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Short Paper

HIFUpm: a visual environment to plan and monitor High Intensity Focused Ultrasound treatments

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Abstract

High Intensity Focused Ultrasound (HIFU) is a non invasive therapeutic method, which has been a subject of interest for the treatment of various kinds of tumors. Despite the numerous advantages, HIFU techniques do not reach the high delivery precision like other therapies (e.g., radiotherapy). For this reason, a correct therapy planning and monitoring in HIFU treatments remains a challenge. We propose HIFUpm, a visual analytics approach which enables the visualization of the HIFU simulation results, while guiding the user in the evaluation of the procedure. We illustrate the use of HIFUpm for an ablative treatment of an osteoid osteoma. This use case demonstrates that HIFUpm provides a flexible visual environment to plan and monitor HIFU procedures.

1. Introduction

High Intensity Focused Ultrasound (HIFU) is a non invasive therapeutic method, which has been a subject of interest for the treatment of various kinds of tumors [FMT*15, HLB*14]. MR-HIFU has been demonstrated to be effective for the treatment of soft tissue tumors, e.g., uterine fibroids [FMT*15], and solid tumors such as osteoid osteoma [YEP*18] and bone metastases [HLB*14]. A detailed explanation of a typical HIFU procedure is shown in Figure 1.

During HIFU treatments, image-guidance using Magnetic Resonance Imaging (MRI) is usually performed through the proton resonance frequency shift (PRFS) thermometry [KMQ*09]. The PRFS thermometry is suitable for monitoring the temperature of water-rich tissues, such as soft tissues, while it fails in water-poor tissues, such as bone.

Despite the numerous advantages, HIFU techniques do not reach the high delivery precision like other therapies (e.g., radiotherapy) [CTJ18]. For this reason, a correct therapy planning in HIFU treatments remains a challenge. Therapy planning involves various aspects, such as the positioning of the focal point, the treatment duration and the definition of the initial power. Herein, computer models for HIFU propagation play a key role at the level of planning and evaluating a procedure. Such models can predict the temperature increase and the consequent ablated volume in the focal region. A correct visualization of the temperature development over space and time and the ablated tissue is fundamental to help clinicians choosing the best treatment and/or evaluating if a patient is suitable for HIFU therapy.

We propose HIFUpm, a visual analytics approach for HIFU thermal planning, to be used in combination with MR-thermometry. HIFUpm enables the visualization of the HIFU therapy, while guiding the user in the evaluation of the procedure. HIFUpm allows the users to visualize and navigate the results (temperature and ablated volume) from a HIFU computer model. Using HIFUpm the user is also able to compare the results of different therapies on the same patient, to establish which therapy is the most effective and/or if a patient is suitable to be treated with HIFU.

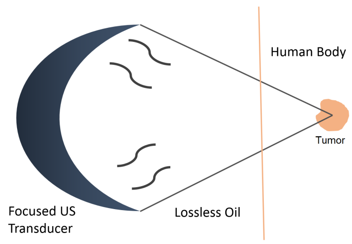

Figure 1: *A schematic representation of an HIFU treatment mechanism. The transducer elements are immersed in a lossless material, which does not attenuate the US waves. After traveling through the lossless oil, the US waves are focused on a specific spot of the human body, usually the tumor, causing temperature increase and a possible ablation.*

2. Related work

In this section we provide an overview of HIFU models and visualization approaches used in HIFU therapy planning.

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The gold standard to simulate HIFU propagation in human body is to solve the wave equation, which considers the propagation and the interaction of shear and longitudinal waves. However, common problems related to this approach are the high computation time and the high memory requirements, which hampers the applicability for real-time therapy planning.

In the literature, various HIFU models which include the shear wave propagation in bone have been proposed [tEBE*16, TS15]. However, these methods omit the interference between shear and longitudinal waves. Nell and Myers [NM10] take this interaction into account, however they used simplified geometries, to reduce the memory consumption. This choice makes the model not adequate to be applied in a real HIFU treatment scenario, with geometries given from segmentation and with complex transducer shapes.

