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Deep-learning and hemodynamics models: efficient complementarity for disease diagnosis and surgery planning

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1. Introduction

Clinicians have high expectations in how bioengineers can build models to assist them in diagnosing perfusion defects or evaluating the risk of a surgery that entails altering the blood vessel system or the organs hemodynamics. If the phenomenon of interest is blood flow, then such models are typically PDEs or ODES, mathematical models representing hemodynamics. If this phenomenon is a mixture of processes for which the mathematical model does not exist, then such model needs to be learned from data through AI. This is the case for example to predict liver surgery complexity from a patient CT (Ali et al. 2022).

We present here examples where hemodynamics models have been developed to predict hemodynamics changes due to disease (Papamanolis et al. 2021) or their treatment (Golse et al. 2021, Pant et al. 2023). These models need however to be personalized from patient data (Sala et al. 2023): model sensitivity analysis, parameterization and uncertainty quantification are steps that can require many costly simulations. Thus, we also exhibit how deep-learning is a promising complement to reduce hemodynamics models (Hanna et al. 2024, Sallé de Chou et al. 2024).

2. Methods

2.1 ODE hemodynamics models of blood flow: further reduction by neural networks

0D cardiovascular models of blood flow are algebraic-differential coupled equations aimed to study the

global dynamics of the whole circulation system. They give estimates of cardiac chamber volumes, organ inflow rates, and pressures in the circulation, which are important biomarkers for surgery planning (Golse et al. 2021), or can provide boundary conditions for 3D perfusion models (Papamanolis et al. 2021). Most 0D models suffer from a high number of independent parameters as inputs, easily reaching 30-60 parameters. Many of these parameters are not clinically measurable and, thus need be tuned from patient-specific data and literature, introducing difficulty in their inference process. In this work, metamodels are built for several 0D models with the aim of alleviating this difficulty: here convolutional neural networks are chosen because of their accurate and fast prediction abilities. Typically, a few layers are enough to provide reasonable outcomes.

2.2 PDE hemodynamics models of blood flow: reduction by neural networks

Organ perfusion in the small vessels can be modelled by Darcy's 3D model of blood flow, coupled to hemodynamics of the feeding vascular network (Papamanolis et al. 2021). In the heart, the myocardium perfusion is then represented by this PDE Darcy model. An inverse problem on such 3D models is costly: physics-informed neural networks are efficient at solving 3D PDEs but lack generalization capabilities, for example to take into account the high inter-patient geometric variability. Graph neural networks (GNN) offer a way to unlock this issue (Sallé de Chou et al. 2024).

3. Results and discussion

The convolutional neural network models have a reduced number of inputs, chosen to be mostly clinically relevant or easy to measure, compared to the full 0D models. The models are trained and tested on synthetic data generated from the 0D models.

Two distinct 0D models are investigated in this study. The first model predicts post-surgery portal vein pressure (Golse et al. 2021), considering local liver hemodynamics' influence on global circulation: the goal is to evaluate the risk of portal hypertension due to surgery. The second model simulates systemic circulation in pulmonary arterial hypertension, aiding intervention planning, particularly for assessing Potts shunt effects on cardiac function and physiology (Pant et al. 2023). The constructed metamodels are differentiable, enabling rapid resolution of inverse problems within seconds or minutes. Additionally, sensitivity analysis can be conducted on input parameters with great efficiency (Hanna et al. 2024).

The large vessel-myocardium coupled model is able to predict severe perfusion deficit from a patient's CT, but for intermediate cases, more information needs to be learned from patient perfusion imaging data.

The GNN underwent successful training and testing using a 3D synthetic dataset, specifically meshes that depict simplified shapes of myocardial tissue (Sallé de Chou et al. 2024). Subsequent evaluation on an actual patient-specific myocardium mesh, showcases encouraging outcomes and broad applicability. This rapid solver, embedded within a differentiable learning framework, offers the potential to address inverse problems from perfusion imaging data.

4. Conclusions

Hemodynamics models can be personalized and run for surgery planning in much reduced time thanks to neural networks. Hemodynamics models and AI are thus highly complementary to assess perfusion changes due to disease or predict the associated surgical treatment. Moreover, when there is no existing biophysical model, a pure AI approach would in principle require several thousand cases to be trained. To lower the amount of data necessary to obtain a predictive model of surgery complexity, we can add to the learning the key components of the organ that make the surgery more or less complex (Ali et al. 2022 MICCAI): the

liver, where tumors are compared to the large vessels, i.e. the biomechanical constraints of surgeons when performing liver resection.

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Conflict of interest

The author has no conflict of interest to declare.

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