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Research Article

An MPI-Compatible HIFU Transducer: Experimental Evaluation of Interference

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Abstract

High intensity focused ultrasound (HIFU) is an early-stage therapeutic technology that allows non-invasive cancer treatment by delivering heat to the target tissue. Monitoring the tissue temperature is challenging and remains a key element for accurate tumor ablation. Recently, the ability of magnetic particle imaging (MPI) to measure the nanoparticle temperature was demonstrated. This can be utilized for measuring the temperature of surrounding tissue during HIFU ablation. To evaluate MPI as a HIFU monitoring modality, a first MPI-compatible HIFU transducer is presented. Its MPI-compatibility was experimentally examined, whereby heating of conducting transducer parts as well as interference with the MPI receive signal chain were addressed. Thermometry measurements showed that temperature rise (< 5 K) of transducer electrodes due to eddy current heating during MPI acquisition can be neglected. Measurements of transfer functions from the transducer to the MPI low-noise amplifier outputs and acquisition of MPI spectra during HIFU operation confirmed that concurrent MPI reconstruction is feasible during HIFU operation. The resulting sound field of the presented HIFU transducer was measured and extrapolation of the applied electrical power reveals that acoustic intensities necessary for rapid tissue ablation can be achieved without causing an MPI signal overload. By operating a HIFU transducer inside the MPI scanner, the feasibility of a HIFU–MPI combination has been confirmed.

I. Introduction

The controlled application of heat to tumors is referred to as local hyperthermia in oncology. One clinically applied hyperthermia modality for various tumor entities is high intensity focused ultrasound (HIFU) [1]. The mechanical energy of an acoustic beam is precisely delivered to organs accessible by ultrasound (US). The acoustic energy is converted into heat, which leads to a rapid ablation of the target tissue in a small focal area of high acoustic intensity. For an efficient and safe application, temperature monitoring of the tissue is necessary.

Monitoring of a HIFU treatment with US imaging is challenging [2, 3]. Techniques for ultrasound-based temperature monitoring can be classified into pulse-echo techniques – from monitoring changes in echogeneity to sophisticated elastography – and passive techniques, e.g., to detect cavitation. However, robust real-time thermography of most relevant temperatures above 50 °C is not feasible to date with US [2]. Therefore, non-portable and cost-intensive magnetic resonance imaging thermometry is the gold standard for HIFU monitoring [4]. The ability of magnetic particle imaging (MPI) to determine the nanoparticle tracer temperature has recently been

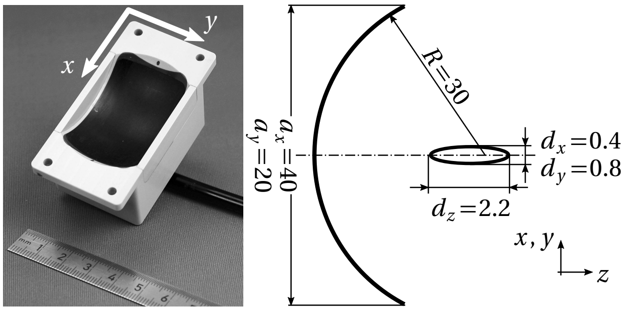

Figure 1: Focused bowl transducer with radius R and dimensions a of intersecting plane, creating a focus of dimensions d. Left: Photograph. Right: Sketch with the dimensions in mm.

demonstrated [5, 6]. Consequently, MPI has the potential to be used as an alternative hyperthermia monitoring device that delivers temperature maps sufficiently fast during rapid HIFU ablation. Further, MPI can be realized as a single-sided device, which would significantly reduce costs compared to a full MRI instrumentation.

During HIFU therapy, MPI is expected to be able to deliver temperature maps in real-time that complement US-based therapy monitoring techniques. However, commercially available HIFU devices usually cannot operate inside MPI scanners. Due to the strong, alternating magnetic fields, eddy currents are induced in transducer components that can lead to a rapid destructive heating. To enable an MPI–HIFU combination, design guidelines for MPI-compatible ultrasound hardware have already been proposed [7, 8].