As stated before, thermal planning with HIFU is still under research. Therefore, visualization approaches which address solving the issues of HIFU therapy planning lack in the literature.

Wu et al. [WARR07] proposed an integrated software platform which allows the user to segment the geometry, perform HIFU simulations and visualize the temperature output. The possibility to define and perform HIFU simulations is given also by the approach proposed by Modena et al. [MDB17]. In this work, they present an environment addressed to researchers to navigate and explore results from an HIFU computer model. Their approach does not allow the user to compare different therapies, as it is not meant for a clinical usage.

Van Straaten et al. [VHV*17] developed a prototype to be used in the MR-guided focused ultrasound workflow. It is mainly related to image processing, allowing the user to segment and define tumors and organ at risk. Using this tool, the user is also able to visualize the treated region before and after the treatment.

Other approaches which make use of models to design treatment planning can be found in the literature [CTJ18, PBC*16]. These works tend to focus on the algorithm/model they use to obtain the results i.e. the temperature evolution, neglecting the role of the visualization in HIFU thermal planning.

3. Approach

The focal point position is defined by the user through the *test sonication*. This involves the positioning of the focal point moving the transducer elements using the graphical user interface of the HIFU system.

Once the position of the focal point has been established the position of the tranducer elements is known. This information is then given to the model and it can generate data varying the initial power and the treatment duration. In our case we used the model proposed by Modena et al. [MBB*18], based on a ray-tracer approach in Python. The outputs of the model are the temperature evolution over time and the Cumulative Equivalent Minutes (CEM). This quantity defines if a region is ablated or not.

3.1. Modeling: the raytracer approach

Here, we briefly summarize the approach by Modena et al. [MBB*18].

In the ray-tracer approach US waves are modeled as rays of power leaving each transducer element. At each interface, the reflected and the refracted rays are computed. The output of the model is the power deposited Q_t. Then Q_t is used as heat source while solving the heat equation. Finally, we calculated the Cumulative Equivalent Minutes (CEM), that is the ablated region. The CEM is calculated with the same approach as used by Sapareto et al. [SD84]. In our use case, the model has been applied to a geometry with fat, muscle and bone, however it can work with other types of tissues and organs (e.g. vessels).

3.2. Visualization

3.2.1. Visualization for ablation procedures

Our visualization approach allows the user to explore and interact with the data available and to easily compare the output of different treatments. To do so, we use 3D, 2D and 1D views. We use 3D views to give a general overview of the geometry e.g. the dimensions of the tumor, where the tumor is positioned with respect to the transducer elements and/or the thickness of the fat and muscle layer (see Figure 2 (a)). Moreover, the user can interact with the view, and he is able to choose the volumetric data to visualize. 3D views are also used to give the exact position of the planes that are shown in the 2D views.

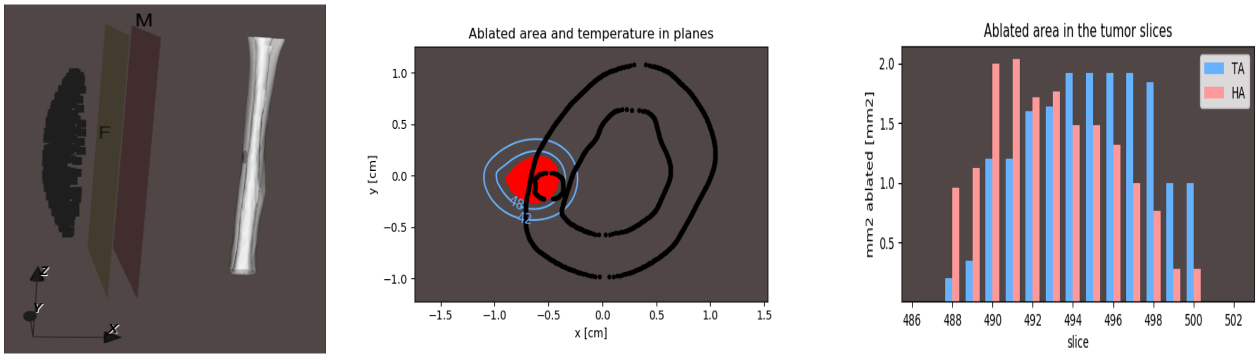
The two 2D views give information about the temperature and the ablated area within a certain plane. The first 2D view (see Figure 2 (b))shows both the temperature and the ablated area. To do so, we represent the ablated area using a solid color, and the temperature regions as isolines. The reason is that a physician might be interested in evaluating the dimensions of the ablated area, as well as where the temperature is higher than a certain value.

