Computational fluid dynamic study of hemodynamic effects on aortic root blood flow of systematically varied left ventricular assist device graft anastomosis design

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ABSTRACT

Objectives: To quantify the range of blood flow parameters in ascending aorta that can result from various angulations of outflow graft anastomosis of a left ventricular assist device (LVAD) to the aortic wall, as a means to understand the mechanism of aortic valve insufficiency.

Methods: A realistic aorta model with LVAD anastomosis was generated from computed tomographic images of a patient. Based on this model, the LVAD anastomosis geometry parameters, such as anastomosis locations, inclination angle, and azimuthal angle (cross-sectional plane) of the graft, were varied, to create 21 models. With the assumption of no flow passing the aortic valve, and a constant flow rate from the LVAD cannula, computational fluid dynamics simulations were used to study the blood flow patterns in the ascending aorta. In addition, pulsatile flows were assumed in the LVAD cannula, with the aortic valve opened during peak systole, for 2 specific anastomosis configurations, to evaluate the influence of the pulsatile flow profile and the transvalvular flow on the aortic flow patterns.

Results: Changes in the inclination angle, from 60° to 120°, or the azimuthal angle, from 90° to 120°, or moving from a lower to a higher anastomosis position, causes significant changes for all flow parameters. A lower anastomosis location, an inclination angle $\geq 90^\circ$, and an azimuthal angle of 60° or 120° are all capable of reducing blood flow stagnation in the aortic root and producing normal wall shear stress and moderate pressure values in the region.

Conclusions: Carefully chosen anastomosis geometry is likely to be able to generate a close-to-normal hemodynamic environment in the aortic root. Greater knowledge of aortic valve remodeling may make possible the creation of favorable flow patterns in the aortic root, through optimization of surgical design to reduce or delay the occurrence of aortic valve insufficiency. (J Thorac Cardiovasc Surg 2015;150:696-704)

Reconstructed aorta with left ventricular assist device anastomosis at 3 inclination angles.

Central Message

This study investigates the effects of varying left ventricular assist device anastomosis geometry on local blood flow, using computational fluid dynamics.

Perspective

A systematic haemodynamic study demonstrated that the design of LVAD anastomosis to the aortic wall will have significant influence to the blood flow in ascending aorta.

See Editorial Commentary page 704.

For advanced stages of heart failure, heart transplantation remains the best treatment for suitable patients.¹ However, the increasing severity of heart failure as a public health

problem and the major lack of donor organs has spurred the evolution of mechanical circulatory support devices in recent decades.^{2,3} These devices, such as ventricular assist devices, are used as a “bridge-to-transplant,” but in addition, increasingly as destination therapy in selected patients. As of 2012, >4000 left ventricular assist devices (LVADs) had been implanted in the United States alone, and this number continues to rise.^{4,5}

However, several adverse effects can result from this treatment; these include high rates of thromboembolic events, infection, bleeding, and device malfunction or failure. Another is aortic valve insufficiency (AVI), which is a known complication after continuous flow LVAD support

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Abbreviations and Acronyms

AVI	= aortic valve insufficiency
CFD	= computational fluid dynamics
CT	= computed tomography
LVAD	= left ventricular assist device
WSS	= wall shear stress

that may result in ineffective biomechanical output and end-organ malperfusion, with substantial effects on both quality of life and survival.⁶ The mechanisms involved with the initiation and progression of AVI are the main focus of this study.

Clinical observation has shown that the start of AVI can in some cases be delayed if blood is still flowing past the aortic valve. Although the nonopening aortic valve is believed to be the main culprit for this complication, this observation indicates that maintaining a physiologic hemodynamic flow in the aortic root after the introduction of an LVAD may delay development of AVI. A few studies published recently have evaluated the effects of both LVAD–ascending aorta anastomosis configurations, along with their long-term impact on the aortic valve,⁷⁻¹² and cerebral embolization,¹³ using computational fluid dynamics (CFD).