To evaluate MPI as a HIFU monitoring modality, a first MPI-adapted HIFU transducer is presented in this contribution. Its MPI compatibility is experimentally confirmed by infrared thermometry and measurements of electromagnetic interference. From these measurements, the maximum possible acoustic intensity is deduced to determine if ablative acoustical intensities can be reached inside the MPI bore without overloading the MPI signal chain.

II. Material and Methods

The custom-made HIFU transducer (Imasonic, Voray sur l'Ognon, France) is a single element spherical transducer focused to a fixed target depth of 30 mm, see Figure 1. With its dimensions, convering a volume of (70 × 35 × 40)mm, it is designed to operate inside a small-animal MPI scanner as a part of a therapeutic insert. The center frequency is 3.5 MHz but the excitation frequency can be adjusted (3-4 MHz) to account for frequency dependent acoustic absorption. The device is designed to achieve an acoustic intensity of 5 kW cm^{-2} in the focus.

Heating

To achieve MPI compatibility [7, 8], eddy current heating induced by drive field coils that are operating at 25 kHz was reduced by removing all replaceable metallic structures, e.g., shielding. The thin transducer electrode surfaces are patterned into 1.47 mm stripes, separated by 0.3 mm kerfs and connected in a meander-line pattern. To reduce the current density in the electrode and prevent transducer self heating, the electrode is further divided up into five sub-electrodes. Thereby, the cross-section of respective cables, that are carried out as twisted-pair, can be reduced to AWG 32. To evaluate the effectiveness of these provisions, the transducer was placed inside the bore of a pre-clinical MPI scanner (MPI 25/20 FF, Bruker BioSpin MRI, Ettlingen, Germany) at a drive field strength of 12 mT/μ_0. Heating was monitored from outside the bore with a thermography camera (VarioCAM, InfraTec, Dresden, Germany). To validate the thermography picture, temperatures were compared to two transducer-integrated type T thermocouples.

Interference

To evaluate the electromagnetic interference in the MPI signal chain, an empty bore measurement was performed for comparison at first. In all experiments, a drive field amplitude of 12 mT (three axis excitation) was used. Afterwards, the passive transducer was placed inside the bore unconnected. Finally, it was connected to the US research platform (Vantage 256 HIFU, Verasonics, Kirkland, WA) via five RG 58 C/U coaxial cables of 9 m length. The coaxial cable was guided through the shielding cabin without an electrical filter but by connecting the signal mass to the shielding cabin potential. Thereby, the shielding is maintained until close to the bore where the coaxial cables are connected to the 1 m long twisted-pair cables of the transducer. Then, HIFU operation was performed. For the examined configurations, MPI spectra were recorded with the Bruker ParaVision software. To evaluate if HIFU levels can be reached with the transducer inside the MPI bore, the maximum electrical power that can be transmitted to the transducer without generating an overload in the MPI signal chain was determined. For this purpose, the signal chain behind the most sensitive components, the MPI low noise amplifiers (LNAs), was disconnected. The transfer functions from the HIFU transducer to the LNA outputs were measured with a network analyzer (E5061B, Keysight Technologies, Santa Rosa, CA). Thereby, anti-aliasing filters of MPI analog-digital-converters do not influence the measurement. With the given maximum allowed output power of the LNA, the frequency dependent attenuation of HIFU interference can be used to calculate in advance the maximum electrical HIFU excitation power for any HIFU sequence. Here, the maximum power for continuous excitation was calculated.

