Developing an augmented blood flow tool for the diagnosis and treatment of congenital heart diseases using echocardiograms and machine learning.

Abstract This project will develop a new tool to improve the diagnosis of congenital heart diseases in low- and middle-income countries (LMICs) by augmenting blood flow measurements obtained via echocardiogram with estimations derived from a machine-learning algorithm, trained via computational fluid dynamics simulations. Congenital heart diseases lead to 200,000 childhood deaths in low- and middle-income countries each year, with an estimated 90% of patients not having access to suitable clinical treatment. There exists a need to develop a low-cost tool that can improve assessment of patients to optimise when surgical intervention occurs and how it is implemented. In order to accurately assess treatment plans, we need to know the blood flow characteristics in the aortic arch. We need to know the key vascular and fluidic metrics that determine flow characteristics. We need to determine the flow characteristics in patient-specific geometries derived from medical imaging. The proposed project will be a mixture of fluid dynamics, biomedical engineering and computer science to develop an augmented blood flow tool combining medical-imaging and machine-learning derived flow data in order to improve assessments of congenital heart diseases in LMICs. This project will use computational fluid dynamic simulations to identify key vascular and fluidic metrics that determine flow characteristics in the aortic arch. This project will develop and train a neural operator model for flow estimation in the aortic arch based on identified key vascular and fluidic metrics and validate using data obtained through computational fluid dynamics. This project will integrate the developed tool with patient-specific geometries derived from medical imaging. The developed tool has the potential to improve healthcare immediately at the Red Cross Children's Hospital where 500 children are treated each year, before improving treatment in further low and middle income countries in the long-term.

Introduction Congenital heart disease (CHD) is the most common birth defect, affecting over 1.3 million newborns each year [1]. While in high income countries the prognosis has improved dramatically in recent years (90% reach adulthood), it is estimated that congenital heart defects result in over 200,000 deaths each year in lower and middle income countries (LMICs) equating to over 14 million years of lost life [2]. It is estimated 90% of patients in LMICs do not have access to suitable clinical treatment.

Clinical diagnosis and monitoring of CHDs involves the use of echocardiograms to investigate vascular structure and blood flow. Echocardiograms use Doppler ultrasound to measure

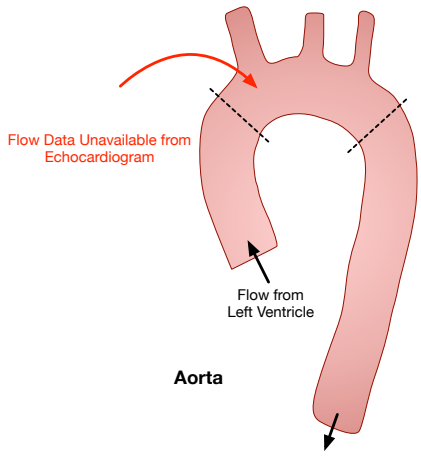

Figure 1: Aortic flow data availability via echocardiogram.

the blood flow velocity in the axial direction of the probe. Estimates of flow patterns in the ascending and descending aorta for healthy patients are readily available. However, blood flow data in the aortic arch and its branching arteries are difficult to obtain due to obstructions from the bones, such as the clavicle and rib cage as shown in Figure 1. Flow conditions in the aortic arch are particularly important in assessing CHDs such as aortic coarctation (a localised narrowing of the arch) and interrupted aortic arch. Complete representations of the instantaneous flow conditions throughout the entire aortic vasculature would aid clinicians in their treatment decisions, increasing the likelihood of patient survival.

There exists a critical need to provide clinicians with comprehensive flow data at the point of care. Recent efforts to provide clinicians with complete flow representations have involved performing Computational Fluid Dynamics (CFD) analysis on individual patients or the use of 4D MRI [3]. While CFD has been successful in many cardiovascular applications, such as coronary heart disease, it has yet to be integrated into mainstream clinical practice in LMICs due to ongoing costs and prohibitive time delays between acquiring the patient data and reporting back to clinicians. Similarly, the use of 4D MRI has also been successfully applied to cardiovascular applications, such as aortic dissection, however, it is also prohibitively expensive. In addition, 4D MRI requires patients to remain motionless during the scan for upwards of 15 minutes, which is difficult to ensure for infant patients.

This project proposes to augment echocardiogram blood flow data with machine learning derived flow estimation, trained via computational fluid dynamic simulations. This novel tool will provide clinicians with comprehensive flow data at the point of care. The supervisory team will consist of Dr Benjamin Owen (Chancellor's Fellow, Engineering) who has expertise in modelling of the cardiovascular system [4] and Dr Joseph O'Connor (Chancellor's Fellow, EPCC) who specialises in integrating machine-learning algorithms with CFD [5]. The project will be in collaboration with a team at the Medical Research Council and Red Cross Children's Hospital in Cape Town, South Africa lead by Professor Liesl Zühkle, a paediactric cardiologist, with whom Dr Benjamin Owen has an active collaboration [6].

