

Hybrid magnetic resonance and ultrasound (MR-US) imaging as a novel method of High Intensity Focused Ultrasound treatment guidance and monitoring

Victoria Bull¹, John Civalè¹, Ian Rivens¹, David J Collins², Gail ter Haar¹, and Martin O Leach²

¹Department of Radiotherapy and Imaging, Institute of Cancer Research and Royal Marsden NHS Foundation Trust, Sutton, Surrey, United Kingdom, ²CR-UK and EPSRC Cancer Imaging Centre, Institute of Cancer Research and Royal Marsden NHS Foundation Trust, Sutton, Surrey, United Kingdom

Introduction

A considerable amount of information is required for the planning and delivery of High Intensity Focused Ultrasound (HIFU) treatments. The main steps required are identification of the target region, monitoring of ultrasonic energy delivery, and visual and quantitative assessment of tissue changes. A hybrid MR-US imaging system has been used to explore the synergistic advantage of the combination of these modalities in this application. Although MR guidance is considered the gold standard for image quality, the relatively high frame rate, dynamic flow information available from Doppler ultrasound, and the ability to detect acoustic cavitation activity through B-mode imaging provide the potential for considerable enhancement of guidance and monitoring of HIFU. Acoustic cavitation is a known safety issue resulting from ultrasound exposure which is not commonly considered during MR-guided HIFU delivery. Data are presented from experiments in a cryogel phantom, a flow phantom and ex-vivo bovine liver. These demonstrate the potential of the system to improve on what is currently available in the clinic, and indicate that translation to in-vivo and eventually clinical applications is possible.

Methods

Simultaneous MR and US image acquisition was achieved using a curvilinear 1-4 MHz clinical diagnostic ultrasound imaging probe with a custom 8-metre cable, mounted inside the bore of a 1.5 T clinical MR scanner, and covered with aluminium foil to minimise the introduction of RF noise. After mounting the US imaging probe head vertically from the MRI head coil into a bath of filtered, degassed water, registration of the ultrasound imaging plane with a known transverse MR image plane was achieved using nylon wires. Cylindrical samples (4.5 cm diameter, 4.5 cm length) of gel (10% PVA cryogel doped with 0.4 mMol gadolinium) or liver tissue were then imaged in transverse cross section, as shown in fig.1. Segmented EPI, T₁ and T₂ weighted and EPI diffusion weighted images were used alongside B-mode and Doppler ultrasound to assess the effects of either modality on the other. Samples were exposed to HIFU (gel: I_{SPTA}=1100 W/cm², p=5 MPa for 5 s; tissue: I_{SPTA}=860 or 1630 W/cm², p=2.3 or 6.5 MPa, 20 or 5 s, respectively) during simultaneous acquisition of RF US data and PRF-based MR thermometry using the seg-EPI sequence. Prior measurements of the proton resonance frequency coefficient and apparent strain vs. bulk temperature were made in the cryogel to give quantitative thermometry through post-processing, thus allowing a comparison of the two methods. A flow phantom, consisting of tubing (Masterflex 06409-25, 4.5 mm inner diameter) in a water bath, was constructed. Hybrid imaging of blood mimic flow along the tube demonstrated the ability to obtain high resolution time-of-flight (TOF) angiographs with simultaneous real-time Doppler flow measurements acquired at 40 Hz.

Results

Susceptibility artefacts from the US probe were minimised by using a probe-sample distance of at least 4 cm. No significant RF noise was observed in MR images due to any US acquisition modes. Maps of the apparent diffusion coefficient suffered from geometric distortion due to the presence of the US imaging probe, with the circular cross section of the sample becoming an ellipse of eccentricity 0.5. Clutter was observed in colour Doppler (CD) images during MR excitation, however this did not influence flow measurements. Using a measured PRF coefficient of -0.012 ± 0.001 ppm/°C and change in apparent strain of $0.16 \pm 0.02\%/^{\circ}\text{C}$ in

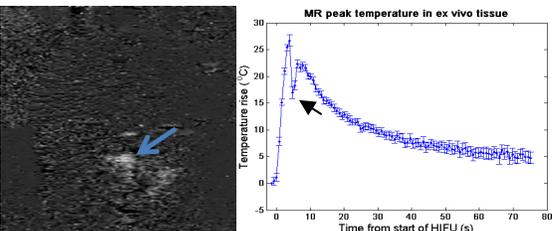


Fig. 3: B-mode subtraction image with bright region indicating cavitation (left) and corresponding temperature fluctuation in MR thermometry (right).

T₁ due to coagulation, demonstrating the ability to detect small (3x3 mm in-plane for a 5 mm slice) tissue changes. Simultaneous TOF and CD imaging allowed retrospective registration of dynamic flow information with high resolution MR angiograms (fig.4), thus indicating the possibility of studying flow velocity and pulsatility during MR imaging.

Discussion/Conclusions

Simultaneous MR and ultrasound data acquisition has been achieved, with co-aligned transverse imaging planes. Through effective shielding and sufficient separation of the US probe from the region of interest, neither MR nor ultrasound image quality was degraded by the introduction of noise or susceptibility artefacts. This system allows comparative studies of quantitative imaging techniques such as thermometry, and adds useful real-time information to MR studies relating to the guidance of HIFU treatments. Two cases have been demonstrated in which ultrasound data has provided additional important information to MR HIFU guidance. The first is the detection of cavitation activity, which has clearly affected the MR temperature profile. The second is the visualisation of blood flow in real time whilst acquiring MRA data. This would allow assessment of cooling effects due to blood flow, and would aid treatments involving vascular occlusion, where it is necessary to target vessels specifically. Further studies are required to quantify the limits of the hybrid imaging system in terms of accuracy and sensitivity, and translate these techniques into the clinic.

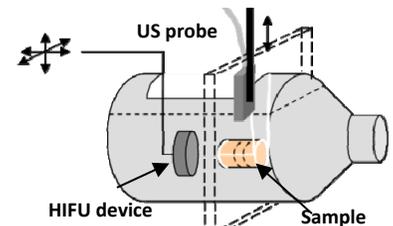


Fig. 1: Schematic showing position of HIFU transducer, US probe and MR slice (dashed lines). Water level shown by dotted line.

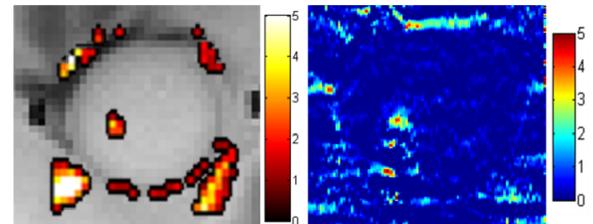


Fig. 2: Peak temperature rise (°C) measured simultaneously in cryogel by MR (left) and US (right) thermometry. Comparison of data taken during the cooling phases of HIFU exposure of multiple samples shows good correlation between temperature changes measured with both modalities ($R^2=0.895, 0.899$ and 0.952 for three samples).

At $p=6.5$ MPa in tissue, cavitation was observed in B-mode data, which corresponded with fluctuations in the temperature rises detected with MR (fig.3). T₁ mapping of tissue samples exposed for 20 s ($p=2.3$ MPa) indicated a 60 ms decrease in

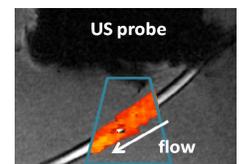


Fig. 4: TOF angiograph with CD overlay (colour window in green) giving real time dynamic flow information.