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Original Article

Blood Flow Simulation in Patient-Specific Segmented Hepatic Arterial Tree

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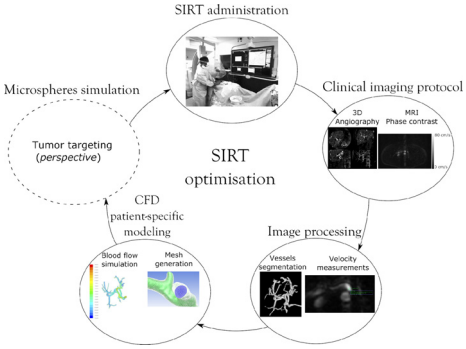
Graphical abstract



Abstract

Purpose: Selective Internal Radiation Therapy is an emerging, minimally invasive therapy of liver cancer. Millions of microspheres are injected through a catheter into tumor vascular supply. Microspheres distribution in liver is strongly dependent on patient's arteries geometry and catheter tip positioning, which is currently chosen by the physician based on qualitative image interpretation. A patient-specific numerical simulation of blood flow would have a crucial importance in therapy optimization, allowing *in-silico* research of microspheres trajectories.
Material and methods: We developed a procedure to segment patient's hepatic arterial vasculature with a Hessian based approach on 3D angiography, and to perform blood flow numerical simulation in the extracted geometry with ANSYS Fluent. In vivo blood velocity measurements were performed using phase contrast MRI to constrain these simulations.
Results: Flow results in the larger vessels are coherent with literature, but very little is known for smaller arteries: simulation results are compared to velocity measures on hepatic arteries down to 2.2 mm of diameter on phase contrast MRI, which gave encouraging results for validation.
Conclusion: A viable procedure for arteries segmentation and patient-specific blood flow simulation is proposed, phase contrast MRI allowing for tuning and validation of velocity values. The proposed personalized blood flow simulation is compulsory for the simulation of microspheres trajectories in the aim of tumor targeting.

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Keywords: Computational fluid dynamics; Hepatic artery; Image processing; Liver tumor; Phase contrast MRI; Radioembolization

1. Introduction

Hepato-cellular carcinoma (HCC) is the fourth cause of mortality in the world. Treatment options are limited, less than 15% of patients are candidates for surgery and half of them for chemotherapy or radiotherapy [1]. A viable option to avoid side effects is the development of local treatments such as Selective Internal Radiation Therapy (SIRT) [13], which brings millions of radioactive microspheres directly into arterial tumor blood supply through a catheter, inducing far less embolizing syndrome than its equivalent in chemotherapy, and comparable (even better in an end-stage HCC) benefits [1]. The hepatic vascular supply is double: 25% comes from the hepatic artery and 75% from the portal vein. HCC is mainly vascularized by the hepatic artery. When the vessels irrigating the tumor are embolized, the arterial vascular supply of healthy liver can be also strongly reduced if the tumor targeting is not optimized. Therefore, if the portal supply does not compensate enough, post-embolization syndrome can be severe.

Administration of SIRT requires a very precise knowledge of the hepatic arterial tree: currently, there is no available tool providing physicians the position where the catheter should be placed in the arterial tree, for the optimization of tumor targeting. In order to identify the best injection point, the physician realizes a cone-beam CT angiography to visualize the arteries geometry. When a therapy delivery point is chosen, biodegradable mock-spheres (Technetium ^{99m}Tc albumin macro-aggregated, MAA) are injected and a scintigraphy acquired one hour later reveals their distribution. The distribution of radioactive microspheres is thus approximately predicted from only one preliminary injection of ^{99m}Tc MAA, and for a same injection site, their behavior can actually be sometimes different [12]. Then, the simulation of several microspheres injection scenarii is of great interest for the clinician.

In the current work we aim at modeling arterial blood flow in a patient-specific hepatic arterial tree. This is a necessary step towards the patient-specific simulation of the distribution of the injected microspheres transported by blood. If the arteries segmentation is fine enough to detect the principal vessels irrigating the tumor, and if the simulation is initialized with patient-specific values of pressure or velocity, then the concentration of microspheres in the tumor can be more accurately estimated by existing appropriate CFD (computational fluid dynamics) methods.

It has been shown [4] that the distribution of microspheres at a bifurcation is not simply proportional to the blood flow distribution in the two descendant vessels, and that it can significantly depend on the vessels geometry, which impacts on the flow streamlines and consequently on the particles trajectories. Blood flow characteristics like pressure and velocity can be deduced from angiography and through CFD if and only if we provide appropriate BC (boundary conditions) like pressure and/or velocity at the inlet and outlets of the vascular tree. This is why, to simulate the flow, we plan to combine these anatomic information with hemodynamics information extracted from PC MRI.

Of course, the vasculature and perfusion in tumors and healthy tissue is a key point to estimate the final microspheres (and thus dose) distributions. Nevertheless, the first step is to have the best estimation of velocity and pressure in the vessels upstream from such vasculature. Clearly the fluid and microspheres propagation in small vessels is far more complex to analyze, and for this reason we cannot expect to have access to a precise vessels network shape: based on angiographic data we can only expect, at this level, to segment the tumor regions, and this is not in the scope of this paper. Let us only indicate here that coupling real data and simulated data based on image characteristics could help solving this scale limitation, that could be achieved using a computational model of the finer vascular network, like the one we previously developed [19,16].

A complete model of SIRT will let the radiologist simulate and quantify the distribution of microspheres in tumor and in healthy tissue, starting from any potential injection points and with different injection modalities, including dose amount and injection site and velocity.

Vessels enhancement from 3D angiography will be described in Section 2.1. Next, the creation of a triangular mesh for numerical simulation on the extracted geometry and the simulation setup are described in Section 2.2. Section 3 presents the principal results we obtained concerning blood flow and the preliminary validations we performed. As shown in Section 4, the procedure we developed opens the way to a patient-specific simulation of microspheres transport by blood flow, able to predict their distribution in liver depending on injection modalities and hemodynamic characteristics.

2. Method

Vessels extraction is performed on cone-beam CT 3D angiography. Data sets are up to $512 \times 512 \times 374$ voxels, and voxel size is $0.463 \times 0.463 \times 0.463$ mm. Images are acquired a few dozens of seconds after the injection of iodine-based contrast media, during the so-called arterial phase, i.e. when contrast agent is only in the arteries and is still not spread in all hepatic parenchyma. This acquisition gives a detailed portrait of the arterial tree until vessels with a diameter of around 0.5 mm.

All procedures involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Declaration of Helsinki. Approval by the institutional Medical Ethics Review Board and proper informed consent were obtained.

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