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Integrated Image-Based Computational Fluid Dynamics Modeling Software as an Instructional Tool

Computational modeling of cardiovascular flows is becoming increasingly important in a range of biomedical applications, and understanding the fundamentals of computational modeling is important for engineering students. In addition to their purpose as research tools, integrated image-based computational fluid dynamics (CFD) platforms can be used to teach the fundamental principles involved in computational modeling and generate interest in studying cardiovascular disease. We report the results of a study performed at five institutions designed to investigate the effectiveness of an integrated modeling platform as an instructional tool and describe "best practices" for using an integrated modeling platform in the classroom. Use of an integrated modeling platform as an instructional tool in nontraditional educational settings (workshops, study abroad programs, in outreach) is also discussed. Results of the study show statistically significant improvements in understanding after using the integrated modeling platform, suggesting such platforms can be effective tools for teaching fundamental cardiovascular computational modeling principles. [DOI: 10.1115/1.4047479]

Keywords: simulation, modeling, blood flow, active learning, hemodynamics, classroom activity

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Introduction

Computational modeling of arterial blood flow has become a common approach to quantify cardiovascular hemodynamics over the past several decades [1]. For example, cardiovascular computational fluid dynamics (CFD) has application in medical device design, nonsurgical procedure planning, and tissue engineering. CFD is becoming increasingly valuable for vascular surgical planning, where changes in flow alter hemodynamic metrics that are linked to vascular wall remodeling. Surgeons currently rely on images showing vascular anatomy to make decisions when evaluating treatment options. A need exists for simulation-based medical planning tools that use computational methods to help clinicians and engineers alike better understand current hemodynamic state and predict the potential impact of various treatment options on vessel wall remodeling. Ideally, image-based modeling involves using patient-specific image data (e.g., CT, MRI, ultrasound) to create computational models simulating cardiovascular flows, which can then be used to evaluate alternative treatment options a priori or provide functional hemodynamic information not available through medical imaging alone. Therefore, several commercial and open-source image segmentation packages (e.g., MIMICS (Materialize), VMTK, ITK-SNAP) and CFD solvers (e.g., ANSYS FLUENT, ANSYS CFX, SIEMENS PLM STAR CCM+, OPENFOAM, OASIS, FEBIO) have been used to perform cardiovascular simulations [2–4]. Several aspects of image-based CFD for modeling biological flows are either not provided in traditional CFD packages or specialized particularly for image-based CFD, including image-segmentation, image-based model creation, patient-specific boundary condition specification, and unstructured meshing. Accordingly, integrated software packages, which include the entire cardiovascular modeling pipeline in a single software package, have been developed specifically for cardiovascular modeling, including SIMVASCULAR [5] and CRIMSON.[2]

As image-based CFD modeling has grown in popularity, it has become an increasingly important tool for biomedical engineer trainees to master. Furthermore, general numerical modeling encompasses fundamental principles important for engineering students to master, such as numerical solution of ordinary and partial differential equations, domain discretization, validation, verification, uncertainty quantification, and impact of boundary conditions. While these integrated CFD software packages are primarily designed for and discussed in the context of research, they can also be used as an innovative educational tool to help teach fundamental biomechanical and physiological principles as students perform CFD simulations. Furthermore, the idea of augmenting traditional pedagogical practices with computational simulations suggests an opportunity to reevaluate traditional engineering education models [6]. Our initial report demonstrated the potential of this technology as an instructional tool [7], and the present work builds upon that work to quantify gains in conceptual understanding via a student learning assessment.

The present study assesses the learning outcomes of students enrolled in upper-level undergraduate and graduate engineering courses at five institutions. Each institution used an integrated open-source image-based CFD package (SIMVASCULAR [5]) to perform image-based blood flow modeling projects as part of the course. This study extends previously published work [7] by including more institutions and participants and discusses our collective experience using the integrated image-based modeling software as an instruction tool outside of a traditional classroom (e.g., workshops, study abroad programs, etc.). The twofold purpose of this work is to demonstrate that an image-based CFD platform can be used as an effective instructional tool to teach students the basic steps and principles involved in image-based CFD modeling and share "best practices" for teaching image-based modeling based on survey results and author experience.

