Published in final edited form as:

Magn Reson Med. 2013 January ; 69(1): 295–302. doi:10.1002/mrm.24247.

An 11-Channel Radio Frequency Phased Array Coil for Magnetic Resonance Guided High Intensity Focused Ultrasound of the Breast

E. Minalga¹, A. Payne¹, R. Merrill¹, N. Todd¹, S. Vijayakumar¹, E. Kholmovski¹, D. L. Parker¹, and J. R. Hadley¹

¹Department of Radiology, UCAIR, Salt Lake City, UT, USA

Abstract

In this study, a radio-frequency (RF) phased array coil was built to image the breast in conjunction with a Magnetic Resonance guided High Intensity Focused Ultrasound (MRgHIFU) device designed specifically to treat the breast in a treatment cylinder with reduced water volume. The MRgHIFU breast coil was comprised of a 10-channel phased array coil placed around an MRgHIFU treatment cylinder where nearest-neighbor decoupling was achieved with capacitive decoupling in a shared leg. In addition a single loop coil was placed at the chest wall making a total of 11-channels. The RF coil array design presented in this work was chosen based on ease of implementation, increased visualization into the treatment cylinder, image reconstruction speed, temporal resolution, and resulting signal-to-noise-ratio (SNR) profiles. This work presents a dedicated 11-channel coil for imaging of the breast tissue in the MRgHIFU setup without obstruction of the ultrasound beam and, specifically, compares its performance in SNR, overall imaging time, and temperature measurement accuracy to that of the standard single chest-loop coil typically used in breast MRgHIFU.

Keywords

RF coil design; phased array; breast cancer; magnetic resonance guided high intensity focused ultrasound

INTRODUCTION

The treatment of early stage breast cancer has evolved from radical mastectomy toward targeted local therapy with breast conserving therapy and most recently extending to partial breast irradiation. The cumulative incidence of a tumor recurrence in the ipsilateral breast 20 years after surgery was 14.3% among the women who underwent irradiation after lumpectomy and 39.2% among those who underwent lumpectomy without irradiation (1,2). An alternative treatment is Magnetic Resonance guided High Intensity Focused Ultrasound (MRgHIFU) (3). MRgHIFU uses focused ultrasound to heat and kill cancerous tumor tissue. This is done completely non-invasively, without any incisions, which reduces the pain and duration of recovery.

The challenge of MRgHIFU is to heat only the cancerous tissue and leave the healthy tissue intact. MRI can help in this process because breast cancer can be well visualized using MRI (4) and MRI can also be used to measure temperature changes in glandular tissue during

treatment (5–9). MRI can, therefore, be used for monitoring the cancerous and healthy tissue during treatment, thus, increasing the efficacy and safety of the procedure. To obtain accurate temperature maps and tissue characterization, specialized MR radio frequency (RF) coils are needed.

The purpose of this work was to design and construct a MRI RF coil array to operate in conjunction with a breast specific MRgHIFU system. The MRgHIFU system was designed to allow maximum space for the RF coil array and for the array to be placed as close as possible to the breast while simultaneously enabling HIFU treatment in the largest possible volume of the breast. Our design minimized the treatment cylinder water volume, which brought the coils and therefore the higher coil sensitivity in close proximity to the breast tissue. The MRgHIFU breast coil array was designed to take the best advantage of the space provided, and experiments were performed to assess the improvement in performance relative to the current standard breast RF coil used in MRgHIFU treatments, a single loop at the chest wall. The specific goal of this work was to increase signal sensitivity in the breast for improved temperature measurement accuracy, tumor visualization, and tissue characterization for MRgHIFU.

Generally, the RF coil design used for breast MRgHIFU is a single coil around the breast, positioned at the chest wall (10). The benefits of one large chest-loop coil for breast MRgHIFU is that it is non-interfering with the ultrasound beam, and, it has a more homogenous signal profile than an array of smaller loops. The drawbacks are it's relatively low signal-to-noise ratio (SNR), limited coverage of the breast, and inability to take advantage of parallel imaging techniques (11–13).