CFD is a technique used to predict fluid flow patterns and distributions of flow parameters, such as velocity, pressure, and fraction force of blood to the arterial wall, which is also called wall shear stress (WSS), by using a computer to solve fluid flow governing equations. A geometry model (ie, patient aorta) is required in CFD simulation. Together with predefined flow information at the model inflow and outflow planes (also called dynamic boundary conditions), CFD simulation can provide flow parameter distributions in the model; these can be changed with time if a time-dependent boundary condition is used.

Studies to date have considered only a limited number of LVAD anastomosis designs. Furthermore, in cases in which aortic WSS and pressure distributions were resolved, localized distributions were not analyzed. The CFD analysis performed in these studies used imaging data from computed tomography (CT) or magnetic resonance imaging to generate the geometry model. Thin volumetric CT data of the thoracic aorta, with electrocardiogram-gating, provides high-resolution 3-dimensional reconstructions and improved model geometry accuracy.

The present study explores the effect of a wide range of LVAD outflow graft anastomotic angles to the ascending aorta, and its location distal to the aortic root, to understand the mechanism of AVI using CFD simulation on patient-specific CT data. Aortic pressure and WSS distributions are resolved at the LVAD jet impact region and in the aortic root. The research presented is used to study the hypothesis

that long-term alteration of the local flow environment is associated with initiation of AVI in LVAD patients. In addition, the current work can help in future long-term studies to determine if an optimal anastomosis to reduce the incidence of AVI is obtainable.

METHODS

The use of the data for this study was approved by the local ethical committee, and a consent waiver was granted because anonymized image data were used. The 3-dimensional geometry of the aorta was extracted from CT scan data in a patient with an LVAD. The scan was performed for clinical reasons, with electrocardiogram-gating, using 85 mL of iodinated contrast (given intravenously), and included the thoracic aorta and proximal branches of the arch, using an Aquilion 64-slice CT scanner (Toshiba Medical Systems Corporation, Otawara, Tochigi, Japan). The images were reconstructed at 0.5-mm slice thickness, with a 0.3-mm increment, resulting in an isotropic spatial resolution of 0.35 mm. These data were used as a template for subsequent geometric reconstructions.

Branching arteries, ie, left/right coronary, brachiocephalic, subclavian, and carotid arteries, were included in the flow domain, which consisted of the aortic root, arch, and ascending and descending aorta. A section (approximately 75 mm) of the LVAD outlet conduit, before the aortic anastomosis, was removed from the original CT geometry, and new LVAD anastomoses were reconstructed in its place. These were described as: lower = just above the aortic sinuses; middle = at the original graft site; and upper = just before the origin of the brachiocephalic trunk (Figure 1). The reconstructed anastomotic angles are described as “inclination” and “azimuthal,” on the coronal and transversal planes, respectively, as shown in Figure 2.

A total of 21 anastomosis designs were studied, exploring the inclination (ϕ) and azimuthal (θ) angles of 60°, 90°, and 120°. An inclination angle (ϕ) of 60° would represent the jet flow pointing away from the aortic root, whereas 120° would mean that the flow direction is toward the aortic root. As a result of unrealistic LVAD graft profiles, $\phi = 60^\circ$ and $\phi = 120^\circ$ were omitted from the lower and upper anastomosis designs, respectively. All geometric reconstructions and mesh generations were carried out using ANSYS ICEM CFD (ANSYS, Inc, Canonsburg, Pa).

Quantification of arterial WSS and pressure distributions in the ascending aorta, aortic root, and LVAD jet impact region are the primary focus of this study. To accurately determine these, circumferential segmentation was carried out for 6 locations on the ascending aorta, with the first band located 6 mm from the aortic valve. Subsequent bands were set at a spacing of 10 mm. Each circumferential band was further segmented 16 times, based on the angle from the lumen center (shown in Figure 1, B, colored bands). WSS and pressure at the aortic root (WSS_root, pressure_root) values, presented in the Results section, are the area-weighted average value at the lowest band.

A mesh sensitivity study was carried out to assess the extent to which the computational solution was affected by mesh parameters. To ensure mesh-independent data, numerical calculations were run on 3 separate mesh grids, consisting of, respectively: 700,000; 1 million; and 1.5 million elements. A few points on the descending aorta wall and in ascending aorta were used to compare the variations in WSS and velocity for the three mesh models. According to the comparison results, the models used in the present study have a mesh of about 1 million elements. To ensure the validity of the study, solver settings, such as the discretization schemes and convergence criteria, remained the same.

