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CLOSED-LOOP CARDIOVASCULAR SYSTEM MODEL AND PARTIAL HEPATECTOMY SIMULATION

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SUMMARY

The present work aims at developing a mathematical model in order to reproduce hemodynamics changes due to liver surgeries. First, a 0D closed-loop model is developed, to simulate hepatectomy and compute post-operative average values. Due to the closed loop, the surgery impact both on and from the whole circulation can be captured, including bleeding and infusion. Then, a one-dimensional artery model is implemented to improve the closed-loop model and simulate better the changes in arterial waveforms due to surgery.

Key words: *Reduced-order model, Closed-loop model, Hemodynamics, Hepatectomy*

1 INTRODUCTION

The liver is an organ which has the capacity to regenerate. To heal some pathology (like liver cancer) a partial ablation of the liver, called partial hepatectomy, is required. For a healthy human liver, the ratio of remaining liver volume to total liver volume must be at least 20 to 25% for functional regeneration of liver mass [1], but sometimes more would need to be resected. Patient undergoing liver surgery often suffer from liver diseases, implying a reduction of liver function and regeneration capacity. Thus, after liver surgery some patients suffer from post-operative liver failure due to insufficient functional liver mass.

The liver has a complex perfusion, and when partial hepatectomy is performed, the remaining liver experiences significant hemodynamics changes. These changes depend on the remaining liver size. The important modifications of liver hemodynamics are hypothesized to be a reason for non-functional liver regeneration. In this context, computational simulations of liver hemodynamics after partial hepatectomy could help to better understand the cause of their modifications. Key parameters such as pressures or flows after different percentage of liver ablation could be predicted.

To our knowledge, few works exist on liver hemodynamics modeling. Chu and Reddy proposed a complex mathematical model of the splanchnic circulation [2]. Their work shows that the elevation of vena cava pressure leads to portal hypertension and increases liver interstitial fluid volume. Rypins *et al.* [3] proposed a Wheastone bridge model for splanchnic circulation modified by a variable resistance. The resistance value is chosen to represent portocaval H-Graft of different diameters. They predicted portal flow for different portocaval H-Graft diameters. Debbaut *et al.* modeled the impact of partial hepatectomy in rat with an electrical analogue [4]. They performed 3D reconstructions of rat liver vasculature to obtain a 0D model with resistances. Parametrization of the model was done based on mean values from the literature.

In this work, temporal dynamics for blood flow and pressure are modeled and, in order to take into account the effects of the global circulation during surgery, a closed-loop model is implemented. First a 0D model is considered to understand the main effects of the surgery. To better capture temporal dynamics, in a second step, the modeled in enriched by replacing part of it by a 1D model.

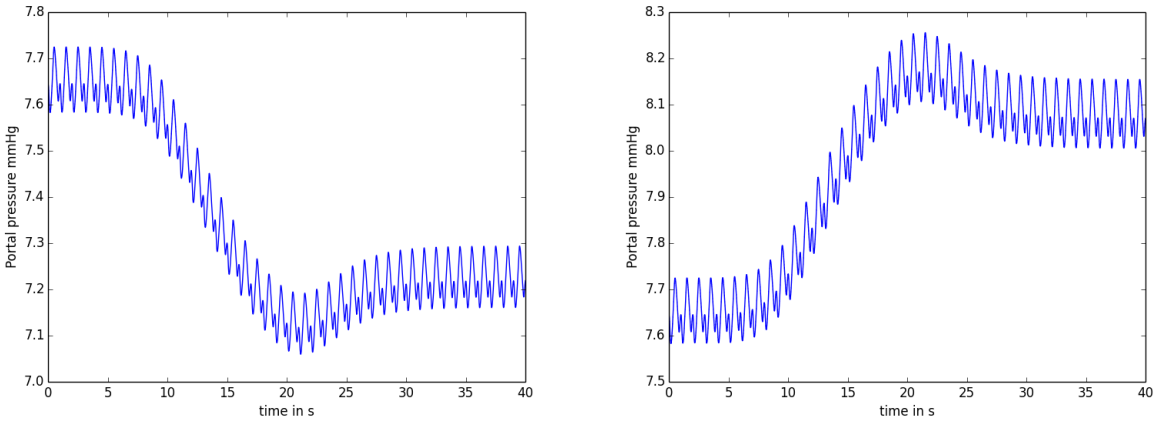

Figure 1: Simulation of bleeding (left) and infusion (right) in a 0D closed-loop model. Pressure in the portal vein is plotted over 40 cardiac cycles.

2 0D CLOSED-LOOP MODEL

The 0D closed-loop model is based on works from Liang and Liu [5] and Blanco and Feijo [6]. Five compartments (heart and lung, liver, gut and other organs) are studied, where each compartment is a resistance-capacitance-resistance unit (Windkessel model). The differential-algebraic equations system is solved with the IDA package from Sundials [7], using Backward Differentiation Formula and Newton method. After manual tuning of the model parameters to have a good agreement with preoperative mean values, partial hepatectomy surgery is simulated. The post operative average values are close to the measured ones, except for the portal vein pressure, which is overestimated. During surgeries, bleeding or infusion occur. Such a global circulation model allows to simulate these changes and take them into account for the liver surgery simulation. Figure 1 shows the portal vein pressure when simulation of bleeding/infusion is performed. As observed during surgeries, infusion increases pressures and bleeding decreases pressures.

In this first model, the change in arterial waveform due to the distance to the heart is not well represented. Instead of adding compartments to the 0D model to improve the wave shapes, a 1D-0D closed-loop model is developed. Indeed, this type of model can more naturally take into account this phenomena than a 0D model.