Phased array receiver coil designs have been used progressively more in MRI (14–18). Use of a phased array coil of smaller loops can provide similar or greater SNR values compared to a volume coil over the imaging volume due to the smaller coils' ability to synthesize larger loops (19,20). Phased arrays are advantageous since multiple channels can provide an increase in signal sensitivity and enable parallel image acquisition techniques (11–13). This helps MRgHIFU by enhancing the temporal resolution of temperature monitoring in tissue (21), potentially reducing motion artifacts such as breathing resulting in improved clinical diagnosis and patient treatment planning.

This work describes the design and characterization of a dedicated 11-channel RF breast coil that is incorporated into a breast MRgHIFU apparatus, for use in a 3T MRI system. This breast-specific MRgHIFU system was designed as an academic/industrial collaboration. Image Guided Therapy (Bordeaux, France) and Imasonics (Besancon, France), respectively developed the ultrasound generator and transducer. The design of the treatment cylinder, and transducer positioning system on which the RF coil array is mounted have been described elsewhere (22). The goal for the RF coil design was to provide increased SNR over the conventional single loop RF coil method and thereby obtain better image quality and more accurate temperature measurements using the breast MRgHIFU system.

METHODS

Initial Considerations

The MRgHIFU breast coil design needed for this work was limited by some atypical constraints. First, the coil was required to be implemented in or around a water bath tank filled with deionized water designed to contain the human female breast. Second, the coil could not interfere with the ultrasound transducer or the propagating ultrasound waves. Third, our entire system needed to have the functionality of rotating around the breast to retain the ability to treat a majority of the breast volume. Fourth, the data acquired with the

coil needed to be reconstructed fast enough for real time temperature monitoring of the treated tissue. Finally, the coil was required to provide a high SNR and parallel imaging performance over the entire volume of a typical breast.

Coil Design and Construction

The MRgHIFU breast coil array as seen in Figure 1 was interfaced and tested on a 32-channel 3T clinical scanner (MAGNETOM Trio, Tim System; Siemens Medical Solutions, Erlangen, Germany). The breast-specific MRgHIFU device was constructed with the intent to treat breast lesions at arbitrary positions within the breast. This required water coupling between the breast and the transducer, however the water volume was minimized to allow the design of an RF coil array to be placed outside of the water volume and yet still in close proximity to the breast (23). The effort placed in keeping the coil outside the water volume was due to our experience that showed coils that were completely surrounded by water had a reduced SNR profile compared to a coil that was air backed. This is believed to be due to the capacitive coupling of the coil with the water because the plastic coating that covered the coil was required to be very thin for minimal ultrasound attenuation. Because the coils were placed outside the treatment cylinder effort was made to make the cylinder smaller in order for the coils to be closer to the breast volume thus bringing the higher coil sensitivity nearer to the breast. Also, with a larger MRgHIFU system water tank we have noticed standing electromagnetic waves that interfered with the coil tune frequency. By choosing a small cylinder for the breast treatment tank, it was necessary to position the transducer so that it can pass into and out of the cylinder. The watertight attachment of the transducer was achieved by the use of a flexible bellows structure. The transducer aperture requires 25% of the cylinder circumference, allowing the remaining 75% to be used for placement of the RF MRgHIFU breast coil array.

