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Hemodynamics of left internal mammary artery bypass graft: Effect of anastomotic geometry, coronary artery stenosis, and postoperative time

Tingting Fan [a,b,1], Yuan Lu [c,1], Yan Gao [d], Jie Meng [d], Wenchang Tan [a,b,e], Yunlong Huo [a,b,*], Ghassan S. Kassab [f,**]

[a] *Mechanics and Engineering Science, College of Engineering, Peking University, PR China*
[b] *State Key Laboratory for Turbulence and Complex Systems, College of Engineering, Peking University, PR China*
[c] *The Affiliated Hospital of Xuzhou Medical College, Xuzhou, PR China*
[d] *The Affiliated Hospital of Hebei University, Hebei University, Baoding, PR China*
[e] *Shenzhen Graduate School, Peking University, Shenzhen, PR China*
[f] *California Medical Innovations Institute, 11107 Roselle St., Rm. 211, San Diego, CA 9212, USA*

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ABSTRACT

Although the left internal mammary artery (LIMA) bypass graft is the best choice for surgical revascularization, its hemodynamics are still complex and can result in long-term graft failure. Here, we performed a hemodynamic analysis of the LIMA-coronary artery with end-to-side/side-to-side anastomoses based on 15 patient-specific CTA images at various postoperative periods. We hypothesize that hemodynamic patterns are determined by the interplay of LIMA geometry, anastomotic configuration, and severity of native coronary artery stenosis, which are strongly affected by the postoperative time. A 3D finite volume method with the inlet pressure wave and outlet resistance boundary conditions was used to compute the distribution of pressure and flow, from which the time-averaged wall shear stress (TAWSS), oscillation shear index (OSI), time-averaged WSS gradient (TAWSSG), and transverse WSS (transWSS) were determined. To characterize the hemodynamic environment, we defined surface area ratios of low TAWSS (≤ 4 dynes/cm^2), high OSI (≥ 0.15), TAWSSG (≥ 500 dynes/cm^3), and transWSS (≥ 6 dynes/cm^2) in the LIMA graft and at the anastomosis between LIMA graft and coronary artery. These ratios were determined by the interplay of multiple morphometric parameters in the LIMA-coronary artery, but increased with postoperative time. These findings have significant implications for understanding LIMA graft patency.

1. Introduction

The left internal mammary artery (LIMA) is an excellent coronary artery bypass graft (CABG), which can relieve symptoms of ischemic heart disease (Goldman et al., 2004; Parang and Arora, 2009; Hillis et al., 2011). Although the LIMA graft has a relatively longer life span than the saphenous vein graft (SVG), it still has about 10% failure at 10–15 years after surgical revascularization (Sims, 1983; Goldman et al., 2004). Abnormal hemodynamic parameters (e.g., low wall shear stress, WSS; and high oscillatory shear index, OSI) were found to contribute to graft failure (Keynton et al., 1991; Fei et al., 1994; Kassab and Navia, 2006; Loth et al., 2008). Computational fluid dynamic (CFD) methods have been used to extensively investigate the hemodynamics in the SVG or idealized grafts (Noori et al., 1999; Ku et al., 2005; Sankaranarayanan et al., 2006; Frauenfelder et al., 2007). Although some researchers applied the CFD simulations to the LIMA graft (Nordgaard et al., 2010; Swillens et al., 2012), there is still lack of a complete patient-specific hemodynamic study in the LIMA-coronary artery of various anastomoses with postoperative time.

The objective of this study is to determine the distribution of hemodynamic parameters in the LIMA graft of end-to-side/side-to-side anastomoses and the left anterior descending (LAD) artery with stenoses of different degrees at various periods after surgical revascularization, based on patient-specific computer tomography angiography (CTA) images. Here, we hypothesize that the hemodynamics in the LIMA-LAD artery are determined by the interplay of

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[*] Corresponding author at: Department of Mechanics and Engineering Science, College of Engineering, Peking University, Beijing 100871, PR China. Tel.: +86 10 62755417.

[**] Corresponding author. Tel.: +1 858 249 7418.

E-mail addresses: yhuo@pku.edu.cn (Y. Huo), gkassab@calmi2.org (G.S. Kassab).

[1] These authors contributed equally to this study.