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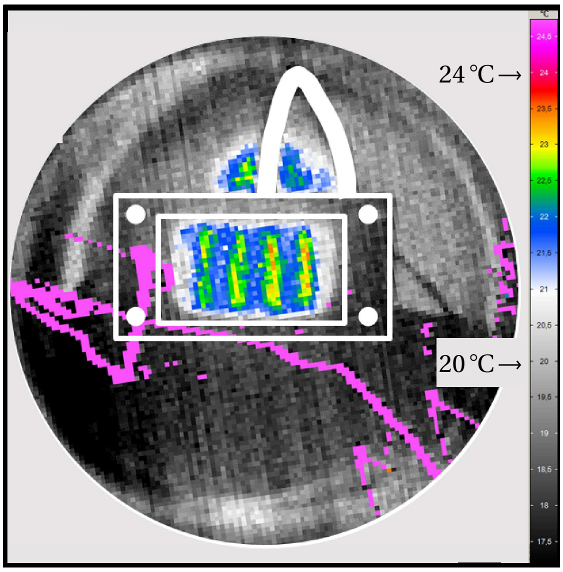


Figure 2: Thermography picture of the transducer inside the MPI scanner after 5 minutes of MPI operation at a 12 mT three axis drive field excitation.

Sound Field Characteristic

To specify the transducer sound field, US simulations were performed with the k-wave toolbox [8] incorporating basic nonlinear ultrasound propagation. Thereof, the focus size was determined using the −6 dB contour of the peak positive sound pressure. The actual sound field under linear conditions was determined with a hydrophone measurement (0.04 mm needle, S/N: 1274 with preamplifier PA07084 and DC2/000686, and booster amplifier HA106, Precision Acoustics, Dorset, UK) around the focus with 200 µm spatial resolution. The simulated sound field was compared with the measurements, to check if the specifications are met and to confirm that the simulation of the sound field is accurate, which is required for simulations of higher intensities.

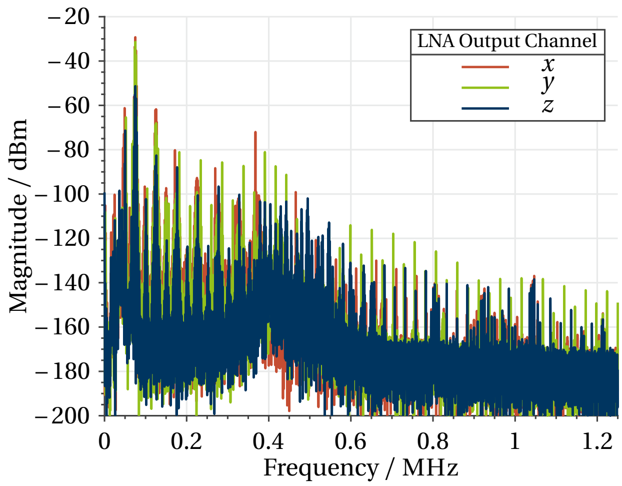
III. Results

Heating

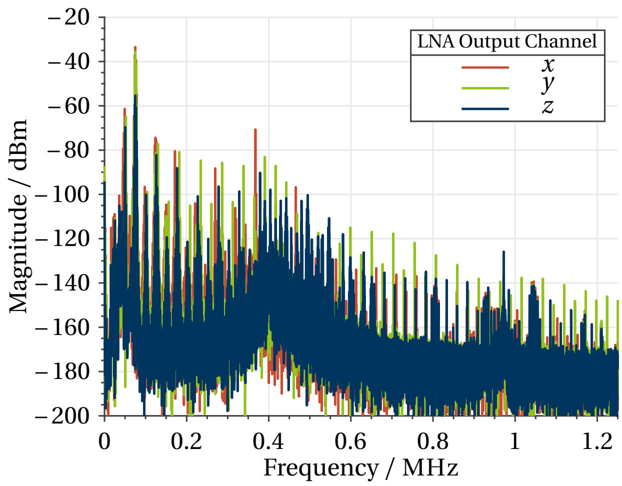
When the transducer was placed inside the scanner bore during imaging sequences, heating < 5 K in steady state at an ambient temperature of 19 °C was observed, see Figure 2. These values were confirmed by reading out the transducer-integrated thermocouples.

