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Analysis of the Preload and Afterload Sensitivity of the Sputnik Rotary Blood Pump

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The reaction of the Sputnik rotary blood pump to preload and afterload was analyzed. A mathematical model of the blood pump was suggested. The characteristics of the Sputnik pump were compared to those of the DuraHeart and INCOR commercial pump models. The effect of afterload on the pump capacity and preload sensitivity was analyzed. The preload sensitivity was shown to correlate with the shape of the head–capacity curves. It was demonstrated that the Sputnik pump had higher sensitivity to preload [mean value, (0.121 ± 0.0092) l·min^{-1}·mm Hg^{-1}] because of the flatter head–capacity curve as compared to the DuraHeart and INCOR commercial pumps.

Introduction

Implantable rotary blood pumps (RBPs) can partially substitute the function of the left ventricle. In addition to differences in construction [1], each RBP model has a unique head–capacity curve (HCC). Comparative tests for evaluation of the ventricular unloading and the physiological support of circulation provided by different RBPs are described in the literature [2, 3]. Different RBP models can be compared by analyzing the shapes of the HCCs, as well as the preload and afterload sensitivity [2, 3].

It was suggested that an increase in the preload sensitivity of an RBP can contribute considerably to the ventricular unloading. The higher the preload sensitivity of an RBP, the more effectively the blood flow rate can be reduced by decreasing the ventricular pressure. This, in turn, reduces the risk of ventricular collapse. In this case, the requirements for rate regulation are minimal [2, 4, 5].

The goal of this work was to analyze the performance of the Sputnik axial-flow RBP by testing its preload and afterload reactions as compared to other RBP types. The RBP model under consideration is used in the Sputnik assisted circulation apparatus, of domestic manufacture, which has been successfully used in clinics [6].

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Methods

A mathematical model of the pump operation was developed. The theoretical expression for the static flow capacity characteristic of the axial pump is [7]

$$H_e = \frac{u}{g}\left(u - \frac{Q_e}{A_2}\cdot \text{cotan}\beta_2\right),$$

where H_e is the Euler head, Q_e is the flow capacity of the pump, u is the peripheral velocity of the rotor, A_2 is the effective area of the outlet, and β_2 is the blade angle at the pump outlet. In this equation, the pressure difference H_e is a quadratic function of the rotor velocity u and a linear function of the capacity Q_e. Therefore, the static HCCs of axial-flow pumps can be described by the following equation:

$$a{\cdot}Q + b{\cdot}H + c{\cdot}\omega^2 + d{\cdot}Q^2 + e{\cdot}Q^3 = 0,$$

where Q is the pump capacity, l/min; H is the pressure difference in the pump, mm Hg; ω is the pump rate, min^{-1}; and a-e are coefficients calculated using optimization methods. Additional factors Q^2 and Q^3 allow the S shape of the static HCC typical of axial-flow rotary pumps to be reproduced [8].

The mathematical model is based on the experimentally obtained static HCCs of the Sputnik pump measured using the hydrodynamic setup at RWTH Aachen

University (Germany) [9]. The liquid viscosity was 2.5 cP. A fixed pressure difference at the pump was maintained using the control unit of the setup. The flow capacity of the pump was measured using an ME-11PXL ultrasonic flow meter (Transonic Systems Inc., Ithaca, New York, USA). The pressure difference varied from 150 to −50 mm Hg with a step of 25 mm Hg.

The accuracy of the initial expression for the static HCCs was improved using an optimization procedure based on nonlinear least-squares methods. A term from a set of pre-specified auxiliary functions was added to the initial expression. Then, the equation was optimized and the criteria of correspondence to the experimental data were established. Thus, an equation specific for the given pump was obtained and coefficients of the HCC equation were estimated with sufficient accuracy ($R^2 = 0.998$). The resulting expression is

$$a{\cdot}Q + b{\cdot}H + c{\cdot}\omega^2 + d{\cdot}Q^2 + e{\cdot}Q^3 + f{\cdot}\omega{\cdot}Q = 0.$$

The model accuracy is illustrated in Fig. 1. The optimization points are shown with open circles, the model values at the optimization points are indicated with black markers, and the resulting HCCs at different pump rates are given with dotted lines. The obtained coefficients and correspondence criteria (RMSE, R^2) are given in Table 1.

