Effects of Eccentric Impeller Position on Radial Passive Stability in a Magnetically Levitated Centrifugal Blood Pump with a Double Volute

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Abstract Evaluation of the impeller radial stability is important from the bioengineering point of view in the development of mechanical circulatory support devices (MCSDs) for safer use as bridge for several months or destination therapy for years. In this study, radial stability of a magnetically levitated impeller in a centrifugal blood pump with an axially magnetic suspension system was evaluated by investigating the effects of the eccentric impeller position on passive stability, aiming to propose a pump design guide for the development and safer clinical use of MCSDs. First, impeller displacements in the prototype pump were measured using a mock loop together with laser displacement sensors. Then, the radial hydraulic forces exerted on an eccentric impeller were calculated using computational fluid dynamics (CFD) analysis for four volute-casing geometries. In addition, hemocompatibility was assessed using CFD calculations of scalar shear stress exerted on blood. Measurement of impeller displacement showed that the displacement varied from 0.56 to 0.27 mm at a rotational speed of 1800 rpm as the flow rate increased from 0 to 6.5 L/min. In the CFD calculation, the radial hydraulic force increased linearly from 0.2 to 1.7 N as the impeller displacement increased from 0 to 0.5 mm for all the double volute geometries, under conditions of a rotational speed of 1800 rpm and flow rates of 3, 5 and 7 L/min. These results indicate that the impeller stability in the prototype pump is acceptable at the operation conditions of ventricular assist devices, because the magnetic bearing stiffness of radial component was 4.1 N/mm. In the pressure recovery analysis of eccentric impellers, a double volute was not effective because of the unbalanced pressure field generated by the unbalanced pressure recovery. Thus, the increase in radial hydraulic force associated with an eccentric impeller could not be avoided by changing the conventional double volute design. The CFD analysis of geometrical variation indicated that widening of the radial clearance is an effective approach to improve the radial stability as well as hemocompatibility, although the radial clearance should be designed based on trade-offs among impeller stability, hemocompatibility and pump performance.

Keywords: eccentric impeller position, double volute, magnetic suspension, hydraulic force, computational fluid dynamics (CFD).

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1. Introduction

Mechanical circulatory support devices (MCSDs) have become the therapy of choice for end-stage heart failure. To use MCSDs for several months and as destination therapy, previous studies have developed rotary blood pumps as MCSDs by investigating the blood pump performance including hemocompatibility. The performance varied depending on numerous factors, and the pump and bearing designs were important for the development of MCSDs [1–4]. Rotary pumps are classified as axial or centrifugal. Several studies have reported that blood shear is lower in centrifugal than in axial pumps [5, 6], although the advantage of centrifugal pumps is controversial [7]. Several types of bearing have been used in these pumps, including pivot (e.g., HeartMateII, Thoratec Corporation), hydrodynamic (e.g., HVAD, HeartWare International Inc.) and magnetic (e.g., HeartMate III, St Jude Medical, LLC) designs. Recently, pumps with magnetic bearing are widely used in implantable ventricular assist devices such as HeartMate III [8], and in extracorporeal circulatory support devices such as CentriMag (Thoratec Corporation) [9].

In a magnetically suspended pump, active stabilization of the impeller/rotor in several directions is achieved

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by using an axial or a radial suspension system. Thus, movement of the impeller in the opposite direction is stabilized passively to achieve the size and power-saving requirements. Compared to a radially suspended centrifugal blood pump, an axially suspended pump contains a simpler flow path design in the radial direction. The simple flow path of the axially suspended pump can improve the washout flow by avoiding a tandem structure of the impeller, thus reducing thrombosis formation in the narrow gap of stagnated flow. Moreover, the radial clearance between the impeller and pump casing can be widened easily to reduce hemolysis in the radial gap of high shear. However, because the radial movement of the impeller is passively stabilized by the axial suspension, the impeller would be displaced toward the radial direction by a centrifugal hydraulic force. On the other hand, in radially suspended centrifugal pumps such as HeartMate III and CentriMag, the radial displacement of the impeller is controlled actively. The axial suspension allows radial displacement of the impeller that may result in touchdown if the passive suspension force is considerably lower than the radial external forces caused by hydraulic force, inertial force of patient motion, gravity, and others.

