

MR-guided acoustic shielding of the ribs for trans-costal MRgHIFU ablation in liver

Magalie Viallon¹, Lorena Petrusca², Vincent Auboiroux², Denis Morel³, Arnaud Mueller⁴, Maria I. Vargas¹, Thomas Goget², Sylvain Terraz¹, Christoph D. Becker¹, and Rares Salomir⁵

¹Radiology Department, Geneva University Hospital, Geneva, Switzerland, ²Radiology Department, University of Geneva, ³Anesthesiology Department, University of Geneva, ⁴Radiology Department, HCL, CHU Lyon Sud, Lyon, France, ⁵Radiology Department, INSERM Rhone-Alpes, University of Geneva

Introduction. One of the main challenge for the HIFU therapy in liver is to prevent (or to avoid) the known high risk of collateral heating and thermal damage in the ribs and ribs-surrounding tissue. Ribs' heating during liver MRgHIFU was a major obstacle for the translation of this technology into a clinical tool (1), whereas the size of the population potentially concerned by such a treatment is very large. Different attempts for solving the problem of ribs heating, that is, avoiding unwanted pre-focal energy deposition inside or around acoustic obstacles in the pathway of the HIFU beam - have been presented in the past: synthesizing of a multiple-focus ultrasound heating patterns through the human rib cage (2), design of a linearly segmented transducer that comprised elements arranged in strips and selective de-activation of edge elements (3), selective de-activation of elements from a 2D phased-array upon the ribs shadow (conical projection), (4) adaptive focusing using the technology of multi-element transducers devices able to work both in transmit and receive modes (5) and finally, partial ribs resection (6). This study investigates a new alternative to solve the problem of ribs heating, using dedicated MR-guided positioning of specific reflective strips for acoustic masking of the ribs.

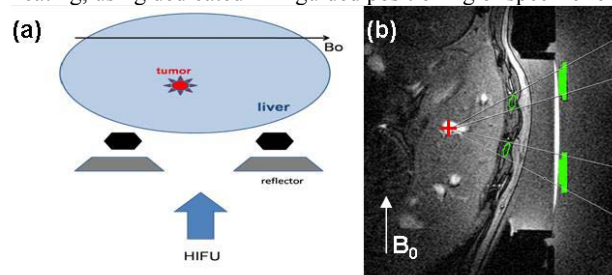


Fig1. (a) Principle of positioning the reflective strips (grey parallelograms) in front of the ribs (black diamonds). (b) Reflectors (overlaid in green) appear hypointense, as well as ribs, in T2*-w GRE. Green contours are also drawn around the ribs. The natural focal point is materialized with a red cross (+) in the MR images.

-mented GRE-EPI sequence with echo train length=11, TE = 8.9 ms, TR=161 ms, FA 15°, BW= 500Hz/pixel, 3 interleaved slices (1 sagittal, 1 transverse, 1 coronal). The effectiveness of the reflecting material was investigated by Schlieren interferometer imaging. Proof of principle was first made in an ex-vivo phantom. Ex-vivo liver tissue was added on a fragment of ex-vivo thoracic cage from sheep, see Figure 3(a-c). The ribs protectors were aligned in front of the thoracic cage using a specific MR guided procedure. In order to evaluate the effectiveness of the protection, each ex-vivo specimen was sonicated twice, allowing 30 minute cooling interval between sonications, with and, respectively, without the protectors. Verification of this protection strategy was then performed post-mortem on a sacrificed animal (immediately after sacrifice), that animal being used for an independent MR study. Finally in-vivo studies were conducted under general anesthesia and sonications were performed under mechanical breath holding in two sheep. Thermal contrast between ribs and focal point was calculated in each case. Post-ablation, the animal was awakened and followed up for 7 days. At day 7, Gd-uptake T1-w imaging was performed and afterwards the animals were sacrificed and digital pictures of the liver and surrounding organs were obtained during the necropsy.

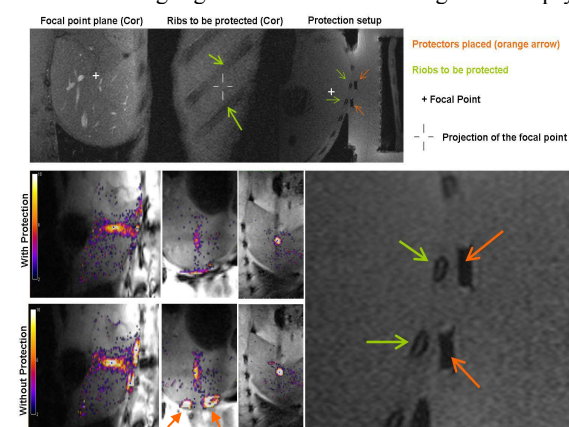


Fig2. Post-mortem results. Magnitude images and overlaid PRFS temperature maps are shown at the end-point of the HIFU sonication. Ribs shielding efficacy is demonstrated with real time MRT in two independent sonications: with (up) and without the protectors (down). Ribs are indicated with green arrows and protectors with orange arrows.

decreases the effectiveness of any ribs sparing method. The current approach for ribs protection is not considered alone as sufficient for volumetric ablation, but permitted safe trans-costal hepatic ablation of small ROI (up to half centimeter size), in single focus sonication mode.