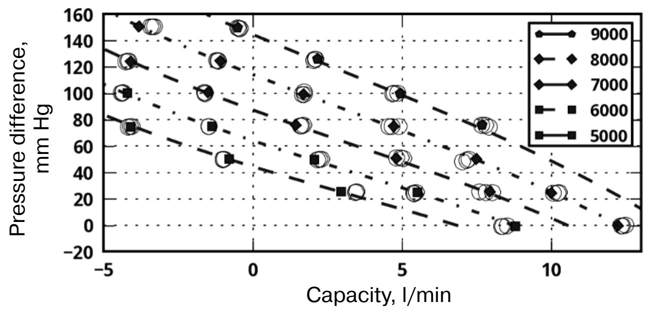


Fig. 1. Visual check of the Sputnik pump accuracy.

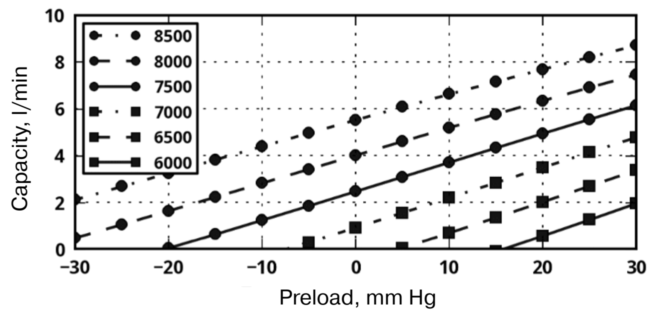


Fig. 2. Variation of the capacity of the Sputnik pump within the input pressure range from −30 to 30 mm Hg at different rotation rates.

Results

The effect of the input pressure on the pump capacity at different rotation rates of the Sputnik RBP and constant afterload (80 mm Hg) is shown in Fig. 2. The input pressure ranges from −30 to 30 mm Hg at rotation rates 6000-8500 rpm. It can be seen that an increase in the rate within the given preload range induces an increase in the capacity.

The preload sensitivity dQ/dP_i (l·min^{-1}·mm Hg^{-1}) was determined as the ratio of the pump capacity Q (l/min) to the input pressure P_i (mm Hg) and calculated by the procedure suggested in [2, 4]. The curves shown in Fig. 2 were used for calculations performed within the physiological range −5-30 mm Hg with a step of 0.25 mm Hg. The results of the calculation are given in Table 2 within the capacity range 1-8 l/min at rotation rates 6500-8500 rpm. The maximal preload sensitivity was 0.14 l·min^{-1}·mm Hg^{-1}; the mean value was (0.121 ± 0.0092) l·min^{-1}·mm Hg^{-1}. The resulting values are larger than similar values for the mean preload sensitivity of an RBP (0.077 ± 0.04), but lower than the mean values for a biological heart (0.241 ± 0.04) [3].

TABLE 1. Coefficients and Correspondence Criteria

a = 0.302344029 mm Hg
b = 0.090447735 l/min
c = −1.61574312·10^{-7} l·min·mm Hg
d = −0.0126948325 min·mm Hg/l
e = 0.00129660584 min^2·mm Hg/l^2
f = 6.24084623·10^{-5} min·mm Hg
RMSE = 0.2269659; R^2 = 0.99817025

The curves of the pressure difference vs. capacity (HCC) and the capacity vs. preload are shown in Fig. 3 for the Sputnik, DuraHeart, and INCOR rotary pumps. The data for the DuraHeart (at 2000 rpm) and INCOR (at 8000 rpm) pumps were taken from [2] and used to obtain these curves. For the Sputnik pump, the rate of 8500 rpm was selected. This rate provides approximate correspondence with the capacity vs. preload curves for the DuraHeart and INCOR pumps obtained at a constant afterload of 80 mm Hg.

