Preventing far-field bone-reflection of HIFU beam by selective elements de-activation is a sub-optimal approach

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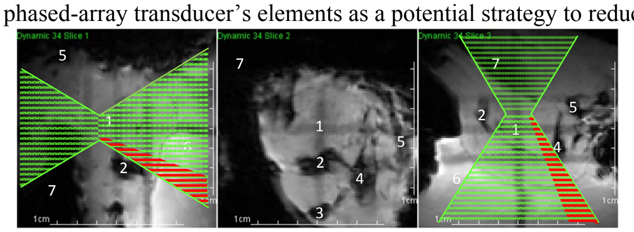
Introduction. MRgHIFU is a hybrid technology which aims to offer efficient and safe thermal ablation of targeted tumors or other pathological tissues, while preserving the normal surrounding structures unaltered. Theoretically MRgHIFU has no limitation on lesion size [1]. The main challenge is to avoid near and far field heating [2]. We demonstrate here that beam reflection on bones is a major problem whenever bone is situated in the proximity of the prescribed region for sonication, even laterally from the main beam axis. This study evaluates selective de-activation of phased-array transducer's elements as a potential strategy to reduce bone reflection.



a. sagittal slice b. coronal slice c. axial slice
1-muscle; 2-femur; 3-tibia; 4-pelvis; 5-vertebra; 6-water; 7-air

Fig. 1: Magnitude GRE-EPI MR images of the ex-vivo rabbit thigh. The incident HIFU beam cone is artificially visualized (green zone) and also the solid angle for elements de-activation (read zone).

Material and Methods. Heating was produced by MRgHIFU in *ex vivo* and *in vivo* rabbit thigh, using a randomized 256 element phased array transducer (Imasonic, Besançon, France) with natural focal length and aperture R = 130 mm and respectively D = 140 mm (f = 974 kHz). The HIFU platform uses a programmable 256 channels generator and a 2D positioning mechanism in XZ plane (both from Image Guided Therapy, Pessac, France). In house written software package was used for on line treatment planning, hardware control and automatic temperature control during volumetric sonication. Temperature elevation was monitored by MR thermometry (MRT) on a 3T whole body MRI scanner (Magnetom Trio @ Tim system, Siemens AG, Germany) using a GRE-EPI sequence with echo train length 9, TE = 8.9 ms , TR=161 ms, FA 15°, BW= 500Hz/pixel, 5 interleaved slices (1 sag, 1 trans, 3 coronal).

Two different configurations of the phased array were compared *ex vivo*: 1). full aperture (i.e. 256 channels) and 2). selectively de-activated elements upon 3D conical projection/shadow of the bones on the spherical surface of the transducer (approx. 15% of the total number of elements). The center of conical projection was the natural focal point position. Apart from the different shape of the active surface, identical experiments were carried on the same *ex vivo* rabbit thigh (30 min interval, +13°C elevation). In each case, a volumetric sonication trajectory consisting of 5 x 2 points (4 mm gap) was performed under automatic feedback control expected to guarantee the same thermal history for the 10 foci and for the two experiments. Selective de-activation of elements was also investigated *in vivo* (+18°C elevation). Contrast agent enhanced MR images were obtained one week after ablation to evaluate the extent of the necrotic lesion, using a T1-weighted 3D fat saturated gradient-echo sequence (VIBE) with following parameters: TE/TR/TA/FA/BW = 1.6 ms, 4 ms, 2.55 min, 10°, 650 Hz and spatial resolution of $0.8 \times 0.8 \times 0.8$ mm^3.

Results. Magnitude images with overlaid PRFS color-coded temperature maps are displayed in Fig.2 (left mosaic) for both strategies *ex vivo*: full set (Fig2.a) and selected sub-set (Fig2.b) of transducer's elements. Significant reflection of the HIFU beam is observed at the bones surface in both cases. Correlation plots are shown in Figure 2 (right mosaic) for the two transducer's configurations. Heating in the target region (red markers) is very similar and the plots closely follow the diagonal direction (within the noise error bar) whatever the transducer's configuration or the imaging plane. This result is due to the automatic tracking of temperature in the target region. Heating at the bones surface (blue markers) is reduced by 20 to 25% with the second strategy. This partial improvement is more clearly visible in the transverse plane (Fig.2 left mosaic 3rd column).

