**Title:**

# Image-Based Computational Fluid Dynamics in Blood Vessel Models: Toward Developing a Prognostic Tool to Assess Cardiovascular Function Changes in Prolonged Space Flights

**Authors:**
George P. Chatzimavroudis,Thomas A. Spirka, Randolph M. Setser, Jerry G. Myers

Department of Chemical and Biomedical Engineering, Cleveland State University, Cleveland, OH; Division of Microgravity Research, NASA Glenn Research Center, Cleveland, OH; Division of Radiology, The Cleveland Clinic Foundation, Cleveland, OH
Phone: (216) 687-5396, Fax: (216) 687-9220, E-Mail: g.chatzimavroudis@csuohio.edu

One of NASA's objectives is to be able to perform a complete, pre-flight, evaluation of cardiovascular changes in astronauts scheduled for prolonged space missions. Computational fluid dynamics (CFD) has shown promise as a method for estimating cardiovascular function during reduced gravity conditions. For this purpose, MRI can provide geometrical information, to reconstruct vessel geometries, and measure all spatial velocity components, providing location specific boundary conditions. The objective of this study was to investigate the reliability of MRI-based model reconstruction and measured boundary conditions for CFD simulations. An aortic arch model and a carotid bifurcation model were scanned in a 1.5T Siemens MRI scanner. Axial MRI acquisitions provided images for geometry reconstruction (slice thickness 3 and 5 mm; pixel size 1x1 and 0.5x0.5 $mm^2$). Velocity acquisitions provided measured inlet boundary conditions and localized three-directional steady-flow velocity data (0.7-3.0 L/min). The vessel walls were isolated using NIH provided software (ImageJ) and lofted to form the geometric surface. Constructed and idealized geometries were imported into a commercial CFD code for meshing and simulation. Contour and vector plots of the velocity showed identical features between the MRI velocity data, the MRI-based CFD data, and the idealized-geometry CFD data, with <10% differences in the local velocity values. CFD results on models reconstructed from different MRI resolution settings showed insignificant differences (<5%). This study illustrated, quantitatively, that reliable CFD simulations can be performed with MRI reconstructed models and gives evidence that a future, subject-specific, computational evaluation of the cardiovascular system alteration during space travel is feasible.

**Description of Purpose:**
There is evidence that prolonged space missions affect cardiovascular function. One of NASA's objectives is to be able to perform a complete, pre-flight, evaluation of cardiovascular changes in astronauts. Computational Fluid Dynamics (CFD) is an established approach to study fluid mechanics, and supplements the experimental and theoretical approaches of study of this field. CFD would provide invaluable information about possible changes in the cardiovascular function in situations where a direct detailed examination *in situ* is impossible, such as during long space flights to Mars or during prolonged stay under micro-gravity conditions. Using a variety of methods, CFD can solve difficult problems of complex flows by using numerical techniques. Traditionally, idealized geometries are constructed using CAD-based software and then meshed in order to allow the CFD program to discretize the partial differential equations of continuity, energy conservation, and motion and provide accurate solutions. In the medical field, this approach can provide useful results, but it reduces the physiological significance of the findings, because of deviations from the true geometry and flow conditions. Recently, with the development of high-resolution imaging techniques, such as CT or MRI, the precise geometry of interest can be reconstructed and imported to a CFD program. One of the advantages of MRI is its ability to provide accurate velocity data, which are very useful as boundary conditions for the simulation and as reference data for the evaluation of the CFD solutions. The objective of this study was to investigate the reliability of MRI-based model reconstruction and measured boundary conditions for CFD simulations.

**Methods:**
A glass non-planar aortic arch model and a glass planar carotid bifurcation model (with the carotid bulb) were scanned in a 1.5 Tesla Siemens Sonata whole-body clinical MRI scanner. After the scout acquisitions, a set of contiguous axial MRI acquisitions were performed to obtain the images for geometry reconstruction. Two slice thickness values were used: 3 and 5 mm. The field of view was 256x256 $mm^2$. Two matrix sizes were studied, 128x128 and 256x256, resulting in two pixel sizes, 1x1 and 0.5x0.5 $mm^2$). Velocity-encoded MRI acquisitions provided the true inlet boundary conditions. Three-directional velocity-encoded MRI acquisitions were performed in several locations to provide the reference velocity data for the evaluation of the CFD data. The studies were done under steady flow conditions of 1.5 and 3.0 L/min for the aortic model and 0.7 and 1.5 L/min for the carotid model. The vessel walls were isolated using NIH provided software (ImageJ) and lofted to form the geometric surface. In addition, idealized geometries of the models were constructed based on the model sizes. Both types of geometries (image-based and idealized) were imported into a commercial CFD code for meshing and simulation. Figure 1 shows the reconstructed geometry of the aortic model.