Methods

Student Participants. Pre- and postassessments were administered to 29 students (14 BS, 22 MS, 38 Ph.D., 1 MD, 4 MD/Ph.D.) in biomedical engineering, mechanical engineering, or computational mathematics programs to quantify (1) their initial familiarity and (2) improvement in understanding of computational techniques for biomedical blood flow simulations. Students were from Purdue University ($N = 28$), Stanford University ($N = 18$), University of California, Berkeley ($N = 15$), Northeastern University ($N = 11$), and Marquette University ($N = 7$). The focus of the courses included in the study varied widely, ranging from biofluid mechanics to cardiovascular imaging. The course structure and learning objectives also varied, but each included a focus on image-based CFD. The students in these courses came from a range of demographics (40 male, 39 female). Seven students whose pre- and postassessments could not be paired were excluded from the study. The study procedures, including informed consent forms for participants, were approved by Institutional Review Boards from each of the participating schools.

Image-Based Computational Fluid Dynamics Platforms. Generally, the steps for image-based computational fluid dynamics modeling include creating a three-dimensional (3D) solid model of the vessel lumen from medical imaging data, generating a mesh of the computational domain, assigning physiological boundary conditions, solving the 3D Navier–Stokes equations, and postprocessing results to obtain clinically relevant quantities of interest. One approach to that process is encapsulated in the SIMVASCULAR package, providing a complete pipeline from medical image data segmentation to patient-specific blood flow simulation and analysis (Fig. 1).

Instructional Efforts. Upper-level undergraduate and graduate-level engineering courses in which student participants were enrolled included online and in-class tutorials, didactic lecture, case study examples, and ultimately, a final project. The initial case study consisted of an online guide to perform a simulation of flow in the aorta and iliac arteries, starting from a magnetic resonance angiography scan of a healthy volunteer. The guide walks the students through multiple steps including general imaging, path planning, vessel segmentation, lofting, meshing, setting boundary conditions, and setting up and running the simulation in the open-source integrated CFD modeling software SIMVASCULAR [5]. Following the simple case study, culminating