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Nomenclature

SAR-TAWSS at the anastomosis Surface area ratio of low TAWSS $\left(=\frac{\text{Surface area}_{\text{TAWSS} \le 4\ \text{dynes}\cdot\text{cm}^{-2}}}{\text{Anastomotic surface area}}\times 100\%\right)$ at the anastomosis between LIMA graft and coronary artery. The end-to-side 'anastomotic surface area' is defined as the surface area of the proximal LIMA graft (5 mm length) to the anastomotic center plus the surface area of the distal coronary artery (5 mm length) to the anastomotic center. The side-to-side 'anastomotic surface area' is defined as the surface area of LIMA graft of 10 mm length (on both sides of the anastomotic center) plus the surface area of the distal coronary artery (5 mm length) to the anastomotic center.

SAR-TAWSS in the LIMA graft Surface area ratio of low TAWSS $\left(=\frac{\text{Surface area}_{\text{TAWSS} \le 4\ \text{dynes}\cdot\text{cm}^{-2}}}{\text{Surface area of LIMA graft}}\times 100\%\right)$ in the LIMA graft. 'Surface area of LIMA graft' refers to the surface area of LIMA graft except for the anastomotic region.

SAR-OSI at the anastomosis Surface area ratio of high OSI $\left(=\frac{\text{Surface area}_{\text{OSI} \ge 0.15}}{\text{Anastomotic surface area}}\times 100\%\right)$ at the anastomosis between LIMA graft and coronary artery.

SAR-OSI in the LIMA graft Surface area ratio of high OSI $\left(=\frac{\text{Surface area}_{\text{OSI} \ge 0.15}}{\text{Surface area of LIMA graft}}\times 100\%\right)$ in the LIMA graft.

SAR-TAWSSG at the anastomosis Surface area ratio of high TAWSSG $\left(=\frac{\text{Surface area}_{\text{TAWSSG} \ge 500\ \text{dynes}\cdot\text{cm}^{-3}}}{\text{Anastomotic surface area}}\times 100\%\right)$ at the anastomosis between LIMA graft and coronary artery.

SAR-TAWSSG in the LIMA graft Surface area ratio of high TAWSSG $\left(=\frac{\text{Surface area}_{\text{TAWSSG} \ge 500\ \text{dynes}\cdot\text{cm}^{-3}}}{\text{Surface area of LIMA graft}}\times 100\%\right)$ in the LIMA graft.

SAR-transWSS at the anastomosis Surface area ratio of high transWSS $\left(=\frac{\text{Surface area}_{\text{transWSS} \ge 6\ \text{dynes}\cdot\text{cm}^{-2}}}{\text{Anastomotic surface area}}\times 100\%\right)$ at the anastomosis between LIMA graft and coronary artery.

SAR-transWSS in the LIMA graft Surface area ratio of high transWSS $\left(=\frac{\text{Surface area}_{\text{transWSS} \ge 6\ \text{dynes}\cdot\text{cm}^{-2}}}{\text{Surface area of LIMA graft}}\times 100\%\right)$ in the LIMA graft.

anastomotic configuration, severity of native coronary artery stenosis, and LIMA geometry, which are negatively impacted with post-operative time. A transient 3D finite volume model (FVM) was used to solve the continuity and Navier–Stokes equations to compute the hemodynamic fields. The inlet (at the inlet of both LIMA graft and LAD artery) and outlet boundary conditions were the aortic pressure waveform and the flow resistances, respectively. The hemodynamic parameters including TAWSS (time-averaged WSS over a cardiac cycle), OSI, TAWSSG (time-averaged WSS gradient over a cardiac cycle) (Kleinstreuer et al., 2001), and transWSS (transverse WSS) (Mohamied et al., 2015) were computed in the LIMA-LAD artery. To characterize the hemodynamic environment, we define several novel parameters as follows: SAR-TAWSS (i.e., TAWSS ≤ 4 dynes/cm^2) (Malek et al., 1999), SAR-OSI (i.e., OSI ≥ 0.15) (Nordgaard et al., 2010, Huo et al., 2013a), SAR-TAWSSG (i.e., TAWSSG ≥ 500 dynes/cm^3) (Kleinstreuer et al., 2001), and SAR-transWSS (i.e, transWSS ≥ 6 dynes/cm^2) (Mohamied et al., 2015) in the LIMA graft and at the anastomosis between LIMA graft and LAD artery (see definitions in the Nomenclature). The significance, implication and limitation of flow simulations are discussed in relation to the long-term LIMA graft patency.