The CFD solver ANSYS Fluent (2014 release; ANSYS, Inc) was used for the simulations. Blood was modeled as a Newtonian fluid, with a constant density of 1060 kg/m³, and a constant viscosity of 0.004 Pa·s. Arterial walls were treated as rigid, with no-slip boundary conditions.

The first part was steady flow simulation, in which flow rate from the LVAD cannula was constant throughout the cardiac cycle, and the aortic valve was closed. A zero gauge pressure mass flow-rate boundary condition

FIGURE 1. A, Original geometry; B, C, and D, Geometric reconstructions; lower, middle, and upper anastomoses. Six 2-mm wide bands, with 10-mm spacing, are shown near the aortic root, for WSS and pressure data area weighted average. WSS and pressure values at the aortic root are the results from the lowest band.

of 0.08833 kg/s was set only at the cannula inlet (providing a volumetric flow rate of 5l per minute to the ascending aorta), normal to the boundary. At this flow rate, the Reynolds's number was 1840, which is smaller than the critical value of 2300 so that the flow could be treated as a laminar flow.

Flow-rate ratios were prescribed for the descending aorta and all other branching arteries as outflow boundary conditions, according to previously published data.¹³ Specifically, the flow rate ratios for the left coronary artery, right coronary artery, brachiocephalic artery, left common carotid artery, left subclavian artery, and descending aorta outlet, respectively, are 0.591%, 0.589%, 18.40%, 8.49%, 9.92%, and 62%. To determine the total pressure drop of the main flow along the ascending aorta, total pressure (the sum of static and dynamic pressure, representing the energy level) values were taken at the lumen center of the aortic root, and approximately three-quarters of the way down along the descending aorta, for each case. The pressure difference of the former minus the latter value was calculated to represent flow resistance.

Owing to the variation of left ventricular pressure during a cardiac cycle, the pressure loading condition on the continuous flow LVAD pump changes with time, causing a pulsatile flow output in the LVAD graft. Simulations with pulsatile flow rate from an LVAD graft were performed. Two conditions were mimicked: (1) Pul_B, a weak pulsatile wave in LVAD graft flow with the aortic valve closed to mimic the high-pump-rate setting (12,000 rpm); (2) Pul_A, a medium strong wave in the LVAD jet, with

the aortic valve opened at around peak systole for a duration of 150 ms (with a heartbeat of 90 bpm),¹⁴ with 5%, 10%, and 20% of total flow rate through the aortic valve, to mimic the medium-pump-rate setting (9000 rpm). The detailed flow rate curve was derived from Figure 6 of Estep and colleagues¹⁵ and is shown in Figure 3. The aortic valve opening is circular at the center of the aortic valve plane, with an area in which the diameter is one-half of the aortic root diameter.

Two specific anastomosis configurations were chosen for pulsatile flow simulation: $\phi/\theta/\text{anastomosis position} = 90^\circ/60^\circ/\text{low}$; and $60^\circ/60^\circ/\text{mid}$ to represent the 2 extreme cases (higher aortic root flow vs low jet resistance flow) obtained from steady flow study. The flow rate curve was derived from the pulse Doppler measurement result of Estep and colleagues,¹⁵ which has a higher mean flow rate 9.35 L/min. A turbulence model named “Realisable $k-\epsilon$ turbulence model” was chosen in the CFD solver. The outflow boundary conditions are the same as those in steady flow of fixed outflow rate ratio.

