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Transcranial magnetic resonance-guided focused ultrasound surgery at 1.5T: a technical note

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Abstract

Magnetic resonance-guided focused ultrasound is one of the emerging non-invasive technologies offering both image guidance and thermal monitoring. In recent years transcranial application of this technology is starting to impact heavily the neuroscience field. We present here the imaging protocol and the technological methods successfully used with a transcranial magnetic resonance-guided focused ultrasound system certified for clinical treatments of functional neurological disorders, integrated for the first time with a 1.5T magnetic resonance scanner. Compared to the body radiofrequency coil (the one commonly used with transcranial magnetic resonance-guided focused ultrasound system integrated with 3T magnetic resonance scanners), the use of a dedicated two channel coil enabled a signal-to-noise ratio gain up to five times higher.

Keywords

Brain, high-intensity focused ultrasound ablation, interventional magnetic resonance imaging, minimally invasive surgical procedures, stereotactic techniques

Introduction

Imaging-based modalities are routinely used for practically all preliminary assessments, preoperative planning and follow-up of many surgical procedures, and they are more frequently being used for real-time image guidance and monitoring also. Furthermore, there is a strong and increasing demand for minimally invasive or non-invasive surgical applications. Magnetic resonance imaging (MRI) is a powerful diagnostic and investigation tool for neurosciences that does not use ionising radiation nor generates any known hazardous bioeffects. Using different pulse sequences MRI can enable key insights not only into the gross anatomy of the central nervous system,[1] but also into white matter pathways,[2] brain function,[3] metabolism[4–7] and microstructure.[8] However, the need for dedicated MRI-compatible devices and monitoring systems, the reduced accessibility to the patient (partially avoided by the use of 'open bore' magnets) and the cost of an MRI scanner are limiting the diffusion of MRI-guided procedures compared to other modalities available in the interventional radiologist's arsenal.

Neurological applications of high-intensity focused ultrasound (HIFU) have always been challenging because the skull presents a unique barrier to the propagation of ultrasound; preliminary applications, both preclinical[9] and clinical,[10] required a craniotomy to reach the planned target. Furthermore, attenuation, aberrations and absorption of the HIFU beam may result in harmful non-targeted heating. This is due to the varying acoustic impedances of the tissues crossed by the beam, thus reducing its intensity. The differing speeds of the ultrasound beam through bone to that of soft tissue, together with the variability in skull thickness, require a phase correction algorithm to achieve a coherent summation of enough energy delivery at the planned target to compensate for these effects.[11] Recent technological developments have enabled MRI-guided therapeutic application of HIFU to the brain through the intact skull (transcranial magnetic resonance-guided focused ultrasound; tcMRgFUS).[12] This technology makes use of a magnetic resonance scanner to

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provide both image guidance and thermal monitoring. In vivo thermometric measurements are possible because many parameters measurable through magnetic resonance show a dependence on temperature, and different techniques have been developed to detect temperature changes.[13,14] Magnetic resonance thermometry based on water molecule proton resonance frequency shift has been shown to be feasible in several clinical studies[15] even if sensitivity to temperature change is lower when using clinical scanners ($\leq$3T) compared to ultra-high field strength scanners.[13] Using a 1.5T scanner allows this method to measure temperature changes with good accuracy in homogeneous gel phantoms ($\pm$0.6°C) and in homogeneous tissue media ($\pm$1.5°C).[16]

Current experience of tcMRgFUS applications using 3T MRI units have already been published for the treatment of movement disorders such as essential tremor,[17,18] tremor dominant unilateral idiopathic Parkinson's disease,[18–20] as well as for the treatment of neuropathic pain[21] and treatment-refractory obsessive–compulsive disorder.[22] Previous experience has been published using a tcMRgFUS system integrated with a 1.5T unit. In their paper McDannold et al.[23] aimed at brain tumour ablation without, however, achieving any significant lesioning within the targeted area due to the low power of the device used that was a one-of-a-kind prototype (ExAblate 3000; InSightec, Haifa, Israel), which consisted of a hemispherical 512-element phased-array transducer operating at 670 kHz. Here we present the imaging protocol and the technological methods successfully used with an improved tcMRgFUS system (commonly used with 3T scanners) that for the first time has been integrated with an affordable 1.5T MRI unit.[24–26]