The second 2D view offers the possibility to compare the ablated areas for different treatments. In particular, a treatment might result in less tumor ablated in a certain plane, and the user might want to find easily a treatment which increases the ablation of the tumor. An example of the use of this view can be found in Section 4.1 and it is shown in Figure 5. In both the 2D views, the user is able to navigate through the volume using the sliders as well as the scroll wheel.

1D views are used to show the ablated area of the healthy tissue and the tumor only in the planes where the tumor is present. In this way, the user can focus on the tumor ablation and its surrounding tissues. The first 1D view (see Figure 2 (c)) shows the ablated region (in mm^2) for a particular treatment. Other than that, the second 1D view shows three different quantities of a certain plane:

- AD : Actual Data. The ablated area in the current plane for the treatment that the user is currently investigating.
- MTAv: Most Tumor Ablated volume. The ablated area in the current plane for the treatment that ensures the maximum volume of tumor ablation.
- LHAs: Least Healthy Ablated slice. The ablated area in the current plane for the treatment that ensures the least area of healthy tissue ablated (in the current plane).

In the second 1D view, the user is able to navigate through the volume using the slider as well as the scroll wheel. An example of the use of this view is given in Section 4.1.



(a) (b) (c)

Figure 2: *3D view of the entire geometry (a). The transducer elements are represented as the black dots, while fat and muscle layer are represented as the flat planes, F and M respectively.In (b) the CEM and the temperature regions for a certain plane. The ablated area is visualized as a solid color (red), and the temperature regions as isolines (green). In (c) the tumor ablated (TA) and the healthy tissue ablated (HA) for every plane.*

2D and 1D views are provided with toolbars which allow the user to interact with the plots (e.g. zoom and/or save).

3.3. HIFUpm

Figure 3 presents an overview of HIFUpm for tumor ablation treatment. The red highlighted area is used to change the treatment to investigate by setting the initial parameters (initial power and treatment duration). The blue highlighted area shows the data calculated only in a portion of the geometry i.e. where the tumor is present, while 2D and 3D views show the data calculated in the total geometry. In the green highlighted area, the user can compare different treatments.

3.4. Implementation

The model has been implemented in Python. The heat equation has been implemented using freeFem++ [Hec12]. The GUI has been written in Python, using PyQt. The 3D rendering has been implemented using VTK, while the 2D and 1D views are implemented using Matplotlib.

4. Results

4.1. Use case: Osteoid Osteoma

Different layers are present: lossless gel, fat, muscle and bone. The bone is composed of the cortical bone and the marrow. The bone and marrow boundaries are extracted from CT data. The tumor is located in the cortical bone, and the focal point is positioned in the tumor. The raytracer computer model is used to obtain the temperature evolution and the ablated region for all the treatments.

HIFUpm provides the possibility to compare the results of different treatments. In Figure 4, the ablated areas (healthy and tumor tissues) in every plane of the tumor for various therapies are shown. The MTAv value corresponds to the treatment which maximizes the volume of the ablated tumor, while the LHAs concerns the treatment which reduces the ablated healthy tissue in the plane. For different planes, the LHAs might show the ablated area for different treatments (see Figure 4 (a) and (b)). Note that the LHAs value depends on the plane the user is considering. This is helpful when the user want to find the treatment that reduces the ablated healthy tissues in a particular plane or a group of planes (e.g. which contain a particular zone like a vessel and/or a vital organ).

Looking at Figure 4 (a) and (b), the user might be interested in investigating the treatment which ensures the maximum volume of tumor ablated (the one with the initial power at 90 W and the treatment duration at 40 s) and the treatment that ensures the minimum healthy tissue ablated in plane 495 (the one with the initial power at 40 W and the treatment duration at 20 s).

