Three dimensional spatial and temporal temperature control with MR-thermometry guided Focused Ultrasound

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Purpose/Introduction

High Intensity Focused Ultrasound (HIFU) is an efficient non invasive technique to produce accurate local heating [1]. MRI temperature maps obtained from the proton resonance frequency shift of water [2] can be used to control the temperature with automatic Proportional, Integral, and Derivative (PID) feedback to the HIFU system. This temperature control has been applied previously to one or several points using a multi-spiral focal point trajectory within a single plane perpendicular to the beam axis [3].

However, near-simultaneous heating of closely spaced HIFU locations induce an effect of beam overlap which tends to enlarge the heated volume along the beam axis [4]. This study presents a flexible method to extend the spatial temperature control in 3 dimensions by taking into account this overlap effect in order to regulate the temperature in a large target region without imposing a specific focal point trajectory.

Material and Methods:

MRI imaging: MR thermal map were acquired dynamically every 2.4s with a Philips Achieva 1.5 Tesla. The gradient echo sequence used was a multi echo planar method (TE=18ms, TR=300ms, EPI factor=9) composed of 6 slices, 128×128 voxels corresponding to 1×1×4mm³.

Focused Ultrasound System: To move rapidly the focal point, a 256 channel phased array transducer was used. This ultrasound probe offers the possibility to steer the focal spot electronically every 60ms along 3 dimensions with a range of 15mm. Acoustic power between 0 to 50 W was used to regulate the temperature increase to 10°C inside an ex vivo pig muscle.
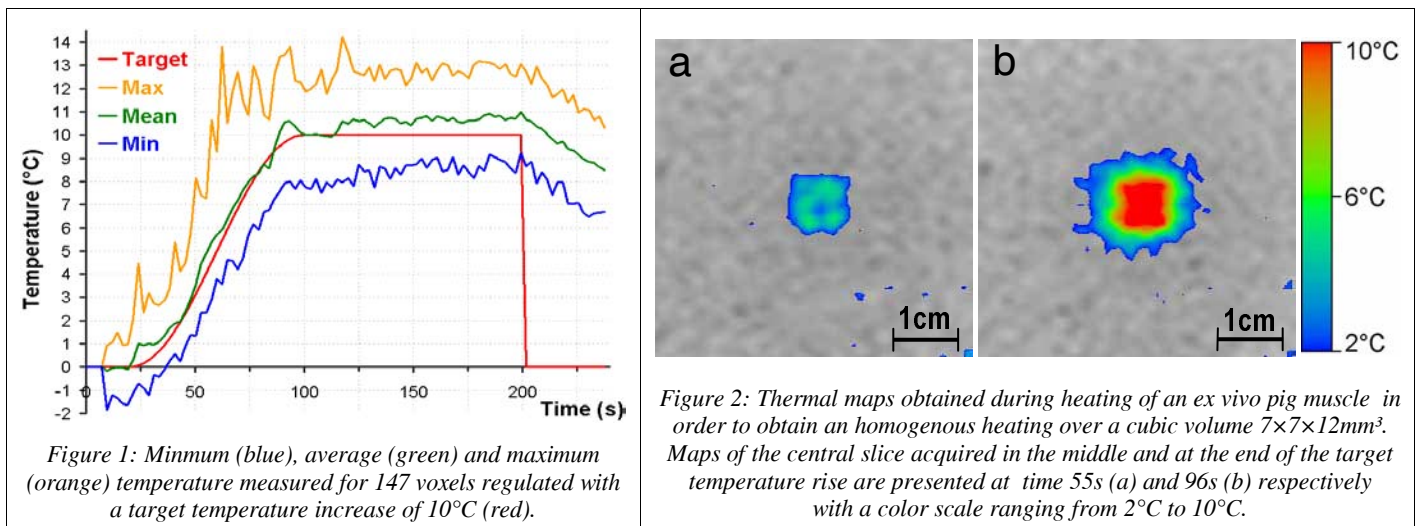
Heating volume: Since the approach proposed offers the possibility to control the temperature over any shape of volume, the spatial temperature control has been tested in the focal point, in linear, cubic and spherical volumes with 1 to 200 voxels located in several images planes.

Feedback temperature control algorithm: The temperature was adjusted by a proportional, integral and derivative controller for each voxel. This automatic control ensures a stable convergence of the temperature. However to avoid overshooting induced by energy accumulation along the beam axis, an iterative maximum detection algorithm is used to take the overlap effect into account.

The localisation and intensity of each sonication to perform is defined from spatial energy distribution required by the feedback controller. The first sonication corresponds to a fraction of the maximum energy required by the controller at the corresponding location. The remaining energy is computed by subtracting the simulated acoustic energy repartition to be produce. And iteratively, the next sonication corresponds to a fraction of the maximum remaining required energy at the next location defined by the controller. Independently to the value of the fraction, this algorithm converges to a spatial sonication repartition mainly located at the edge of the volume and, for an angular volume, predominantly at the corners.

Results and Discussion

Figures 1 and 2 present an example of PID control performed over a cubic volume of 7×7×12 mm³ of 147 voxels located in 3 slices of 4mm. The temperatures were regulated at each dynamic acquired every 2.4s with a target temperature increase of 10°C during 100s. Figure 1 describes a statistical analysis with a comparison of the minimum (blue), average (green) and maximal (orange) temperature increase of all 147 voxels under control. The average temperature corresponds precisely to the target temperature (red) with an accuracy of 1°C. The difference between the minimum and the maximum temperature is 4°C mainly because of noise measurements observed over such a larger number of voxels. Figure 2 illustrates this homogenous heating obtained inside the cubic volume with the central MR slice acquired at different time which corresponds to the middle (image a) and the end (image b) of the target temperature rise respectively. Despite overlap effect and thermal diffusion, the homogenous heating produced sharp edges and corners with a clearly visible square area at the predefined target temperature.

Figure 1: Minmum (blue), average (green) and maximum (orange) temperature measured for 147 voxels regulated with a target temperature increase of 10°C (red).

Figure 2: Thermal maps obtained during heating of an ex vivo pig muscle in order to obtain an homogenous heating over a cubic volume 7×7×12mm³. Maps of the central slice acquired in the middle and at the end of the target temperature rise are presented at time 55s (a) and 96s (b) respectively with a color scale ranging from 2°C to 10°C.

Perspectives and Conclusion

The 3D spatial and temporal temperature control offers the advantage to regulate the temperature in each point of any volume shape as it has been demonstrated for an angular cubic volume. Because the maximum detection algorithm takes overlap effect into account, it avoids over-shooting and minimizes the deposed energy. As a consequence, this heating procedure improves safety for thermal ablation. However this method is limited by the elongated shape of the focal point which precludes flat volumes. Also energy accumulation along the beam axis increases with the size of the volume. In addition, the 3D MR sequence required relatively long acquisition duration limiting the number of points under control per time unit.

References

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