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[2] www.crimson.software

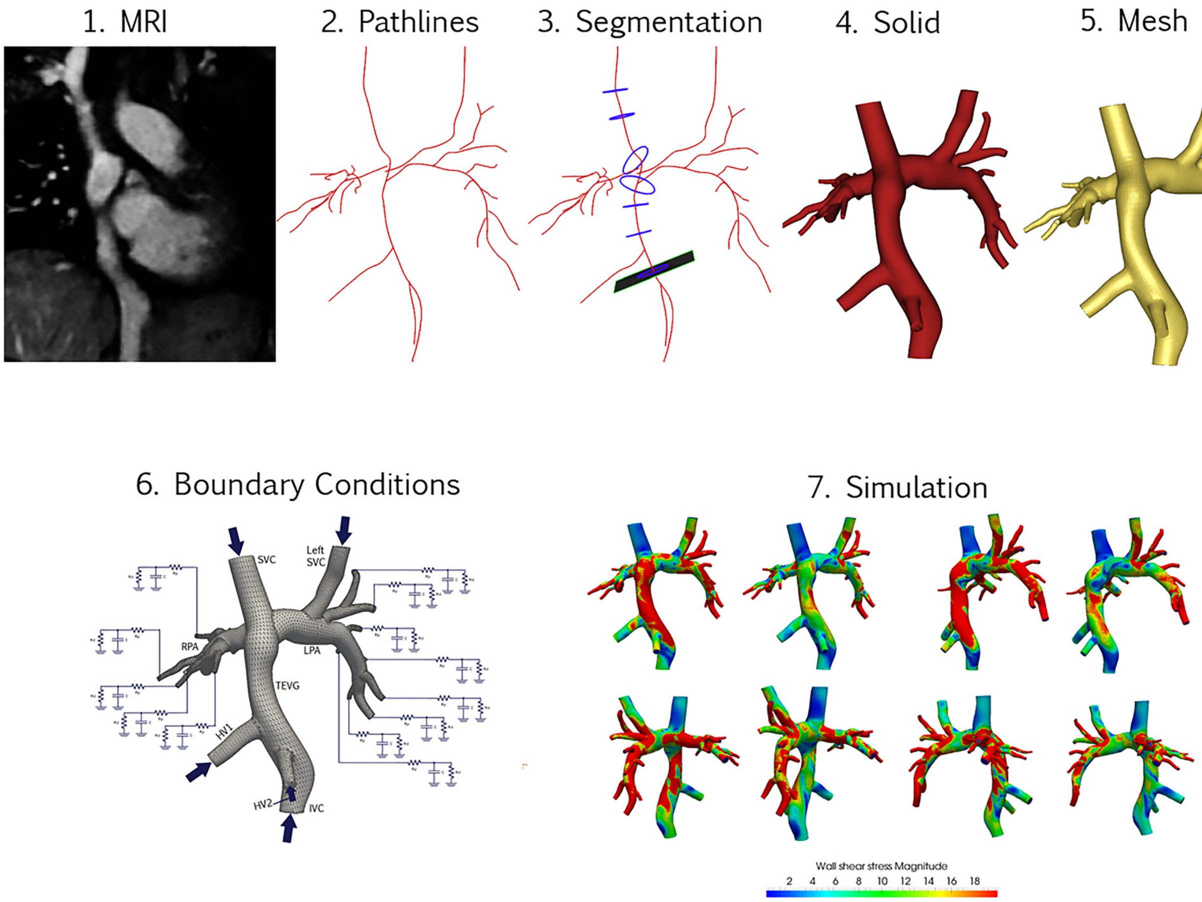

Fig. 1 The workflow for image-based anatomic model construction and blood flow simulation in SIMVASCULAR. Users build models from MRI data (1) by generating pathlines (2), segmenting along the pathlines (3), and then lofting and unioning the segmentations to create a single, solid model representing the flow domain (4). The model is then discretizing into a finite element mesh (5), and assigned physiologic boundary conditions (6) in order to run a simulation (7).

projects allowed the students to select medical imaging data from anonymized patient data sets, then build models, and perform cardiovascular simulations. The students chose a dataset according to their own interests. While some students obtained already segmented models from the Vascular Modeling Repository [8], most students used medical imaging data obtained from external sources (e.g., from their own research or research groups) and created models based on segmentation of the medical images. These datasets include patients with healthy coronary and pulmonary arteries and those with frequently observed vascular diseases including thoracic aortic coarctation, abdominal aortic aneurysms, cerebral aneurysms (Fig. 2), peripheral artery disease, pulmonary hypertension, Kawasaki disease, Marfan syndrome, and Tetralogy of Fallot, among others. Other image datasets selected by the students were from patients undergoing coronary artery bypass graft surgery, the Fontan procedure, or the Glenn procedure. Instruction on using the integrated CFD solver was covered over a period of 3–8 weeks, depending on the institution, with several in-class discussions, interactive tutorials, working sessions, journal clubs, and office hours after class for questions. While many students created simple models with one inlet and one outlet as shown in Fig. 2, the integrated CFD software was also used by more advanced students to create complex models with multiple outlets and a variety of lumped parameter boundary conditions [5].

Assessment Statements. The students rated their agreement with 11 different statements on a scale of 1–10, with a response of 1 indicating that they *strongly disagreed* and a response of ten indicating that they *strongly agreed*. These assessment statements were:

(1) I am familiar with the role of hemodynamics in cardiovascular disease initiation or progression.
(2) I am familiar with different volumetric biomedical imaging techniques.
(3) I am familiar with the concept of volume rendering.
(4) I am familiar with different image segmentation techniques.
(5) I am familiar with the difference between a discrete and analytic solid models.
(6) I am familiar with the concept of a boundary representation.
(7) I am familiar with different computational meshing techniques.
(8) I am familiar with a variety of boundary conditions and their effects.
(9) I am familiar with the process of running a computational fluid dynamic simulation.
(10) I am familiar with a variety of different applications of patient-specific cardiovascular simulations.
(11) I am familiar with how cardiovascular simulations results can be quantified.

The student responses were anonymized. When a student responded with ten on the pre-assessment (corresponding to the highest level), these data and the subsequent postassessment responses were excluded from the analysis since our objective was to assess the efficacy of the tool to instruct those who were not already experts in image-based modeling techniques. Overall, fewer than half (35%) of students responded with an answer larger than 5 to Question 9, suggesting that most of the students involved in the study did not have prior noteworthy experience with CFD.

