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NUMERICAL ANALYSIS OF THE EFFECT OF THE DESIGN OF AXIAL-FLOW PUMP CANNULA TIP ON STAGNATION AND RECIRCULATION ZONES IN THE LEFT VENTRICLE

M.S. Nosov[1, 2], *G.P. Itkin*[1, 2], *V.M. Zaiko*[1, 2], *V.A. Malgichev*[3]

[1] Shumakov National Medical Research Center of Transplantology and Artificial Organs, Moscow, Russian Federation

[2] Moscow Institute of Physics and Technology, Moscow, Russian Federation

[3] DONA-M Ltd, Moscow, Russian Federation

Objective: to analyze the inflow cannula of an implantable axial-flow blood pump for a long-term left ventricular assist system in order to minimize thromboembolic complications. **Materials and methods.** Hemodynamics was considered for 4 different designs of the inflow cannula, from 0 mm to 25 mm long. Areas at the base of the cannula received the most attention. Analysis was performed using the *OpenFOAM* software. **Results.** It was revealed that sizes of stagnation and recirculation zones directly depended on the length of the cannula when placed in the left ventricle. Accordingly, longer cannula increases the risk of thrombosis. **Conclusion.** The design of an inflow cannula determines the likelihood of thrombosis in the cannula. Longer inflow cannula increases stagnation and recirculation zones. This provides a basis for a search for other possible modifications.

Keywords: end-stage heart failure, artificial circulatory support, left ventricular bypass, inflow cannula, thromboembolic complications.

INTRODUCTION

Cardiovascular diseases (CVDs) are one of the leading causes of death in developed countries. According to various sources, over 1 million people die annually from CVDs in Russia and in the USA. Most heart diseases are amenable to drug treatment, but in end-stage heart failure (ESHF), heart transplantation is the only way out. However, organ shortages limit treatment options for such patients. In recent decades, this has led to the appearance of a new technology for treating patients with heart failure by means of long-term mechanical circulatory support (MCS) using implantable centrifugal axial-flow rotary blood pumps. Despite successful application of such systems in clinical practice, thrombolytic complications remain one of the main problems, which are a consequence of the combined effect of shear stress, as well as formation of stagnation and blood recirculation zones. In this case, the area of the inflow cannula is the most critical site of thrombus formation [1–4]. The causes of blood clots are not fully known. However, several factors that affect ventricular hemodynamics and the safety of the cannula can be identified:

1) Position of the cannula relative to the heart, including its tilt angle [2, 5–7];
2) Shape and size of the cannula [8–11];
3) Coating of the cannula surface [1, 12].

In this paper, the influence of the tip length of an inflow cannula on formation of stagnation and recirculation zones is investigated via numerical analysis.

MATERIALS AND METHODS

Direct-type blood intake cannulas are used in most foreign-made long-term MCS systems which incorporate the rotary assisted circulatory support (HeartMate II, HeartMate III, Jarvik 2000), as well as in the Russian-made assisted circulatory support (ACS) AVK-N. Fig. 1 shows the AVK-N cannula (Russia).

This design is fairly simple, symmetrical, and performs its function well. However, the clinical experience of using this cannula has shown a high probability of thrombosis at the pump inlet (Fig. 2) [1, 13].

Our preliminary analysis of relevant literature showed that the imperfect design of the cannula in terms of local hemodynamics can lead to negative consequences:

1) obstruction of blood flow due to thrombocytic masses and connective tissue [14];
2) suction of the cannula lumen to the ventricular wall [15];
3) formation of blood clots at the site of the cannula's contact with the myocardium [16].

In this work, we conducted studies to assess the effect of the length of the inflow cannula of an axial-flow blood pump on intraventricular hemodynamics. Fig. 3 shows the models of cannulas studied in this work.

Corresponding author: Mikhail Nosov. Address: 1, Shchukinskaya str., Moscow, 123182, Russian Federation.
Phone: (903) 265-92-50. E-mail: nosovmi@yandex.ru