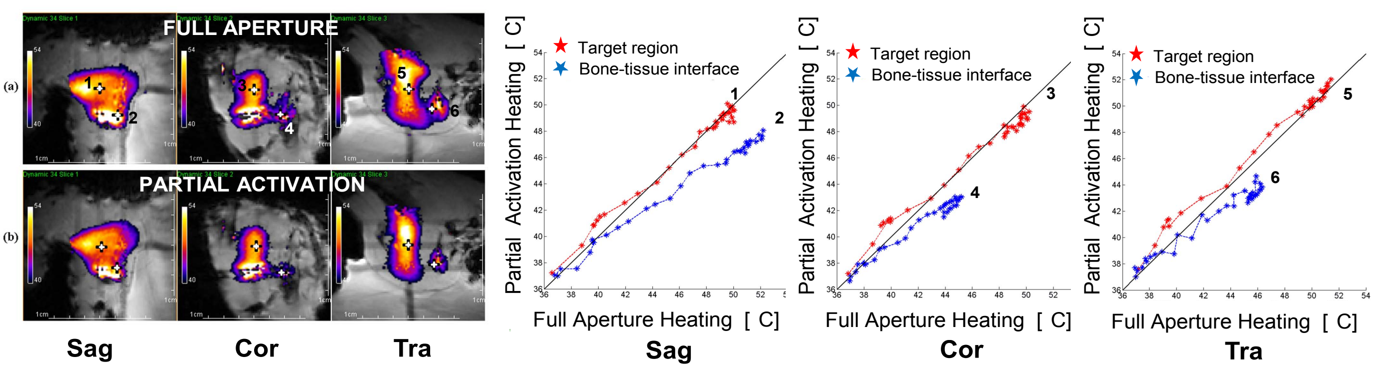


*Fig.2 Left mosaic. Magnitude images with overlaid PRFS color-coded temperature maps for the two heating strategies: (a) full aperture versus (b) partial activation of elements. Correlation plots (right mosaic) comparing the thermal history for the two strategies are provided for the center of the target region (red * legend 1,3,5) and for the tissue layer in front of the femur and pelvis bones (blue * legend 2,4,6), see cross markers on left mosaic.*

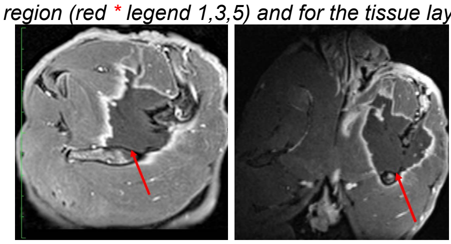


Fig.3: In vivo Gd-T1w 3D GRE MR image, rabbit thigh, coronal and sagittal slices (FOV = 128 mm). The large hypo-intense area with hyper-intense border (HIFU-ablated volume) extends largely towards the bone-muscle interface (red arrow).

Discussion. The lesion was well centered in rabbit thigh and no thermal shift did occur towards the near transducer field i.e. no skin burn. Our results evidenced beam reflection and unwanted thermal damage at the bone to tissue interface, despite selective de-activation of elements upon the conical projection algorithm. Bone structures were situated at 15 to 25 mm laterally from the main beam axis, not along it. The latter strategy improves the results but remains largely insufficient. This evidence is explained by the divergent radiation diagram (i.e. diffraction) of each individual element of transducer. Here d/λ=4.2 hence ± 9 trigonometric degrees emission cone or ±19 mm elementary beam spread in the focal plane at 130 mm distance from transducer. The geometrical projection is inappropriate in case of structures distant from the emitting surface. This major safety problem needs to be addressed when performing HIFU ablation. Whereas creating large and uniform lesions in short time is required for effective MRgHIFU treatments, further strategies must be investigated to protect tissues adjacent to bones or air-filled bowel.

References. (1) Jolesz FA. Annu Rev Med 2009. (2) Kopelman et al. Annals of Surg Oncol 2007