MRI Guided Focused Ultrasound: Automatic spatial-and-temporal control of temperature evolution within a large treatment volume

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Objective. To design an automatic spatial-and-temporal controller for temperature evolution within an extended treatment volume during local hyperthermia by MRI guided focused ultrasound.

Introduction. Local hyperthermia is used for treatment of malignant tumors. Cell death can be achieved directly (i.e. thermo-ablation [1]) or indirectly (local drug delivery [2], gene therapy [3]). Focused ultrasound allows non-invasive deposition of a sharp thermal build-up deep inside the body. MRI appears an ideal tool for guiding focused ultrasound treatments [4]. MRI can provide real-time thermometry and allows automatic control of temperature evolution. Uniform treatment of a tissue volume large with respect to the focal spot size can be efficiently achieved by moving the focal point along an inside-out spiral trajectory [5,6].

Materials and Methods. Experiments were performed on a 1.5T Philips clinical MR-scanner (Intera) equipped with an MR compatible 14-ring spherical ultrasound transducer integrated in the bed of the MR system (Imasonic, Besancon, France, f = 1.5 MHz, D = 96 mm, R = 80 mm). The ultrasound probe can be hydraulically moved in the horizontal plane with a spatial resolution of 0.25 mm in each direction. The focal length can be electronically adjusted, between 60 to 110 mm. Maximum acoustical power is approximately 70W. Ex-vivo experiments were performed on inhomogeneous pieces of pig thigh including muscle, fat tissue and fascia. In-vivo experiments were performed on six white New Zealand female rabbits (weight 3-3.5 kg). Real-time PRF based MR-thermometry was performed using fast 3D or 2D-multislice gradient echo sequences with following parameters: a). 3D: FOV=128 x 128 x 60 mm, acquisition 128 x 78 x 12, reconstruction 128 x 128 x 12, TR = 50ms, TE = 15 ms, 13 k-space lines /TR, flip angle 20°, 3.6 sec per volume and b). 2D multi-slice : FOV=128 x 128 mm, 7 slices of 6 mm thickness, acquisition 128 x 90, reconstruction 128 x 128, TR = 80ms, TE = 18ms, 15 k-space lines /TR, flip angle 30°, 5.12 sec per volume. MR phase maps were on-line transferred to a PC-workstation, that was also running the software to control the FUS transducer. Elliptical regions of different size and eccentricity (10 to 20 mm diameter) were repeatedly covered with 5 to 10 successive inside-out spiral trajectories, calculated as in ref[5,6], see Figure 1. Sampling time was 1.6 sec per sonication. The objective was to reach a predefined temperature profile, proportional to the theoretical thermal build-up as it should be obtained in homogeneous tissue.
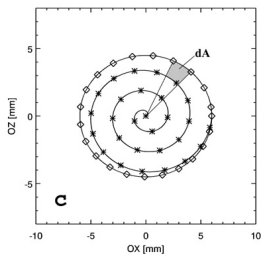

Fig 1. Elliptical spiral trajectory of the focal point (14 mm x 10 mm)
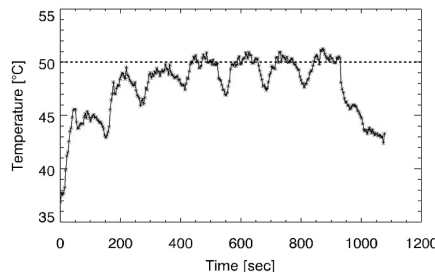

Fig 2. Time course of the absolute temperature at the center of a 11mm x 11mm circular ROI, in-vivo.
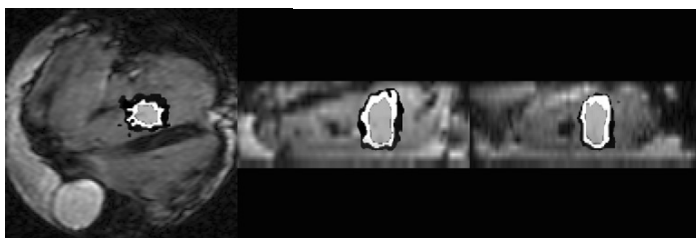

Fig 3. Temperature map in-vivo, same experiment as for Fig 2. FOV = 128 x 128 mm. Gray-scale temperature levels (41°C, 44°C, 47°C) are overlaid on magnitude gradient-echo images (3D acquisition)
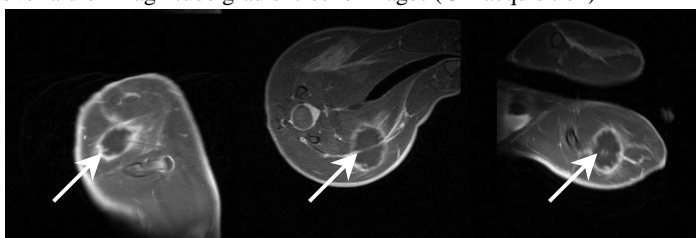

Fig 4. Gd uptake images (same experiment as for Fig 2 and 3, coronal, transverse, saggital planes), at 3 days post treatment. Arrows indicate the thermal lesion.

For each new passage, the temperature controller modifies the time course of the focal point displacement, based on MR thermometry data, in order to change the local deposition of thermal energy. Total time was proportional to the treated area, on the order of 10 min/cm^2.

Post-treatment MRI follow-up was performed at 3 and 10 days post-treatment (Gd-uptake images).

Results and Discussion. Standard deviation in temperature measurement was 1°C ex-vivo and 1.5°C in-vivo. Performance of the temperature controller showed good stability with respect to the experimental noise, both ex-vivo and in-vivo. The target temperature profile was reach after two to four passages and a periodic steady-state was further maintained. Figure 2 shows an example of temperature evolution at the centre of the trajectory in-vivo; targeted temperature value was 50°C. Seven successive spirals were performed, which can be identified on the temperature time course.

A good spatial uniformity of the temperature increase was obtained (less than 10% fluctuations within the target region, relative to the average temperature increase). Figure 3 shows a temperature map acquired during the treatment, for three orthogonal planes (coronal, transverse and saggital). Note the elongated shape of the thermal build-up, along the beam axis, perpendicularly to the spiral trajectory plane. Excellent agreement was obtained between the MR-thermometry data and the post-treatment MRI follow-up (Figure 4).

Conclusion. Coupling of focused ultrasound and MR thermometry, combined with a temperature regulation algorithm, can provide spatial and temporal control of the temperature within an elliptic ROI, which is much larger than the dimension of the focal region. Electronic displacement of the focal point using phase-array technology may further improve the precision of the control algorithm and reduce the treatment time.

References
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