RESULTS

Qualitative Flow Pattern

Transversal plane secondary velocity vectors showed that the LVAD flow resembled a jet as it entered the aorta, hitting

FIGURE 2. Definitions of inclination angle and azimuthal angle used in the study. A, Diagram for the definition of inclination angle ϕ . B, Diagram for azimuthal angle θ . LVAD, Left ventricular assist device.

the opposing inner wall (Figure 4, A; $\theta = 60^\circ$; (B) $\theta = 90^\circ$; and (C) $\theta = 120^\circ$, while $\phi = 90^\circ$, middle anastomosis). For azimuthal angle $\theta = 90^\circ$, the jet flowed across the center of the aorta, creating recirculation regions at either side. Varying θ away from 90° changed the radial jet impact region, ie, the azimuthal angle changed from 90° , ie, to 60° and 120° ; consequently, one recirculation region was suppressed while the other grew in size and intensity. The flow was directed around the circumference of the aorta, which produced higher WSS values than in the $\theta = 90^\circ$ cases, likely as a result of the swirling effect of particles. The addition of centrifugal forces of the jet flow here would have a notable

impact on particle distribution and the level of exposure to shear forces to which the arterial walls were subjected. In addition, the cross-sectional velocity vectors showed visibly higher near-wall velocity gradients as the flow swirled around the aorta (Figure 4, A-C).

The influence of inclination angle ϕ on the flow can be seen qualitatively in Figure 4, D: $\phi = 60^\circ$; E: $\phi = 90^\circ$; and F: $\phi = 120^\circ$ (while $\theta = 90^\circ$, middle anastomosis). At $\phi = 60^\circ$, the jet flow from LVAD cannula followed the curvature of the aorta and did not hit the aortic wall until it reaches the aortic arch. At $\phi = 90^\circ$, the jet flow was divided into 2 parts: most of the flow was still going

FIGURE 3. Velocity temporal wave curve in LVAD cannula used as boundary condition in pulsatile flow simulation. For Pul_A, the aortic valve opens within the shadow period. The aortic valve remains closed for the whole cycle for Pul_B. LVAD, Left ventricular assist device; Pul_A, medium strong pulsatile wave curve; Pul_B, weak pulsatile wave curve.

FIGURE 4. A, B, and C, Example of velocity vectors at transversal plane of anastomosis, when $\phi = 90^\circ$, middle anastomosis; 3-dimensional streamlines for the middle anastomosis case with (D) $\phi = 60^\circ$; (E) $\phi = 90^\circ$; and (F) $\phi = 120^\circ$, with $\theta = 90^\circ$. Color code: velocity.

into the descending aorta; a small portion of flow turned toward the direction of the aortic root after the jet hit the aortic wall, which provided some “washing out” force in the aortic root. At $\phi = 120^\circ$, the flow was directed toward the valve, creating large vortices near the center of the aortic root.

The anastomosis location had a substantial impact on root dynamics. A lower anastomosis provided greater root WSS, which was reduced as the anastomosis location was moved up the ascending aorta. A similar relationship was found with aortic root static pressures. Furthermore, bulk fluid velocity below the graft increased, as the angle of inclination increased, which substantially enhanced the blood particle washout in the aortic root (Figure 4, D-F).

Quantitative Results for Steady Flow at the LVAD Cannula, With the Aortic Valve Closed

Quantitative results of the effects of LVAD anastomosis design on the flow parameters, such as WSS and pressure at the aortic root and the anastomosis jet impact region, and the pressure difference between the aortic root and the descending aorta, are shown in Table 1. In general, a lower anastomosis will produce a higher WSS at the root

region and greater root pressure. A higher inclination angle ϕ will normally produce higher values of WSS and pressure in the aortic root region, for all anastomosis locations, because of the partial backward flow from the anastomosis to the aortic root. For the same anastomosis location and inclination angle, the change in azimuthal angle θ has additional noticeable influences on the aortic root WSS value. For cases of a lower inclination angle ($\phi = 60^\circ$, or 90°), a change of θ away from 90° (ie, to 60° or 120°), can almost double the WSS value in the aortic root region, owing to the strong swirling flow effect.

With various anastomosis configurations, the range of the flow parameter change is: (0.082 Pa, 3 Pa) for WSS; and (−11.7 Pa, 130 Pa) for pressure. In the jet impact region, ranges for WSS and pressure are (6 Pa, 20 Pa) and (47 Pa, 280 Pa), respectively. The range of pressure drop from the aortic root to the descending aorta is (−55.7 Pa, 108 Pa). The model generally created high values of all flow parameters at a lower anastomosis site, with $\phi = 120^\circ$, $\theta = 120^\circ$. We obtained the lowest values at a middle anastomosis site, with $\phi = 60^\circ$, $\theta = 90^\circ$, which happens to be similar to the anastomosis configuration used for the patient.

