Computational fluid dynamics in patients with continuous-flow left ventricular assist device support show hemodynamic alterations in the ascending aorta

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Objective: Increased use of continuous-flow left ventricular assist devices for long-term mechanical support necessitates a better understanding of hemodynamic changes in the native heart and the ascending aorta. By using patient-specific computational models, correlations of potentially adverse hemodynamic conditions with the orientation of the left ventricular assist device outflow graft and their relationship with aortic insufficiency and ischemic events were investigated.

Methods: Computed hemodynamic parameters, including wall shear stress, pressure in the ascending aorta, and dissipation of turbulent energy, were correlated with the orientation of the left ventricular assist device graft outflow in 5 patients (4 with the HeartMate II device [Thoratec Corp, Pleasanton, Calif] and 1 with the HeartWare Ventricular Assist Device [HeartWare Inc, Framingham, Mass]; 3 patients experienced moderate aortic insufficiency, and 2 patients experienced ischemic events). Hemodynamic conditions for aortic insufficiency and ischemic events were differentiated by linear discriminant analysis.

Results: Positive correlations between left ventricular assist device outflow graft orientation and wall shear stress, pressure, and turbulent energy dissipation in the ascending aorta were found ($R^2 > 0.68$). Linear discriminant analysis indicated a relationship of the velocity magnitude of retrograde flow toward the aortic root with aortic insufficiency and of the turbulent energy and wall shear stress with ischemic events.

Conclusions: Computational fluid dynamic simulations using clinical image data indicate altered hemodynamic conditions after left ventricular assist device implantation. Consequently, the left ventricular assist device outflow graft should be placed so the jet of blood is aimed toward the lumen of the aortic arch to avoid turbulences that will increase wall shear stress and retrograde pressure of the aortic root. Further investigations are warranted to confirm these findings in a larger patient cohort. (J Thorac Cardiovasc Surg 2014;147:1326-33)

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Patients with end-stage heart failure who are not eligible or waiting for a heart transplant may undergo implantation of a left ventricular assist device (LVAD) to improve functional capacity and quality of life and prolong survival.[1-4] The concept of long-term mechanical support is bridge to decision, bridge to transplantation, or destination therapy.[5-7] In some cases, mechanical circulatory support may allow for the recovery of the native heart.[8,9]

The long-term use of continuous-flow LVAD support requires a better understanding of the alterations in hemodynamics and their impact on the native heart and major vessels. One of these well-known architectural changes after LVAD implantation includes the development or progression of aortic valve diseases, mainly aortic insufficiency (AI).[10-12] In turn, AI may compromise LVAD function, eventually causing multiple organ malperfusion. Moreover, severe AI may prevent the recovery of the native heart after LVAD support and require aortic valve implantation.[13]

Patient-specific modeling of hemodynamic conditions using computational fluid dynamics (CFD) has been demonstrated in a variety of vascular diseases (ie, cerebral aneurysms, aortic dissections, aortic aneurysms, and carotid atherosclerosis).[14-18] From these computational simulations, a variety of hemodynamic parameters, in

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Abbreviations and Acronyms

AI = aortic insufficiency
CFD = computational fluid dynamics
CT = computed tomography
CTA = computed tomography angiography
IE = ischemic event
LDA = linear discriminant analysis
LVAD = left ventricular assist device
WSS = wall shear stress

particular wall shear stress (WSS), are available that are not reliably accessible by clinical imaging methods.[19-21] CFD is a clinical research tool that is gaining increasing popularity in a complementary approach to clinical imaging toward revealing distinct features of altered hemodynamics in the course of vascular diseases in individual patients.[19]

CFD was used in the current study to characterize potentially adverse hemodynamic conditions in 5 patients with continuous-flow LVAD devices and to explore the relationship of selected hemodynamic parameters with AI and ischemic events (IEs). The study was motivated by the increased incidence of AI and IEs in this patient group.[13,22]

