Integrated MRI and HIFU Control System: Towards Real Time Treatment of the Liver

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Introduction: High Intensity Focused Ultrasound (HIFU) of the abdomen is a complex endeavor requiring integrated real time control of MRI imaging and the HIFU transducer. Rapid real time control with feedback is critical for treatments that are susceptible to respiratory motion. We present our work towards integrating MRI and HIFU under a single software platform, allowing for flexible control and monitoring of both systems, from device localization to treatment planning to therapy monitoring. The software was tested by performing sonications in phantoms and *in vivo*.

Methods: A real time MR-guided liver ablation monitoring and control system was developed in collaboration with InSightec, Ltd (Tirat Carmel, Israel), utilizing RTHawk (HeartVista Inc, Los Altos, CA), a flexible real time environment and interventional platform, to serve as an interface between our MRI and HIFU systems [1]. RTHawk allows for the ability to run multiple pulse sequences simultaneously while also creating sequence specific reconstructions and feedback. A custom graphical user interface was developed as an extension to RTHawk for seamless pulse sequence integration with HIFU treatment planning and monitoring.

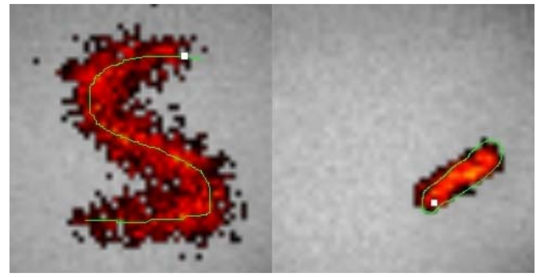

Figure 1: Example sonication treatments created. The left shape was created by sequentially cycling through subsonications that were along the green line. The right shape was created by randomly cycling through subsonications populating the region inside the green line.

An MR tracking sequence and a thermometry sequence and their respective reconstruction algorithms were incorporated into RTHawk. The MR tracking sequence was a 4 shot Hadamard encoding sequence [2], and there were two options for the thermometry sequence: a faster 3 shot RS-EPI sequence using referenceless thermometry [3], and a slower GRE sequence using baseline subtraction. The system can acquire temperature images continuously in any slice orientation. When desired the software can switch to MR tracking to determine the transducer location. This was accomplished by simultaneously acquiring data from two sets of coils: MR tracking coils on the InSightec transducer, and an 8-channel cardiac array coil. RTHawk does not require stopping the scan to run MR tracking, and information such as the transducer location can automatically be transferred from the MR tracking data processing to the thermometry reconstruction.

Sonications were prescribed graphically by clicking on the most recent image. Three different types of sonications are currently implemented: point, path, and region sonications. The path and region sonications were defined by a series of subsonication points between which the transducer rapidly switches through electronic beam steering. For path sonications, the user draws a path, and subsonication points are spread equidistantly along this. For region sonications, the user draws an enclosed path, and points are spread inside it according to the theory of electrostatic repulsion, with weights assigned to the points and the region boundary to determine the compactness of the distribution. This theory can also be extended to defining point distributions in 3D.

During a sonication, multiple options for HIFU can be controlled in real time. For all sonication types, the power can be modulated. For paths and regions, subsonication location can also be changed on the fly, or automated subsonication switching algorithms can be used. For lines, the subsonication could continuously cycle to the next point ("sequential" mode). For regions, the system can randomly change subsonication point ("random" mode), or it can follow a line vector, moving with sinusoidally-varying velocity to simulate respiration. A "gated mode" was also developed, where HIFU was cycled on and off for user defined time periods to simulate respiration.

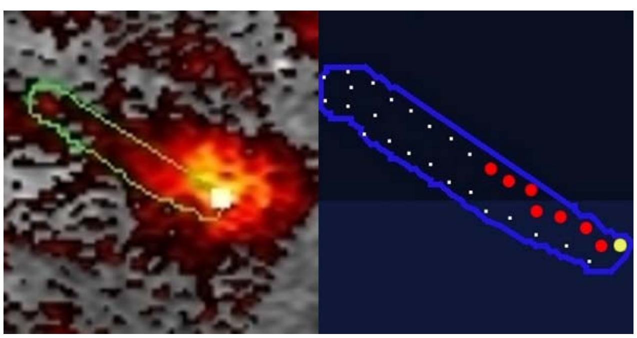

Figure 2: Example in vivo sonication created in a rabbit thigh (left). The subsonication profile for the region (right) showed the utilized points for the sonication. The timing was based on simulated respiration, where the sonication would hold at the yellow dot for 1 second, and then move with sinusoidal velocity along the red dots, returning back at the yellow dot 1 second later, simulating respiration.

All of these features were integrated to form the real time system. A gel phantom was placed into a GE Signa Excite 3.0T scanner (GE Healthcare, Waukesha, WI) and heated using the InSightec ExAblate2000 550kHz extracorporeal phased array transducer. After determining the transducer location using the MR tracking sequence, the location was calibrated using a low-power test spot, turning off the power once the spot was visualized. Next, various treatment locations were prescribed and sonicated, monitoring with temperature imaging with the GRE thermometry sequence.

Additionally, a test was performed in a new Zealand white rabbit. Its shaved thigh was placed above the transducer in a water bath, and spots were prescribed with the software in the same way, using the RS-EPI thermometry. The subsonication timing was set to simulate respiration.

Results: Figure 1 shows demonstrations of a sequentially-sonicated path (left) and a randomly-sonicated region (right) sonications prescribed on the phantom. The green line denotes the prescribed path and the region boundaries, respectively. This test demonstrates the system's ability to not only plan treatments from the MRI images, but also control them to perform custom sonication shapes.

Figure 2 shows a region sonicated along a line with a sinusoidally determined velocity. The red dots were sonicated for approximately 1/7th of a second, and the yellow dot for 1 second. Given the amount of time and subsequent energy deposition at the yellow dot, it is reasonable that most of the temperature build up would be present there.

Conclusions: We have introduced a real time, integrated MRI and HIFU software package capable of transducer localization, treatment prescription, and sonication control and monitoring. The ability to treat complex prescriptions both in phantoms and *in vivo* was demonstrated. Future work will involve more *in vivo* validation, as well as integration of additional feedback mechanisms like physiological information and vessel tracking.

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