MRI, computed tomography and tcMRgFUS equipment

The focused ultrasound (FUS) equipment (ExAblate 4000; InSightec Ltd., Haifa, Israel) installed at our university hospital integrates with an MRI unit operating at 1.5T (Signa HDxt; GE Medical Systems, Milwaukee, WI, USA) and consists of a hemispheric 1024-element phased-array transducer operating at 650 kHz, similar to those used with the 3T MRI units. Current use of high-field MRI scanners allows the use of the magnetic resonance system body radiofrequency coil for both intra-procedural treatment planning and real-time thermal monitoring with a reasonable trade-off in terms of the signal-to-noise ratio (SNR).[27] Following internal analysis of some preliminary imaging sessions, preoperative scans obtained using the standard GE eight-channel high resolution brain array coil showed anatomical details with the required accuracy; planning images obtained using the MRI body radiofrequency coil showed generally reasonable quality in terms of anatomy visualisation and SNR, but thermal image noise was above acceptable standards for treatment. For this reason, a dedicated flexible head coil was developed (two-channel FUS-Head; InSightec Ltd., Haifa, Israel). This coil consists of two silicon-coated rings that are embedded into an elastic membrane (Figure 1(a)) used to ensure an optimal transducer to patient's head coupling once the helmet is filled with cooled and degassed water, as described by Ghanouni et al.[27] The two rings of this coil are positioned to either side of the patient's head (Figure 1(b)) and allow whole head coverage with a very good SNR (Figure 2(a–c)). If compared to that achieved using the 1.5T MRI body radiofrequency coil, this dedicated coil enabled up to 10 times larger SNR (see Appendix 1 for more details).

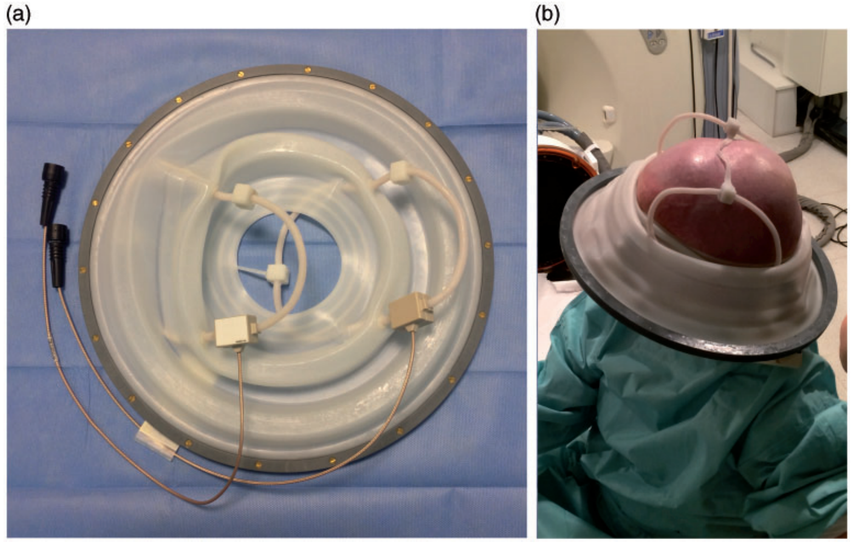

Figure 1. Dedicated two-channel FUS-Head coil embedded into the elastic membrane (a) used to ensure an optimal transducer to the patient's head coupling. Final positioning of the two rings to either side of the patient's head is shown in (b).