The MRgHIFU breast coil was constructed on a cylindrical plexi-glass former that fit tightly around the treatment cylinder, which has a radius of 8.5 cm. The dimensions of the treatment cylinder were minimized to reduce the volume of water and thus minimizing the distance between the RF coils and the anatomy of interest. This resulted in significant improvement to the achievable SNR at the region of interest. The selected dimensions also accommodate a wide range of breast sizes. The 11-channel MRgHIFU breast coil consisted of a 10-channel ladder phased array coil wrapped around the water tank leaving a window for the transducer. The coil also had a single loop coil placed at the chest wall around the breast giving a total of 11-channels. Each rectangular channel was 4 cm wide and 11 cm in length. The channels were positioned side-by-side and each had a shared leg trace with its neighbor, for a total width of 40 cm. Adjacent coils in the ladder phased array coil were decoupled using a decoupling capacitor, C_D , in the shared leg (24) (22). The copper strip conductors for the coils (Figure 1) were etched from 1 g/m² copper-clad kapton material (DuPont Pyralux, Durham, NC, USA). The conductor width was 5 mm. Gaps were etched through the copper coating of each coil to allow the insertion of six capacitors for each loop (22). These capacitors include a tuning capacitor, C_T , a match capacitor, C_M , two nearest-neighbor decoupling capacitors, C_D , a detuning capacitor for detuning during transmit, C_{AD} , and a blocking capacitor C_B to block DC from going straight from one coil's signal line its neighboring coil's ground. The coils were attached to the input of the preamplifier board with 24 cm of RG-316 cable (Thermal-wire, Naples, FL, USA). This short cable length was used to reduce the electrical length of the outer shield in order to minimize cable-coupling problems that might otherwise arise from interactions with the body coil and with cables from adjacent channels.

The MRgHIFU breast coil channels were bench-tested for the following parameters: tune, match, nearest-neighbor isolation, active and passive detuning, optimization of the

preamplifier detuning, the phase length between coil and preamp, and cable trap resonance. Each coil channel was tuned to 123.223 MHz with a 50-ohm match.

Each coil channel was actively decoupled during the transmit portion of the imaging sequence (25). Each coil was also passively decoupled, for patient safety in the case that active decoupling failed.

Low-input impedance preamplifiers (Siemens Medical Solutions, Erlangen, Germany) were used to decouple the non-nearest neighbor coil channels (26). A pi-network phase shifter was used to adjust the electrical length of the transmission line needed for the preamplifier decoupling.

The homogeneous breast phantom, placed in the treatment cylinder (Figure 1), was constructed from fiberglass using half of a small football shaped 13 cm largest-diameter mold. The phantom was filled with 1.5 liters of deionized water, and 1.955 g/L of Copper Sulfate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ Fisher Scientific Company, Fair Lawn, NJ, USA) (27). Several coils were then tuned and matched on the breast phantom former to a human breast that had average loading. Then NaCl was added to the phantom until similar loading to that of a breast was achieved.

SNR Analysis

For SNR comparisons, a gradient-echo sequence was used with 1 mm³ isotropic spatial resolution, a TR/TE of 500/4.12 ms and a 25° flip angle. Phantom images were used to assess the relative SNR between the 11-channel MRgHIFU breast coil array and a single chest-loop coil. Three orthogonal (axial, coronal, and sagittal) SNR profiles through the phantom at the approximate location of expected MRgHIFU heating were obtained. Both magnitude images and raw data were saved, and a noise reference image was obtained by recording an image without RF excitation. The SNR plots for each channel were calculated from the raw data by dividing the signal sensitivity by the standard deviation of the noise for each channel. Composite image SNR maps were created by combining the SNR images from all the channels using the square root of the sum-of-squares method (28–30).

Imaging experiments were performed on the homogenous breast phantom and on human subjects to evaluate and quantify the effectiveness of the MRgHIFU breast coil array.

Human Breast Imaging

The University of Utah's Institutional Review Board for human research approved the studies and informed consent was obtained from each volunteer. Five female human volunteers were scanned using the MRgHIFU breast coil and the single-channel chest-loop coil. For the human imaging studies, sagittal slices of the breast were obtained using a gradient echo acquisition with a 1 mm³ voxel size and TR/TE of 11/4.7 ms and a flip angle of 25°.

