ABSTRACT

LONGEST, PHILIP WORTH, Jr. Computational Analyses of Transient Particle Hemodynamics with Applications to Femoral Bypass Graft Designs. (Under the direction of Clement Kleinstreuer.)

Mounting clinical and biological studies indicate that excessive blood particle interactions with a dysfunctional vascular surface trigger and sustain a cascade of biophysical processes which may lead to stenotic developments and/or thrombus formations, potentially resulting in vessel occlusion. Novel contributions of this work include the conceptualization and development of a particle-based hemodynamic parameter intended to quantify the likelihood of significant particle-to-wall interactions, including adhesion and deposition, based on local discrete near-wall residence times and concentrations. Particle-hemodynamic simulations have been conducted in multiple three-dimensional branching vascular geometries to validate the performance of the proposed near-wall residence time (NWRT) model and to further evaluate the biophysical mechanisms responsible for vascular diseases, including intimal hyperplasia (IH) formation in distal femoral anastomoses.

Based on comparisons to blood particle deposition studies, results indicate that: (a) the discrete element approach, which accounts for finite micro-particle size and inertia, is advantageous in the context of non-parallel flow domains including stagnation, recirculation, and reattachment; and (b) the likelihood of particle deposition may be effectively approximated as nonlinearly proportional to local particle concentration, residence time, and wall proximity. Including approximations for particle-to-surface hydrodynamic interactions, the NWRT-approach was found to be a particularly effective indicator for the deposition of monocytes ($r^2 = 0.74$) and platelets ($r^2 = 0.57$) given that nano-scale physical and biochemical effects must be greatly approximated in computational simulations involving relatively large-scale geometries and complex flow fields. In order to efficiently compute the large number of trajectories required to resolve regions of particle stasis, a highly effective and parallelized particle-tracking algorithm was implemented.

To account for reactive vascular surfaces, composite NWRT models have been proposed based on the hypothesis that blood particle deposition is most likely in regions of near-wall particle stasis and/or elevated concentrations, coincident with regions of activated or dysfunctional endothelial cells. Local shear stress conditions have been used to assess factors such as endothelial expression of adhesive molecules, up-regulation of surface-bound coagulate and anti-coagulate proteins, and mechanical platelet activation. The resulting composite NWRT models have been evaluated in the rabbit aorto-celiac junction, the human carotid artery bifurcation, and the distal femoral anastomosis. Agreements with monocyte deposition data, sites of atherosclerotic lesion initialization, and IH occurrence suggest that the composite NWRT-based models are sufficiently detailed, yet computationally efficient, as required for application in complex branching blood vessels. Furthermore, results of the current study indicate that particle-to-wall interactions appear to be a significant component for intimal thickening (IT) initialization and progression in all systems considered, whereas relations to other hemodynamic wall parameters, such as low WSS and high OSI, were not consistent.

Considering a multiple-pathway model for IH-formation in distal femoral bypass anastomoses, the performances of currently implemented and virtually prototyped configurations have been assessed. Of the conventional anastomoses evaluated, straight and curved graft-end cuts and a graft-to-artery diameter ratio of 1.5:1 were found to significantly reduce the potential for IH development at locations critical to flow delivery, while maintaining a graft lumen sufficient to reduce the risk of early thrombotic occlusion. Considering the clinically successful Miller cuff, hemodyamically induced conditions appear to be partially responsible for the improved patency rates associated with below-the-knee applications. For virtually prototyped models, anatomic features consistent with venous anastomoses were found to reduce the particle-hemodynamic potential for IH at locations critical to flow delivery; however, implications for IH were not eliminated. In conclusion, the application of a multiple-pathway particle-hemodynamics model for IH in distal anastomotic designs indicates that occlusive formations are an inevitable consequence of the non-physiological distal end-to-side anastomosis, particularly for the case of proximal outflow. Nevertheless, surgical benefits of the end-to-side distal anastomosis, such as ease of construction and proximal revascularization, ensure its continued implementation until a more effective alternative is clinically proven.

COMPUTATIONAL ANALYSES OF TRANSIENT PARTICLE HEMODYNAMICS WITH APPLICATIONS TO FEMORAL BYPASS GRAFT DESIGNS

by

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BIOGRAPHY

Philip Worth Longest, Jr. is the son of Philip and Georgia Longest and was born on May 12, 1974 in Wilmington, NC. Living in Wallace, NC, the author graduated from Wallace-Rose Hill High School in June of 1992. The following fall, he entered North Carolina State University in Raleigh, NC. Becoming a third-generation graduate of the NCSU College of Engineering, the author received a Bachelor of Science degree in Mechanical Engineering (December 1996) and a Master of Science degree in Mechanical Engineering (May 1999). The author continued study under the direction of Dr. Clement Kleinstreuer, beginning work on this dissertation in the summer of 1999.

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