Fig 1. AVK-N input cannula

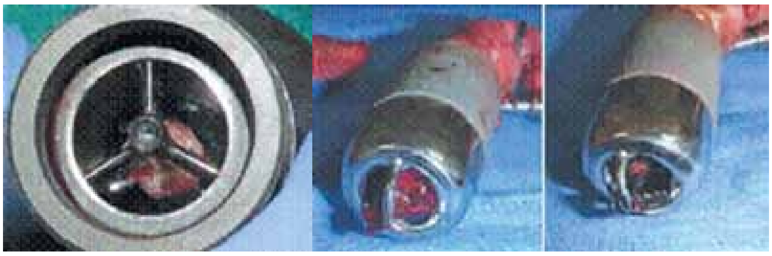

Fig 2. Pump inlet thrombosis

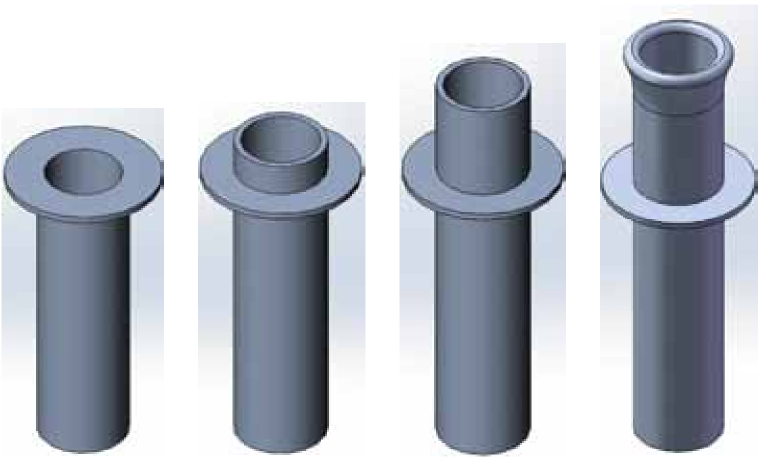

Fig 3. Cannulas with different tip length (from left to right) 0 mm, 5 mm, 15 mm and 25 mm AVK-N

Blood flow through the left ventricle (LV) with a cannula placed inside it is simulated in the absence of wall movement, in ESHF conditions, when the LV is practically not reduced, and the aortic valve is closed.

The LV geometry is shown in Fig. 4. Each cannula model is placed in the LV, forming the required volume for numerical simulation. The presence and size of stagnation and recirculation zones for different cannula lengths in the LV cavity were investigated. Zero blood flow speed and closed trajectories are the criteria for such zones.

Simulation is done using the OpenFOAM software. Blood parameters are set by the Navier-Stokes equation for a viscous liquid (the icoFoam utility included in OpenFOAM). A 120-mmHg pressure is set at the outlet of the model, then the computational process is started until a stationary flow regime is configured.

