GPU-Accelerated Real Time Simulation of Radio Frequency Ablation Thermal Dose

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***Abstract*—In this paper we present results showing that Graphic Processing Units (GPUs) can be used to accelerate the simulation of the thermal field dose during Radio Frequency Ablation (RFA). Specifically we show that this simulation can be conducted in real-time, allowing the development of intraoperative guidance platforms that track and display the thermal lesion as it forms during the intervention. Real time simulation has not been reported before, and has been a critical factor preventing development of intraoperative guidance tools.**

I. Introduction

RFA is a thermally mediated ablation technique, where an applicator carrying one electrode is inserted into tumors percutaneously (or via laparoscopy, or open surgical approaches). Radio Frequency (RF) energy is applied, denaturating and coagulating tissues in a volume of 2cm to 5cm diameter [1]. Some RFA electrodes are shaped as straight elements, others deploy an umbrella of tines to ablate a larger volume. RFA is attractive as it can be used percutaneously for a minimally invasive, possibly out-patient, procedure.

The typical approach for RFA is percutaneous. Physicians therefore have no direct view of the location of electrodes within tissues. CT and Ultrasound (US) are used intraoperatively to track the location of electrodes, but both CT and US have limited ability to distinguish the necrotic tissue produced by RFA from normal tissue. US images are compromised by gas bubbles that form from evaporation of water in the tissues, and differentiation by CT would require repeated administration of contrast agent [2]. The inability to properly assess the necrotized tissues by imaging makes it difficult to assure uniform and complete necrotization of targets. Complete target necrotization is particularly challenging for larger tumors requiring a series of overlapping ablations. Currently physicians rely on “mental maps” of where they have previously ablated tissues and estimate where to go next. The necrotization volume is “mentally estimated” from lesion geometry diagrams provided by electrode manufacturers. These images show the expected ablation geometry for a uniform tissue.

One solution to the above problem that has been envisioned is to intraoperatively simulate the electrical and thermal phenomena in RFA, to compute the boundary of the necrotized volume, and to fuse this information with preoperative or intraoperative CT or US images, developing therefore a guidance system. Such system has been prototyped, for example, in [2] and other works. A limitation of all these approaches is that intraoperative guidance requires real time calculation and display of the ablation contours, while computation times for simulating a 15 minute procedure have been reported to be 3 to 6 hours [3], [4]. Acceleration approaches, based on the use of Graphic Processing Units (GPUs) - highly parallel and powerful processors - have been proposed in [5], [6], but these are based on gross simplifications of the physical laws. We have been able, with no simplification of the physics, to achieve real time simulation of the thermal field in RFA. To the best of our knowledge this is the first time this is demonstrated. Achievement of accurate description of RFA-generated temperatures / necrotization contours will enable the development of intraoperative guidance platforms.

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A. Analytical Modeling

The RFA thermal field is described by the Pennes bioheat equation [7]

$$\rho C \frac{\partial T}{\partial t} = \nabla \cdot k \nabla T + Q + Q_B + A \quad (1)$$

where ρ is the density of the tissue, C is the specific heat, T is the temperature, t is time, k is the thermal conductivity, Q is the electrical power density deposited by the application of RF energy, and A is a metabolic heat generation term. Given the knowledge of the tissue thermal properties and of the applied RF energy term Q, the above equation allows computing the temporal and spatial evolution of the temperatures set by RFA electrodes in the course of an intervention. This process is a time-stepping process, where at each time-step temperatures are updated using (1). At each time instant also the term Q needs to be computed. Frequencies used in RFA are typically in the range of 350 to 500 KHz, and the energy deposited by RFA electrodes can be simulated using the Laplace equation [7]:

$$\nabla \cdot \sigma \nabla u = 0 \quad (2)$$

where σ is the electrical conductivity of the tissues and u is the electric potential that develops under the effect of the electrodes. We describe electrodes using boundary condition called Complete Electrode Model, which accounts for the presence of a contact impedance at the electrode-tissue interface and for a non-uniform current density flow from the electrode surface [8]. The term Q to be plugged into (1) is easily computed from u as $Q = \sigma \nabla u \cdot \nabla u$.

