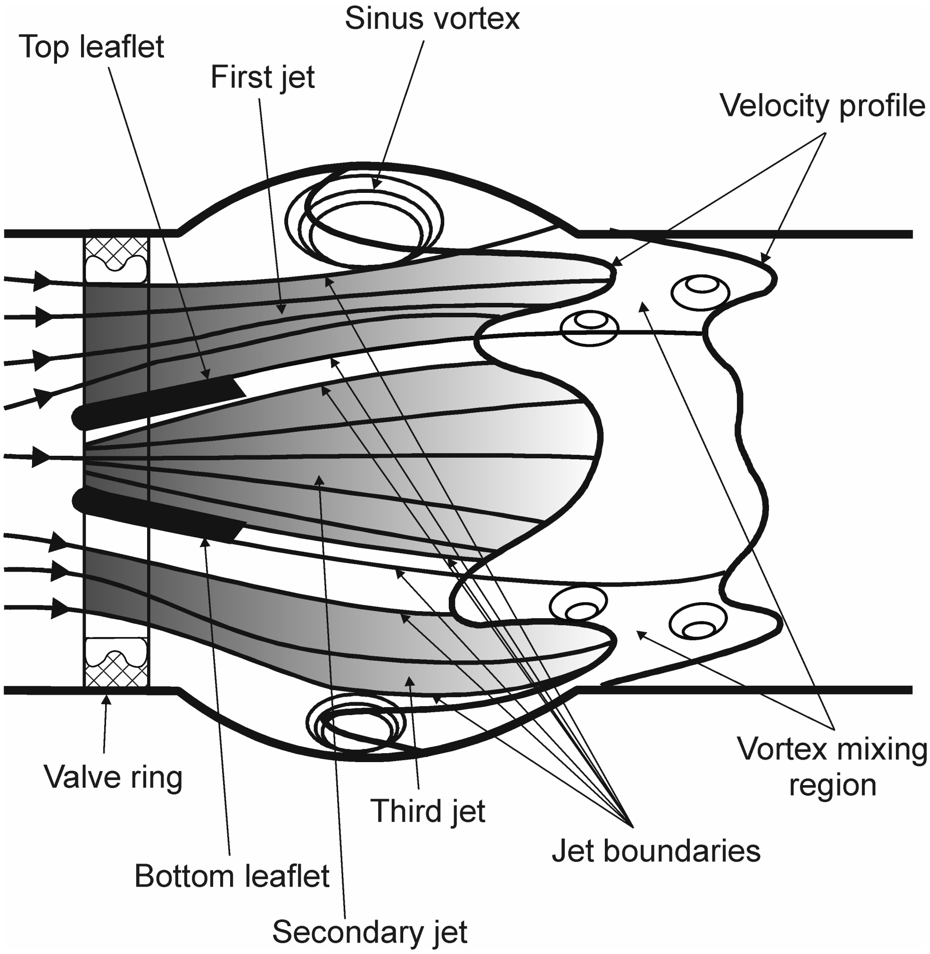

Fig. 5. Schematic presentation of the flow field of ROSCARDICS at the peak systole.

The effective orifice area of a valve with common leaflets turning axis is wider than that of valves with different leaflets turning axes. Figures 5, 6 give a schematic example of the flow structure behind such valves. It is necessary to point out that on the boundary-line between the areas of jet flows, as well as between the area of a jet flow and a stagnation area, there appear areas of vortexes' shifting at the outlet of the sinus. Appearance of such areas results in turbulence character of the flow.

ST. JUDE valve also shows formation of stagnation areas between leaflets, as the flow between leaflets goes out in the form of a narrow jet. Areas of jet flows when it passes through a narrow orifice, leads to a high gradient of shear stresses in the jet which gives rise to a high level of hemolysis.

Thus, widening the bileaflet valve orifice results in decreasing a load on a cordial muscle, bringing down a hemolysis level, and if the hydrodynamic characteristics are also improved, it means that a valve, which will provide better long-term results following the implantation has been created.

The investigation results obtained by applying the photochromic visualization method when a linear color tracer is formed in a flow and the width of a tracer in the plane perpendicular to the plane of filming is equal to 6 mm, have shown that in cases when ST.JUDE and ROSCARDICS valves are used above the upper and lower leaflets there is a jet flow area between leaflets and closed circulation zones formed in sinus areas. The flow structure between leaflets is rather complex, and both jet flow and stagnation areas can be observed.