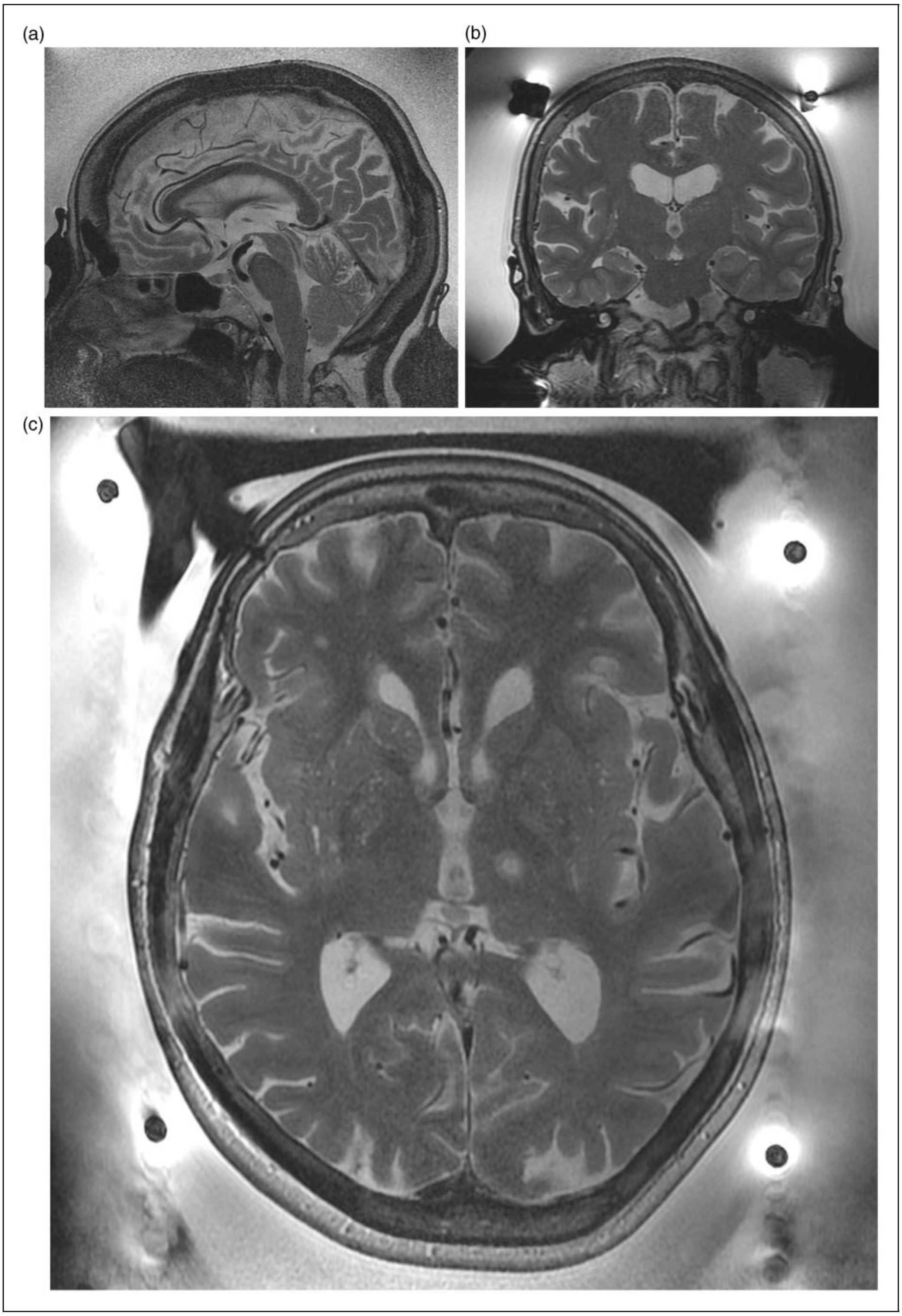

Figure 2. High resolution fast recovery fast spin echo T2-weighted (2 mm, no gap) images acquired during a treatment session using the dedicated two-channel FUS-Head coil (72-year-old essential tremor patient presenting with debilitating tremor severely affecting his right hand). Sagittal (a) and coronal (b) planning scans. Axial (c) scan acquired after the last high energy sonication (before discharging the patient from the treating table) showing the resulting thalamic therapeutic lesion. Target: left ventralis intermedius nucleus.

If it can be assumed that the SNR linearly increases with magnetic field strength,[28] we can estimate that the SNR for acquisitions with the dedicated two-channel FUS-Head with a 1.5T scanner is up to five times larger than for acquisitions with the body radiofrequency coil performed through a 3T scanner.

Table 1 reports MRI protocol parameters for screenings and follow-ups using the GE eight-channel high resolution brain phased array coil, and for intra-operative planning and monitoring using the InSightec dedicated flexible head coil. Pre-treatment computed tomography (CT) was performed using a multidetector

Table 1. Magnetic resonance sequence parameters used for screening, follow-up scans and/or magnetic resonance guidance.

	MR sequences (coil)			
Acquisition parameters	Sagittal T2 FRFSE	Cor T2-FRFSE	Axial T2 FRFSE	Axial T2-FSE IR
	(8-ch/2-ch)	(8-ch/2-ch)	(8-ch/2-ch)	(8-ch)
Slice thickness (mm)	2			
Gap (mm)	0			
TR (ms)	5269/4461	4387/5344	4380/4461	4500
TE (ms)	97/103	108/100	108/103	44
IT (ms)	–	–	–	300
ETL	24/19	21/24	21/19	8
FOV (cm)	24 × 24/22 × 22	24 × 24/22 × 22	24 × 24/22 × 22	24 × 24
Matrix	224 × 224/384 × 288	320 × 288/320 × 224	320 × 288/384 × 288	320 × 288
NEX	4–6/2	5/2	5/2	1