The Sputnik pump, with an axial rotor, has a flatter HCC as compared to the DuraHeart pumps, with a centrifugal rotor. This difference is more pronounced at a

TABLE 2. Preload Sensitivity ($l \cdot min^{-1} \cdot mm\ Hg^{-1}$) for the Sputnik RBP at Different Values of Capacity and Rate

Rate, rpm	Capacity, l/min							
	1	2	3	4	5	6	7	8
6500	0.1317	0.1344	0.1356	-	–	–	–	–
7000	0.1261	0.1284	0.1295	0.1292	–	–	–	–
7500	–	0.1230	0.1240	0.1237	0.1221	0.1192	-	–
8000	–	–	–	0.1186	0.1171	0.1146	0.1110	–
8500	–	–	–	–	0.1126	0.1102	0.1070	0.1030

small pressure difference in the pump (30-70 mm Hg). It also leads to a flatter capacity vs. preload dependence for the Sputnik pump. It should be noted that the decrease in the afterload from 100 to 60 mm Hg leads to a considerable increase in the capacity of the Sputnik and DuraHeart pumps. The curve slope in this case differs from pump to pump. Therefore, the pumps have different sensitivities to preload (the sensitivity also depends on the afterload variation).

The curves of the preload sensitivity vs. pump capacity calculated from the data of Fig. 3 are shown in Fig. 4. It follows from Fig. 4 that the Sputnik pump is characterized by the maximal sensitivity to preload (about 0.11 $l \cdot min^{-1} \cdot mm\ Hg^{-1}$) at the afterload of 100 mm Hg. The INCOR pump has lower sensitivity to preload (about 0.04 $l \cdot min^{-1} \cdot mm\ Hg^{-1}$), i.e., its capacity depends only slightly on the preload. As a result, the INCOR pump curve in Fig. 3 is the flattest.

The decrease in the afterload from 100 to 60 mm Hg leads to a decrease in the preload sensitivity, while the ratio of the pump sensitivities is maintained at an invariable level. The Sputnik pump has the maximal sensitivity to changes in the preload, while the INCOR pump has the minimal preload sensitivity. At the same time, the decrease in the afterload to 60 mm Hg causes the maximal preload sensitivity change in the DuraHeart pump (from ~0.09 to 0.05 $l \cdot min^{-1} \cdot mm\ Hg^{-1}$).

It should be noted that the maximal preload sensitivity is observed in the Sputnik pump because its HCC is flatter as compared to the other pumps.

