Advancing Focused Ultrasound surgery through Robotics, Simulation, and Augmented Reality: the FUtuRo project

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***Abstract*— This study introduces a comprehensive system designed to elevate both the planning and evaluation phases of Focused Ultrasound Surgery (FUS) interventions. Through the seamless integration of mechanical, acoustic, and thermal simulations alongside robotic assistance, our approach empowers precise treatment planning and parameter optimization. Leveraging advanced imaging modalities enhances the accuracy of target delineation, while computational modeling provides invaluable insights into therapeutic efficacy. Specifically, this paper will assess the acoustic pressure field and the dimensions of ablated tissue in a custom-made phantom resembling human tissue layers using an appropriate library for acoustic wave simulation.**

I. INTRODUCTION

FUS is the engine core of the project **FUtuRo** (Focused Ultrasound Surgery enabled by Robotics and Simulation) to enhance the versatility of the existing device developed within the project FUTURA (Focused Ultrasound Therapy Using Robotics Approach). **FUtuRo** project primarily consists of three components: (i) patient-specific treatment registration and thermo-acoustic-mechanical simulation; (ii) integration of an Augmented Reality (AR) interface to significantly improve treatment planning and management intuitiveness; and (iii) robot control to ensure precise positioning, target motion compensation (e.g., respiration), and contact force control between the transducer and the patient's body.

In this paper, it will analyze an initial approach with results utilized for point (i) by employing the SOFA framework for deformation, K-WAVE for simulation of acoustic waves and thermal dose, and Unity 3D for visualization.

II. METHODOLOGY

A. System Components and Overall View

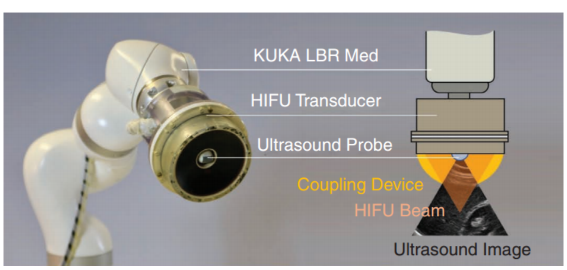

Fig. 1. System components of the HIFU platform.

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As depicted in Fig. 1, a 7-DoFs robot (*LBR Med, KUKA, Germany*) is used to hold a 16-channel phased annular array transducer. A 2D linear US probe is seamlessly integrated with the HIFU (High Intensity Focused Ultrasound) transducer to facilitate precise therapy positioning. Moreover, a specialized *Coupling Device* (a balloon) is adopted to achieve optimal acoustic coupling.

Fig. 2 gives the overall workflow: during the pre-operative phase, medical images (e.g., MRI, CT, or ultrasound) are segmented to create a 3D anatomical model of the target. Then, it's subsequently utilized to simulate the treatment, and the patient-specific 3D model is visualized with the acoustic beam focused on the target identified by the physician.

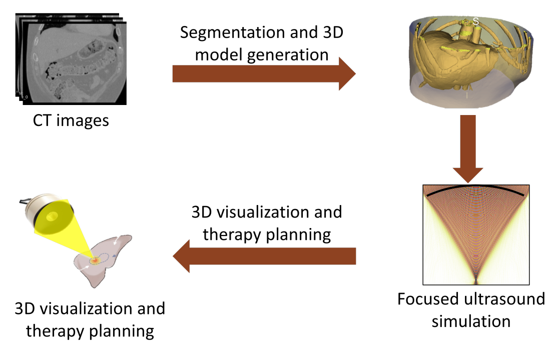

Fig. 2. Illustration of workflow.

B. k-WAVE: Mathematical Formulations

Acoustic: *k-WAVE* is used for time domain simulation of propagating acoustic waves [1]. The ultrasound power deposition with heat generation is calculated by $Q = 2\alpha_0 I(x,y,z)$ and the acoustic intensity is given by:

$$I(x,y,z) = \frac{1}{\rho c_0 \omega_0^2} \frac{1}{t_p} \int_{t'}^{t'+t_p} (\frac{\partial p(x,y,z)}{\partial t})^2 dt \qquad (1)$$

where c_0, ω_0, and t_p are the sound speed, angular frequency, and the time of the acoustic wave propagation, respectively. t' is the time cost for the ultrasound wave to reach the steady state.

Thermal: The volumetric heat generation is used in *Pennes bioheat transfer equation (BHTE)* model:

$$\rho_t C_t \frac{\partial T}{\partial t} = k\nabla^2 T - w_b C_b (T - T_{art}) + Q + Q_m \qquad (2)$$