Parallel Imaging Capabilities

Inverse g-factor maps were computed from phantom data to assess parallel imaging performance of the MRgHIFU breast coil. These maps were plotted to show the characteristic parallel imaging performance that might be achieved with the 11-channel MRgHIFU breast coil. The mean g-factor in the area of the breast was recorded.

Temperature Measurements

MRgHIFU experiments were performed with an MR compatible 256-element phased array MRgHIFU system (IGT, Inc. Bordeaux, France). An in vivo porcine muscle sample was

heated with 10 acoustic watts for 30s. Phase difference temperature maps were acquired every 3.2 s using a 2-D GRE sequence with $1 \times 1 \times 3 \text{ mm}^3$ resolution and a TR/TE of 35/8ms and a flip angle of 25° . In addition, in-vivo human breast non-heating acquisitions were taken in order to compare the precision of the temperature measurements acquired with each coil configuration. Phase difference temperature maps were acquired every 5.05 s using a 2-D GRE sequence with $1 \times 1 \times 3 \text{ mm}^3$ resolution and a TR/TE of 35/8ms and a flip angle of 25° .

For thermal imaging, the complex images from each channel are combined in such a way that preserves the phase information. For each channel, the phase of the initial image is subtracted from all time frames using complex subtraction. The phases from the separate channels are then added together at each time frame, weighted by the square of their respective magnitudes, and the magnitudes are combined in a sum of squares fashion.

In order to show the temperature imaging performance of the MRgHIFU breast coil using parallel imaging, standard deviation through time in a human breast was measured with the chest-loop coil only, and the MRgHIFU breast coil with R=0, 2 and 4 in the left/right direction. Temperature maps were acquired using a phase difference calculation using a 2D GRE sequence, TR/TE = 25/9ms, $1.5 \times 1.5 \times 3 \text{ mm}^3$ resolution, 20° flip angle, 1 slice. The time of acquisition without GRAPPA was 3 s. Using a reduction factor of 2 reduced the acquisition time to 1.8 s and a reduction factor of 4 reduced the acquisition time to 1.2 s.

RESULTS

Coil Construction

The neighboring channels of the MRgHIFU breast coil array were decoupled sufficiently from each other where the lowest nearest neighbor noise correlation was 0.303, the median was 0.474, and highest value was 0.554. The active decoupling measurements for all loops had a median of -44.6 dB isolation and a passive decoupling of better than -39.0 dB isolation. The preamplifier decoupling for all channels had a median of -25.0 dB reduction of coil current amplitudes compared to the case where the coil is matched to 50 ohms.

SNR Analysis

For the breast phantom SNR studies shown in Figure 2 the 11-channel cylindrical MRgHIFU breast coil had a 131% SNR improvement over the single chest-loop coil at the center of the breast. With the transducer positioned inferior to the breast, there was an average of 295% improvement at lateral edge of the breast and a 173% improvement at the superior edge of the breast and a 108% improvement at the inferior edge of the breast. The improvement at the inferior edge was lower because there were no coils over the transducer window. There was a 247% improvement at the nipple area of the breast and a 21% improvement near the ribs. The SNR maps showed the extent to which the MRgHIFU breast coil provided increased SNR over the entire region of the breast.

Human Breast Imaging

The MRgHIFU breast coil provided better SNR coverage over the entire breast region in a normal volunteer as shown in Figure 3. Because of the disparity in SNR profiles of the chest-loop coil compared to the MRgHIFU breast coil the images in these sagittal slices had to be windowed and leveled differently. Human images were obtained as a measure of coil sensitivity and image quality and demonstrated the increased image quality throughout the breast volume that resulted from using the MRgHIFU breast coil.

Parallel Imaging Capabilities

Maps of the inverse g-factor are shown in Figure 4. Note that the chest-loop coil alone is not capable of parallel imaging. The g-factors show that a 2×2 reduction factor can result in a reduction of less than 1.446 in SNR beyond the unavoidable factor of 2. An unavoidable hindrance on acceleration imaging is that there were no coils located in front of the transducer, which causes a larger g-factor to occur within the sample compared to a coil built with channels continuously placed around the treatment cylinder. Despite this hurdle, much of the treatment cylinder volume still has better SNR using a 2×2 reduction factor than achieved with the chest-loop coil alone without acceleration.