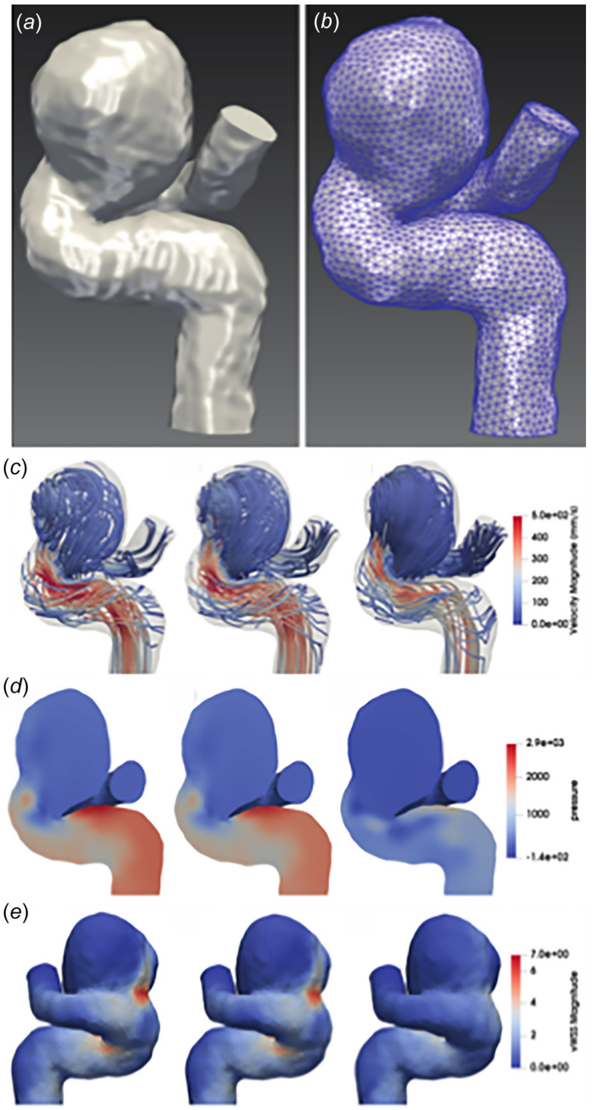

Fig. 2 Example results of a simulation from a student project highlighting simulation geometry (*a*) and mesh (*b*) from a human cerebral aneurysm. Three different CFD simulations are shown with varying inlet boundary condition flow rates corresponding to average flow (left column), high flow (middle column), and low flow (right column). Results are highlighted for velocity magnitude in mm/s (*c*), pressure in Pa (*d*), and vascular wall shear stress magnitude in Pa (*e*).

Statistics. All data are shown as mean ± standard error (SE). A Shapiro–Wilk test was used to determine if the data were normally distributed. A paired Student's *t*-test was used to compare between pre- and postassessments with a Bonferroni–Holm correction for multiple comparisons. To compare between institutions, a Kruskal–Wallis test was used. Internal consistency was determined using Cronbach's alpha, and the difference in pre-and postassessments was determined using a Wilcoxon Signed Rank. Cohen's *d* was calculated to indicate the effect size. A $p < 0.01$ was considered significant.

Results

No Difference Between Institutions. No statistically significant difference was observed when comparing the assessment responses of either the pre- or postassessments between institutions using the Kruskal–Wallis test ($p > 0.01$), suggesting student populations with similar prior CFD experience at all five institutions. The combined response data had a Cronbach's alpha of 0.96, indicating internal consistency between the pre- and postsurveys.

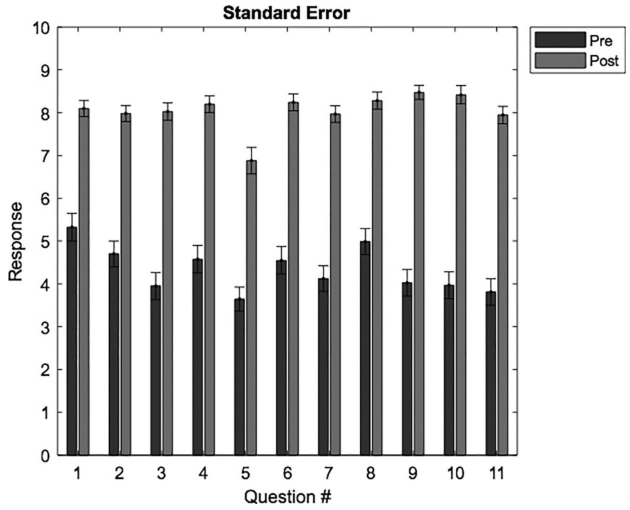

Fig. 3 Student responses indicating degree of agreement with assessment statements assessing their understanding of image-based blood flow modeling principles (mean ± SE). The increase between pre- and postassessment responses was significant ($p < 0.001$), suggesting improved understanding.

