*Presented during the Annual Meeting of the Biomedical Engineering Society. Minneapolis, MN, Oct. 5-8, 2016*

# Immersive visualization for comparative viewing of CFD results with associated multiscale data

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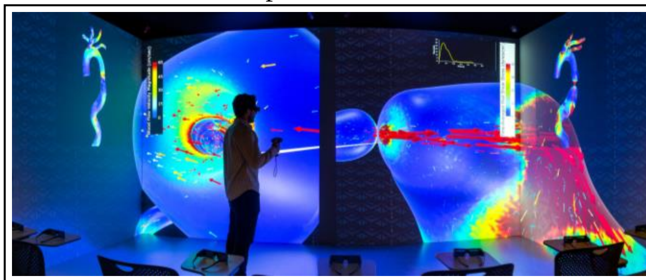
**Introduction:** A biomedical computational fluid dynamics (CFD) researcher can spend weeks obtaining imaging data, determining boundary conditions, and solving the governing equations via high performance computing. However, CFD results are typically viewed on a 2D display, at one point in time, or very slowly for multiple time points as sequential time steps are read into memory and rendered. Results from different pathologic states or cases are rarely compared in real time. Moreover, images used to construct a CFD model and complementary data are seldom included. This means only a fraction of the CFD results are typically studied and associations between related data sources may not be apparent. Large-scale visualization environments with 3D stereoscopic capability offer a way of extracting more information from CFD results by taking advantage of improved depth cues, a larger display canvas, custom interactivity, and an immersive (>180 degree field of view) approach that surrounds the user. The objective of this study was to create a workflow that facilitates comparative viewing of CFD results and imaging data in an immersive virtual environment (IVE). The workflow also aimed to include multiscale data from complementary sources to show association with indices within CFD results.

**Materials and Methods:** The workflow was developed for MARVL: the MARquette Visualization Lab, a state-of-the-art, $1.2M, 1,700 sq ft space with hardware and software that produces 3D, immersive, virtual reality environments. The Unity game engine was selected for this work over more traditional scientific visualization software packages for its speed, flexibility and, hence, ability to integrate data from multiple sources. MARVL uses a proprietary plugin for Unity called MiddleVR to facilitate clustering, nonplanar camera alignment, and infrared tracking of an interaction device. Unity requires CFD results (i.e. scalars and vectors) to be converted into textures and 3D objects. Together with images of complementary multiscale data, these representative versions of CFD results are placed into position within 3D space, informed by details in the CFD simulation. This involves several steps after CFD results are obtained in vtk format. Depending on the desired index such as velocity streamlines or glyphs, ParaView or Matlab is used, respectively, to convert vtk files into a polygonal format (.ply) as well as assign vertex color information indicative of magnitude. The files are then brought into the graphics program Blender where the CFD model geometry is organized, scalar color maps are converted to textures, and planes containing imaging slice data, histological photomicrographs or vascular function data are positioned using semi-automated approaches. The Blender file is then loaded into Unity where it can be studied immersively. Genes of interest from microarray analysis showing pathways, interactions, co-localization, etc. are also loaded into Unity for display.



**Comparative multiscale data from the workflow. CFD results from CoA (right, note velocity jet) vs treatment (left). Data includes time-averaged wall shear stress, oscillatory shear index, flow waveforms showing current time, velocity, histology, and microarray results.**

**Results and Discussion:** Most CFD studies for biomedical applications involve some type of complementary data; the most basic being imaging and boundary condition data. Results of the current workflow are exemplified using data from an animal model of a congenital cardiovascular disease called coarctation of the Aorta (CoA). Imaging data, flow and pressure measurements, CFD results, vascular function in response to contractile or relaxation agents, histology, and microarray results were all obtained from each animal experiencing control, CoA, or treatment conditions. The figure shows a screen shot of a researcher comparing CFD results and spatially-localized complementary data. Each additional data type is toggleable using buttons that have been assigned to the interaction device.

**Conclusions:** The current workflow facilitates viewing and interacting with comparative CFD results and their potential association with related data. This approach is now being applied to CFD results of other pathologies including cerebral aneurysms, coronary artery disease, and nasal airway obstruction. The utility of this approach for hypothesis generation and longitudinal study of disease progression will be quantified for each pathology.