For the pump design, the radial passive stability can be improved with an optimal volute design by reducing the radial hydraulic force on the impeller [10–13]. Under the wide range of flow rate conditions that vary with the beating heart, a double volute would be adequate to cancel the radial hydraulic force generated by an unbalanced pressure field around an impeller at an off-design point [12, 14]. Although a double volute is effective for a centered impeller position as previously reported [12, 14], its effectiveness for an eccentric impeller position in a magnetically suspended pump remains unclear. Because a passively suspended impeller may move in a double volute depending on the operating condition, investigation of the eccentric effects on the stability in a double volute pump could provide an essential design guide of the pump flow path for safer clinical use.

As described above, evaluation of the impeller radial stability is important to improve hemocompatibility of a centrifugal blood pump with a double volute. In this study, radial stability of a magnetically levitated impeller in a centrifugal blood pump with a double volute was evaluated by investigating the effect of the eccentric impeller position on passive stability, aiming to suggest a pump design guide for the development and safer clinical use of MCSDs. First, the impeller displacement that was passively stabilized by an axial magnetic suspension system was measured, and then the effect of the eccentric position on the stability was numerically analyzed by calculating the radial hydraulic force on the impeller in a double volute pump using computational fluid dynamics (CFD). In the CFD analysis, four volute-casing geometries were used to analyze the effects of the volute-casing design on the stability as a first step for a design guide. In addition, the effect of eccentric impeller position on hemocompatibility was assessed by calculating the scalar shear stress.

2. Methods and Theory

2.1 In vitro experimental setting

The device used in this study (referred to as the prototype geometry hereinafter) is shown in Fig. 1. The impeller was axially suspended by the magnetic bearing, and the radial movement was stabilized passively. The details of the magnetic bearing and control system have been reported previously [15]. The radial stiffness of the magnetic bearing, which was measured experimentally as the static radial component of the axial magnetic suspension force by a load cell, was 4.1 N/mm. A closed-type impeller of the pump comprised six vanes and two central perfusion holes with an inner diameter of 18 mm, an outer diameter of 52 mm and a discharge vane height of 6 mm. Both the inlet and outlet had a diameter of 9.5 mm.

The impeller displacements and the pressure head characteristics of the prototype geometry were measured experimentally using a mock circulation loop as shown in Fig. 2. The radial displacements of the impeller center were acquired using laser displacement meters (LC-2440 and LK-G30A, KEYENCE Corporation, Osaka, Japan). The working fluids were an aqueous solution of 40 wt% glycerol with a viscosity of 3.1 mPa·s at 25°C as blood analog for the displacement measurement, and bovine blood for measurement of the pressure head characteristics. The flow rate was measured using an electromagnetic flow meter (MFV2100, Nihon Koden Corporation, Tokyo, Japan). The pressure head was acquired by mea-
suring the inlet and outlet pressures with strain pressure transducers (9E02-PB-200KPA, NEC San-ei Instruments Inc., Tokyo, Japan).

2.2 Numerical analysis setting

Four geometries of the pump double volute casing were used to analyze the effects of the geometry on the radial stability of the eccentric impeller. The geometric features are listed in Table 1. The design rule corresponds to the method of the volute path design. The path of the prototype geometry was designed using a combination of semicircles to reduce the expansion of the radial size. The constant angular momentum (CAM) method was used for the H6DL series with a constant \( \theta \) low angle of 3.55\(^\circ\) according to a previous report [10]. The position of 15\(^\circ\) was determined following a recommendation from Wong et al. [11] The radial clearance was widened by changing the diameter of the volute base circle.

