Perspectives for Pneumatic and Hydraulic Circulatory Assist Devices and Their Application for Heart Transplantation

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Abstract: Intraventricular blood-forcing-principle-based pneumatic- or hydraulic assistance circulation device test results are proposed. The system consists of a uninipple valveless dome pump, a pneumatic- or hydraulic drive, and an artificial pericardium. Stand tests of these systems and medical-biologic experiments on dogs and 17 calves were performed. The duration of these experiments was up to several days. In this report, the features of surgical techniques, perfusion parameters, control principles, hemodynamic variations, complications, and other problems concerning realization of the proposed method are discussed. Key Words: Mechanical circulatory support—Heart transplantation—Artificial heart assist devices.

Mechanical circulatory support of critical-state recipients remains one of the important problems of heart transplantation. In these cases the following requirements are put forward for mechanical assist devices: they must be easily connected to the patient's heart, and they must exclude blood trauma, thrombus formation, bleeding, and other complications. The means of connection should not complicate further heart transplantation.

On the basis of the requirements mentioned above, we developed a number of pneumatic and hydraulic circulatory assist systems.

The first model consists of the patient's functionally defective heart, single-sleeve valveless pumps, an artificial pericardium, and a control system.

Instead of the right pump, an elastic pneumatic pusher may be used, which is installed on the inner surface of artificial pericardium in the right ventricle zone. In this model the natural heart ventricles are used as reservoirs for blood pumping. From the cavity of the ventricles, blood is actively aspirated to the pumps. After filling, the blood in the pumps is forced under pressure to the cavity of the appropriate ventricle and further to the aorta or the pulmonary artery. At the moment of forcing from the pump, the blood flow coming to the cavity of the ventricle lifts the folds of atrioventricular valves, thus safely preventing regurgitation to the atrium.

This phenomenon was verified through test-bed simulations. The myocardium is not stretched during intraventricular blood forcing because externally the heart is limited by rigid artificial pericardium excluding dilation of the walls of the ventricles.

The system may work and support circulatory dynamics of the organism even with an operating (left) pneumatic pump.

The system has been experimentally proven on 17 calves weighing 80–100 kg and 48 breedless dogs weighing 16–38 kg during 12–24 h. With the animals under intubational narcosis, left-side thoracotomy in the sixth intercostal zone was performed with the sixth rib removed. The fixing cuff was sewn to the top of the heart with separate seams. In the center of the sewn cuff the pricking of myocardium was done through which the connector of the valveless pump was introduced to the lumen in the left ventricle of the animal's heart. Externally, the connector was fixed to the cuff by means of ligature. By
the same method the connector of the second pump was introduced to the right ventricle, and then the heart was placed into the artificial pericardium and the pumps were connected to the control system. The experiments were conducted in conditions of heart fibrillation.

The pneumatic-drive operating mode was set so that the time of forcing from the pump was one-third of the whole mechanical cycle.

Hemodynamic control was performed by measuring the pressure in heart cavities, aorta, and pulmonary artery.

During heart fibrillation, the mean aortal pressure was set at the level of 5–7 mm Hg without blood flow. Meanwhile, the mean right atrial pressure was 5.1 ± 0.2 mm Hg, mean right ventricle pressure was 7.2 ± mm Hg, and the mean pulmonary pressure was 7.5 ± 0.6 mm Hg.

The engaging of the system was accompanied by the increasing of blood flow along the aorta up to 1,658.4 ± 72.5 ml/min, maximum aortal pressure increasing up to 118.3 ± 10.8 mm Hg. The diastolic aortal pressure was 77.6 ± 6.5 mm Hg. Meanwhile, the mean right ventricle pressure reached 33.0 ± 2.7 mm Hg, the mean pulmonary pressure reached 25.6 ± 0.8 mm Hg, and the right atrial pressure slightly increased up to 6.7 ± 0.5 mm Hg.

After 3–4 h from the start of operation, there was a certain decrease of diastolic arterial pressure compared with the initial (before fibrillation) pressure, which evidently might be explained by the decrease of vascular tone.

While using the pneumatic pusher to the right ventricle instead of a pump, a slight increase of pulmonary pressure (up to 23.5 ± 2.4 mm Hg) and systemic blood flow was registered.

Of great interest is the possibility of electric activity resumption using this method. Thus, in 4 of 48 dog experiments the appearance of spontaneous cardiac rhythm on the electrocardiogram during the first 12 h of the operation was registered. However, complete recovery of central circulatory dynamics did not occur.

The described pneumatic circulatory assist device has a rather massive drive.

Further development of the system continued by construction of the model consisting of a natural heart and a hydraulic assist device providing blood pumping. It includes an artificial ventricle with one chamber connected to an artificial pericardium cavity (compensating chamber) filled with inertial biological liquid, and a reversing pump based on a brushless DC motor and connector with a cannula having a valve.

The artificial ventricle’s connector with a cannula is introduced through the natural cavity of the ventricle to the ascending part of the aorta. An artificial pericardium–compensating chamber, filled with inertial biological liquid and connected to the reversing pump, is placed on the heart.

At the systolic moment, the axial pump reverse with the help of a brushless motor blade provides the movement of the liquid from under the diaphragmal space of the pump into the compensating chamber, creating pressure on the myocardium. Meanwhile, the natural heart’s systole increases, providing better filling of the artificial ventricle with blood.

During the diastole of the natural heart, the blood output from the artificial ventricle to the ascending aorta is performed through a cannula with a valve. Meanwhile, back reverse of the axial pump occurs and the liquid moves from the compensating chamber to the underdiaphragmal surface, providing the falling of the compensating chamber wall and the decreasing of its pressure on the myocardium.

The testing of this model was performed on 17 calves weighing 70–85 kg with acute cardiac failure.

The acute cardiac failure model demonstrated the falling of aortal pressure from 120/70 to 90/50 mm Hg, and the blood flow decrease from 3,260.6 ± 234.2 ml/min to 2,217.5 ± 208.7 ml/min. Meanwhile, the left atrial pressure increased from 7.3 ± 0.6 to 10.8 ± 0.4 mm Hg. Pulmonary pressure and right atrial pressure remained at the upper critical level from the norm. Central venous pressure (CVP) increased from 17.4 ± 0.8 to 22.3 ± 0.6 mm Hg.

After 15–20 min from the start of the operation of the system, the aortal blood flow increased up to 3,027.6 ± 253.5 ml/min, the systolic arterial pressure increased up to 112.8 ± 6.3 mm Hg, and the diastolic pressure increased up to 73.5 ± 4.6 mm Hg. The pulmonary pressure was in the limits of 23.4 ± 0.9 mm Hg, the right atrial pressure was 8.2 ± 0.4 mm Hg, and the CVP was 21.3 ± 1.8 mm Hg.

In this asynchronous operating mode with hybrid artificial heart frequency of 60–106 beats per minute and heart fibrillation, the increasing of maximum aortal pressure was up to 114.6 ± 8.7 mm Hg and the diastolic was up to 72.3 ± 6.8 mm Hg. Right atrial pressure increased up to 8.6 ± 0.7 mm Hg, and pulmonary pressure was up to 20.3 ± 1.2 mm Hg. Meanwhile, the aortal blood flow was in the limits of 2,945.4 ± 182.7 ml/min.

Thus, the application of the developed systems in the conditions of acute heart failure and fibrillation during the first day provides the maintenance of adequate central circulatory dynamics. This makes them prospective for temporary recipient support before heart transplantation.