References (1) Jung et coll Abdom. Imaging 2011 (1) Botros, Volakis et coll. IEEE Trans Biomed Eng 1997. (2) Civale, Clarke et coll. Ultrasound Med Biol 2006. (3) Quesson, Merle et coll Med. Phys. 2010 (4) Ballard, Casper et coll IEEE Trans Biomed Eng 2010. (4) Tanter, Pernot et coll. Int J Hyperthermia 2007. (5) Zhu, Zhou et coll. Eur J Radiol 2009.

Material and Methods. The coupling medium between a HIFU transducer and the sonicated tissue is a liquid or a gel that is directly visible in MRI. A physical mask can be inserted in the beam pathway, pre-focal and external to the body, such as to block a fraction of acoustic energy otherwise directed into the ribs (Figure 1). The reflective material used in this study is made of polystyrene foam, that is low cost, readily available, MR-compatible and easily shapeable. The alignment of the protectors with the animal ribs was made in multiple steps under MR control using the graphic slice positioning of the MR scanner, 2D T2*-w images in appropriate planes and 3D high resolution MRI. Heating was produced using a randomized 256 element phased array transducer with natural focal length and aperture $R = 130$ mm and respectively $D = 140$ mm ($f = 1031$ kHz). The HIFU platform uses a programmable 256 channels generator and a 2D positioning mechanism in XZ plane. In house written software package was used for on line treatment planning, hardware control and on line temperature display during sonication. Temperature elevation was monitored by MR thermometry (MRT) on a 3T whole body MRI scanner using segmented GRE-EPI sequence with echo train length=11, TE = 8.9 ms, TR=161 ms, FA 15°, BW= 500Hz/pixel, 3 interleaved slices (1 sagittal, 1 transverse, 1 coronal). The effectiveness of the reflecting material was investigated by Schlieren interferometer imaging. Proof of principle was first made in an ex-vivo phantom. Ex-vivo liver tissue was added on a fragment of ex-vivo thoracic cage from sheep, see Figure 3(a-c). The ribs protectors were aligned in front of the thoracic cage using a specific MR guided procedure. In order to evaluate the effectiveness of the protection, each ex-vivo specimen was sonicated twice, allowing 30 minute cooling interval between sonications, with and, respectively, without the protectors. Verification of this protection strategy was then performed post-mortem on a sacrificed animal (immediately after sacrifice), that animal being used for an independent MR study. Finally in-vivo studies were conducted under general anesthesia and sonications were performed under mechanical breath holding in two sheep. Thermal contrast between ribs and focal point was calculated in each case. Post-ablation, the animal was awakened and followed up for 7 days. At day 7, Gd-uptake T1-w imaging was performed and afterwards the animals were sacrificed and digital pictures of the liver and surrounding organs were obtained during the necropsy.

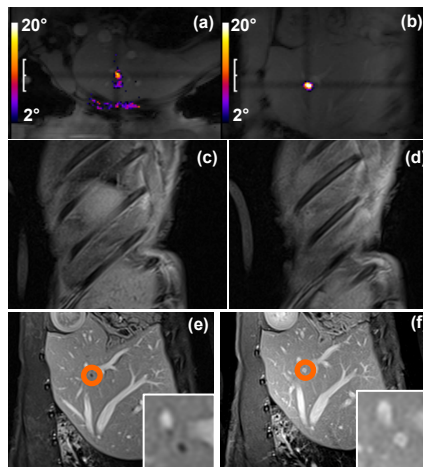


Fig3. In vivo results. (a-b) End sonication PRFS MRT maps obtained with the proposed ribs protection. (c-f) 3D Gd-uptake at D7 (early and late stages), showing no skins or burn, nor fibrotic attachment as confirmed by necropsy (fig3).

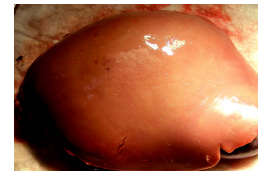


Fig 3. Post-mortem liver from Fig 2. Its surface is free of thermal lesion.

Results. Schlieren imaging of the HIFU beam scattering on the reflectors indicated no measurable acoustic intensity behind the strips. MR-guided positioning of dedicated reflective strips to protect the ribs during trans-costal HIFU liver ablation provided a fourfold reduction of the maximum temperature elevation at ribs surface and a reduction by a factor of 100 to 1000 of the peri-costal volume ending above the lethal dose threshold. Restricting the beam entry window leads to more elongated focal spot shape, hence more energy deposition in the inter-costal beam pathway.

Discussion. Volumetric sonication inherently decreases the thermal contrast foci versus near field and proportionally