Interference

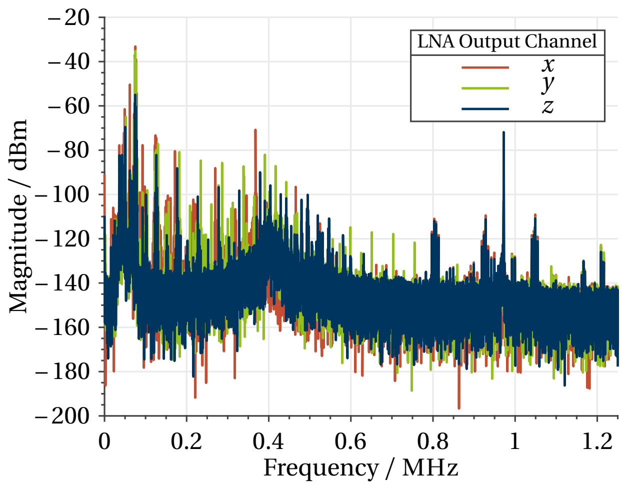
The empty bore spectra recorded with the ParaVision software, see Figure 3a, did not change conspicuously when the transducer was placed inside the bore and



(a) Empty bore, averaged over 1000 acquisitions.



(b) HIFU, averaged over 1000 acquisitions.



(c) HIFU, non-averaged with interference at 974.2 kHz.

Figure 3: MPI spectra acquired with the Bruker ParaVision software for an empty bore and during HIFU operation.

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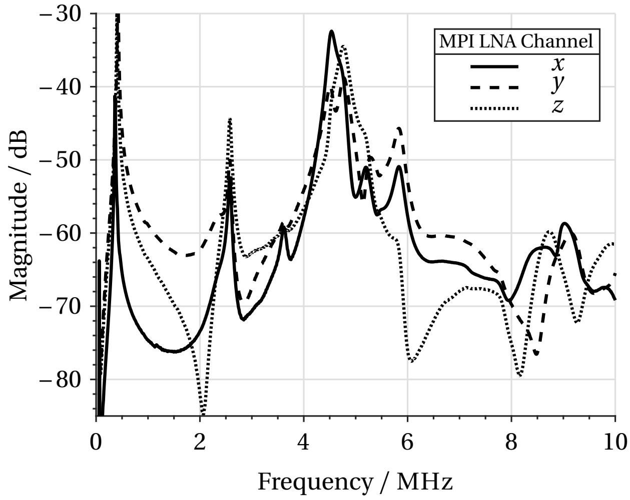

Figure 4: Transmittance from the electrical HIFU transducer input to the output of the MPI LNA amplifiers. The maximum allowed LNA output power is 0 dBm.

maintained the characteristic of the empty bore spectrum. Also the connection to the US hardware did not lead to noticeable interference in the spectra. Even spectra recorded during HIFU operation with an electrical transducer input power of L(re 1 mW)=43 dBm did not contain strong crosstalk, see Figure 3b. However, non-averaged spectra depicted in Figure 3c obviously contain the interference signal. A clear peak in all channels arose at $f = 974.2$ kHz which is exactly the aliasing frequency $f = f_0 - f_s$ of the HIFU excitation frequency $f_0 = 3.4742$ MHz at an MPI sampling frequency of $f_s = 2.5$ MHz.

The transfer functions between the transducer and the MPI LNA outputs are depicted in Figure 4. The maximum LNA output power was defined as 0 dBm by the manufacturer to prevent the amplifier or analog-digital converter from either a destructive condition or output signal saturation. As the transmittance was −58 dB at the transducer center frequency, the maximum allowed electrical input power is 58 dBm.