Temperature Measurements

As seen in Figure 5 the temperature maps in ex-vivo pork were less corrupted by noise for the MRgHIFU breast coil compared to the chest-loop coil. The temperature standard deviation seen through time in a non-heating study for a normal human volunteer is shown in Figure 6. Figure 6 displays temperature standard deviation maps that are overlaid on the respective magnitude images, and masked for water-based tissue only, showing that the standard deviation through time in the human breast was smaller for the MRgHIFU breast coil versus the chest-loop coil. The 11-channel MRgHIFU breast coil provides more precise temperature measurements throughout a larger volume of the breast tissue than the single chest-loop coil. Figure 6 shows the spatial resolution that is achievable while retaining accurate temperature maps and assess the functionality of the MRgHIFU breast coil array for temperature imaging.

The temperature standard deviation through time maps when using parallel imaging techniques with the MRgHIFU breast coil are shown in Figure 7. The standard deviation for the MRgHIFU breast coil with an $R=2$ is similar to the standard deviation through time for temperature measurements using the chest-loop coil. The temperature standard deviation using the MRgHIFU with an $R=4$ is more noisy as expected (Figure 7). However, there are still regions of the breast where temperature measurements would be within a reasonable error.

DISCUSSION

The MRgHIFU breast coil gave much better SNR than the single chest-loop coil. This SNR increase translates directly to higher resolution both spatially and temporally. The g-factor maps and values showed that a reduction factor of 2×2 could be achieved while maintaining a higher SNR than the chest-loop coil for most of the breast volume. The temperature maps for the MRgHIFU breast coil have less noise as indicated by the lower standard deviations in the volume through time. This will allow the spatial resolution to be increased, which has been shown previously (31) to provide more accurate temperature profile measurement that would increase both patient safety and treatment efficacy. In addition to online treatment monitoring, the anatomy images showed that the increased SNR directly translates to better tissue characterization and the improvement in spatial resolution helps to improve the visualization of fine detail in the breasts. This detail will aid in treatment planning and will ease registration efforts between pre-treatment scans and treatment monitoring data.

The breast-specific MRgHIFU system has several unique features that enable improved RF coil design. Because the transducer is located outside of the treatment cylinder, the cylinder can then be made as small as possible enabling an increase in SNR while remaining functional for treatment of breasts of arbitrary sizes. This cylinder shape with transducer positioned out of the cylindrical volume reduces the required water volume over other

possible designs (32). This design enables the MRgHIFU breast coil to be much closer to the tissue of interest.

The MRgHIFU breast coil was successfully integrated into the treatment cylinder and breast MRgHIFU system with reduced water volume. This coil was easier to implement and maintain because of the capacitances in the shared legs of adjacent channels. The visibility through the coil into the treatment cylinder was increased because there were no extra copper traces from overlapping coils. This increased visibility is helpful when trying to position the breast within the treatment cylinder.

Limitations of the presented MRgHIFU breast coil include remaining unnecessary water volume in the tank and the lack of coils present over the transducer window. Initial system evaluation has shown that the MRgHIFU treatment cylinder volume can be reduced even further to decrease the water volume and thus the resulting noise contribution to the images. More importantly, a further reduced treatment cylinder size allows the MRgHIFU breast coils to be closer to the imaging volume and increases the signal sensitivity over the volume of interest. Future design modifications could address these limitations by using a shoot-through coil design to allow for placement of coils in the transducer region.