Assessment Response. The mean and standard error of the pre- and postassessment results from all respondents are shown in Fig. 3. The mean response to all of the assessment statements increased, encompassing a range of percent increase from 52% (statement one) to 112% (statement ten), as shown in Table 1. The data were non-normally distributed, as determined by the Shapiro–Wilk test (pre $W = 0.92$; post $W = 0.88$; $p < 0.001$ for both). However, the paired *t*-test was considered to be robust to non-normality due to the central limit theorem given the large sample size. The paired *t*-test indicated a difference between pre- and postassessments for each question ($p < 0.001$), and postassessment survey responses were also shown to be significantly larger than pre-assessment responses by a Wilcox Signed Rank test ($p < 0.001$). The large Cohen's *d* values suggest a large effect size for each of the eleven statements.

Student Feedback. Once the final project was completed, we asked students for their feedback to understand student reception of the software and teaching methods. Though qualitative, student feedback helped us understand which aspects of the instructional efforts were most helpful and which could be improved. Each

Table 1 The difference between post- and pre-assessments and percent increase in mean student responses for each assessment statement. Effect size was determined using Cohen's *d*.

Statement number	Post-pre-difference	Percent increase (%)	Effect size
1	2.8	52.2	1.3
2	3.3	69.9	1.6
3	4.1	103.1	1.9
4	3.6	79.1	1.6
5	3.2	88.7	1.3
6	3.7	81.2	1.7
7	3.8	93.2	1.8
8	3.3	66.2	1.6
9	4.4	110.4	2.2
10	4.4	112.0	2.0
11	4.1	108.4	1.9

question and representative student responses are described below.

> Q: What did you learn about the steps involved in performing a computational fluid dynamics simulation?
>
> Responses to this question generally included listing steps involved in image-based computational fluid dynamics, e.g., some variation of image acquisition, creating pathlines, segmentation, creating a model, meshing, creating boundary conditions, running the simulation, and analyzing results. Other themes were the importance of mesh size, time step, number of cardiac cycles, and boundary condition selection. One student's succinct response captures a general sentiment expressed in several responses: "I learned that details are important and no model is perfect." Additional representative responses are included below:
>
> A: The first step is to determine what question you are trying to answer or the purpose of the simulation. Then you can use imaging data to create a model of the patient's geometry. In SimVascular you would draw a path, perform segmentation and generate your model. Next, a mesh is created. Things like blood viscosity, blood density, initial pressure/velocity, distal pressures/velocities, resistance, and rigid/deformable wall are important for the actual simulation. The time step, number of cardiac cycles, etc., are all critical for simulation convergence.
>
> A: I was able to gain hands on experience understanding the segmentation, meshing, model smoothing, and implementation of boundary conditions in creating the simulation. In particular, I realize the sensitivity of the solution to the implementation of different boundary conditions.
>
> Q: What biomedical applications or diseases did you find most interesting?
>
> Nearly, 30% of respondents indicated interest in aneurysms from various cardiovascular territories. Other popular responses included coronary artery disease (8%), atherosclerosis (6%), virtual surgeries (6%), and stenoses (6%). Other responses included aging, aortic coarctation, aortic dissections, congenital and pediatric heart defects, the influence of exercise, Glenn surgery, hypertension, Kawasaki disease, Marfan syndrome, pulmonary artery disease, renal artery disease, single ventricle disease, valve related issues, stent placement, Tetralogy of Fallot, tissue engineering, and vasculitis.
>
> Q: What helped you learn the most efficiently when trying to understand this technical process?
>
> Over 40% of respondents indicated that hands-on practice and trial and error was the most helpful. Twenty percent indicated that online documentation provided with the software was helpful, and fifteen percent indicated that receiving help from the teaching team (instructors and teaching assistants) was most helpful. Some classes used video demonstrations of various steps, and students in those classes responded very positively regarding its utility. Several students from classes that did not utilize video even suggested that videos would be helpful tool when demonstrating how to use the software, since they could watch them at their own pace, while using the software, and refer to them outside of class. Other popular responses included working with others and in-class tutorials and exercises. A few students expressed that they would have liked time to practice the steps prior to beginning their projects, and one requested more clear documentation, though generally feedback regarding the documentation was positive.
>
> Q: For what reasons (if any) will you use this open-source software package in the future?
>
> Twenty-five percent of respondents mentioned plans to use the package in research while 17% described plans to use the software to gain insight into specific diseases. Other common responses included device design (13%) and for projects of personal interest (6%). One notable theme in the responses to this and other questions was recognition that the specific software package taught in the class, SIMVASCULAR, while a stand-alone package convenient for teaching, was not the only software package that may be useful in cardiovascular modeling. One student stated, "I may use SimVascular to continue simulating the carotid artery but may explore other software packages for modeling." Other students mentioned using other software packages for parts of the image-based modeling process. Another interesting sentiment repeated by a few students was an interest in using the software for nonbiomedical flow modeling applications.
>
> Q: What did you most get out of this project?
>
> Responses to this question were varied. Oft-repeated themes included the sensitivity of the results to decisions regarding segmentation and boundary conditions. Additional representative answers are included below.
>
> A: The importance of explaining and justifying your boundary conditions based on what you are trying to accomplish with your simulation.
>
> A: Learning about the boundary conditions and verification versus validation were most useful.
>
> A: I gained an understanding of the utility of CFDs as well as the amount of info needed to run a physiologically relevant simulation.
>
> A: From this project, I gained an understanding of modeling and how it can help further understand and analyze various diseases.
>
> A: A basic understanding of how hemodynamics can have a significant impact in understanding disease progression.
>
> A: Understanding the sensitivity of the results to boundary condition implementation and differences from slight geometry modification.
>
> A: A better understanding of the tradeoffs between 1D and 3D simulations as well as differences in their solutions.
>
> A: Obtained a great general introduction to computational and mathematical modeling and simulation of the cardiovascular system for the purposes of understanding how mechanical cues might influence or cause disease; got good practice with running cardiovascular simulations and learning how to use SIMVASCULAR.