TABLE 1. Quantitative results of aorta hemodynamic parameters for all testing cases

Parameter	Test case ($\varphi^\circ/\theta^\circ$)								
	60/60	60/90	60/120	90/60	90/90	90/120	120/60	120/90	120/120
Lower									
WSS_root				0.809	0.784	1.703	1.845	1.201	3.027
Pressure_root				60	72	90	66.5	103.7	130
WSS_jet				12	12	17.5	20	17	20
Pressure_jet				190	190	250	280	270	233
Pressure_drop				23	42	50	22.7	60	108
Middle									
WSS_root	0.228	0.113	0.31	0.45	0.2	0.702	1.26	0.603	1.292
Pressure_root	14.6	−11.7*	27	40.4	18.4	48.4	72.2	76.5	83.1
WSS_jet	13	6	11	11.7	9.1	12	12.5	11	12
Pressure_jet	110	47	137	162	118	180	215	198	198
Pressure_drop†	−28.1	−55.7	−16.3	−7.6	−22.3	0.6	28	33	41
Upper									
WSS_root	0.133	0.082	0.183	0.119	0.111	0.356			
Pressure_root	15	5.8	33	66.5	64.3	71.8			
WSS_jet	9.4	7.5	11	12	11	12.8			
Pressure_jet	117	70	147	162	148	195			
Pressure_drop	−34	−49	−9.53	21	8.9	17			

Values are given in Pa units. Except for pressure_drop, pressure values are static pressure. WSS, Wall shear stress. *Zero pressure was assigned at the joint plane of the left ventricular assist device graft and the ascending aorta. Therefore, if a lower pressure occurs at the aortic root, it is negative. †The pressure drop was comparing the total pressure difference between the aortic root and the descending aorta. If the pressure at the aortic root is lower than the pressure at the descending aorta, a negative pressure drop was expected.

The results indicate that more blood flow can be induced in the aortic root when $\phi \geq 90^\circ$. A drawback of this arrangement, however, is the increased flow resistance of the main flow stream through the aortic arch, or the increasing pressure drop from the aortic root to the descending aorta. To quantify flow resistance, the difference between the total pressure at the aortic root and the descending aorta was calculated (Table 1). A higher pressure drop means a higher flow resistance from the aortic root to the descending aorta. In general, the flow resistance increased with increasing inclination angle ϕ .

The influence of the anastomosis location on the pressure drop was smaller, compared with that of the inclination angle change. Further analysis showed that anastomoses displaying less-complex rotational flow structures produced lower total pressure drops through the aorta, as demonstrated in a case with a middle anastomosis location of $\phi = 60^\circ$; $\theta = 90^\circ$. The LVAD flow in this case was directed almost entirely around the arch, resulting in negative pressure in the root region (ie, negative compared with the zero pressure at the LVAD inlet plane set as a boundary condition), where the likelihood of near-stagnant particles was high.

Pulsatile Flow Results

Figure 5 shows the average value of WSS at the aortic root at various points in a cardiac cycle, for all pulsatile cases. First, Model_1 ($\phi = 90^\circ$; $\theta = 120^\circ$; low anastomosis site) produced a significantly higher WSS, compared with model_2 ($\phi = 60^\circ$; $\theta = 60^\circ$; middle anastomosis site); the

same was true for the steady flow simulation. The WSS values for the pulsatile condition are generally higher than those for the steady flow condition, possibly because of the almost-doubled LVAD temporal mean flow rate (9.4 litre per minute vs 5 litre per minute), but are still low compared to the physiological WSS range, especially for the model_2.

Second, no noticeable difference was found in the aortic root WSS value when the flow rate passing though the aortic valve was increased. The aortic valve opening area may have played a role in this result. In addition, the differences in WSS between the 2 pulsatile index cases, as described earlier, for each model are minor. Third, when the LVAD flow rate curve (Figure 3) is compared with the WSS variation (Figure 5), WSS can be seen to have more complex time variations during a cycle, compared with the input flow rate variation. They do not peak at the same time.