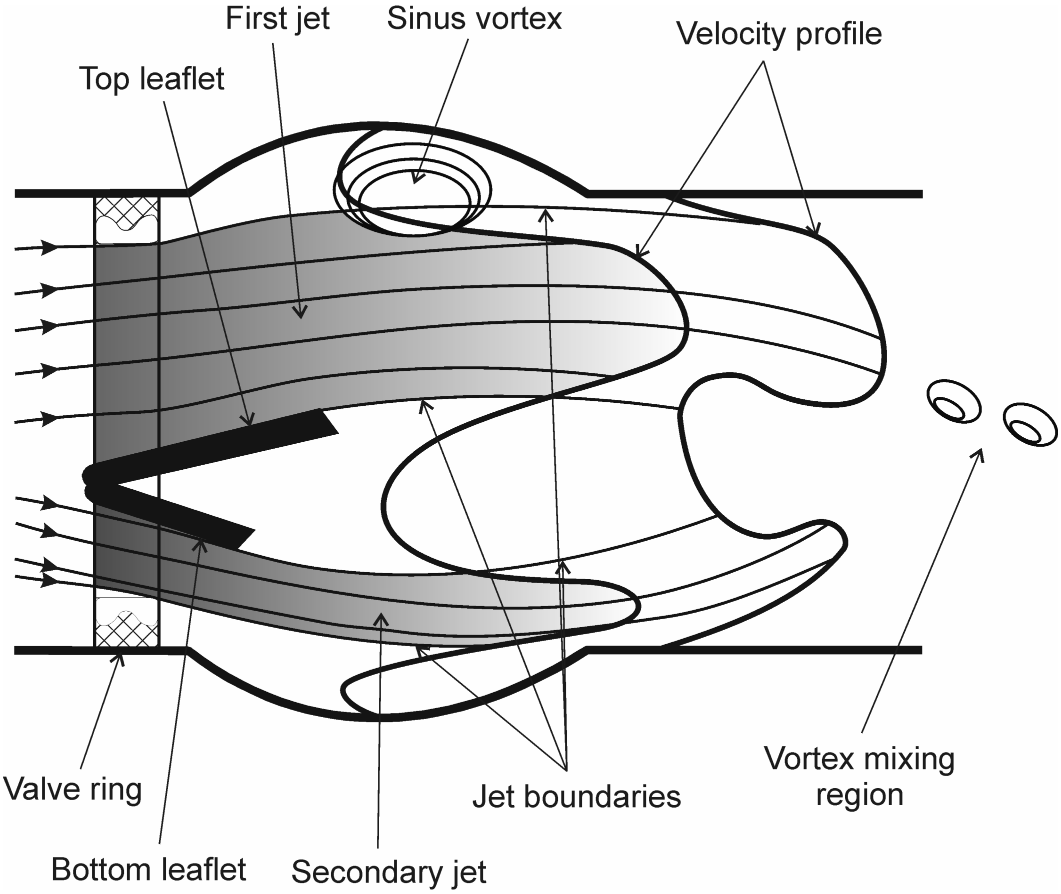

Fig. 6. Schematic presentation of the flow field of BUTTERFLY at the peak systole.

The existence of jet flow and stagnation areas between the leaflets indicates that the jet flow area is located in a narrow sector. To explain this, it is necessary to answer the question regarding the width of the jet flow area between the leaflets in the Y-Z plane. The analysis of the results received using a linear and flat color tracer shows that the width of the jet flow area in the *Y-Z* plane (Fig.1. A) amounts to approximately 5 mm. In order to support the obtained result it was necessary to carry out research with a linear color tracer, when the tracer was scanned in the *X*-axis and a flat tracer, which considerably increases the volume and the cost of investigation.

The carried out study of hydrodynamic characteristics of ROSCARDICS cardiac valve prosthesis proves that there has been created a valve of a new generation, possessing improved hemodynamic characteristics.

The present article contains comparison of ST. JUDE, which at present occupies the leading position among valves and which has been used clinically for 20 years with good long-term results, with a new generation bileaflet valve ROSCARDICS, developed by ROSINVEST Ltd., the leading manufacturer of CVPs in Russia.

The obtained functional characteristics of ROSCARDICS allow drawing the conclusion that clinical use of this new generation valve gives good long-term results following the implantation. ST. JUDE and ROSCARDICS have similar times of opening and closings of leaflets. But on the other hand, the operation of an implanted valve is greatly affected by the mechanical side of this process. ST. JUDE valve is characterized by “rigid closing”, when both leaflets are closed simultaneously. Such closing result in a flow pattern behind the valve, which can lead to creation of areas of blood clots formation. The closing techniques of ROSCARDICS differ from that of ST. JUDE. The main difference lies in the fact that there is no "rigid closing" of leaflets. In the process of closing the lower leaflet begins to close first and then the upper leaflet begins to close. It should be noted that investigation of functional features of the valve operation was conducted in a horizontal plane. When the lower leaflet of ROSCARDICS closed, there was an extensive area of closed circulation, formed behind the valve, which moved in the direction to the upper leaflet and closed it. The formation of large areas of closed circulation with small velocities is a positive factor for the valve opening process, as during the opening closed circulation areas are moved away by the incoming blood flow. In ST. JUDE valve, closed circulation zones are formed in the sinus area, which increases the probability of formation of blood clots in these sectors.