Solution (1) allows therefore to compute the temporal evolution of temperatures inside the body of the patient, and

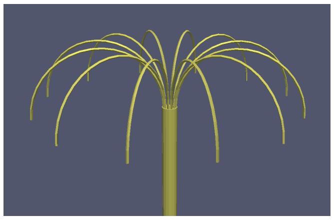

Fig. 1. Rendering of a finite element mesh capturing the geometry of an RFA electrode.

therefore of the thermal does, allowing the prediction of the induced lesion boundaries.

B. Finite Element Modeling

A software library developed at NE Scientific in C/C++ language was used for Finite Element (FE) modeling of a Boston Scientific LeVeen 4cm electrode (Figure 1). The electrode model was embedded in a cylindrical volume of 8cm diameter and 10cm height to simulate the tissues around the electrode. The overall mesh has approximately 40,000 nodes and 227,000 tetrahedral elements. Equations (1) and (2) are turned respectively in two sparse linear systems with the FE method. Time steps of 0.25 seconds have been used in (1) in RFA modeling [3], [4]. The simulation of an intervention of 10 minutes requires solving therefore 2400 steps. Overall solution times of 3 to 6 hours have been reported in relatively recent publications [3], [4], preventing application in the operating room.

C. GPU Acceleration

Simplificative approaches have been considered in [5], [6] where empirical approximations have been made to the physics of RFA. We have taken a different approach, developing a GPU sparse linear solver based on Wavelet Algebraic Multigrid Methods (AMG) [9]. This sparse linear solver is particularly fast as AMG methods are known to be the fastest solvers for elliptic PDEs, and as GPUs are particularly powerful computational means with hundreds of computational cores. While parallelizing AMG methods on GPUs is not trivial, the speed-up obtainable is significant. Specifically we use a Conjugate Gradient method with a V-Cycle preconditioner, 3 cycles of pre- and post- preconditioning, and diagonal scaling. The solver utilizes a setup phase, which is a one-time operation implemented on the the CPU and, and a solution phase. On an Intel Core i7 based PC, equipped with a NVIDIA Tesla S1070 GPU, WAMS was able to perform the setup phase in 285 milliseconds, and to solve (1) to a precision of $1 \times 10 - 4$ in 82 milliseconds. This allows, for example, to simulate a 10 minutes intervention in 3 minutes 16 seconds, as opposed to the several hours reported by other previous works [3], [4]. The ability to simulate at a faster speed, or at the same speed, an RFA intervention while it is occurring is critical in the development of intraoperative guidance tools that show the formation of lesions as they occur.

II. Conclusion

Development of an intraoperative guidance platform for RFA would potentially improve outcomes of this cancer ablation technology as surgeons would be able to see the formation of thermally induced lesions during intervention. This information would be generated by simulations which could be superimposed on the intraoperative CT images. One critical factor that has prevented this development so far is the fact that simulations are computationally intensive and took too long time to be useful. By using GPU accelerated sparse linear solvers we were able to simulate the temporal evolution of the RFA thermal field at $3\times$ real time speed.

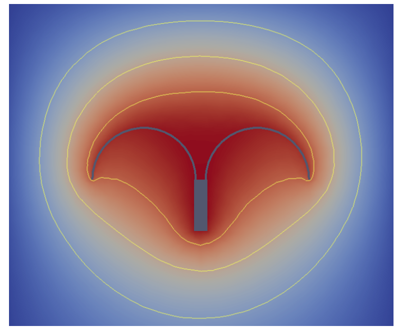

Fig. 2. Two dimensional cross section of the simulated volume showing computed temperatures. The red color indicates higher temperatures and the blue color lower temperatures. Iso-temperature lines, for the temperatures of 50°C, 60°C, and 70°C, are shown in yellow color.

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