This can be achieved by comparing the ablated areas using the 2D views (see Figure 5). These views helps the user to evaluate the different treatments, e.g., he might decide to change the treatment (choosing the one which shows the higher volume of tumor ablated). The user is then able to change the parameters to investigate using the red highlighted area in Figure 3. This way, HIFUpm gives the possibility to explore the treatment options, while making the results of the other treatments always available for comparison.

In general, HIFUpm allows to investigate the effect of the treatment duration on the ablated region and/or the effect of the initial power in order to choose the best treatment. This cannot be done by simply computing the results of the HIFU model, but it requires also the expertise and evaluation of the user. In fact, the user might select a different combination of treatments according to the specific case (e.g. presence of vessels and/or organs or the thickness of the soft tissue layers to avoid burns on the skin). Moreover, HIFUpm allows the user to easily compare different combinations of treatments in the same views, and this is not possible using the existing tools for HIFU simulations.

5. Conclusion and Future work

We have introduced HIFUpm, a visualization environment to explore the results of different HIFU therapies. Using HIFUpm the users is able to easily visualize the ablation treatment, as well as

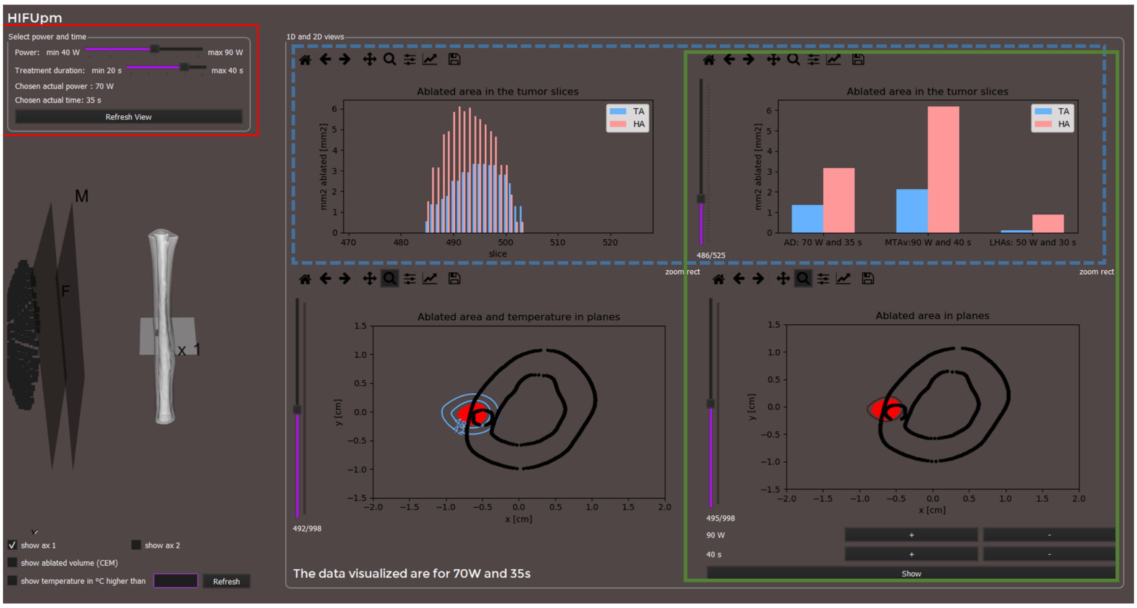
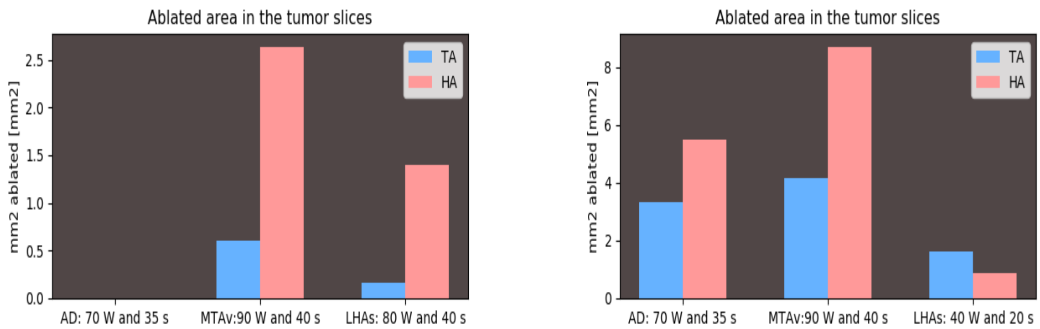