Data and Methodology The main aim of this project is to develop a novel data-driven approach for inferring the instantaneous flow conditions throughout the entire aorta, based on incomplete and noisy measurements of flow velocity from echocardiogram. Recent advances in machine learning are having a transformative impact on solving this type of flow construction/state estimation problem. In particular, physics-informed neural networks [7], which incorporate the residuals of the known physics (e.g. conservation laws) into the loss function to improve the learning, have found significant success for these types of inverse problems. However, they do not generalise well, requiring retraining for specific flow instances, making them unsuitable for interactive/real-time applications. Instead, neural operator approaches, such as DeepONet [8], learn a mapping between function spaces and can generalise across a family of differential equations. This makes them suitable for mapping measurements to 3D flow fields with fast/instantaneous inference times, potentially leading to improved flow

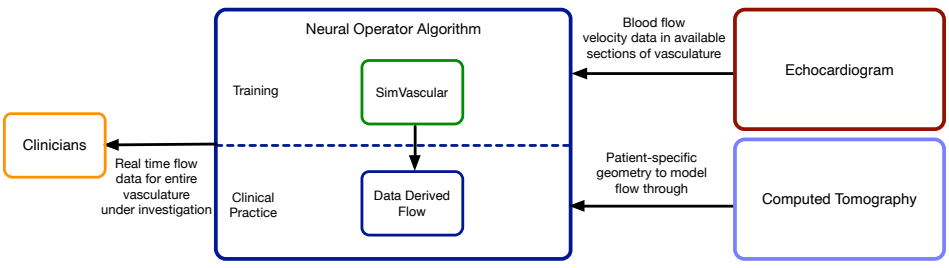

Figure 2: Overview of augmented flow tool components and fit within a point-of-care setting.

estimation in the aortic arch and treatment decisions.

Datasets to train the algorithm will be created using an existing open-source CFD code specific to hemodynamics, SimVascular, a toolkit able to generate patient-specific geometries and run CFD simulations. In the initial stages, patient-specific geometries of the vasculature will be obtained via an open-source repository available through SimVascular. Once the tool has been established, patient-specific geometries will be obtained from the Red Cross Children's Hospital using CT scan as shown in Figure 2. In the long-term, follow-on work will focus on integrating geometries derived from ultrasound but beyond the scope of this project.

The PhD project has the following objectives:

1. Identify key vascular and fluidic metrics that determine flow characteristics.
2. Develop and train a neural operator model for flow estimation in the aortic arch based on identified key vascular and fluidic metrics and validate using data obtained through computational fluid dynamics for an idealised aorta case.
3. Integrate flow estimation tool with patient-specific geometries.
4. Investigate effect of measurement data (e.g. noise level of ultrasound data, frequency)
5. Investigate performance of generalising across different patient-specific geometries.

Responsible AI/Ethical Considerations Patient data will be anonymised while the augmented flow tool will be designed so users understand how it works. Furthermore, AI estimations will be quality controlled via simulations at regular intervals during its implementation. The tool will also be designed so clinicians are in the loop during quality control via the flow data comparison. We will aim to incorporate physics-informed approaches – making model more interpretable/trustworthy and less of a black box. We expect the tool to reduce overall resource requirements in comparison with simulation only flow estimations, i.e. the resource requirement of CFD training + non-CFD point of care $<$ CFD @ point of care.

Expected Outcome and Impact The augmented flow tool will initially be applied the patients with aortic coarctation and an interrupted aortic arch. In both these diseases, clinicians currently struggle to assess the flow conditions and make informed clinical decisions - deciding if surgical intervention is required, and if it is, optimising the surgical intervention. The Red Cross Children's Hospital treat around 500 patients each year, conducting around 1600 echocardiograms. Development of the augmented flow tool will directly improve the quality of these assessments while also potentially reducing the need for further investigation via CT scans which are limited due to available resources and radioactive exposure risks to children. Beyond the PhD project, the lost-cost nature of echocardiograms and the augmented flow tool, along with the high-portability of the system, open up the opportunity to supply point-of-care assessments in more informal settings than the Red Cross Children's Hospital in other LMICs. Furthermore, the augmented flow tool can be modified for other diseases currently assessed via ultrasound, such as abdominal aortic aneurysms and carotid atherosclerosis.

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