CONCLUSIONS

Simultaneous design of the MRgHIFU system with a matching optimized phased array RF coil created a coil that provides improved visualization of the breast and increased diagnostic capability of breast imaging in the MRgHIFU system. The new MRgHIFU breast coil array has more than double the SNR of a single chest-loop coil over the entire breast volume. The multiple channels of the MRgHIFU breast coil allow the use of parallel imaging techniques where it was not possible with a single chest-loop coil. The use of this coil in MRgHIFU breast treatments will provide greater temperature measurement accuracy that will aid in providing safer and more efficacious treatments for patients.

Acknowledgments

Thanks to Robert Roemer, Doug Christensen, Josh de Bever, Yi Wang and other members of the University of Utah MRgHIFU team. This work is supported by NIH grant R01 CA134599, the Ben B. and Iris M. Margolis Foundation, The Mark H. Huntsman chair, and the Focused Ultrasound Surgery Foundation, Siemens Medical Solutions.

References

1. Fisher B, Anderson S, Bryant J, Margolese RG, Deutsch M, Fisher ER, Jeong JH, Wolmark N. Twenty-year follow-up of a randomized trial comparing total mastectomy, lumpectomy, and lumpectomy plus irradiation for the treatment of invasive breast cancer. *N Engl J Med*. 2002; 347(16):1233–1241. [PubMed: 12393820]
2. Hill-Kayser CE, Chacko D, Hwang WT, Vapiwala N, Solin LJ. Long-term clinical and cosmetic outcomes after breast conservation treatment for women with early-stage breast carcinoma according to the type of breast boost. *Int J Radiat Oncol Biol Phys*. 2011; 79(4):1048–1054. [PubMed: 20510548]
3. Jolesz FA, Blumenfeld SM. Interventional use of magnetic resonance imaging. *Magn Reson Q*. 1994; 10(2):85–96. [PubMed: 7986703]
4. Apesteguía Ciriza L, Ovelar Ferrero A, Alfaro Adrián C. Review of interventional radiology techniques in breast disease. *Radiologia*. 2011
5. Furusawa H, Namba K, Nakahara H, Tanaka C, Yasuda Y, Hirabara E, Imahariyama M, Komaki K. The evolving non-surgical ablation of breast cancer: MR guided focused ultrasound (MRgFUS). *Breast Cancer*. 2007; 14(1):55–58. [PubMed: 17244995]