ROSCARDICS valve is characterized by formation of a jet flow area with a slanting profile of velocity in the sector located over the upper leaflet, while the profile formed in this sector in ST JUDE is “steeper”. This results in formation of higher level of tangent stresses in a flow and later gives rise to a higher level of hemolysis in case of a long-term exploitation of the valve.

In the area between leaflets, which is an area of high shear stresses, ROSCARDICS demonstrated widening the jet flow area and, as a result, a decrease in the level of shear stresses, as well as pressure drop on the valve, as compared to ST. JUDE valve.

Under the lower leaflet, washing by a flow is practically identical in both ROSCARDICS and ST. JUDE. In general it is possible to say that ROSCARDICS possesses better hydrodynamic characteristics in comparison with ST. JUDE and, as a result, a smaller hydraulic resistance. Therefore, after implantation of ROSCARDICSC the patient will experience smaller loads in his cardiovascular system, which is a positive factor.

In Fig. 5, the flow pattern behind the valve is schematically shown at the moment of the maximum flow through the valve. Figure 5 also shows the formation of a jet flow between leaflets as well as in the outlying areas. Peak velocities in all three areas are similar. It allows concluding that ROSCARDICS is a valve with a central flow, and also lowering profile as compared with ST. JUDE. The achieved hydrodynamic characteristics of ROSCARDICS also proved to be better as compared with the characteristics of ST. JUDE owing to widening the area of an effective orifice, and also to widening the area of an orifice between leaflets. In the valves of ST. JUDE-type the main resistance to a flow of blood is created by the space between leaflets. In general, ROSCARDICS has better hemodynamic characteristics in comparison with ST. JUDE. The response times (times of opening and closing of leaflets) of these valves are very similar, both valves have a faster response in comparison with disk valves.

Therefore, on the basis of the conducted investigation it is possible to conclude that ROSINVEST Ltd. has created a bileaflet valve, the functional characteristics of which exceed other models of bileaflet valves. The valve exhibits a smaller gradient of pressure drop and greater cardiac load in a comparison with ST. JUDE valve.

It is recommended to use ROSCARDIACS for installation in an artificial heart.

Valve BUTTERFLY, which is in the stage of development, has better hydrodynamic characteristics as compared with ROSCARDIACS and ST.JUDE bileaflet CVPs, but only the full range study of its functional characteristics will allow to draw the full conclusion about this valve.

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ГИДРОДИНАМИКА ИСКУССТВЕННЫХ КЛАПАНОВ СЕРДЦА НОВОГО ПОКОЛЕНИЯ

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В работе приводятся результаты экспериментального исследования гидродинамических и кинематических характеристик двухстворчатых искусственных клапанов сердца нового поколения. В настоящее время искусственные клапаны сердца (ИКС) используются в кардиохирургии для замены пораженных естественных клапанов. Имплантация ИКС является наиболее эффективным способом лечения болезней клапанов сердца. На протяжении 10-15 лет в кардиоцентрах всего мира используются двухстворчатые клапаны “ST. JUDE” (США) и “CARBOMEDICS” (США), имплантация этих клапанов дает хорошие клинические результаты. Характеристики этих клапанов далеки от естественных, поэтому поиск новых моделей ИКС является актуальной задачей. В этой работе приводятся результаты исследования двухстворчатых клапанов нового поколения, “РОСКАРДИКС” (Россия) и “BUTTERFLY” (Германия). Двухстворчатый клапан “РОСКАРДИКС” имеет симметричное расположение лепестков относительно несущего кольца клапана. Этот клапан в настоящее время проходит клиническую апробацию. Другой двухстворчатый клапан “BUTTERFLY” (Германия), имеет два лепестка, расположенных на одной оси, смещенной относительно оси симметрии несущего кольца клапана, и находится на стадии разработки. Эти клапаны имеют увеличение площади проходного отверстия для кровотока, по сравнению с клапанами “ST. JUDE” и “CARBOMEDICS”. Приводятся результаты гидродинамических и кинематических характеристик клапанов “РОСКАРДИКС” и “BUTTERFLY”. Гидродинамика клапанов исследовалась методом фотохромной визуализации. Метод основан на создании в среде моделирующей кровь цветовых меток под действием лазерного излучения. Регистрация движения в потоке за клапаном цветовых меток скоростной кинокамерой позволяет получить информацию о структуре течения. Проведенные исследования показали, что клапаны нового поколения имеют лучшие гидродинамические характеристики по сравнению с лучшими моделями современных ИКС, широко используемыми в клинической практике. Библ. 6.

Ключевые слова: метод фотохромной визуализации, искусственные клапаны сердца

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