2. Materials and methods

2.1. Study design

The main purpose of this retrospective study was to investigate the distribution of atherosclerosis-prone hemodynamic parameters in the LIMA-LAD artery during various periods postoperatively. Fifteen human subjects underwent CTA of LIMA and coronary arteries at ~1 year (9 subjects including 3 subjects with mild coronary stenosis and end-to-side anastomosis, 3 subjects with severe coronary stenosis and end-to-side anastomosis, and 3 subjects with severe coronary stenoses and side-to-side plus end-to-side anastomoses), 4–5 years (3 subjects with severe coronary stenosis and end-to-side anastomosis), and ~10 years (3 subjects with severe coronary stenosis and end-to-side anastomosis) after surgical revascularization. We also obtained pressure waves that were measured during the angiography before the graft surgery in a single patient. The retrospective imaging study was approved by the Institutional Review Board (IRB) for the affiliated hospital of Xuzhou Medical College and human subjects gave the signed informed consent.

2.2. Imaging acquisition

Similar to previous studies (Huo et al., 2013a, 2013b), all patient scans were performed on a dual-source CT scanner (Siemens Definition, Forchheim Germany) when heart rate was ≤ 65 bpm. After an initial survey scan, CTA images were acquired when contrast agent (Iopromide-Ultravist 370, Bayer Healthcare, Morristown USA) at the dose of 1.0 ml/kg was injected at a rate of 5 ml/s followed by IV injection of 50 ml saline at a rate of 5 ml/s. Study parameters included the following: $2\times 64\times 0.6$ mm collimation, tube voltage -120 kV; tube current – adjusted to body size; gantry rotation time -330 msec; pitch -0.2 to 0.43 depending on heart rate. The simultaneous acquisition of multi-parallel cross sections enabled the imaging of LIMA graft and coronary arteries in a single breath hold. Images were reconstructed with a slice thickness/increment of 0.7/0.4 mm with B26f at temporal resolution of 83 msec (half-scan). The initial data window was positioned at 70% of the R–R interval, with additional data sets reconstructed at $\pm 5\%$ intervals to compensate for motion artifacts in coronary arteries as needed.

2.3. Aortic pressure wave

Before the graft surgery, the invasive coronary angiography was performed in patients by standard catheterization in accordance with the American College of Cardiology Guidelines for Coronary Angiography (Scanlon et al., 1999). The blood pressure wave was measured by a pressure catheter inserted into the ascending aorta of a patient, which was monitored by a pressure control unit (Millar INC, Houston).

2.4. Geometrical models

As shown in Fig. 1A–E, morphometric data of LIMA graft and coronary arteries were extracted from CTA patient images using MIMICS software (Materialise, NV, Belgium). Based on these morphometric data, geometrical models were created using Geomagic Studio software (3D Systems, Rock Hill, USA), which were meshed using ANSYS ICEM (ANSYS Inc., Canonsburg, USA). A mesh dependency was conducted such that the relative error in two consecutive mesh refinements was $<1\%$ for the maximum velocity of steady state flow with inlet flow velocity equal to the time-averaged velocity over a cardiac cycle. A total of approximately 600,000–700,000 tetrahedral shaped volume elements (element size = 0.29 mm) were necessary to accurately mesh the computational domain.

2.5. 3D computational model

The Navier–Stokes and continuity equations in the Appendix were solved to determine the laminar blood flow patterns using the FVM solver FLUENT (ANSYS, Inc., Canonsburg, USA) when the LIMA graft and coronary arteries were assumed to be rigid and impermeable. Three cardiac cycles were required to achieve convergence for the transient analysis similar to the previous studies (Huo et al., 2007, 2009, 2012, 2013a). A constant time step was employed, where $\Delta t = 0.01$ s with 84 total time step per cardiac cycle. Although blood is a suspension of particles, it behaves as a Newtonian fluid in vessels with diameters >1 mm (Nichols and McDonald, 2011; Huo et al., 2013a). A representative aortic pressure wave measured from a patient, as shown in Fig. 1F, was set as the boundary condition at the inlet of LIMA graft and LAD artery. The resistance boundary condition was assigned to each outlet (see details in the Appendix). The viscosity (μ) and density (ρ) of the solution were assumed as 4.5×10^{-3} Pa s and 1060 kg/m^3, respectively, to mimic blood flow with a hematocrit of about 45% in these