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A Magnetic Resonance Compatible E4D Ultrasound Probe for Motion Management of Radiation Therapy

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Abstract

We developed a magnetic resonance compatible real-time, three-dimensional imaging ultrasound probe for motion management of radiation therapy for liver cancer. The probe contains an 18,000-element, 46.8 mm $\times$ 21.5 mm matrix array constructed from three tiled transducer modules with integrated beamforming ASICs. The center frequency and -6 dB fractional bandwidth of the probe was 3.6 MHz and 85 percent respectively. Ferromagnetic materials in the acoustic stack, flex interconnect and electronics boards were greatly minimized for magnetic resonance compatibility. The probe and cable were shielded to minimize the impact of radiofrequency noise on both the ultrasound and magnetic resonance images. The probe's low-profile, side-viewing design allows it to be strapped to a patient so that images may be acquired hands-free. We present simultaneously acquired ultrasound and 3 Tesla magnetic resonance images with minimal artifacts in both images.

Keywords

E4D; matrix array; 2D array; real-time three-dimensional; magnetic resonance; MR; radiation therapy

I. Introduction

The objective of radiotherapy treatment of cancer is to cure or locally control the disease while minimizing complications to the surrounding healthy tissue. The complex radiotherapy treatment process introduces geometrical uncertainties that are managed by adding margins around the gross tumor volume during treatment planning. These margins include the clinical target volume and the planning target volume which account for tumor delineation uncertainty and positional variations, respectively. For example, liver tumors can move more than 30 mm due to respiration [1], [2], representing a substantial volume of healthy tissue at risk of collateral damage from radiation effects. The ability to manage motion and reduce margins around the tumor permits escalation of dose or improved dose conformity, leading to improved control of cancer or reduced toxicity to surrounding healthy

tissue and better patient outcomes. Proposed methods for motion management include forced shallow breathing, abdominal compression [3], [4] breath-holds [5], [6], and respiratory gating [7], though quality assurance challenges associated with these techniques have been documented [8]. Other methods for tumor tracking involve implantation of fiducial markers [9], but many of these methods are not well tolerated in sick patients.

In the last decade, systems integrating imaging and therapy have been developed, with the imaging system used to improve accuracy of radiotherapy treatments by confirming the radiation beam placement at the time of treatment [10], [11]. Magnetic resonance (MR) imaging systems produce excellent soft tissue image quality and have been integrated with linear accelerators (LINAC) [12], however, the integrated systems are expensive and the magnetic field deflects charged particles that can impact the outcome of the radiotherapy treatment [13]. Although ultrasound (US) has shown promise to manage real-time motion during radiotherapy, the static or robotic arms used to position imaging transducers [14] in the LINAC environment are awkward and may compromise treatment effectiveness.

The goal of this research is to develop a MR-compatible, hands-free, electronic real-time three-dimensional (E4D) US imaging probe. The probe will be used in a multi-modality imaging system which combines the real-time volumetric imaging capabilities of an E4D US probe with the excellent soft tissue contrast and spatial resolution of MRI for non-invasive motion management of radiation therapy.

II. Methods

A. Motion Management System Concept

Our motion management process consists of two stages, with initial work focused on radiotherapy for liver cancers. First, pre-treatment calibration images consisting of simultaneous 4D US and MRI are acquired. Offline, respiratory states corresponding to the patient's respiratory motion are determined using fiducials in the immediate vicinity of the tumor target identified in the 4D US images. MRI images corresponding to the 4D US images at each time point are then resorted according to the patient's different respiratory states. Second, during radiation treatment, the E4D US probe and system images tumor target motion, including the fiducial markers around the tumor target. US image analysis processing algorithms rapidly determine fiducial marker displacement (i.e., the respiratory states) and match the marker displacements to the pre-treatment US images. Once the respiratory state match is found, the corresponding pre-treatment MR images that are indicative of that respiratory state are displayed, allowing high resolution and contrast visualization of the tumor target motion to help guide the radiation therapy procedure. Hence, MR image guidance during radiation therapy can be realized without the need for costly combined MR-LINAC systems. The system is illustrated in Fig. 1.

B. Probe Mechanical Design

Special design requirements are imposed on the E4D probe due to its intended use in both MR and LINAC environments. Clearly, the probe should perform with minimal interference both from, and to the MR and LINAC systems. These requirements are discussed in a

subsequent section. In addition, the limited space available between the patient and inside wall of the MR bore necessitates a low-profile form factor for the probe. Further, the probe must be able to be fixed to the patient so that hands-free images of the liver can be obtained, avoiding subjecting a sonographer to radiation dose during the therapy stage. A design meeting these criteria is shown in Fig. 2.