DISCUSSION

The current work presents a systematic study of the hemodynamic properties that have been hypothesized to be associated with initiation of AVI after LVAD implantation. The general flow features of WSS distributions and flow patterns in the ascending aorta and aortic arch are in agreement with the result of Inci and colleagues.¹¹ In the present work, more emphasis was put on the aortic root region, especially the root WSS and pressure given various anastomosis configurations. The study demonstrated the significant influence of the type of anastomosis design on the aortic root flow.

FIGURE 5. Average WSS variations in a cardiac cycle for pulsatile flow condition. Model_1: $\phi = 90^\circ$; $\theta = 60^\circ$; low anastomosis configuration. Model_2: $\phi = 60^\circ$; $\theta = 60^\circ$; middle anastomosis configuration. Pul_A: lower temporal mean flow rate but higher pulsatile index at LVAD cannula with aortic valve open; Pul_B: higher temporal mean flow rate, low pulsatile index at LVAD cannula with a closed AV. WSS, Wall shear stress; AV, aortic valve; Pul_A, medium strong pulsatile wave curve; Pul_B, weak pulsatile wave curve.

A well-documented potential obstacle to the success of long-term LVAD support is the native heart's inability to withstand the hemodynamic changes that result from sustained mechanical assistance. A serious complication is the AVI. Studies have indicated that one cause of AVI is a closed aortic valve. LVADs, on the other hand, introduce complex nonphysiologic hemodynamics into the aortic root, which are directly or indirectly involved in the instigation and development of AVI and several cardiovascular diseases.¹⁶⁻¹⁸ Flow patterns that exhibit disturbed or turbulent characteristics, stagnation, recirculation, as well as altered aortic WSS and pressure distributions, are the main areas of investigation. WSS is an important hemodynamic measure that is difficult to accurately quantify using clinical techniques, such as magnetic resonance imaging, alone.^{19,20} Low and/or oscillating WSS distributions have been associated with the pathogenesis of atherosclerosis.²¹ Studies have additionally shown that nonphysiologic WSS could lead to arterial remodeling.²²

Given its ability to resolve quantitative flow information, the CFD technique has been used, in recent years, to investigate the influence of an LVAD on aortic flow.⁷ The most active group working in this area recently is Karmonik and colleagues.⁸⁻¹⁰ In 2012, they published⁸ a CFD analysis of blood flow in ascending aorta on data from 2 patients. More recently, they increased the number of patients to 5 and analyzed the correlation between the flow pattern and AVI⁹; in addition, they have studied the influence of pulsatile and continuous flow LVAD on the flow patterns

in the ascending aorta.¹⁰ Their work demonstrated the influence of anastomosis on blood flow in the ascending aorta. However, with the very small number of patients, drawing conclusions from this work is difficult. With regard to development of AVI after LVAD implantation, some researchers believe that the primary factor may be high aortic root pressures caused by the jet flow.²³⁻²⁵ The current study demonstrates that configurations with a high inclination angle ϕ will indeed produce higher aortic root pressures. However, the highest root pressure value from all simulation cases was 130 Pa, or 1 mm Hg, compared with the anastomosis plane, where the pressure was assigned to be zero in the CFD simulations. Thus, if the diastolic blood pressure is 80 mm Hg at the anastomosis location for a patient, the aortic root pressure will be 81 mm Hg, a minor aortic root pressure increase.

A clinically desirable setting of the LVAD device is at a level that allows the aortic valve to open in systole intermittently, and maintains the valve leaflet motion. In practice, ensuring that this occurs is difficult, because of the change in the patient's condition. Kirmonik and colleagues⁹ conducted a CFD simulation in which the aortic valve was open during systole and had approximately 5% of normal flow passing the valve. They found that this transvalvular flow has only a minor impact on model WSS distribution. Based on 5 case comparisons, they suggested that an anastomosis design similar to that in our model_2 ($\phi = 60^\circ$; $\theta = 60^\circ$; middle anastomosis site; as in Figure 5) may be better because it produces the least

disturbance to the LVAD graft jet flow that flows smoothly toward the aortic arch. However, the present study shows that with a closed aortic valve and no transvalvular flow, anastomosis setting as in model_2 would represent the worst case for blood stagnation in the aortic root, according to Table 1. Even with flow passing through the aortic valve for 15% of a cycle duration, the WSS value at the aortic root is still significantly smaller than the value with a low anastomosis, as in Figure 5. A long blood residential time in the aortic root region can be expected in this graft configuration, increasing the potential for thrombosis formation and aortic wall remodeling, a potential risk factor for development of AVI.