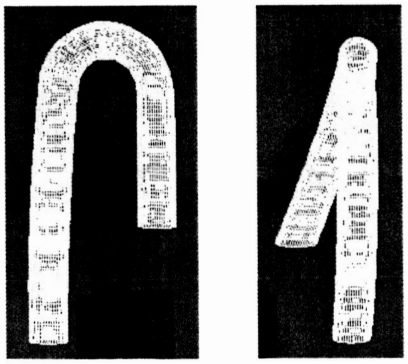


*Figure 1: MRI-based reconstructed geometry of the non-planar aortic arch model*

**Results:**
Contour and vector plots of the velocity were created using the experimental MRI velocity data and the image-based-geometry and idealized-geometry CFD data. Figure 2 shows the through-plane velocity at the top of the arch for the lower resolution acquisitions (matrix size 256x256). As seen, there is a general qualitative agreement. The maximum velocity is approximately 15

cm/s. Quantitatively, there was relatively small differences in the localized velocity values (<10%) between the three cases shown in Figure 2.

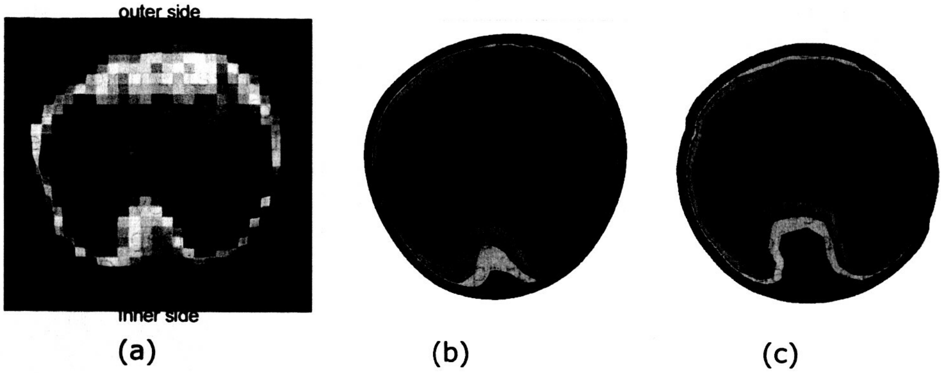



*Figure 2: Through-plane velocity at the top of the arch: (a) MRI velocity data; (b) Image-based CFD data; (c) Idealized-geometry CFD data*

Figure 3 shows the in-plane velocity vector plots at the top of the arch (matrix size 256x256). Because of the non-planarity of the arch, there is an absence of the traditional oppositely-moving double helices. Instead, there is a tendency for a single vortex (mainly seen at the bottom right side). Qualitatively, there is a general agreement between the experimental data and both CFD data.

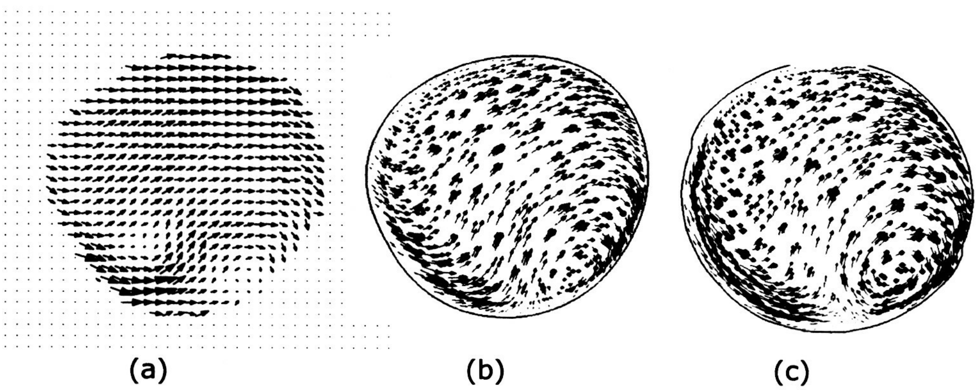



*Figure 3: In-plane velocity vector plots at the top of the arch: (a) MRI velocity data; (b) Image-based CFD data; (c) Idealized-geometry CFD data*

An overall agreement between the velocity patterns along the centerline slightly oblique coronal plane of the model can be seen in Figure 4. Quantitatively, the maximum velocity measured with MRI and reproduced by CFD was approximately 15 cm/s.

