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EDITORIAL COMMENT

A Multidisciplinary Approach to Patient-Specific Surgical Planning in Congenital Heart Disease

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Precision medicine dictates the integration of a personalized approach to therapy with the goal of improving outcomes. Within congenital heart disease, we have seen an uptake of 3D printed models to aid surgical decision-making in complex intracardiac repairs and the use of virtual reality in both surgical planning and in the operating room.[1,2] While these modalities provide anatomical or structural details, they do not necessarily consider the physiological consequences of a given repair strategy. Computational fluid dynamics (CFD) is a numerical simulation method that allows for the modeling and quantification of fluid behavior in many biomedical engineering applications, including the simulation of blood flow in the cardiovascular system. Paired with virtual surgery techniques, CFD has been used to predict postsurgical hemodynamics in single ventricle patients, as well as in the application of surgical planning for other congenital heart diseases including Tetralogy of Fallot and coarctation of the aorta.[3] CFD analysis also has the added benefit of allowing for the high-resolution quantification of hemodynamic features which may not be possible to capture using clinical imaging and physiological data alone.

In this issue of *JACC: Advances*, Hoganson et al[4] integrate imaging and physiological data to develop patient-specific CFD models to inform surgical strategy for single ventricle patients with interrupted inferior vena cava. Using a prospective approach, Hoganson et al compared multiple surgical repair strategies to predict and improve the distribution of hepatic venous flow (HVF) in the pulmonary arteries and hemodynamic efficiency in the Fontan connection. MRA/CTA imaging data was segmented and reconstructed for 4 patients to generate baseline anatomy models, and virtual surgery was performed on each model to simulate a range of intervention strategies. Subsequent CFD simulations were performed, employing preoperative 4D flow MRI and cardiac catheterization data. Novel to this work is scaling of flow conditions to represent a range of physiologic conditions, including normal physiological, postprandial, and exercise conditions. Through these simulations, the changes in hemodynamics during different physiological states allowed for robust testing of the surgical strategies.

The authors demonstrated the potential for CFD and virtual surgery to aid pre-operative planning and utilized postoperative imaging to validate postsurgical hemodynamic predictions. The Fontan completion plans proposed without CFD input resulted in unequal distribution of HVF through the pulmonary veins, attesting to the difficulty of preoperative prediction through conventional surgical planning. Predicted balanced HVF pulmonary blood flow was optimized using multiple CFD simulations with alternative surgical strategies. Input from these simulations aided selection of the final surgical strategy, and postoperative validation by 4D-MRI flow measurements confirmed the predicted pulmonary artery flow splitting. Hoganson et al have reported good agreement between postoperative 4D-MRI and model-predicted pulmonary artery volumetric flow splitting. Simulation of the postoperative anatomy and subsequent calculation of HVF and

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power loss for comparison with the pre-operative predictions could serve as an additional avenue to validate the proposed methods providing strong evidence to support use of the virtual surgery techniques to accurately predict postsurgical changes.[4]

In future work, follow-up imaging and subsequent CFD model generation can be employed to assess the durability of the selected surgical procedure in the long-term to maintain balanced pulmonary HVF. Additionally, tracking of patient outcomes over several years can be performed to assess the extent to which virtual presurgical planning can reduce the formation of arteriovenous malformations for patients who have undergone Fontan completion surgery. Accounting for long-term changes in anatomy due to patient growth and vascular remodeling is another avenue that is currently being explored in surgical planning for congenital heart defects.[5]

The framework proposed in this paper illustrates the potential benefits of incorporating virtual surgery and patient-specific computational modeling in the pre-operative surgical planning for complex congenital cases. However, the use of techniques such as CFD in cardiovascular applications and the uptake of these technologies into regular clinical practice currently faces several challenges, including the need for extensive computational resources, long simulation times, and the requirement of user manual intervention from both clinicians and engineers in several steps of the simulation workflow.[6] Successful generation of CFD models for presurgical planning involves multidisciplinary collaborations and buy in across departments within an institution. Establishing standardized procedures to acquire and process the necessary clinical data, streamlining the model generation process, and investing in required computational infrastructure are all necessary steps to integrate technologies such as these in standard clinical practice. Currently, work is being performed to begin addressing these challenges, including the use of machine learning (ML) methods to automate aspects of the workflow, such as image segmentation procedures.[7] Additionally, the integration of ML methods with established physics-based high-fidelity CFD modeling techniques can improve the resolution of available clinical data and allow for the modeling of complex physical phenomena at lower computational costs.[8] Moreover, ML-based surrogate models created with CFD data such as the one presented in this paper by Hoganson et al would enable rapid prediction of hemodynamic outcomes, faster overall optimization process, and thorough exploration of the optimization space.

The approach of coupling virtual surgery techniques with physics-based high-fidelity CFD modeling has the potential to inform personalized surgical decisions for complex cardiac operations. Through multidisciplinary collaboration, the advancement of high-performance computing, and the integration of ML-based methods, the introduction of these technologies in standard clinical care is becoming increasingly more feasible and will enhance our pre-operative surgical planning for patients with congenital heart disease.

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