Structured hexagonal meshes for the inlet and outlet domains were created using ANSYS Meshing (ANSYS, Inc., Canonsburg, PA, USA). The domain of the pump core was meshed using tetrahedral elements with \( \theta \) five prism layers near the wall, as shown in Fig. 3. An eccentric distance was defined as the displacement of the impeller center from the base circle center in a direction toward the volute tongue, as shown in Fig. 3. The mesh quality was assessed by calculating the discretization errors at the maximum aspect ratio below 100 [16] according to the mesh refinement study proposed by Roache [17], as listed in Table 2. The refinement ratio was calculated as \((\text{number of mesh elements in the finer mesh} \div \text{number of mesh elements in the coarser mesh})^{1/3}\). The maximum error of 57.4\% for the middle mesh was large. Therefore, fine meshes with approximately 17 million elements were used for subsequent calculations in this study.

The blood flow field in the pump was calculated using a commercial finite volume software program CFX 14.0 (ANSYS, Inc., Canonsburg, PA, USA). The rotational boundaries were connected by a Frozen-Rotor interface as a steady-state approximation. For the boundary conditions, the \( \theta \) low rates and a static pressure of 0 mm Hg were given at the inlet and outlet. The wall of the pump casing and impeller were modeled using a no-slip boundary condition. The \( k-\varepsilon \) RNG turbulence model was adopted in this study because previous studies showed that the \( k-\varepsilon \) RNG model was the most accurate among several models, including the \( k-\omega \) SST model, in predicting the velocity field by comparing the CFD and experimental results [9, 18]. The calculation was considered convergent when the velocity and the mass \( \theta \) low rate residuals were smaller than \( 10^{-4} \). The working fluid which is a blood analog was treated as an incompressible

![Fig. 2](image2.png) The mock flow loop and laser displacement meters used for measurement of the radial impeller displacement.

![Fig. 3](image3.png) Unstructured computational mesh of the prototype pump and eccentric direction \( x \) of the impeller. Image (a) shows the horizontal cross section and (b) shows vertical cross section.

| Geometry    | Design rule | Volute height [mm] | Tongue position [degrees] | Radial clearance [mm] |
|-------------|-------------|--------------------|----------------------------|-----------------------|
| Prototype   | Two semi-circles | 11                 | 0                          | 1                     |
| H6DL_RC1    | CAM         | 6                  | 0                          | 1                     |
| H6DL15_RC1  | CAM         | 6                  | 15                         | 1                     |
| H6DL_RC2    | CAM         | 6                  | 0                          | 2                     |
Newtonian fluid with a viscosity of 3.1 mPa·s and a density of 1050 kg/m³. The blood trauma was predicted numerically by calculating the scalar shear stress (S) proposed by Bludszuweit [19, 20] as follows, with the shear stress in a turbulent flow of $\sigma_{ij}$.

$$S = \frac{1}{6} \left( \sum (\sigma_{ii} - \sigma_{jj})(\sigma_{ii} - \sigma_{jj}) + \sum (\sigma_{ij}\sigma_{ij}) \right)^{\frac{1}{2}}$$  \hspace{1cm} (1)

The equation was implemented as a user defined expression in the post-processing of CFX.

3. Results

3.1 Radial displacement measurement

Figure 4 shows the radial displacements of the impeller center averaged over 1 s for the prototype geometry. Displacement of 1 mm corresponds to radial touchdown. The measured displacements were in the range of 0.27–0.56 mm as the flow rate was changed from 6.5 to 0 L/min at a rotational speed of 1800 rpm. Although the displacement range and direction of the impeller could vary dramatically as the volute geometry was changed, an eccentric distance range of ±0.5 mm was determined according to the results of the measurements in the following CFD analysis.

3.2 Pressure and hydraulic force analysis

The pressure heads calculated by CFD for the prototype geometry were compared with the pressure heads obtained experimentally to validate the CFD accuracy (Fig. 5). The CFD calculation was 1.8% greater than that of the experimental results at a rotational speed of 1800 rpm and a flow rate of 5 L/min.

Figure 6(a), (b) and (c) show the pressure head changes with respect to the impeller displacement for each geometry. The difference between maximum and
minimum pressure heads for each eccentric distance was up to approximately 10% in all conditions. The H6DL_RC2 and prototype geometry showed small changes of pressure head, but the values for H6DL_RC2 were higher than those for the prototype geometry.