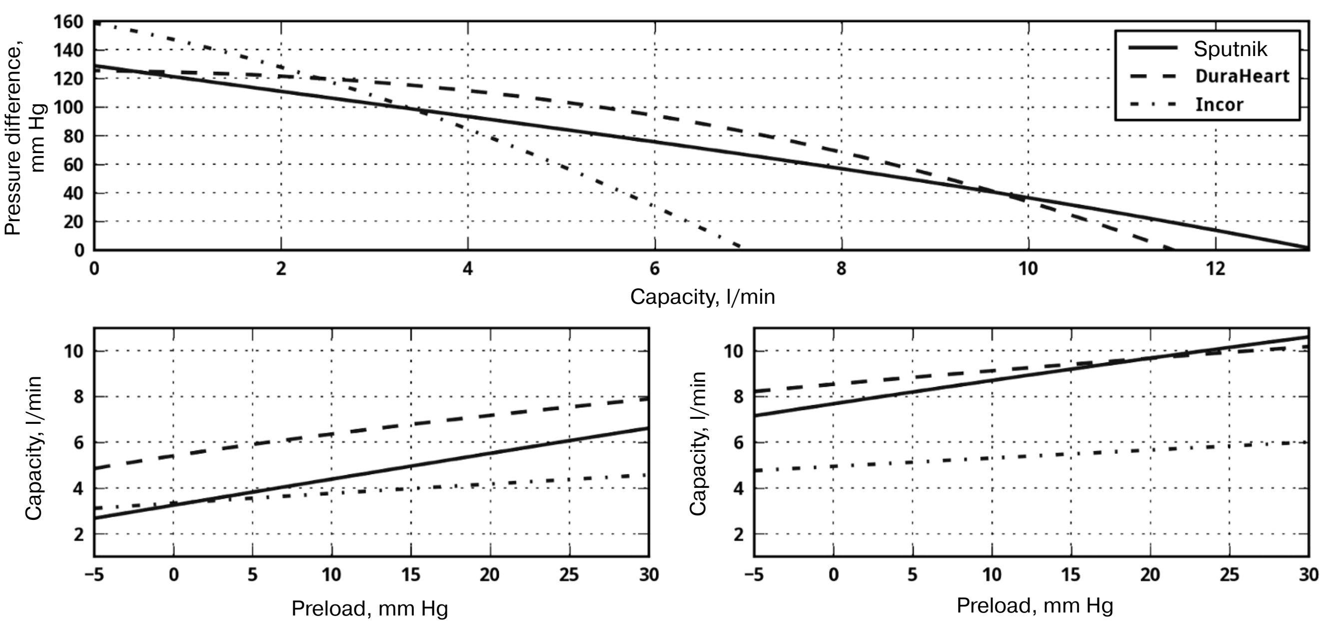
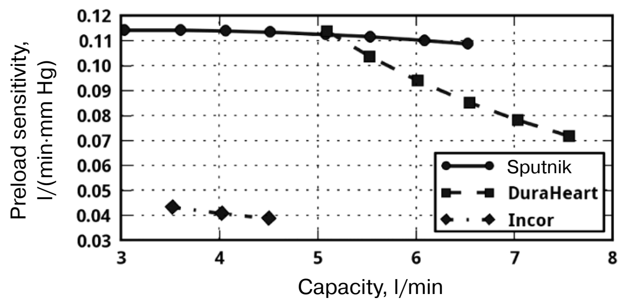


Fig. 3. Curves of the pressure difference vs. capacity (HCC) and the capacity vs. preload for the Sputnik, DuraHeart, and INCOR pumps at two values of afterload: 100 mm Hg (left) and 60 mm Hg (right).



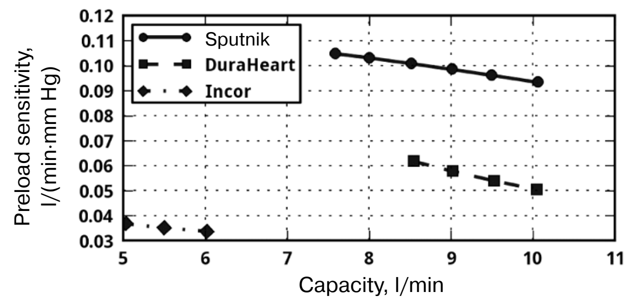


Fig. 4. Comparison of the preload sensitivities of the Sputnik, DuraHeart, and INCOR pumps at two values of afterload: 100 mm Hg (left) and 60 mm Hg (right).

Conclusion

The performance of the Sputnik rotary pump was analyzed. The preload sensitivity was considered as the main characteristic of the pump performance and used for its comparison with other pumps.

It was demonstrated that the three pumps considered in this work had different preload sensitivities within broad ranges of flow capacity and pressure values. The maximal afterload sensitivity was demonstrated by the DuraHeart centrifugal pump.

At the same time, the Sputnik axial pump had maximal preload sensitivity (about 0.11 $l \cdot min^{-1} \cdot mm\ Hg^{-1}$ at an afterload of 100 mm Hg), because its HCC is flatter as compared to the other pumps. Thus, in accordance with the results of this work, higher sensitivity to preload is due to constructive parameters of the pump and does not depend on the rotor type [1].

It should be noted that, in addition to the HCC shape, the preload sensitivity is a parameter that should always be taken into account in comparing RBP models. It was demonstrated in earlier works that an improvement in the preload sensitivity of implanted RBPs might reduce the necessity for pump rate adjustment, and might also reduce the risk of collapse or ventricular arrhythmia [4, 5].

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