Discussion

The results of this study suggest that integrated CFD software can be a helpful tool to teach hemodynamic and patient-specific modeling principles. Even though previous reports have described interactive educational resources for simulation-based teaching and learning [9–11], integrated CFD software provides a single resource for medical image data segmentation to patient-specific blood flow simulation and analysis.

The student feedback following the project highlights several important points. First, students using the software learned the sensitivity of the solutions to the inputs, particularly boundary condition selection. This fundamental engineering concept is essential for users of image-based CFD to understand, and also increases general understanding of cardiovascular physiology. Second, interest in cardiovascular modeling can be fostered by letting students apply the steps to problems in which they are personally interested. The specificity and breadth of topics in which students expressed interest supports this idea. Allowing students flexibility in choice of disease and project topics enabled us to tailor the difficulty level to individual students' experience and also facilitated students learning from each other during final presentations. Third, considering that 40% of students mentioned the importance of hands-on practice in understanding the steps involved in image-based modeling, it is clear that hands-on learning is an important part of learning image-based CFD. Step-by-step video tutorials are also useful since they allow students to watch the steps at their own pace. The ability of students to learn the importance of input conditions while using an integrated CFD solver, importance of video and hands-on practice in learning, and interest generated by allowing students to select projects of personal relevance should be considered by educators teaching topics related to image-based CFD.

Image-based CFD modeling requires a solid understanding of concepts from several disciplines, including cardiovascular physiology, medical image processing, 3D computer-aided modeling, flow and transport physics, numerical methods, high-performance computing (HPC), data visualization, and statistics. As each of these concepts and topics is covered in a course aiming to introduce patient-specific flow modeling, the students benefit from hands on experience provided by an integrated CFD modeling platform. This approach provides a step-by-step introduction to the image-based modeling pipeline, thus illustrating the material covered in lectures as well as training students in practical aspects of modeling that requires hands on experience.

While modeling principles can be demonstrated by using a combination of commercial and/or in-house software tools, an integrated, open-source platform is likely better suited for educational purposes. Using an open-source software allows the instructor and students to avoid dealing with licensing installation and cost, as well as the data formatting and transport issues typically requiring dedicated scripts and patches. In addition, the access to the online forums provides additional help on top of the lectures and tutorials.