Figure 6(d), (e) and (f) show that the radial hydraulic force exerted on the impeller varied with the impeller displacement for the four geometrical variations. The minimum forces of a centered impeller were below 0.5 N, and then, the hydraulic forces increased dramatically as the displacement increased (above 1.5 N at a displacement distance of +0.5 mm) for all of the geometries, and were accompanied by direction changes, as shown in Fig. 7.

To investigate the unbalanced pressure field around the eccentric impeller, the pressure recoveries in the inner volute and outer volute paths of a centered impeller were compared to those of an eccentric impeller at position x = −0.5 mm, as shown in Fig. 8. The pressure differences between the inner and outer volute paths varied between the centered impeller and the eccentric impeller, and the variation was smaller for the H6DL_RC2 than for the H6DL_RC1. In addition, the integration of increase in pressure difference from the impeller displacement for the H6DL_RC2 was approximately half of that for the H6DL_RC1.

3.3 Shear stress analysis

Blood damage associated with the eccentric impeller was assessed by calculating the scalar shear stress (S) for the four geometries, as shown in Fig. 9. The thresholds of 150, 50 and 1 Pa were used to evaluate the risks of hemolysis, platelet activation and blood stagnation, respectively, according to Fraser et al. (5) The fractions of high shear volumes (S > 150 and 50 Pa) and low shear
volume (S < 1 Pa) for the H6DL series, specifically for H6DL_RC2, were significantly lower than those for the prototype geometry.

4. Discussion

The calculated pressure heads corresponded well to the
measured pressure heads, as shown in Fig. 5. Although differences of a few percent were observed, use of the CFD approach was considered appropriate for comparison among geometrical variations in subsequent investigations.

The radial passive stability of the impeller in a pump with the prototype geometry was evaluated using the results of displacement measurement and radial hydraulic force simulation. The prototype pump has sufficient pressure-flow characteristic as a ventricular assist device at a rotational speed of 1800 rpm, because the pressure heads were higher than 100 mm Hg (aortic pressure) at physiological flow rates, as shown in Fig. 5. Under operating conditions, the impeller was stabilized with displacements up to 0.56 mm, as shown in Fig. 4. The radial displacement of the impeller center, which corresponded to average impeller center position, was determined by the equilibrium of the magnetic force for the radial passive suspension and hydraulic force of the static radial component. The radial stiffness of the magnetic bearing was 4.1 N/mm and the radial hydraulic force with impeller displacement of 0.5 mm was approximately 1.7 N, which corresponded to a stiffness of 3.4 N/mm. Therefore, the magnetic bearing of the centrifugal blood pump analyzed in this study can suspend the impeller passively even if the displacement and the hydraulic force are in the same direction. Although the impeller stability is acceptable at the ventricular assist device operating condition, the displacement should be reduced for improving the pressure head characteristic and for safer use under conditions of higher pressure head, such as extracorporeal membrane oxygenation.

The results of Fig. 8 explain why the hydraulic force was increased in the double volute by the eccentric impeller position. With a centered impeller, the double volute effectively improved the radial stability because the radial hydraulic force was reduced by balancing the pressure recovery in the inner and outer paths. However, with an eccentric impeller, the double volute was not effective because of the unbalanced pressure field generated by the unbalanced pressure recovery. The maximum pressure imbalance at an angular position of 50 degrees was 3793 Pa for H6DL_RC1 and 2451 Pa for H6DL_RC2. This pressure imbalance is caused by the increased difference in flow resistance between the inner and outer paths in the case of the eccentric impeller. Therefore, the increase of radial force with the eccentric impeller cannot be avoided geometrically by changing the conventional double volute design. The results shown in Figs. 6 and 8 indicate that the increase of radial hydraulic force may be reduced by widening the radial clearance.