MATERIALS AND METHODS

Patients

The study was approved by the local ethics committee, and the patients gave written informed consent. Clinical computed tomography angiography (CTA) images were retrospectively collected from 5 patients (cases). The geometry of the LVAD graft inflow varied among patients with respect to the angle at which the LVAD outflow graft was inserted into the ascending aorta (azimuth angle), allowing for a systematic investigation of this angle on the hemodynamics at the aortic root. In the 5 patients, 4 HeartMate II devices (Thoratec Corp, Pleasanton, Calif) and 1 HeartWare Ventricular Assist Device (HeartWare Inc, Framingham, Mass) were implanted. The flow of the device in all patients was 4 to 5 L/min. The time of LVAD implantation to computed tomography (CT) investigation was on average 11.6 months (range, 5-30 months). At the time of the CT study, all patients were mobile. AI developed in patients 1, 2, and 5 after LVAD implantation (grade I-II). AI was measured noninvasively by transthoracic echocardiography according to the guidelines and standards of the American Society of Echocardiography. None of the patients had preoperative AI or developed AI postoperatively on echocardiography until discharge from the hospital. Patient 3 had an ischemic stroke 3 months after LVAD implantation, and patient 5 had an IE (colon ischemia) 12 months after LVAD implantation.

Geometric Characterization

For quantitative assessment, the position of the LVAD outflow graft was characterized by 2 angles (Figure 1). The first angle describes the lateral aspect of the LVAD graft orientation: First, the computational model was oriented to provide a view from the head down to the arch (Figure 1, *A*). Then, a line through the 2 midpoints of the ascending and descending aorta was drawn. Another line was drawn as the midline of the distal LVAD outflow graft. The angle between these 2 lines was defined as the azimuth angle. The second angle describes the horizontal alignment of the LVAD graft relative to the ascending aorta: First, the midline of the ascending thoracic section of the aorta was drawn. Then, the midline of the distal LVAD outflow graft was drawn. The angle between these 2 lines was defined as the polar angle.

Computational Fluid Dynamics Simulations

CFD, as a branch of fluid dynamics, uses numeric methods to solve problems that involve fluid flows. Computational algorithms that approximate the real system and use boundary conditions define the geometry and the inflow and outflow parameters of the model, and calculate the velocity vector field and other derived hemodynamic parameters, such as pressures and WSS (ie, forces), which the fluid exerts onto the wall. In the first step of this process, the physical bounds of the computational model are defined.[18] This defined volume is then divided into small elements (cells) that constitute the computational mesh. The governing physical equations, for this case, the Navier–Stokes equations, are then iteratively solved on the computational mesh taking into consideration the boundary conditions. Post-processing software is then used for further analysis and visualization.[23]

The methodology for the CFD simulations for these kind of computational models of LVAD devices have been developed previously.[24] Technical details on how the computational models were created from the boundary conditions and the CFD simulations were carried out are provided in Appendix 1.

Qualitative analysis. For a qualitative overview, 3-dimensional surface reconstructions of the contours for the dynamic pressure, WSS, and streamlines were created for systolic flow.

Quantitative analysis. Pressure, velocity magnitude, turbulence dissipation, and turbulence energy were averaged over the cardiac cycle in a region of interest, which comprised the aortic lumen from the aortic root to a distance 3 cm distally. WSS was averaged over the cardiac cycle at the wall segment located contralaterally to the LVAD graft by extending a straight line across the aorta from the mid-point of the anastomotic opening. Potential relationships of these averaged hemodynamic parameters with the azimuth and the polar angle were evaluated with the Pearson correlation coefficient.

Exploratory linear discriminant analysis (LDA) (R-language, lda function of the ‘‘MASS’’ package) was used to investigate the relationships of the geometric parameters (azimuth and polar angle) and hemodynamic parameters (averaged velocity magnitude, WSS, pressure, turbulence dissipation, and turbulence energy) with the occurrence of AI (patients 1, 2, and 5) and IE (patients 3 and 5).

RESULTS

Geometric Characterization

The azimuth angle varied between 2 and 51 degrees because of the difference in location of the LVAD graft (anterior or lateral) and the difference in angle of the aortic arch relative to the LVAD graft (Figure 1, *A*). The polar angle varied between 29 and 78 degrees, with the largest value for patient 1.

Computational Fluid Dynamics Simulation Analysis

Qualitative analysis. No significant variation of the relative spatial distribution of the 3-dimensional velocity field and the streamlines derived from it was found during the cardiac cycle, motivating the use of averaged values for the hemodynamic parameters in the consequent