We have identified several best practices and common pitfalls when using an integrated CFD solver for project-based learning in the classroom. These include the following points.

- The project helped the medical students understand the flow physics and engineering aspects of the tool, and it helped the engineering students understand more of the anatomy and cardiovascular physiology in classes with students from a mix of engineering and medical backgrounds.
- For engineering students without experience viewing medical images, detailed explanations of the anatomy or example models are helpful.
- In situations where instruction time is limited (e.g., shorter classes, workshops, outreach activities), providing students with 3D geometries and/or partially completed models at various steps along the image-based CFD pipeline can be beneficial. This way students can focus on the principles involved rather than spending substantial time troubleshooting. Completed 3D models can be obtained, for example, from the Vascular Model Repository [8]. We found that the students can efficiently learn how to create the 3D models with online tutorials.
- It is helpful to have teaching assistant support when using an integrated modeling platform in the classroom to help the students debug and run their simulations. If available, teaching assistants can become familiar with the details of integrated modeling platforms by attending workshops prior to the class. One strategy that could reduce the need for instructor/teaching assistant-led troubleshooting is utilizing peer-to-peer and think-pair-share strategies, which have been shown to be an effective model for teaching [12,13].
- In addition to learning how to perform image-based CFD, knowing how to postprocess, visualize, and interpret simulation results is also important. In these courses and workshops, students used Paraview [14], an open-source data analysis and visualization application, to postprocess and visualize their results.

One challenge with image-based CFD modeling is the large amount of computing power required for meaningful simulations. However, these packages can also be paired with HPC resources such as science GATEWAYS [15–17], which can provide access via a web portal for students to run computationally expensive simulations that may be intractable on a personal computer. This feature also expands access to students at institutions lacking HPC resources on campus. A GATEWAY was used for the simulation projects at several of the institutions, facilitating supercomputer access for students. However, for some classes, the process of obtaining access to the cluster was time-consuming and difficult. Educators should consider approaches by which to shorten this process to allow students time to focus more on learning the principles of image-based CFD.

Another educational opportunity was during a study abroad trip in May of 2019 with 18 engineering undergraduate students from Purdue University as they traveled over 14 days through Denmark, Sweden, and Finland. The course title was Biomedical Modeling for Global Health in Scandinavia and included visits with faculty at several Scandinavian universities who are leading research programs focused on biomedical imaging and modeling [18,19]. The students were expected to download the required software beforehand, build a model based on images from an aortofemoral case study, and run a steady flow simulation with rigid walls on their personal laptops before the end of the trip. While traveling in a foreign country provided some challenges regarding internet access and power adapters, all 18 students were able to successfully run a simulation and analyze their results. The case study project was supplemented by multiple lectures that introduced basic concepts and group sessions to troubleshoot common issues. The students provided feedback that the modeling project involved both “a lot of thought” and teamwork as the class was “encouraged to talk to each other to pick up strategies.”

While more in-depth instruction would be required for a complete understanding of computational hemodynamic modeling, this experience highlighted the usefulness of project-based CFD exercised during shorter programs in unusual environments.

Integrated open-source computational fluid dynamics software has also been used in outreach programs for middle school students to introduce them to computational fluid dynamics and cardiovascular simulations. In these 1 h demos, we walk the students through simplified steps of model building (image, paths, segmentations, and model) on an aorta or aortafemoral demo data and then show examples of meshing, simulation, and clinical applications. Though they did not complete surveys, the students generally responded well and were very curious about the open-source software and the modeling process.

Though the results presented herein are promising, further work is still required to show that integrated CFD solvers are effective educational tools in the classroom and other educational settings. The fact that data regarding students’ perceptions of their understanding and improvement are self-reported is one limitation in this study. The fact that the data came from five different institutions is a strength, suggesting the results are generalizable for similar educational settings; however, additional research is required to more definitively assess the effectiveness of integrated CFD solvers as educational tools in other settings. Future research could devise more direct and quantifiable measures of students’ knowledge to better measure the efficacy of an integrated CFD solver for instructional purposes.

In conclusion, the use of integrated CFD software shows promise beyond biomedical research applications as an interactive educational tool to demonstrate hemodynamic principles and current image-based modeling techniques.

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