C. Transducer Array

A matrix array transducer containing 18,000 elements with an active aperture of $46.8 \text{ mm} \times 21.5 \text{ mm}$ was designed for the liver imaging application. For the probe to operate on the 192-channel GE Vivid E95 US system, signal count reduction was achieved by processing subsets of elements with the internal beamforming ASIC. An FPGA board inside the probe communicates with the US system and configures the internal beamforming ASIC. The acoustic stack consists of an interface layer, a single crystal PMN-PT piezoelectric layer, a filled graphite inner matching layer and a polymeric outer matching layer.

For improved fabrication yield, the active aperture was composed of three identical modules which were tiled side by side to form the full aperture. The modules were designed to allow the elements to remain on a consistent pitch even across module boundaries. An illustration of the probe and the internal components is shown in Fig. 3.

D. MR & LINAC Compatibility

For MR compatibility of the probe, there are two main criteria that need to be satisfied: (1) The probe should not contain a significant amount of ferromagnetic materials, and (2) The probe and cable should be thoroughly shielded from RF emissions both to and from the MRI system. To evaluate probe materials for MR compatibility, components were individually tested inside the GE MR750 (3 Tesla) MR system, and the amount of distortion in the B_0 field was quantified. For materials with significant B_0 distortion, suitable lower susceptibility replacements were sought. Table I contains a summary of probe materials which were specifically chosen for MR compatibility, and Fig. 4 shows MR susceptibility test images for the interface layer in the acoustic stack.

To gauge the level of electromagnetic interference (EMI) shielding required of the probe and cable, an existing E4D probe was tested in the GE MR750 with different shield configurations. It was observed that the optimal shielding configuration enclosed the entire US probe and cable as an extension of the MR room shield. Fig. 5 shows a 3D printed aluminum EMI shield which enclosed the probe except for the active acoustic aperture, which was shielded with a 0.012 mm thick aluminum foil. The thin foil had negligible impact on acoustic performance. The probe shield was continuous with aluminized polyester and copper braid shields surrounding the cable.

To test LINAC compatibility, probe components including the beamforming ASIC, FPGA board, and single crystal piezoelectric transducer were subjected to a radiation dose of 25 Gy (equivalent to 50 patients), with intermittent testing. No change in performance was observed for any component.

E. Ultrasound System Integration and Placement

The probe was integrated with a standard 192-channel GE Vivid E95 US system. To avoid the requirement that the US system also be MR compatible, the system was placed in an adjacent control room and the probe was connected via an 8.5 m cable that passed through an opening in the wall of the MR room shield as illustrated in Fig 6. The probe cable shield was coupled to the MR room shield as it passed through the wall. In imaging performance comparisons between a standard 2.5 m length probe cable and a 8.5 m length probe cable, we noted no significant imaging performance degradation from the extended cable length. This was because the low-noise amplifier (LNA) incorporated into the beamforming ASIC inside the probe handle drove the extended length cable without a significant degradation in noise figure. Fig. 7 shows a 4.0 MHz, 12 cm deep tri-plane image of the CIRS 040GSE tissue-mimicking phantom. With these imaging parameters, imaging rate was 4 tri-planes/sec.

III. Results

A. Pulse-Echo Impulse Response and Spectrum

Fig. 8. shows the average pulse-echo impulse response and frequency spectrum for the three modules in the probe as measured in a water tank.

B. Simultaneous Ultrasound & MR Images

The probe was image tested in a GE MR750 MR system. Fig. 9 shows simultaneous US and MR images of the CIRS 040GSE tissue mimicking phantom, which provided contrast in both imaging modalities though the intensity of the contrast targets is inverted. The US imaging frequency was 3.5 MHz, and the image depth was 12 cm. The MR image was obtained with a fast gradient echo sequence (FGRE) (Matrix = 256×256 , FOV=24cm, Thickness=7mm, Flip=60, TR=30ms, TE=3.3ms, NEX=4, BW=31kHz). By greatly reducing the ferromagnetic content of the probe, signal dropout in the MR image was limited to the first 1-2 cm beneath the probe surface. No additional MR image artifacts due to the electronic operation of the E4D probe were observed. With the probe positioned near isocenter of the MR system, negligible artifact was observed in the US image. As the probe position neared the MR bore wall, a “streak” artifact could be observed near the bottom of the US image, which was found to be due to electronic interference from the MR system’s RF transmit and was dependent on the amplitude and duty cycle of the MR transmit pulse. US image artifacts due to the MR system’s gradient switching were not observed. Through our testing, there were no MR imaging sequences that caused the E4D US probe to cease functioning.

