MEDICAL AND BIOLOGICAL MEASUREMENTS

MEASUREMENT OF THE HYDRODYNAMIC CHARACTERISTICS OF ARTIFICIAL HEART VALVES BY PHOTOCHROMIC VISUALIZATION

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We propose using photochromic visualization to measure the hydrodynamic characteristics of artificial heart valves under simulated physiological flow conditions. The photochromic visualization method is based on generation of colored markers in the flow behind the artificial heart valve in a time equal to $10^{-6}$ to $10^{-9}$ sec. We use high-power laser radiation as the source for generating the colored markers.

Artificial heart valves are used in clinical practice for replacing damaged valves in the living organism. A number of cardiovascular diseases lead to damage of human heart valves and impairment of the pumping function of the heart. The use of artificial heart valves for transplants is associated with restoration of the pumping function and return of the patient to a normal life. The post-transplant outcome depends on the characteristics of the artificial heart valves.

In developing artificial heart valves used in medical practice, data are used from bench tests measuring the values of the pressure of the working liquid modeling blood before and after the valve, the instantaneous flow rate, the regurgitation, the parameters of motion of the leaflet, and the strength characteristics of the leaflets for multiple cyclic loads. In such studies, it has not been possible to fully determine and measure the hydrodynamic characteristics of the flow behind the artificial heart valves, which play an important role in the hemodynamics of the blood and in creating the load on the human cardiovascular system. The use of prosthetic devices such as artificial heart valves in the cardiovascular system may be accompanied by separation of the blood flow with formation of eddy zones in the chambers of the heart. The separation leads to turbulent flow and increase in the hydrodynamic resistance, the appearance of large velocity gradients, and undesirable biomedical effects (such as thrombosis, failure of the leaflet, etc.). The need for detailed study of these phenomena in the flow behind the artificial heart valves, especially in the stage of creating new designs, means that new experimental methods play an important role in the study of the hydrodynamics of artificial heart valves.

When experimentally studying the hydrodynamics of artificial heart valves under simulated physiological flow conditions, we need to determine and measure such important characteristics of the flow behind the valve as the presence and size of stagnant zones, the position of separation points and lines, the nature of the backflow, the structure of the shear layer, and the region of mixing between the main and recirculation flows. In solving this problem, very effective methods are ones which allow us to determine both the local and the integral characteristics of the flow behind the valve in real time [1–3].

Investigation method and experimental setup. To study the hydrodynamics of artificial heart valves, we used the photochromic visualization method, based on the photochemical reaction in a photochromic simulated physiological medium occurring when the medium is exposed to laser radiation. In a time of $10^{-6}$ sec, linear colored markers are generated in the flow and their motion in the flow is registered using a high-speed motion picture camera [3–6]. As the photochromic material, we used indoline spiropyran, in which rearrangement of the molecular structure occurs upon exposure to laser radiation.

Colored regions appear at the site of contact with the laser radiation in a solution of photochromic material, as a result of a photochemical reaction.

In measuring the hydrodynamic characteristics of artificial heart valves by photochromic visualization, we had to design a photochromic simulated physiological medium (simulating blood) containing salt and a photochromic material with a kinematic viscosity in the range 3–12 cp. In the hydrodynamic experiments, to obtain the required viscosity we used glycerin.
which was mixed with the aqueous photochromic solution. In performing the experiments measuring the hydrodynamic characteristics of artificial heart valves, we used a simulated physiological photochromic solution, the preparation of which is a rather lengthy process. The simulated physiological solution included the following components: glycerin; distilled water; salt; a surfactant; a photochromic material; a blood substitute (Rheopolyglucinum).

Addition of a blood substitute to the photochromic solution was done here for the first time. The result of this addition was to increase the lifetime of the prepared solution from three days to thirty days. The effect was connected with the fact that the blood substitute eliminated precipitation of molecules of the photochromic material, since the photochromic solution in the original state is a micellar solution. In the experiments, we used simulated physiological photochromic solutions with kinematic viscosity \( \nu = 0.03 \text{ cm}^2/\text{sec} \) and maximum viscosity \( \nu = 0.1 \text{ cm}^2/\text{sec} \).

The photochromic simulated physiological solution with kinematic viscosity \( 0.03 \text{ cm}^2/\text{sec} \) had the following proportions: glycerin 31.6%; distilled water 62.7%; photochromic material 0.002%; salt 0.8%; surfactant 0.85%; blood substitute 4.048%.

This composition of the photochromic simulated physiological solution was used only in measuring the valve opening and closing time. The basic simulated physiological photochromic solution had a kinematic viscosity of \( 0.1 \text{ cm}^2/\text{sec} \) and the following proportions: glycerin 59.6%; distilled water 35.4%; photochromic material 0.002%; salt 0.74%; surfactant 0.57%; blood substitute 3.688%.

Using a photochromic simulated physiological solution with elevated viscosity (compared with blood) made it possible to obtain laminar flow at the valve inlet on a hydrodynamic bench. This allowed us to study the degree to which the valve geometry introduced turbulence into the flow behind the valve. To form a simulated physiological flow in front of the valve, we used various hydrodynamic benches whose designs are described in detail in [6,7].

We set the valve to be tested into a round transparent tube which was part of the hydrodynamic bench and made of organic glass. In the cross section under test, where we made all the measurements 15 mm away from the edge of the ring of the valve, a linear colored marker was created and its motion in the flow was registered by a high-speed motion picture camera. In [7], a typical curve is shown for the flow rate of the photochromic simulated physiological solution in front of the valve for pulsating flow conditions in front of the valve. The moment the valve began to open was taken as the reference time = 0. We used a laser apparatus described in detail in [3] to generate the colored markers in the flow. As the sources of laser radiation, we used Q-switched ruby solid-state lasers followed by conversion of the main radiation to UV radiation using nonlinear crystals. From the high-speed cinematography results, we determined the valve opening and closing times and also the velocity profiles behind the valves. The procedure for determining the velocity field from the photochromic visualization data is described in detail in [3].

Now let us consider the results in the form of graphs of the velocity distribution \( U(y) \) over the tube diameter, behind the artificial heart valve at different moments of time, and analysis of the flow. For both flow regimes through the valve (steady-state and pulsating), we measured the hydrodynamic characteristics of the domestic disk valve ÉMIKS [1].

**Experimental results.** The experimental measurements of the hydrodynamic characteristics of the disk artificial heart valve ÉMIKS for the steady-state flow regime were made on the hydrodynamic bench described in [1]. The valve was mounted in a detachable holder made from organic glass. The experiments were done in the steady-state flow regime, when the opening angle for the disk valves has its maximum value, while the maximum flow rate at which the studies were done corresponded to the condition

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Re < Re_{cr},
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where \( Re_{cr} \) is the critical Reynolds number at which turbulent flow developed on the hydrodynamic bench without the valve. The critical number \( Re_{cr} \) depends on the design used for the hydrodynamic bench and is determined by photochromic visualization, as was shown in [3, 8–10].

Mounting an artificial heart valve of any design on the hydrodynamic bench leads to deviation of the velocity profile in the cross section behind the valve from a parabolic profile. The degree of deviation depends on the valve design.

The domestic disk valve ÉMIKS is presently used in clinical practice [11,12]. The measured velocity profiles for \( Re = 181,549,958, 1380 \) and different distances from the edge of the ring are shown in Fig. 1. Mounting the disk closer to the axis of the tube at a distance of \( 0.1d \) from the axis allows us to obtain more symmetric flow patterns relative to the axis of rotation of the disk, and thus to reduce the velocity gradients. The wake behind the disk is short and even at a distance of 15 mm