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COMPARISON OF IN VIVO MRI FLOW MEASUREMENTS AND PREDICTED FLOW SIMULATION RESULTS

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INTRODUCTION

We have developed a simulation-based medical planning system that utilizes computational methods to predict changes in blood flow resulting from alternate possible surgical procedures based on patient-specific anatomic and physiologic data [1]. Clearly, these methods must be validated with experimental measurements. While computational methods have been used in the past to study blood flow [2-5], few studies have validated their results against *in vivo* measurements. Only with the recent advances in imaging technologies has it become possible to perform experiments to compare the computed quantities against non-invasively acquired physiologic measurements [6, 7]. In this study, we have utilized medical imaging techniques to compare *in vivo* post-operative measurements against flow values predicted by our simulation-based medical planning system for geometric models based on post-operative imaging data.

MATERIALS AND METHODS

Thoraco-thoraco aortic bypass surgery was performed on a series of pigs to create the desired anatomy. A Dacron band was placed around each pig's thoracic aorta to simulate a stenosis, or narrowing of the artery. A Dacron graft was also attached to the thoracic aorta so that blood could bypass the stenosis. A balloon occluding device was placed around the Dacron graft. By inflating or deflating the balloon, the graft could be opened or closed. With the graft open, blood could either flow through the graft or through the native aorta, simulating our post-operative condition. Our pre-operative condition existed when we occluded the graft, so that blood could only flow through the native, stenosed aorta.

For both the pre-operative and post-operative states, we acquired anatomic and physiologic data using magnetic resonance technology. Magnetic resonance angiography (MRA) was used to obtain volumetric anatomical data, while cine phase contrast magnetic resonance imaging (PC-MRI) was used to obtain blood flow velocity information. The PC-MRI data was acquired at three locations along the aorta for both the pre- and post-operative cases and processed using software developed by Stanford University's Radiological Sciences Laboratory. In addition, we acquired velocity information in the bypass graft for the post-operative state. We used the through-plane component of the velocity data in our simulations.

Using custom software, we then generated three-dimensional geometric models from the MRA data. We employed the level set method [8] to segment out the vessel lumen, producing a series of two-dimensional segmentations along the vessel axis. These segmentations were then used to produce a solid model, which could then be unioned with other solid models to construct our final geometry. We applied this method to generate post-operative models from the images of the native aorta and the bypass.

Automatic mesh generating software (SCOREC, Rensselaer Polytechnic Institute, Troy, NY) converted these models into finite element meshes, which were then used as inputs for computing the flow solutions. We assumed the vessel was rigid and represented the blood as an incompressible, Newtonian fluid. The inlet flow was described by a Womersley velocity profile that was based upon the PC-MRI data at the inlet, and the outlet pressure was prescribed to be zero. Under these conditions, we computed the resulting pulsatile

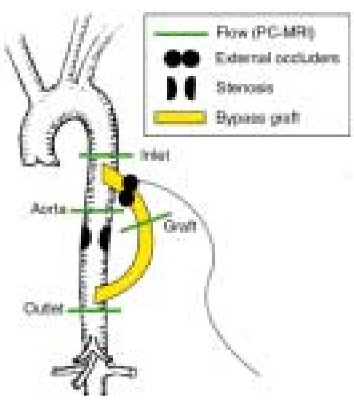

Figure 1. Diagram of the protocol used for the experiment

flow over 5 cardiac cycles using a previously validated finite element method [2].

RESULTS

The resulting average flows for these post-operative models were compared to the measured post-operative average flow, as computed using the PC-MRI data. The simulations had reached steady state by the third cardiac cycle so we report flow values for that time period or later. The three locations we examined were at the inlet, through the native aorta, and through the bypass graft (Table 1). The difference between the average predicted flow value and the MRI-measured flow value varied between 0.8 cc/s and 5.3 cc/s for the native aorta, and between 0.7 cc/s and 5.4 cc/s for the bypass graft. Figure 2 displays the velocity magnitude contours for pig 1 halfway through the first cardiac cycle.

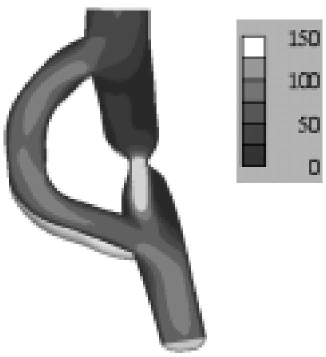

Figure 2. Contours of velocity magnitude in cc/s for pig 1 halfway through the first cardiac cycle

DISCUSSION

The contours of velocity magnitude demonstrate the velocity patterns that occur for a bypass procedure. As expected, higher velocities occur in the bypass graft and just downstream of the stenosis. We also note that the regions along the outer wall of the aorta immediately upstream and downstream of the stenosis have low velocities. Quantitatively, the numerical simulation flow results for the post-operative models are in good agreement with those measured *in vivo* with PC-MRI. The discrepancies we observe in the native aorta and bypass graft flows could be due to physiologic changes that were not reflected in the PC-MRI data, to inaccuracies in the geometric model, or to the assumptions in our simulations. We also note that there are slight differences in the inlet flows, which can be attributed primarily to the use of a Womersley profile, instead of the PC-MRI data, as a boundary condition in our flow solution.

Future work will focus on determining the sensitivity of our numerical simulation results to factors such as the inlet boundary condition and the accuracy of the geometric model. We also plan to compare the *in vivo* post-operative flow results with computed flow results based on pre-operative data. This is an essential part of assessing the usefulness of our system. Preliminary experiments utilizing the pre-operative model show that our system is able to accurately predict flow distributions, e.g. the native aorta-to-inlet flow ratio and the bypass-to-inlet flow ratio, but significant differences between the pre-operative and the post-operative inlet flow lead to inaccuracies in the predicted flow quantities. While additional validation studies obviously need to be performed, these initial results are a promising indicator of the predictive capabilities of our simulation-based medical planning system.

	Pig 1 Flow (cc/s)		Pig 2 Flow (cc/s)		Pig 3 Flow (cc/s)	
	MRI	FEA	MRI	FEA	MRI	FEA
Inlet	51.9	49.5	68.8	66.2	60.4	59.1
Native Aorta	18.3	13.4	13.9	14.7	13.3	8.0
Bypass Graft	36.9	35.9	46.0	51.4	50.1	50.8

Table 1. Comparison of average flow values. MRI flow values are derived from PC-MRI images. FEA flow values are computed using our simulation-based medical planning system.

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