If LVAD-induced nonphysiologic hemodynamic conditions in the aorta are the factors to be blamed for AVI development, then maintaining a physiologic level of WSS and pressure in the aortic root may delay aortic wall remodeling and prevent thrombosis formation. The present study indicated that few designs can be used to produce a physiologic WSS (in the range of 0.35 to 1 Pa)^{26,27} in the aortic root, even with a closed aortic valve. A low anastomosis position can generally produce a WSS in that range, in the root. If a high inclination angle (ie, 120°) of the guiding jet that is heading directly toward the valve creates too violent a motion, then the low anastomosis position $\phi = 90^\circ$ may be a good choice. This position produces a WSS_{root} of 0.78 to 1.7 Pa, and a moderate aortic root pressure of 60 to 90 Pa. Higher anastomosis locations will have difficulty creating an aortic root WSS value that is in the physiologic range, unless a high inclination angle is chosen.

This study has limitations, owing to several assumptions that were made. First, the low anastomosis position may be a bit too low in terms of actual surgical practice; the position in practice may be a few millimeters higher than the position used here. Second, we have applied relatively simple treatment to the model boundary conditions, such as a fixed flow rate ratio at all outflow vessels. Third, blood viscosity value of normal blood was used in the CFD simulation; LVAD patients are often subject to strict anticoagulant regimes that would lower blood viscosity.

CONCLUSIONS

This study, which uses CFD, demonstrates that the hemodynamic environment can be changed significantly by varying the geometry of the outflow graft of LVADs. Aortic root WSS can be altered from almost zero (blood stagnation) to the normal range of blood flow in aorta, with only a small rise in pressure in the root region. Among all test scenarios, a low anastomosis position, an inclination angle $\phi = 90^\circ$, and an azimuthal angle $\theta = 60^\circ$ result in an aortic root WSS in the normal range, and a moderate aortic root pressure. More knowledge of aortic valve remodeling may make possible the creation of a favorable flow pattern

in the aortic root, through optimization of surgical design to prevent or reduce the occurrence of AVI.

Conflict of Interest Statement

Authors have nothing to disclose with regard to commercial support.

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EDITORIAL COMMENTARY

Computational fluid dynamics: Solidifying fluid concepts in left ventricular assist device therapy

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See related article on pages 696-704.

The opinions that are held with passion are always those for which no good ground exists; indeed the passion is the measure of the holders lack of rational conviction.

—Bertrand Russell, *Sceptical Essays*, 1928

The study of viscous fluids, predicting their behavior under the influence of outside forces and constraints, is of ever-increasing importance for the everyday cardiac surgeon, and is especially important to the heart failure surgeon. To understand the short- and long-term consequences of

differing device designs and anastomotic factors (angle, length, location in relation to structural components), and the impact that conduit selection, design, size-matching, and tailoring have on outcomes after cardiac surgery, requires an appreciation for the parameters that influence blood flow.

The first description of the physiology of the circulatory system, where the blood is described as a fluid pumped by the heart, was made by William Harvey in 1628 in the *Exercitatio Anatomica de Motu Cordis et Sanguinis in Animalibus*. Theoretical advances in our understanding of blood flow, and the ability to predict the impact of various anatomic defects or structural lesions on blood flow, would have to wait for developments in the fundamental understanding of fluid dynamics as ultimately described by the Navier-Stokes equations.

The Navier-Stokes equations are mathematical relationships describing the behavior of viscous fluids, applying the general principles of the conservation of mass, energy, and momentum within the context of Newtonian dynamics. This set of nonlinear partial differential equations describes a velocity field in a given volume of space. The velocities at various points can be utilized to calculate other useful characteristics of the fluid, such as pressure, stress, or shear. Given that they are nonlinear equations, the solutions are cumbersome to derive, and whether

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