Sound Field Characteristic

The measured characteristics of the generated sound field in water are depicted in Figures 5a, 5b, and the simulated characteristic in Figures 5c, 5d. The focal size, defined as the area of −6 dB decrease of the peak pressure, was measured as $(0,8 \times 0,4 \times 2,0)$ mm in x-, y-, and z-direction. At an electrical input of 22.5 dBm, the maximum sound pressure level measured was 889 kPa, which corresponds to an intensity of 52.6 W cm^{-2}. Simulated focal dimensions using the same parameters are $(0,8 \times 0,4 \times 2,2)$ mm.

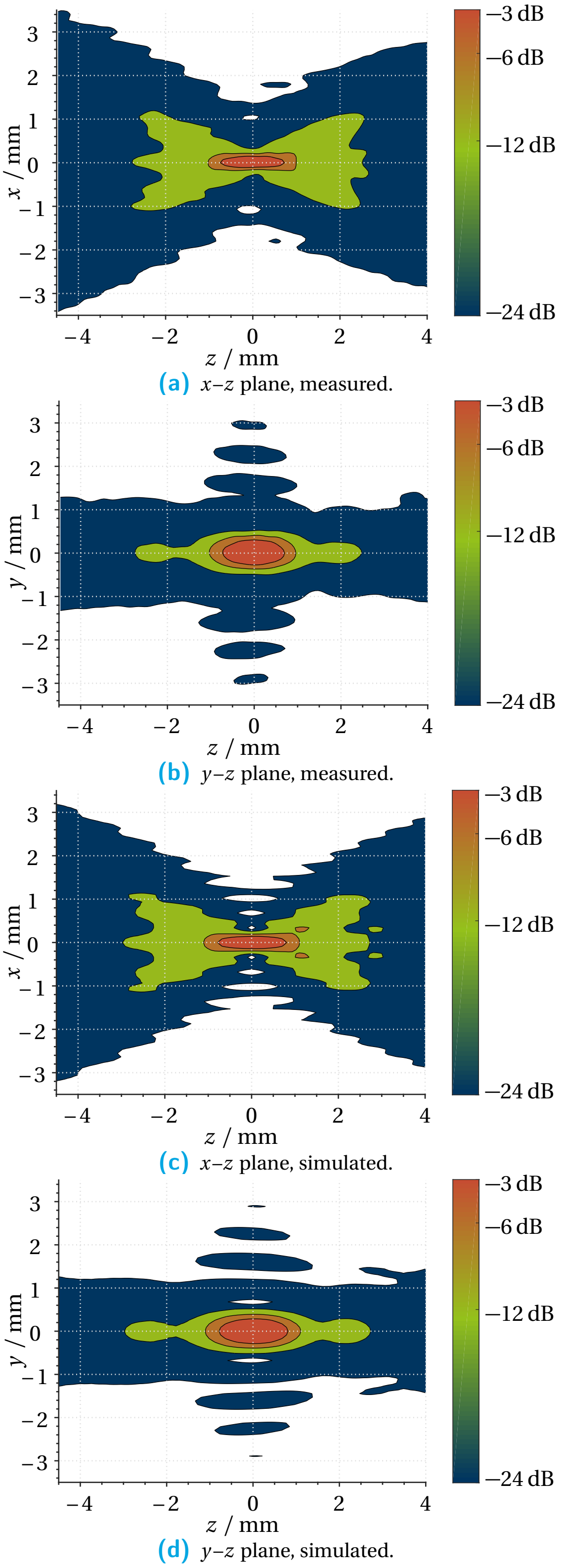

Figure 5: Focus intersecting planes of the peak positive sound pressure field of the HIFU transducer. The focus area is defined according to the −6 dB contour.

IV. Discussion

Heating

The previously presented guidelines [7], [8] lead to an MPI-compatible transducer. With a temperature rise of 5 K in steady state using maximum gradient fields, eddy current heating is negligible compared to transducer self-heating that is within seconds in the order of 20 K at an electrical input power of 43 dBm.

