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CFD case study to optimize surgical adjustment of ventricular assist device implantation to minimize stroke risk part I: steady-state CFD modeling

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Summary

Presently, mechanical support is the most promising alternative to cardiac transplantation. Ventricular Assist Devices (VADs) were originally used to provide mechanical circulatory support in patients waiting planned heart transplantation ("bridge-to-transplantation" therapy). The success of short-term bridge devices led to clinical trials evaluating the clinical suitability of long-term support ("destination" therapy) with left ventricular assist devices (LVADs). The first larger-scale, randomized trial that tested long-term support with a LVAD reported a 44% reduction in the risk of stroke or death in patients with a LVAD. In spite of the success of LVADs as bridge-to-transplantation and long-term support. Patients carrying these devices are still at risk of several adverse events. The most devastating complication is caused by embolization of thrombi formed within the LVAD or inside the heart into the brain. Despite anticoagulation management and improved LVAD design, there is still significant occurrence of thromboembolic events in patients. Investigators have reported that the incidence of thromboembolic cerebral events ranges from 14% to 47% over a period of 6-12 months.

Accepting the current rate of thrombus formation within the LVAD, an alternative method to reduce the incidence of cerebral embolization is hypothesized: thromboembolism to the carotid and vertebral arteries can be minimized by adjusting the placement of the LVAD outflow conduit, or by the placement of an aortic-to-innominate artery bypass graft, or by the placement of an aortic-to-left-carotid artery bypass graft, or possibly a combination of these. We present a computational fluid dynamics (CFD) study of the aortic arch bed hemodynamics using a representative geometry of the human aortic arch and an alternative aortic bypass whose express purpose is to investigate the hypothesis.

We utilize the CFD code, STARCCM+, in which a Lagrangian particle-tracking model is coupled to the fluid flow solver to predict particle trajectories. In this

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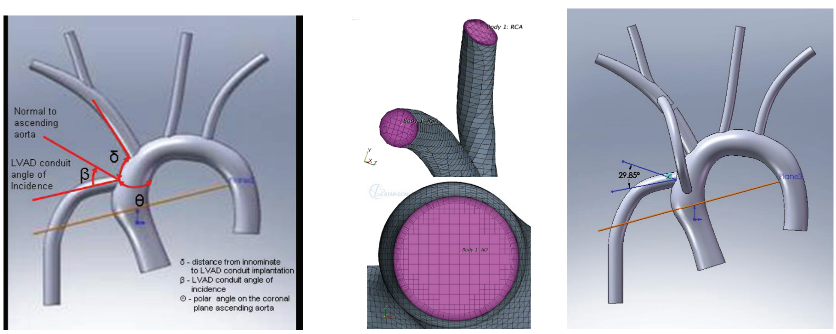
study, we then explore the possibility of finding an optimal configuration of the LVAD conduit angle and anastomosis location (that is both distance from the innominate and polar angle in the coronal plane of the ascending aorta), and we seek to establish the benefits of the ligation of the innominate artery and placement of an aortic-to-innominate artery bypass graft or the ligation of the left carotid artery and placement of an aortic-to-left-carotid artery bypass graft. LVAD conduit flow is assumed to be steady (non-pulsatile), with negligible pulsatile flow originating from the aortic root. Although not always the case, steady or near steady flow characterizes the flow regime in many patient with LVAD support. Continuous-flow LVADs have predominantly become the device of choice. Consequently, the focus of this study is to investigate steady flow conditions.

Results are presented in the form of percentage of thrombi of diameters 2mm, 4mm and 5 mm reaching the carotid and vertebral arteries as a function of LVAD conduit placement and aortic bypass implantation, revealing promising improvement: significant (50%) reduction in thromboembolism by proper adjustment of the LVAD inflow cannula. We present adult and pediatric cases as well as a patient-specific model generated from image segmentation of a CT scan. We also discuss progress of a benchtop model devised to buttress the CFD study.



(a) (b) (c)

Figure 1: (a) Solid model of adult aortic arch with LVAD conduit at intermediate $\beta = 30^\circ$ angle of incidence, (b) close-up of computational mesh, and (c) close-up of solid model of aortic arch with LVAD conduit at a intermediate $\beta = 30^{circ}$ angle of incidence with aortic-to-innominate artery bypass graft.

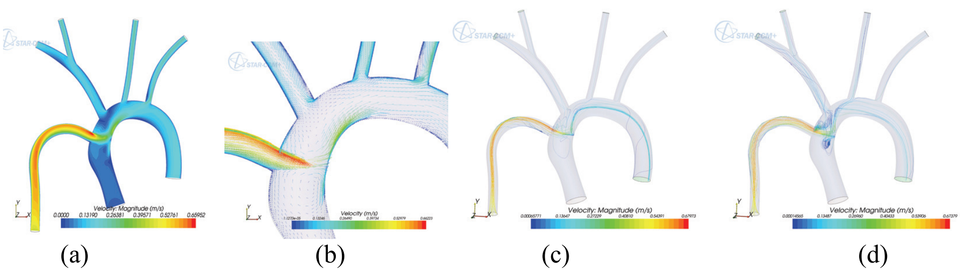


Figure 2: Computational results with LVAD conduit at $\beta = 0^{circ}$ incidence: (a) velocity magnitude, (b) close-up of velocity field in vicinity of anastomosis, (c) 2 mm and (d) 5 mm thrombi traces.

Table 1: Percentage of Thrombi flowing to the carotid (LCA and RCA) arteries at fixed, δ=1.5cm, with flow field and particle path illustrated to the right for the case of no bypass graft.

Configuration	2mm Thrombi [%]	4mm Thrombi [%]	5mm Thrombi [%]	Overall [%]
Standard 0 deg	16.66± 26.14	21.21± 16.47	32.78± 13.11	25.6± 17.06
IA Bypass 0 deg	8.33± 17.56	24.18± 12.55	21.69± 8.53	20.54± 10.06
LCA Bypass 0 deg	8± 8.43	46.17± 18.43	59.46± 12.03	40.93± 17.88
Standard 30 deg	39.42± 13.31	15.45± 11.82	6.76± 5.7	20.57± 9.33
IA Bypass 30 deg	19.78± 11.28	11.28± 10.34	12.63± 17.44	14.51± 7.62
LCA Bypass 30 deg	8.39± 8.04	16.13± 4.52	13.79± 11.69	12.72± 5.3
Standard 60 deg	56.78± 7.87	51.79± 7.6	33.19± 10.16	47.43± 6.44
IA Bypass 60 deg	71.05± 15.96	55.64± 5.84	45.99± 9.25	55.66± 8.31
LCA Bypass 60 deg	59.65± 7.25	33.15± 12.22	13.65± 6.9	34.74± 9.3
Standard 30 deg 22.5	24.41± 14.18	33.8± 25.58	36.56± 17.08	31.69± 10.74
Standard 30 deg 45.0	24.52± 16.18	10.57± 8.41	11.2± 5.44	15.09± 10.1
IA Bypass 30 deg 22.5	18.18± 22.21	10.4± 9.98	20.39± 4.76	16.44± 10.74
IA Bypass 30 deg 45.0	9.73± 8.51	24.15± 10.95	29.38± 12.93	21.54± 8.66
LCA Bypass 30 deg 22.5	21.39± 8.83	17.2± 5.59	9.58± 7.04	15.82± 6.18
LCA Bypass 30 deg 45	10.25± 9.23	23.9± 17.92	3.69± 3.69	11.77± 11.35

β θ