SIMULATION-BASED MEDICAL PLANNING FOR CARDIOVASCULAR DISEASE: CHALLENGES AND OPPORTUNITIES

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INTRODUCTION

One of the primary purposes of congenital and adult cardiovascular medicine and surgery is to restore blood flow to organs and tissues. Ideally, therapeutic procedures result in sufficient blood flow at appropriate physiologic pressures while avoiding adverse flow conditions including flow recirculation and stasis, low shear stress, and high temporal oscillations and spatial gradients of shear stress hypothesized to promote atherosclerosis, intimal thickening and thrombosis. For a given clinical problem there are often multiple potential treatments with varying effects on blood flow. Unfortunately, physicians do not have the information tools needed to explore these alternate treatment strategies and design optimal corrective procedures.

We have proposed a new paradigm of "predictive medicine" in which a physician utilizes computational tools to construct and evaluate a combined anatomic/physiologic model to predict the outcome of alternative treatment plans for an individual patient [1]. To support predictive medicine applications in cardiovascular surgery we have developed a Simulation-Based Medical Planning system including techniques to: (i) construct geometric models from three-dimensional magnetic resonance imaging (MRI) and computed tomography (CT) data, (ii) extract preoperative physiologic data from cine phase contrast magnetic resonance imaging data, (iii) modify the preoperative model to incorporate an operative plan, (iv) assign boundary conditions appropriate for the postoperative state, (v) discretize these models using an automatic mesh generator, (vi) solve the governing 3D or 1D equations using finite element methods, and (vii) visualize and quantify resulting physiologic information. Recent progress in developing Simulation-Based Medical Planning tools for cardiovascular treatment planning is presented followed by a discussion of the challenges and opportunities that lie ahead.

MATERIALS AND METHODS

We recently developed a new software system for Simulation-Based Medical Planning that greatly simplifies the process of building preoperative vascular models from medical imaging data and performing subsequent postoperative planning [2-5]. We have applied these methods to create patient-specific models from CT and MRI data sets. Figure 1 depicts the postoperative model from a recent patient.

Figure 1. Operative Plan and blood flow velocity magnitude for 10 year old boy with trauma to right iliac artery. A femoral to femoral bypass graft was used to restore blood flow to the right leg.

Three-dimensional and one-dimensional methods can be used to simulate blood flow in idealized and patient-specific models of human arteries. The time-dependent, three-dimensional equations governing blood flow can be solved to obtain detailed data on blood flow distribution, wall shear stress, particle residence time, and flow recirculation [1,6]. We recently developed a space-time finite element method for solving the one-dimensional equations of blood flow [7].

This method, based on methods for advective-diffusive systems common in fluid mechanics, includes the enforcement of pressure continuity and mass conservation at branch points as well as flow rate, pressure, resistance and impedance boundary conditions. This method has been shown to yield good agreement with flow distributions predicted by three-dimensional methods in spite of neglecting secondary flow due to curvature, taper, expansions, and branching [8].

DISCUSSION

Current methods for simulation-based medical planning for cardiovascular disease, while showing great promise, require substantial user intervention and often several days to construct patient-specific geometric models, operative plans, and discretizations. Direct reconstruction of finite element meshes from discrete surfaces constructed using three-dimensional segmentation techniques applied to imaging data have application in creating pre-operative models, but do not interface with standard geometric solid modeling kernels used to create operative plans. Either discrete solid modelers will have to be used to create operative plans or analytic surfaces will have to be fit to triangulations resulting from three-dimensional segmentation methods. An additional challenge in model construction lies in the fact that current methods create three-dimensional models for a small part of the vascular system. Hybrid modelers employing methods to create coupled three-dimensional and one-dimensional domains are needed. This could result in tremendous savings in computational cost by restricting complex three-dimensional analyses to regions where these features are desired.

Additional challenges lie ahead in regards to blood flow analysis methods. Three-dimensional pulsatile blood flow simulations used in Simulation-Based Medical Planning are time-consuming and do not capture basic features of the human cardiovascular system such as wall compliance and the coupling between the major arteries and microcirculation. While flow velocity patterns may be well-represented, fundamental quantities of interest, e.g. blood pressure and volume flow rate wave propagation phenomena are not modeled accurately and rarely reported. Simplified methods for fluid-structure coupling and multidomain 3D/1D/0D analysis are desirable. Finally, techniques for the quantification and visualization of the results of blood flow solutions can be tedious and non-intuitive to physicians. Deployment of computational methods in a clinical setting mandate further advances in data visualization. In summary, significant research and development in computational methods is needed to bring the concepts of predictive medicine “from the bench to the bedside”.

Predictions of outcomes of cardiovascular surgery and interventions will need to be evaluated retrospectively against post-treatment data before these techniques are used prospectively to plan treatments for patients. *In vivo* validation of flow rate and velocity fields predicted using computational methods can be performed using cine phase contrast magnetic resonance imaging data [9]. However, it is worth keeping in mind that these techniques have limitations and yield variable results based upon what sequences are used and the variability in the underlying physiology.

Computational methods could revolutionize the planning of treatments for patients with cardiovascular disease. It is likely that in the not too distant future virtual plans will be created and tested in operative theatres (Figure 2) prior to implementation in patients.

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Figure 2. Conceptual Simulation-Based Medical Planning Suite.

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