Interference

The minimization of eddy currents in passive components also means a reduction of retroactive effects that can appear as noise in the MPI spectra. Since no differences were observed between the recorded spectra with and without HIFU hardware in the bore, it is expected that the MPI image quality will not deteriorate significantly if the HIFU hardware is present in the bore. Also the connection via SMA cables to the HIFU hardware outside the shielding cabin did not cause any noticeable interference, so that additional filters in the transducer cables are not necessary.

Since the attenuation between the transducer electrical input and MPI LNA output, as determined with the transfer function, is −58 dB at the transducer center frequency, maximum continuous mode HIFU power of 43 dBm is not limited by MPI constraints. A margin for higher intensity pulse operation even exists. Furthermore, interference is weaker in averaged spectra and appears as a deterministic narrow-band peak in the non-averaged spectra for CW excitation. For the center frequency $f_0 \approx 3.5$ MHz of the transducer used here, its aliasing frequency appears in a higher frequency band that is not necessarily needed for MPI image reconstruction. The frequency of interference can furthermore be varied by shifting the HIFU excitation within the transducer bandwidth. Contrary to prior assessment [8], this suggests that concurrent MPI reconstruction and HIFU therapy is feasible without further hardware modifications.

Sound Field Characteristic

The measured sound field characteristic agrees well with simulations and confirms the agreement with transducer specifications. The focal dimensions as measured under linear conditions also specify the HIFU treatment area. Linear scaling of the peak intensity measured under linear conditions to a HIFU excitation level of 20 V or 43 dBm results in a maximum sound intensity of 6 kW cm^{-2} and in acoustic intensities exceeding those required for rapid ablation (2 kW cm^{-2} [3]) without overloading the MPI signal chain.

V. Conclusion

By operating a HIFU transducer inside the MPI scanner, the MPI compatibility of the adapted transducer design has been approved. Thereby, the general feasibility of a HIFU–MPI combination is confirmed. Since simultaneous HIFU operation with the presented HIFU transducer and MPI image reconstruction is expected to be possible, MPI can now be evaluated as a novel alternative for HIFU monitoring.

Acknowledgements

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References

[1] Focused Ultrasound Foundation, Focused ultrasound state of the field, 2017. URL: www.fusfoundation.org.

[2] M. A. Lewis, R. M. Staruch, and R. Chopra. Thermometry and ablation monitoring with ultrasound. *International Journal of Hyperthermia*, 31(2):163–181, 2015, doi:10.3109/02656736.2015.1009180.

[3] E. S. Ebbini and G. Ter Haar. Ultrasound-guided therapeutic focused ultrasound: Current status and future directions. *International Journal of Hyperthermia*, 31(2):77–89, 2015, doi:10.3109/02656736.2014.995238.

[4] D. Schlesinger, S. Benedict, C. Diederich, W. Gedroyc, A. Klibanov, and J. Larner. MR-guided focused ultrasound surgery, present and future. *Medical Physics*, 40(8), 2013, doi:10.1118/1.4811136.

[5] J. B. Weaver, A. M. Rauwerdink, and E. W. Hansen. Magnetic nanoparticle temperature estimation. *Medical Physics*, 36(5):1822–1829, 2009, doi:10.1118/1.3106342.

[6] C. Stehning, B. Gleich, and J. Rahmer. Simultaneous magnetic particle imaging (MPI) and temperature mapping using multi-color MPI. *International Journal on Magnetic Particle Imaging*, 2(2), 2016, doi:10.18416/ijmpi.2016.1612001.

[7] T. C. Kranemann, T. Ersepke, and G. Schmitz, Design of a magnetic particle imaging compatible HIFU transducer array, in *2016 IEEE International Ultrasonics Symposium (IUS)*, 1–4, IEEE, 2016. doi:10.1109/ULTSYM.2016.7728476.

[8] T. C. Kranemann, T. Ersepke, and G. Schmitz. Towards the Integration of an MPI Compatible Ultrasound Transducer. *International Journal on Magnetic Particle Imaging*, 3(1), 2017, doi:10.18416/ijmpi.2017.1703016.