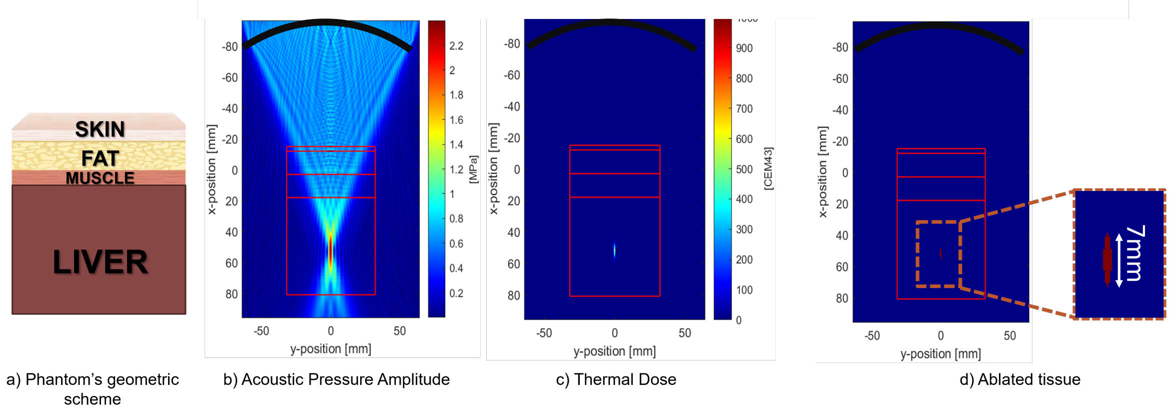

Fig. 3. The simulation outcomes of acoustic wave propagation, along with the figure derived from the thermal simulation

where ρ_t, C_t, and k are the density, specific heat, and thermal conductivity of the tissue, respectively. C_b and w_b is the specific heat of blood and the blood-perfusion rate. T and T_{art} represent the tissue and arterial blood temperatures, respectively. Q is the volumetric heat generation and Q_m represents the metabolic heat generation in the tissue medium.

To standardize measurements, the thermal dose is calculated with $CEM43 = \sum_{i=1}^{n} t_i \cdot R^{(43-T_i)}$, which stands for Cumulative Equivalent Minutes at 43°C. and quantifies the cumulative thermal exposure at 43°C over time intervals (t_i), where i represents each interval, R is the temperature dependence of cell death rates ($R(T < 43°C) = 1/4$, $R(T > 43°C) = 1/2$), and T is the average temperature during each time interval t_i. The resulting CEM43°C value integrates the entire heat exposure history, providing insight into the cumulative effect on cell death.

III. Simulation Experiment Setup

Acoustic Simulation: As shown in Fig.3, an initial setup comprising a concave single-element transducer with a focal point at 120 mm, submerged in a water medium is set. A cubic phantom was simulated, consisting of various layers to mimic the acoustic and thermal properties of human tissues, such as skin, fat, muscle, and liver, the parameters are listed in Table. I. This setup aims to investigate the impact of the absorption coefficient on wave attenuation and, consequently, on the variation of the axial position of the focal point. The acoustic wave amplitude and sonication time are set as 4000 Watts and 10^{-5} seconds, respectively.

TABLE I
Acoustic Properties

	Water	Skin	Fat	Muscle	Liver
Density ($\frac{kg}{m^3}$)	1000	1100	910	1050	1055
Sound speed ($\frac{m}{s}$)	1520	1540	1430	1560	1570
Attenuation ($\frac{dB}{MHz \cdot m}$)	0.217	40	45	57	45

Thermal Simulation: The solution of the pressure wave equation has been coupled with Pennes' biological heat transfer equation (Eq. 2) to identify temperature distribution. After identifying the temperature distribution within the domain, it is possible to compute the thermal dose from the temperature history over time and ablated tissue. Tissue ablation pertains to the region surpassing a defined temperature threshold, typically 60°C [2].

IV. Simulation Results

Fig. 3 illustrates the acoustic pressure amplitude, and thermal dose in CEM43°C, and ablated tissue, respectively. The thermal dose in CEM43°C emerges as a pivotal metric for assessing the efficacy of thermal treatments, providing a standardized measure to compare thermal damage induced by varying exposure durations. This parameter proves critical in predicting the biological effects of thermal treatments. In figure *3.d*, the simulation solution aligns with approaches proposed in previous studies and works [3], where the ablated tissue dimension is associated with an oblate ellipsoid. Specifically, it has been observed that the length of minor axis is approximately 3mm, while that of the major axis is about 7mm.

V. CONCLUSION

This study presents a comprehensive system aimed at improving Focused Ultrasound Surgery (FUS) interventions. By integrating mechanical, acoustic, and thermal simulations with robotic assistance, our approach enables precise treatment planning and optimization. Leveraging advanced imaging and computational modeling enhances accuracy and provides valuable insights into therapeutic efficacy. The preliminary simulation results lay the groundwork for further research.

References

[1] P. Gupta, "Multiphysics numerical modelling for hifu-induced bioeffects and controlled delivery of ablation dosage for oncological applications," Ph.D. dissertation, Monash University, 2020.

[2] T. Sheu, M. Solovchuk, A. Chen, and M. Thiriet, "On an acoustics-thermal-fluid coupling model for the prediction of temperature elevation in liver tumor," *International Journal of Heat and Mass Transfer*, vol. 54, pp. 4117–4126, 2011.

[3] V. Simoni, A. Cafarelli, S. Tognarelli, and A. Menciassi, "Ex vivo assessment of multiple parameters in high intensity focused ultrasound," pp. 5705–5708, Jul 2018.