6. Wu F, Wang ZB, Cao YD, Zhu XQ, Zhu H, Chen WZ, Zou JZ. "Wide local ablation" of localized breast cancer using high intensity focused ultrasound. *J Surg Oncol*. 2007; 96(2):130–136. [PubMed: 17443737]
7. Furusawa H, Namba K, Thomsen S, Akiyama F, Bendet A, Tanaka C, Yasuda Y, Nakahara H. Magnetic resonance-guided focused ultrasound surgery of breast cancer: reliability and effectiveness. *J Am Coll Surg*. 2006; 203(1):54–63. [PubMed: 16798487]
8. Gianfelice D, Khiat A, Amara M, Belblidia A, Boulanger Y. MR imaging-guided focused ultrasound surgery of breast cancer: correlation of dynamic contrast-enhanced MRI with histopathologic findings. *Breast Cancer Res Treat*. 2003; 82(2):93–101. [PubMed: 14692653]
9. Huber PE, Jenne JW, Rastert R, Simiantonakis I, Sinn HP, Strittmatter HJ, von Fournier D, Wannemacher MF, Debus J. A new noninvasive approach in breast cancer therapy using magnetic resonance imaging-guided focused ultrasound surgery. *Cancer Res*. 2001; 61(23):8441–8447. [PubMed: 11731425]
10. Orsi F, Arnone P, Chen W, Zhang L. High intensity focused ultrasound ablation: a new therapeutic option for solid tumors. *J Cancer Res Ther*. 2010; 6(4):414–420. [PubMed: 21358073]
11. Sodickson DK, Manning WJ. Simultaneous acquisition of spatial harmonics (SMASH): fast imaging with radiofrequency coil arrays. *Magn Reson Med*. 1997; 38(4):591–603. [PubMed: 9324327]
12. Pruessmann KP, Weiger M, Scheidegger MB, Boesiger P. SENSE: sensitivity encoding for fast MRI. *Magn Reson Med*. 1999; 42(5):952–962. [PubMed: 10542355]
13. Griswold MA, Jakob PM, Heidemann RM, Nittka M, Jellus V, Wang J, Kiefer B, Haase A. Generalized autocalibrating partially parallel acquisitions (GRAPPA). *Magn Reson Med*. 2002; 47(6):1202–1210. [PubMed: 12111967]
14. Wiggins GC, Polimeni JR, Potthast A, Schmitt M, Alagappan V, Wald LL. 96-Channel receive-only head coil for 3 Tesla: design optimization and evaluation. *Magn Reson Med*. 2009; 62(3):754–762. [PubMed: 19623621]
15. Wiggins GC, Triantafyllou C, Potthast A, Reykowski A, Nittka M, Wald LL. 32-channel 3 Tesla receive-only phased-array head coil with soccer-ball element geometry. *Magn Reson Med*. 2006; 56(1):216–223. [PubMed: 16767762]
16. Wiggins GC, Potthast A, Triantafyllou C, Wiggins CJ, Wald LL. Eight-channel phased array coil and detunable TEM volume coil for 7 T brain imaging. *Magn Reson Med*. 2005; 54(1):235–240. [PubMed: 15968650]
17. Kraff O, Bitz AK, Kruszona S, Orzada S, Schaefer LC, Theysohn JM, Maderwald S, Ladd ME, Quick HH. An eight-channel phased array RF coil for spine MR imaging at 7 T. *Invest Radiol*. 2009; 44(11):734–740. [PubMed: 19809342]
18. Breslau J, Dalley RW, Tsuruda JS, Hayes CE, Maravilla KR. Phased-array surface coil MR of the orbits and optic nerves. *AJNR Am J Neuroradiol*. 1995; 16(6):1247–1251. [PubMed: 7677017]
19. Hayes CE, Hattes N, Roemer PB. Volume imaging with MR phased arrays. *Magn Reson Med*. 1991; 18(2):309–319. [PubMed: 2046514]
20. Wright SM, Wald LL. Theory and application of array coils in MR spectroscopy. *NMR Biomed*. 1997; 10(8):394–410. [PubMed: 9542737]
21. Quesson B, de Zwart JA, Moonen CT. Magnetic resonance temperature imaging for guidance of thermotherapy. *J Magn Reson Imaging*. 2000; 12(4):525–533. [PubMed: 11042633]
22. Payne A, Merrill R, Minalga E, Vyas U, de Bever J, Todd N, Hadley JR, Dumont E, Meumayer L, Christensen D, Roemer R, Parker D. Design and characterization of a laterally mounted phased-array transducer breast-specific MRgHIFU device with integrated 11-channel receiver array. *Medical Physics*. 2012
23. Payne, A.; Merrill, R.; Minalga, E.; Hadley, R.; Vyas, U.; Bever, Jd; Dumont, E.; Roemer, R.; Christensen, D.; Neumayer, L.; Parker, D. Design and Initial Evaluation of a Breast-specific MRgFUS Treatment System. 2010; Washington, D.C. USA. MR-guided Focused Ultrasound, 2nd International Symposium;
24. Edelstein WA, Hardy C, Mueller O. Electronic decoupling of surface-coil receivers for NMR imaging and spectroscopy. *Journal of Magnetic Resonance*. 1986:156–161.