3 1D-0D CLOSED-LOOP MODEL

A 1D-0D closed-loop model is developed. Blood in the main arteries is modeled by the one-dimensional Euler equations of blood flow; the rest of the circulation, mainly the liver and the heart, are modeled with 0D equations (figure 2). The 1D system of equations is discretized with a first order Taylor-Galerkin approach. The 0D equations are discretized with an implicit Euler scheme. The coupling between the two models is carried out during the 1D two-step algorithm (details can be found in [8]):

- First, the 1D problem is solved for the internal degrees of freedom. At the boundaries of each branch, the values of the variables at the previous time step are imposed.
- Then, an update of the boundary node values is performed: the system of 0D equations is solved jointly with the equations for the backward (at the inlet) / forward (at the outlets) characteristics, and continuity of pressure, by a Newton method.

The two steps are iterated until convergence. The algorithm goes then to the next time step.
With this model, changes of waveform as the artery is further away from the heart are represented. Hepatic artery pressure and flow waveforms before surgery are better captured. Their changes due to surgery are then simulated (see Figure 3). They are coherent with the one observed during experiments.

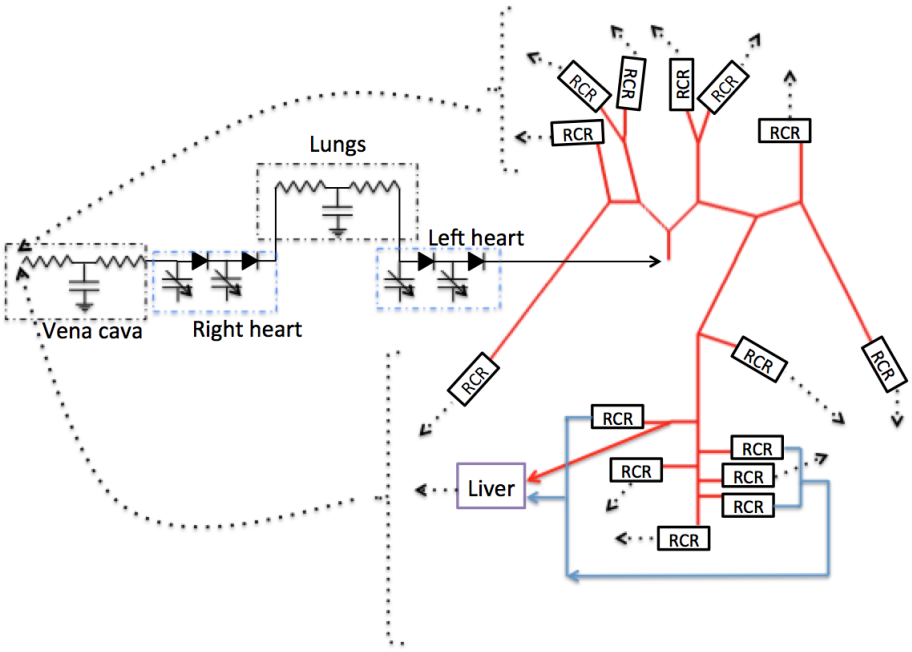

Figure 2: Scheme 1D-0D closed-loop model. The dotted line arrows are all related to the vena cava compartment.

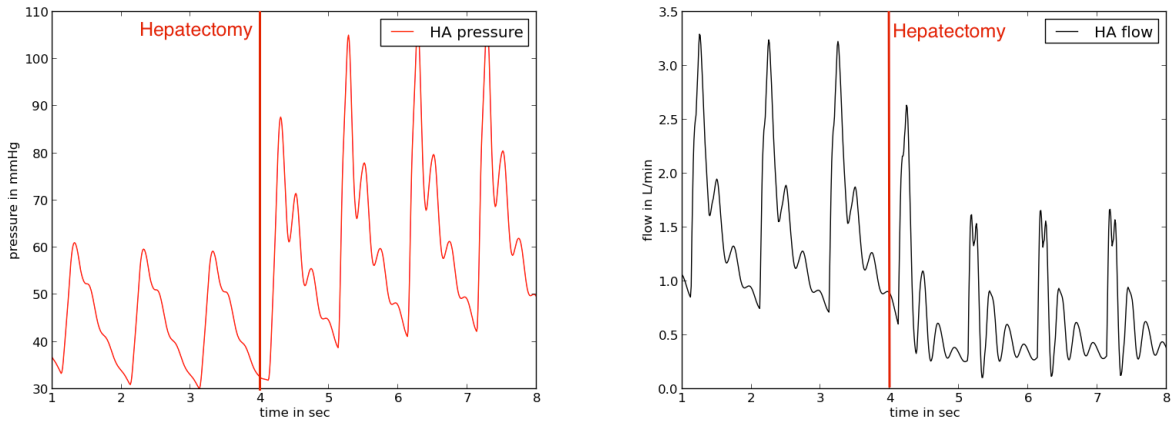

Figure 3: Hepatic artery pressure (left) and flow rate (right) over time during hepatectomy simulation.

4 CONCLUSIONS

A 0D closed-loop model was developed. Partial hepatectomy and other phenomena such as bleeding and infusion during liver surgery were simulated. The simulation results behaved like experimentally observed. Then, to reproduce typical changes in arterial waveforms distally from the heart, a 1D-0D closed-loop model was implemented. Liver resection surgery was simulated and hemodynamics changes computed: the dynamics changes are in good qualitative agreement with the experiment measurements. Future work will include better parametrization of the model (inverse problem could be run to identify specific parameters) and finer quantification of the different mechanisms interplay. Different size of liver resection could also be simulated to understand how the changes in wave forms dependent on the percentage of hepatectomy.

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