IV. Conclusion

We have described the design, fabrication, characterization and testing of an 18,000 element, low-profile, hands-free, MR compatible E4D US probe. Special design considerations were taken to minimize the ferromagnetic material content of the probe and to minimize radiofrequency interference through prudent EMI shielding practices. In simultaneous US and MR image testing, minimal artifacts were seen in both US and MR images. The probe

will initially be used in a multi-modality imaging system which combines the real-time volumetric imaging capabilities of an E4D US probe with the soft tissue image quality of MRI for non-invasive motion management of radiation therapy. The unique capabilities of the probe may also be useful in other image guided procedures such as proton therapy, brachytherapy, biopsies, surgery and drug delivery.

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Fig 1.

Motion management system concept. (1) A pre-treatment MR + US image data set is acquired and linked to the patient's respiratory state. (2) While the patient is in the LINAC during therapy, the E4D probe and US system image the tumor motion. (3) Real-time US images are rapidly matched to a pre-treatment volumetric US + MR data set where tumor targets have been marked on the MR images. (4) When the tumor target is aligned with the LINAC beam, the beam is activated.

Fig. 2.

Low-profile, hands-free probe design. (A) The probe has a side-viewing configuration with overall dimensions of $116 \text{ mm} \times 65 \text{ mm} \times 36 \text{ mm}$. (B) An attachment to the back of the probe contains loops allowing an elastic strap with hook and loop fasteners to secure the probe to the patient. The attachment also allows the probe to rotate to any desired orientation while the strap remains stationary.

Fig. 3. Illustration of the probe internals. The active aperture is composed of three transducer modules which are connected via a multi-layer flex interconnect to the FPGA board. Two system channel boards interconnect 192 system channels to the transducer modules.

Fig. 4. MR compatibility test images. (A) Unmodified acoustic stack interface layer material with 10% ferromagnetic material content, resulting in signal loss in a hemispherical region ~ 4 cm deep. (B) MR-compatible interface layer material with <0.2% ferromagnetic material content showing greatly reduced artifact.

Fig. 5. Probe EMI shield. (A) Aluminum EMI shield enclosure for the probe. (B) 0.012 mm thick aluminum foil shield covering the active acoustic aperture.

Fig. 6.

US system placement. A GE Vivid E95 US system was located in the control room adjacent to the MR room. The probe was connected to the US system via a 8.5 m probe cable. The probe cable's shield was coupled to the MR room shield as it passed through the wall.

Fig. 7.

Tri-plane image of the CIRS 040GSE tissue mimicking phantom. Imaging frequency = 4.0 MHz, Image depth = 12 cm. The four anechoic cylinders along the vertical mid line in the upper left image have stepped diameters which are seen as lengthwise cross-sections in the lower left image.

Fig. 8. Average pulse-echo impulse response and frequency spectrum for the three modules. (A) Impulse response. The -20 dB pulse length was 1.10 microseconds. (B) Spectrum with center frequency of 3.6 MHz and -6 dB fractional bandwidth of 85%.

Fig. 9. Simultaneous US and MR imaging, with the probe near isocenter of the MR system. (A) 12 cm deep, 3.5 MHz 2D ultrasound image of the CIRS 040GSE tissue mimicking phantom. (B) Fast gradient echo MR image of the same phantom. The red box indicates the region simultaneously imaged with ultrasound.

TABLE I**ULTRASOUND PROBE COMPONENTS CUSTOMIZED FOR MR COMPATIBILITY**

Component	Changes for MR Compatibility
Interface Layer	Ferromagnetic content reduced from 10% to <0.2%
Outer Matching Layer	Elimination of Ni in ground metallization
Acoustic Backing	Replaced with non-magnetic filled Al foam
Flex Interconnect	Non-magnetic passive components, connectors
FPGA Board	Non-magnetic passive components, connectors
System Channel Board	Non-magnetic connectors, direct solder coax
Mechanical Fasteners	Non-magnetic brass screws utilized