Figure 3: *HIFUpm interface for treatment planning of tumor ablation. The red highlighted area is used to set the initial power and treatment duration of the treatment to investigate. The blue highlighted area shows the data calculated only where the tumor is present, while 2D and 3D views show the data calculated in the total geometry. In the green highlighted area, the user can visualize and compare the results of different treatments.*



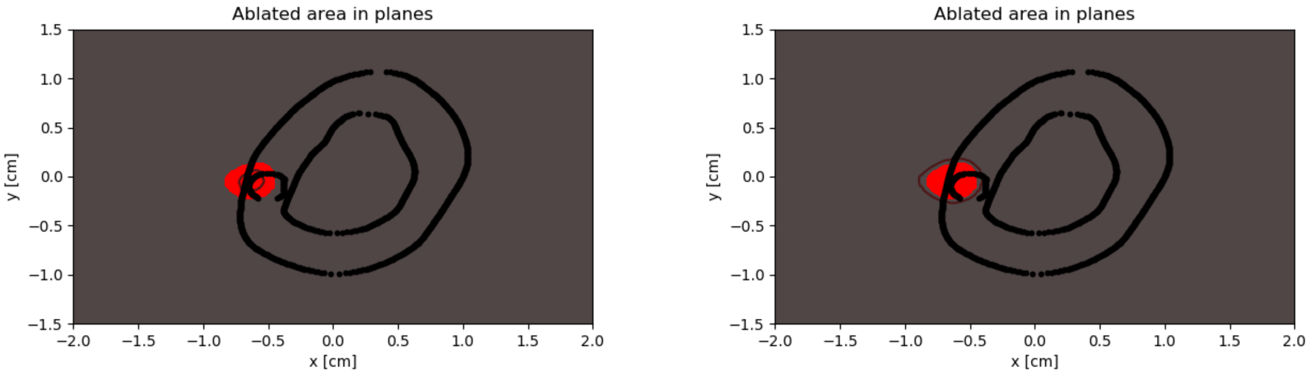
(a) (b)

Figure 4: *Ablated area of plane 484 (a) and 495 (b). It is important to underline that LHSs shows the ablated area for two different treatments in the two different planes.*

to compare different therapies in multiple linked views. HIFUpm gives to the user the possibility to explore the different options available (in terms of initial power and treatment duration). Using our application, the user always has the total control on the results of the visualized treatment, maintaining the results of the other treatments always available for comparison. HIFUpm simplifies the evaluation of multiple treatments (in our use case 30) and consequently the visualization of a high amount of data.

Future extensions of this work may investigate the use of model order reduction methods [BCOW17], to ensure real time efficient computations, when multiple recalculations of the system are expected and/or the dimensionality of problem is too large for reasonable computational times. Moreover, the possibility to define particular zones of the geometry will be added. This involves the definition by the user of the various parts (e.g. the tumor, vessels, other organs) as well as the definition of zones where the temperature should remain below a certain value. It would also be valuable to add another view which compares the surviving tumor tissue in terms of area and percentage for each treatment. Regarding the modeling, the effects of motion on simulating a treatment should be further investigated. Moreover, the model needs to be validated experimentally.

Acknowledgments



(a) (b)

Figure 5: *The ablated area in plane 495 of the chosen treatment is represented as a solid color ((a) and (b)) while the ablated area of the treatment with 40 W and 20 s as initial parameters is represented as the isoline (a). In the same fashion, in (b) the isoline represents the ablated region when the initial parameters are set at 90 W and 40 s.*

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