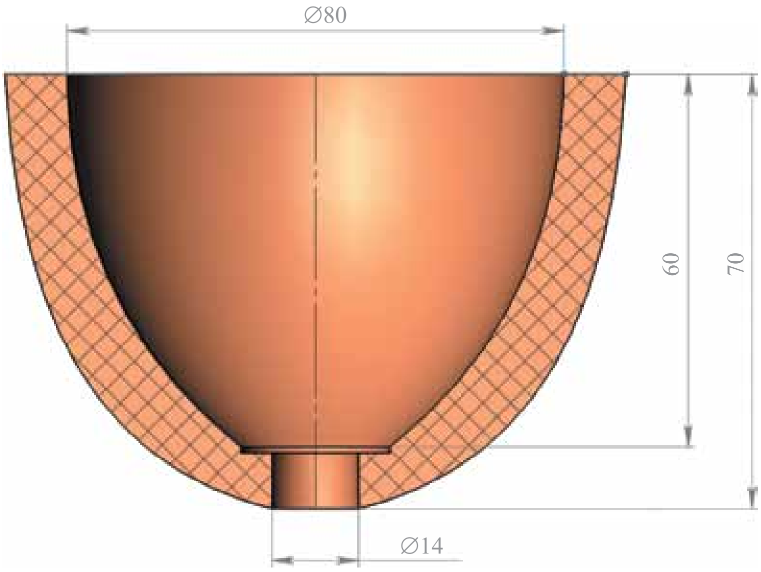

Fig 4. The geometry of the ventricle model

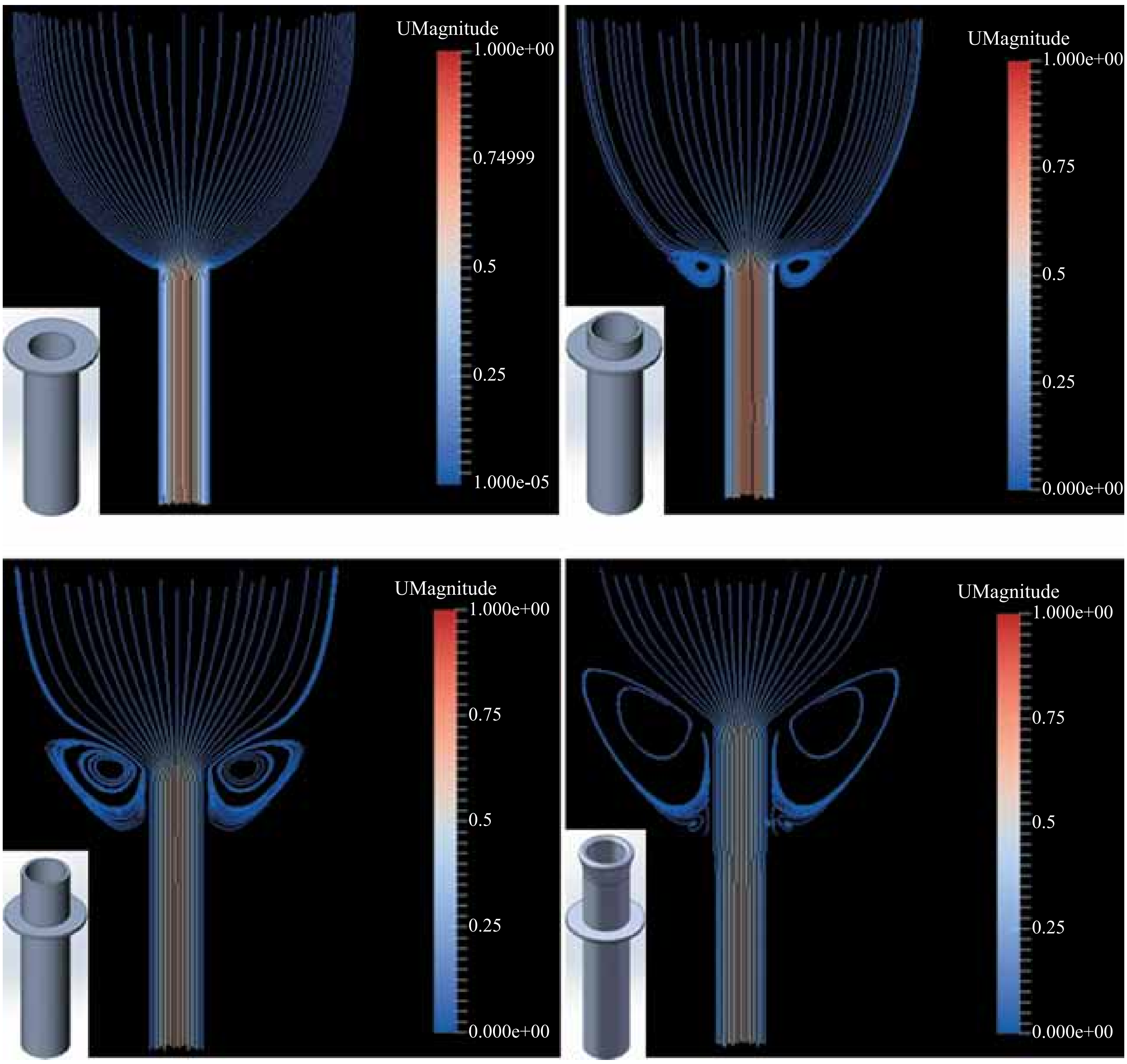

Fig 5. Results of modeling blunt tip cannulas

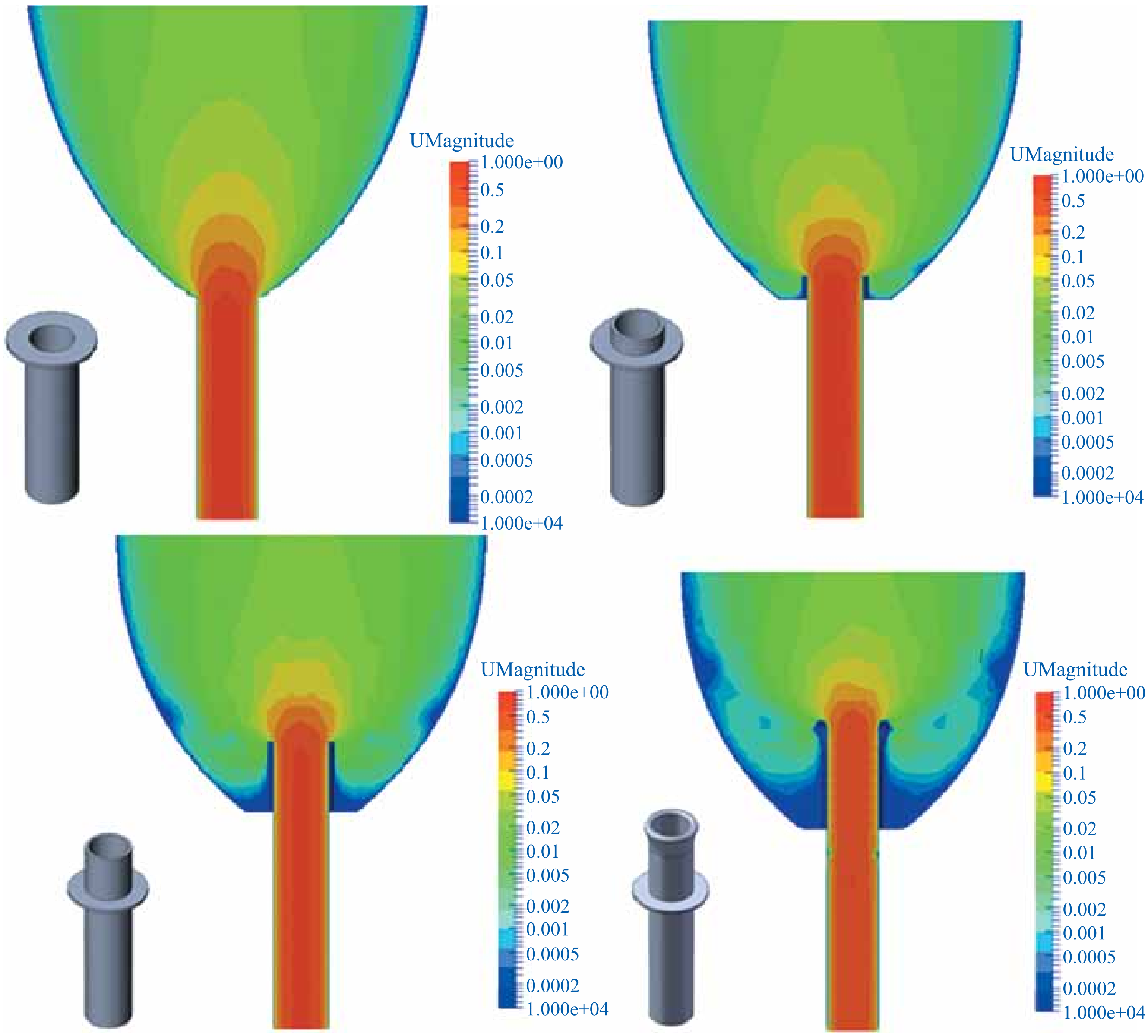

Fig. 6. Results of modeling blunt tip cannulas. Absolute speed

RESULTS

Simulation results for straight cannulas are shown in Fig. 5. The lines in the figure are fluid flow lines. The color corresponds to the local velocity on a scale from 0 m/s (blue) to 1 m/s (red).

There is clear tendency that the size of the recirculation zones increases with longer tip length of the cannula. For a 0 mm-tip length cannula, there is no such recirculation zone, but for a 25 mm-cannula (AVK-N), the zone is maximum. Velocity profiles and contours are shown in Fig. 6. Here you can see a similar relationship with stagnation zones. The more the cannula protrudes, the larger the stagnation zone.

DISCUSSION

The direct cannula with zero tip length allows for minimal stagnation and recirculation zones. In this case, a cannula's tip length other than zero, is the source of appearance of stagnation and recirculation zones inside the LV. The size of these zones is proportional to the tip length. Besides, increased cannula protrusion leads to increased hydraulic resistance of the system. In spite of this, a cannula with zero tip length under typical conditions can become overgrown with connective tissue over time [14]. This process can be blocked by using systems for enhanced pulsatile flow generation [17].

CONCLUSION

Results obtained show that an inflow cannula design has a direct influence on the likelihood of thrombus formation in the cannula. It is clearly obvious that stagnation and recirculation zones tend to be larger with longer cannula tip. This makes it necessary to search for other possible inflow cannula configurations. At the same time, for a zero-tip-length cannula with very good hemodynamic parameters, implementation of such a design requires further research to minimize the clogging of the cannula lumen with connective tissue.

The authors declare no conflict of interest.

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