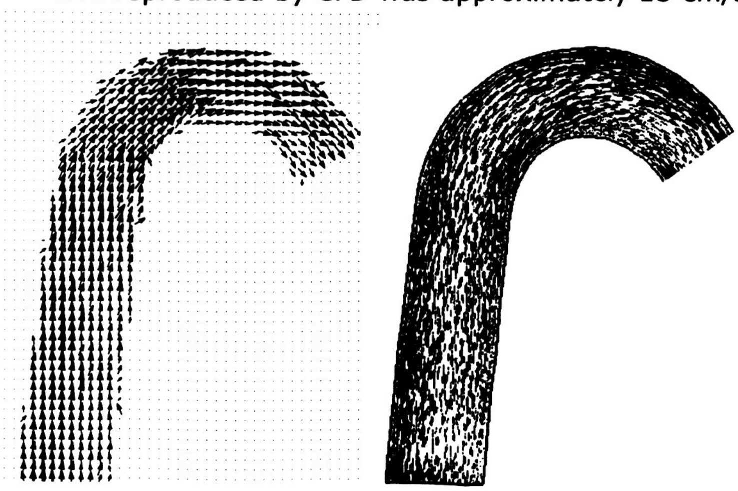
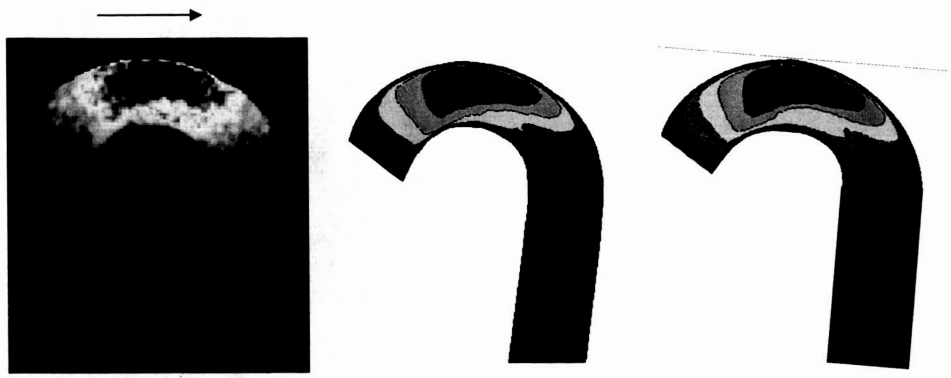


*Figure 4:In-plane velocity vector plots through the ascending part and the arch: left, MRI velocity data; right, image-based CFD data*

Qualitative and quantitative agreement can be seen in Figure 5 that shows an oblique sagittal plane along the centerline of the model. The left-right velocity displayed is almost identical in all three plots.



(a) (b) (c)

*Figure 5: Oblique sagittal centerline velocity plots through the ascending part and the arch: (a) MRI velocity data; (b) Image-based CFD data; (c) Idealized-geometry CFD data (arrow shows the velocity encoding direction)*

Similar results were obtained with the carotid model (due to space limitations, we decided to focus on the aortic model and show as much data as possible). CFD results on models reconstructed from different MRI resolution settings showed insignificant differences (<5%).

**New or Breakthrough Work to be Presented:**

The limitation of imaged-based CFD analysis has been the relatively unknown accuracy of the reconstructed model in combination with the uncertainty in appropriate boundary conditions. Ultimately, to adequately utilize CFD (along with other computational approaches) for health management during long duration space flights it must be determined at what accuracy and fidelity astronaut (patient) specific parameters (geometry, boundary conditions, material properties) must be obtained through non-invasive imaging. The results of this preliminary study confirmed that it is feasible to reconstruct the geometry of realistic vessels and perform diagnostically equivalent CFD simulations with them without prior knowledge of the target vessel geometry. More interestingly, this study has illustrated the need for accurate boundary conditions (in this case the inlet velocity profiles) and the great potential of MRI to adequately provide these three-dimensional boundary conditions. This was illustrated by the ability of MRI-CFD, using reconstructed geometries and measured boundary conditions, to reproduce experimental MRI downstream velocity data in models with three-directional flow patterns. This finding adds more promise to the future development of a tool that will predict changes in cardiovascular mechanics using detailed geometrical and minimal flow information from MRI images.

**Conclusions:**

This study illustrated, quantitatively, that reliable CFD simulations can be performed with MRI reconstructed models and gives evidence that a future, subject-specific, computational evaluation of the cardiovascular system alteration during space travel is feasible.

**Important Note:**

This work is not being and has not been submitted for publication or presentation elsewhere.