25. Lee RF, Giaquinto RO, Hardy CJ. Coupling and decoupling theory and its application to the MRI phased array. *Magn Reson Med*. 2002; 48(1):203–213. [PubMed: 12111947]
26. Roemer PB, Edelstein WA, Hayes CE, Souza SP, Mueller OM. The NMR phased array. *Magn Reson Med*. 1990; 16(2):192–225. [PubMed: 2266841]
27. Och JG, Clarke GD, Sobol WT, Rosen CW, Mun SK. Acceptance testing of magnetic resonance imaging systems: report of AAPM Nuclear Magnetic Resonance Task Group No. 6. *Med Phys*. 1992; 19(1):217–229. [PubMed: 1620053]
28. Wang J, Reykowski A, Dickas J. Calculation of the signal-to-noise ratio for simple surface coils and arrays of coils. *IEEE Trans Biomed Eng*. 1995; 42(9):908–917. [PubMed: 7558065]
29. Kellman P, McVeigh ER. Image reconstruction in SNR units: a general method for SNR measurement. *Magn Reson Med*. 2005; 54(6):1439–1447. [PubMed: 16261576]
30. Constantinides CD, Atalar E, McVeigh ER. Signal-to-noise measurements in magnitude images from NMR phased arrays. *Magn Reson Med*. 1997; 38(5):852–857. [PubMed: 9358462]
31. Todd N, Vyas U, de Bever J, Payne A, Parker DL. The effects of spatial sampling choices on MR temperature measurements. *Magn Reson Med*. 2011; 65(2):515–521. [PubMed: 20882671]
32. Mougenot, C.; Kohler, M.; Tillander, M.; Moonen, C.; Barteks, W.; Ehnholm, G. Large aperture transducer designed for MR-HIFU treatment of breast tumors. Proceedings of the 19th Annual Meeting of ISMRM; Montreal, Canada. 2011. p. 1727

Figure 1.

The 11-channel MRgHIFU breast coil mounted on the MRgHIFU transducer treatment cylinder. The fiberglass MRI copper sulfate phantom is placed in the system. A. Pre-amplifier board. B. MRgHIFU Breast coil. C. US transducer. Also shown is a circuit diagram of four of the ten channels of the ladder phased array. The tune capacitors, C_T , match capacitors, C_M , and the nearest-neighbor decoupling capacitors, C_D , blocking capacitor C_B , active detuning capacitor, C_{AD} , are labeled and also how each channel shares a leg trace with its neighbor is shown.

Figure 2. SNR maps of a homogeneous phantom in the treatment cylinder. Top row: images obtained using the chest-loop coil. Bottom row: images obtained using the MRgHIFU breast coil. First column: Coronal. Second column: Sagittal. Third column: Axial.

Figure 3. Anatomy image of a breast. Sequence: Gradient echo TE: 4.7ms TR: 11ms FA:25° Left: chest-loop coil. Right: MRgHIFU coil.

Figure 4.

Inverse g-factor maps of 2×2, 2×3; 3×2, 1×4 reduction factor in coronal plane. The mean g-factor for a circular region of interest (radius = 4cm) in the center of the treatment cylinder for each reduction factor is equal to 1.446 (2×2), 1.551 (2×3); 1.566 (3×2), and 1.990 (1×4) respectively.

Figure 5.

Temperature maps at the point in time where the highest temperatures were measured in an ex-vivo porcine model. Left: Maps obtained using the chest-loop coil only. Right: Maps obtained using the MRgHIFU coil. Less noise is seen in the non-heating regions of the map obtained with the MRgHIFU coil.

Figure 6.

Maps of the standard deviation of the temperature through time overlaid on the respective magnitude images, and masked for water-based tissue only. Temperature standard deviations are displayed in color and magnitude images in black and white. Left map: chest-loop coil only. Right map: MRgHIFU coil.

Figure 7.

Standard deviation of temperature through time maps in a human volunteer. Maps are overlaid on the respective magnitude images and masked for water-based tissue only. Shown are maps corresponding to four cases. The temperature maps are obtained using A) the single chest-loop coil with no parallel imaging, and B) the MRgHIFU coil with no GRAPPA and a GRAPPA factor of C) 2 and D) 4. Temperature standard deviations are displayed in color and magnitude images in black and white.