Computational fluid dynamics based design of artificial heart
- An axial flow pump as a right ventricular assist device -

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Abstract: In recent years, computational fluid dynamics (CFD) has been used for designing rotary blood pumps. The secondary flow in the pump, especially between the blades, can be simulated by CFD and more precise prediction of pump performance at design and off-design points can be made. The US Food and Drug Administration (FDA) is engaged in establishing guidelines for the usage of CFD in the research and development phase of medical devices in order to help speed up the FDA approval process. The utilization of CFD is expected to increase further. In this study, we designed an axial flow blood pump and the flow field within the pump was calculated by CFD analysis. It was confirmed that the pump performance was suitable for right heart assistance.

Keywords: Axial Flow Blood Pump, Ventricular Assist Device (VAD), Computational Fluid Dynamics (CFD)

1. Introduction

Right ventricular assist device (RVAD) is crucial for the treatment of severe right heart failure. Although many left ventricular assist devices (LVADs) have been already developed and clinically used, rotary blood pumps specially designed for RVAD has not provided for clinical use. The pump characteristics suitable for RVAD is much different from that of LVAD. By operating LVAD at low speed, pump operation at a standard point for right heart assist can be achieved. However it is not suitable because it derives regurgitation and low blood compatibility due to the regurgitation. Therefore, RVAD with a specially designed impeller rotor is required.

We have designed and manufactured a prototype model of LVAD axial flow blood pump ValvoPump 2. The impeller rotor of the pump is suspended in radial and axial directions by hydrodynamic and passive magnetic bearings, respectively. The pump is connected in series to systemic circulation by putting the pump between both cut ends of aorta. An acute animal experiment of the pump has been conducted and the unique characteristics were revealed, e.g. the amplitude of aortic pressure and flow rate waves are increased. In this study, we designed a new RVAD axial flow pump based on the ValvoPump 2. The blood flow in the pump was calculated by computational fluid dynamics (CFD) to assess the pump hydraulic performance.

2. Methods

2.1 Computational model

A three-dimensional model of a miniature axial flow pump as a right ventricular assist device was constructed using a computer-aided design (CAD) software (Creo Parametric 4.0, PTC). The design parameters of the impeller rotor for ValvoPump 2 RVAD is summarized in Table 1. The fluid region of the pump model was divided into three regions, inflow, impeller and outflow regions, and each of them was discretized by unstructured grids. Pentahedrons with six nodes were generated at near wall region and then tetrahedrons with four nodes were generated in the remaining regions.

<table>
<thead>
<tr>
<th>Vane height [mm]</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clearance [mm]</td>
<td>0.1</td>
</tr>
<tr>
<td>Housing inner diameter [mm]</td>
<td>16.6</td>
</tr>
<tr>
<td>Hub diameter [mm]</td>
<td>12.4</td>
</tr>
<tr>
<td>Vane outer diameter [mm]</td>
<td>16.4</td>
</tr>
<tr>
<td>Axial vane length [mm]</td>
<td>27.9</td>
</tr>
<tr>
<td>Number of vanes</td>
<td>3</td>
</tr>
<tr>
<td>Vane inlet angle (Tip side) [deg]</td>
<td>11.0</td>
</tr>
<tr>
<td>Vane outlet angle (Tip side) [deg]</td>
<td>62.7</td>
</tr>
</tbody>
</table>

2.2 Calculation conditions

The pump model composed of three regions were transferred to the preprocessor (CFX-Pre) of a CFD software package (ANSYS CFX, ANSYS, Inc.) and physical properties of fluid and boundary conditions were defined. Blood was assumed to be an incompressible fluid with a density of 1,060 kg/m³ and dynamic viscosity of 3.6 mPa·s. A uniform velocity derived by dividing a certain volumetric flow rate by a cross sectional area was applied to the inlet plane. The outlet plane was defined as an opening boundary and a static gauge pressure of 0 Pa was applied to the plane. No-slip condition was applied to all walls of the pump model. The inflow and outflow regions were defined as stationary regions and the impeller region was defined as rotating domain with a constant speed. A frozen rotor boundary conditions were applied to the boundaries between the neighboring regions (inflow-impeller and impeller-outflow). The flow field in the pump model was calculated by solving Navier-Stokes equations using a CFD solver (CFX-Solve).
CFD analysis. It was confirmed that the pump performance was suitable for right heart assistance. It is expected to increase further. In this study, we designed an axial flow blood pump and the flow field within the pump was calculated by solving Navier-Stokes equations using a CFD solver (CFX-Solve). The hydraulic performance of an axial flow pump with newly designed impeller blades was investigated by CFD. The pump performance is suitable for right heart assistance.

3. Results and discussion
The area averaged pressures at inlet and outlet planes, $p_i$ and $p_o$, were calculated and the difference ($p_{oa} - p_i$) was dealt as the pump head. The pump performance curves (HQ curve; $H$: Pump head; $Q$: Pump flow rate) predicted by CFD analyses is shown in Fig. 2. The slope of the HQ curve is gentle at low flow rate region ($Q < 5 \text{ L/min}$) and abruptly steepens at high flow rate region ($Q > 6 \text{ L/min}$). Because of this characteristics, at early systolic phase, the pump flow rate rapidly increase with the slight decrease of pressure gap between the right ventricle and pulmonary artery. The shut-off head was up to 31 mmHg at a pump rotational speed of 4,500 rpm. These characteristics play a role in preventing extremely high pressure and flow rate in pulmonary artery.

4. Conclusions
The hydraulic performance of an axial flow pump with newly designed impeller blades was investigated by CFD. The pump performance is suitable for right heart assistance.

Reference