Volumetric MRgHIFU Rapid Ablation: In vivo Demonstration of Non-Parametric Automatic Temperature Control

L. Petrusca[1], M. Viallon[1], T. Goget[1], D. Morel[2], V. Auboiroux[1], S. Terraz[1], C. Becker[1], and R. Salomir[1]
[1]Radiology Department, University Hospitals of Geneva, Geneva, Switzerland, [2]Anesthesiology, University Hospitals of Geneva, Geneva, Switzerland

Introduction. MRgHIFU has outstanding therapeutic potential for localized cancer under the condition that uniform 3D volumetric thermal ablation of oncologic quality is acceptable. Considering the case of liver malignancies, a total volume of 1 to 20 cc should to be treated in one session, whilst the individual volume of the focal zone is 100 to 1000 times smaller than that. Moreover, ablation margins of 5 to 8 mm are required to reduce the risk of local recurrence. The volumetric sonication (i.e. focal sweeping) technique is based on the displacement of the focus along a predefined trajectory while sonicating (near-) continuously (i.e. duty-cycle near to 100%) [1,2]. The natural heat diffusion of tissue is exploited to homogenize the thermal buildup. The temperature elevation at the borders of the heated region limits the cooling down of the central zone. A new automatic, non-parametric (i.e. tissue independent) temperature controller, using non-linear negative reaction, was designed and tested, both *ex vivo* and *in vivo,* for the delivery of an equivalent thermal dose at every sonicated point during volumetric MRgHIFU.

Methods. The present controller is based on a generic ("universal") algorithm and thus no input parameter is necessary. Experiments were performed using an MR compatible HIFU phased-array (256 elements, Imasonic, Besancon, FR), a multi-channel power-generator with on line power reading and a 2D piezoelectric positioning system (both from Image Guided Therapy, Pessac, FR). Firstly, *ex vivo* experiments were conducted on degassed porcine muscle, followed by *in vivo* investigations performed on 6 sheep thighs upon an IRB-approved protocol. Different sonication trajectories were executed by fast electronic switching of foci. In particular, line-scan and circular-scan trajectories were applied in the treatment plane (orthogonal to the HIFU beam). Different segment length and circle diameter were tested (8, 16 and 24 mm, respectively), adjusting the total duration of sonication proportionally to the pattern size. The acoustic energy at each focus was *a priori* time-compensated for the steering profile and further controlled by the closed feedback loop. High resolution PRFS MR thermometry was performed in 5 slices (sagittal and transverse, both aligned to the beam symmetry axis, plus 3 coronal with 10 mm gap; voxel size 1x1x5mm^3; temporal resolution 4s).

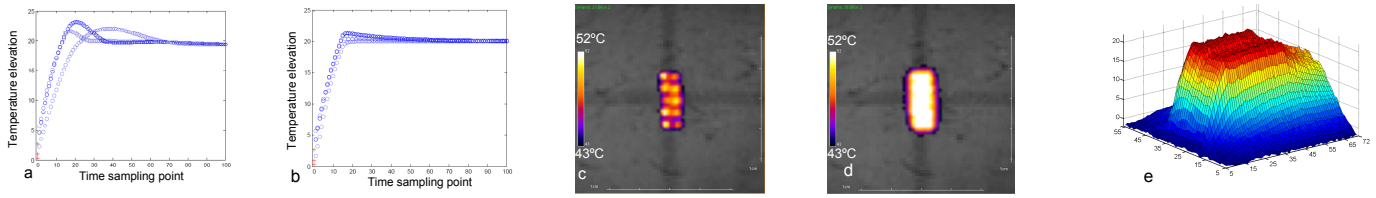

Fig 1. a),b) Numerical simulation of controller's convergence (target: 20ºC) in heterogeneous tissue using the PID algorithm and the actual convergence; **c),d)** ex-vivo evaluation of the new temperature controller for 10 sonicated foci (time point 8s and 60s) **e**) surface representation of a 1D central temperature profile crolled over time.

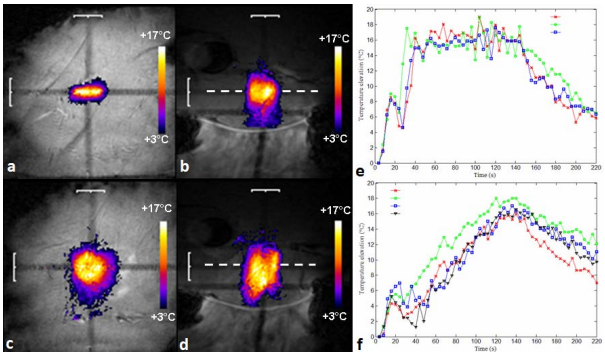

Figure 2. In vivo temperature maps in coronal (**a**,**c**) and axial (**b**,**d**) planes at the end of sonication process along a trajectory describing a line (**a**,**b**, 16 mm length), and a circle (**c**,**d**, 16 mm diameter). **e**,**f**: Temperature elevation of different foci, plotted versus time.

Results. The convergence capability of the implemented controller was numerically simulated and found to be suitable for fast volumetric MRgHIFU. The currently used algorithm requires 5 sampling points to recover the target, compared to 20 sampling points required by the past extensively used PID controller (Fig 1) [3,4]. The preliminary *ex vivo* evaluation of the temperature controller for volumetric MRgHIFU demonstrated a homogenous thermal build-up in the line-scan or double line-scan sonicated volume (Fig 1**c-e**). The temperature gradients at the margins of the heated zone gradually attenuated over time due to heat diffusion (Fig 1**d**). A steady state regime was reached at the sonication foci and their temperature accurately matched the pre-defined target (Fig 1**e**) within 3% fluctuation. Accurate feedback control was demonstrated for each volumetric sonication pattern tested *in vivo* in sheep thigh muscle. The thermal history of all foci was found to be systematically similar for line (Fig 2**e)** and circles (Fig 2**f)** trajectories. It consisted of an initial rising-temperature, followed by a steady-state regime once the prescribed temperature was reached (17°C here). Note that in the post sonication period the edges of the thermal build-up cool faster than the central region.

Discussion. A new temperature controller was developed and validated *in vivo* for MRgHIFU. Accurate control of the temperature of all foci situated in the HIFU trajectory was demonstrated for different volumetric sonication strategies. The power of convergence of the controller was sufficient for accurate performance without requiring *a priori* knowledge of tissue thermo-acoustic parameters. This feature simplifies the overall workflow of the treatment procedure as it avoids the need for the preliminary estimation/identification of parameters. The spatio-temporal control of the temperature in the focal plane enables meaningful comparison of different sonication patterns in terms of dosimetry and near field safety. Volumetric sonication along circular patterns produced longitudinally asymmetric heating and significant thermal drift towards near field; such effects were demonstrated to be dependent on the trajectory size and the ultrasound attenuation coefficient. Thus 2D patterns appear to be unsuitable for rapid volumetric HIFU ablation. 1D patterns are recommended as the best option for complex treatments, with uniform and drift-free thermal build up. Standardization of therapeutic procedure may be required to guarantee safe ablation.

References. 1. Salomir et al JMRI 2000; 2. Palussiere et al MRM 2003; 3. Salomir et al, Magn Res Med 2000; 4. Salomir et al Med Phys 2009