The relationship between the eccentric impeller position and hemocompatibility is also an essential factor for pump design. The prototype geometry has an acceptable hemolytic property for short-term use of several hours. However, when used as bridge for several months, hemolysis should be further reduced. Hemocompatibility improvement may be achieved by an optimal design of the double volute casing, as shown in Fig. 9. Widening of radial clearance decreased the high shear volume (S > 150 and 50 Pa) and low shear volume related to thrombosis formation (S < 1 Pa). In addition, this study showed that widening of radial clearance contributed to improve passive stability at an eccentric impeller position, as shown in Figs. 6 and 8. An additional comprehensive pump design including the design of volute, gap flow path and impeller vane should be investigated to reduce the increase of hydraulic force and to improve the radial stability of the impeller in a magnetically levitated blood pump with a small and power-saving suspension system. Widening of the radial clearance is an effective approach in the blood pump design for safer clinical use because it improves the radial stability of the impeller as well as hemocompatibility.

Conversely, widening of the radial clearance may compromise pump performance such as pressure head and hydraulic efficiency. In the CFD calculation shown in Fig. 6, pressure heads for H6DL_RC2 were lower than those for H6DL_RC1. The maximum decrease in pressure head by widening the radial clearance was 5.8% at a flow rate of 7 L/min for an eccentric distance of 0.25 mm. On the other hand, the decrease in pressure head by widening the radial clearance may be reduced as the impeller displacement increases. For instance, no decrease in pressure head was observed for an eccentric distance of –0.5 mm, at flow rates of 5 and 7 L/min. Therefore, the decrease in pump performance by widening the radial clearance can be reduced by changing the eccentric impeller position. Nevertheless, the radial clearance should be designed based on trade-offs among impeller stability, hemocompatibility and pump performance, because reduction of the decrease in pump performance is uncertain.

Finally, several limitations are mentioned below. First, the CFD analysis contains uncertainties owing to the solver, mesh quality, turbulence model, and modeling of blood properties [1, 17–21]. Numerous studies have focused on the modeling of blood shear and hemolysis prediction [22–24]. In previous studies, hemolysis was directly related to the blood exposure time (t) and the magnitude of shear stress (τ) as follows:

\[ \Delta Hb/Hb = C \tau^\alpha \beta \]  \hspace{1cm} (2)

where \( \Delta Hb/Hb \) denotes the ratio of released hemoglobin to total hemoglobin within the red blood cells. The constants of C, \( \alpha \) and \( \beta \) are obtained from fitting measurements. Equation (2) shows the transient effects of shear.
stress change in a MCSD. For eliminating the clinical complications of hemolysis, the transient effects of shear stress change are important from the fluid dynamics point of view because of the unsteady flow field in a MCSD caused by the beating heart. Accurate CFD prediction of hemocompatibility, including the risk of platelet activation and vWf cleavage, could reduce the development cost of the MSCD and provide quantitative evaluation of the blood pump. Therefore, the effects of eccentric impeller position should be further investigated using an accurate prediction model. Moreover, a transient approach can calculate the dynamic hydraulic force more adequately than that of a steady approach [25, 26]. The steady approximation in this study was adequate for the calculation of the static force, which was related to the static equilibrium of the impeller displacement analyzed in this study. However, a transient approach has to be used for investigations of dynamic impeller motions such as whirlming. Furthermore, validation of the CFD analysis should be performed with additional experiments, such as the measurement of hydraulic force exerted on the impeller [14, 27, 28].

There are numerous geometrical parameters that should be used to investigate flow path design, in addition to the parameters used in this study. The throat area and cross-sectional shape are important geometrical factors in volute design [10, 29, 30]. Various geometrical parameters of dynamic impeller movement should be investigated to evaluate pump performance and hemocompatibility in future studies. The investigations would provide rigid guides for MCSD design for safer clinical use.

5. Conclusion
Radial passive stability of a magnetically levitated impeller at different eccentric positions was evaluated using eccentric displacement measurements and radial hydraulic force simulations for safer clinical use of a centrifugal blood pump. The impeller stability in the prototype pump is acceptable at the operation conditions of a ventricular assist device. The CFD analysis revealed that with a double volute, an unbalanced pressure field around the eccentric impeller increases the radial hydraulic force. The radial force increase cannot be avoided by changing the volute casing design using a conventional approach, although hemocompatibility is improved with an optimal volute casing design. Widening of the radial clearance is an effective approach in blood pump design for safer clinical use, although the radial clearance should be designed based on trade-offs among impeller stability, hemocompatibility and pump performance.

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