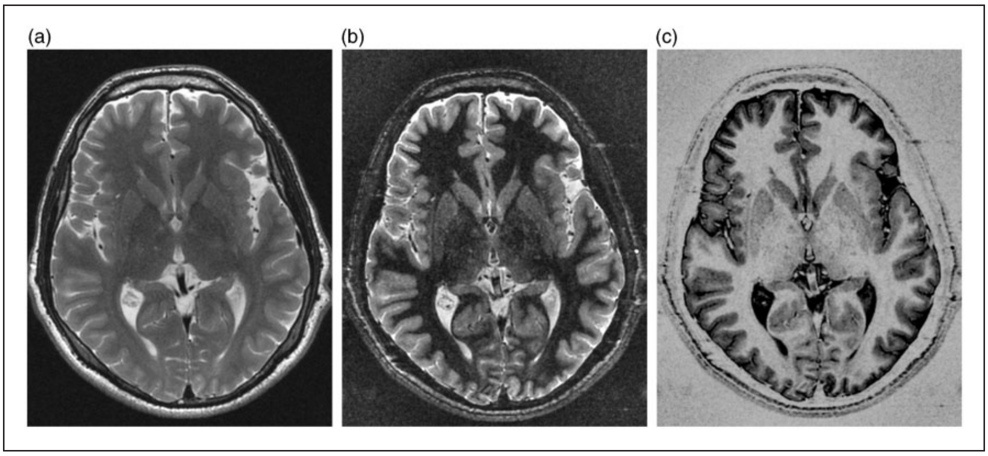

Figure 3. Example of high resolution (2 mm, no gap) images acquired with a 1.5T scanner and the standard GE eight-channel high resolution brain array coil used for off-line planning and treatment simulations: fast recovery fast spin echo T2-weighted (a), fast spin echo T2-weighted inversion recovery for white matter (b) and fast spin echo T2-weighted inversion recovery for white matter with inverted look-up table (c).

16-slice scanner (Brightspeed; GE Medical Systems, Milwaukee, WI, USA). The CT protocol employed was the following: sequential acquisition with no gantry inclination; tube voltage 120 kV; tube current 220 mAs; slice thickness 1.25 mm; spacing 0 mm; reconstruction kernel bone plus. Collected CT datasets are mandatory to calculate the skull density ratio factor using ExAblate Neuro software. The skull strongly affects the focusing and releasing energy into the planned target and, consequently, the treatment feasibility and duration.[29]

In our preliminary experience, we preferred to use fast recovery fast spin echo T2-weighted and fast spin echo inversion recovery for white matter T2-weighted sequences for planning and monitoring the procedures eventually using an inverted look-up table. This enables a very good imaging quality for the identification of the anterior and posterior commissures (Figure 2(a)) that are conventional anatomical markers during stereotactic procedures and an optimal white-to-grey matter contrast in the basal ganglia region (Figure 3).

Rarely, T1-weighted sequences were used during treatment sessions. The reason for this choice is because T2-weighting allows a better identification of the HIFU-induced lesions during the treatment session as well as signs of vasogenic perilesional oedema. Although we never had such a case, a further reason for this choice would be the better visualisation of diamagnetic blood products which characterise the acute phase of an intracranial haemorrhage; oxyhaemoglobin has a hyper-intense signal on T2-weighted sequences but only an iso or mildly hypo-intense signal on T1-weighted sequences. Each tcMRgFUS procedure performed at our centre was successfully completed without any MRI guidance-related complications with the described protocol and set-up. The ExAblate Neuro software was used for real-time MRI thermometry. All the patients received clinical relief immediately, and they were all discharged within 48 hours after the treatment.[26]

Discussion

TcMRgFUS is taking place as a revolutionary treatment modality for several neurological disorders. MRI plays a central role in these treatments. It is necessary for optimal targeting, real-time thermal monitoring and to verify intra and post-treatment effects of the focused ultrasound beam in the targeted area. In our experience with a 1.5T based tcMRgFUS installation (using the two-channel FUS-Head coil), thermal imaging was reliable and T2-weighted sequences provided the expected SNR for planning and monitoring the procedure thanks to an optimal contrast, resulting in precise treatment planning and a good localisation of the lesion during the ongoing treatment. On the other hand, when using a 3T based tcMRgFUS installation and body radiofrequency coil for imaging and thermometry, the treating physician is still required to plan a MRI brain scan post-treatment for an optimal visualisation of the generated lesion in the expected target. This is of course time consuming: emptying the water-filled transducer, releasing the patient from the treating table, stereotactic frame removal and a fast neurological examination (usually performed once the patient is out of the MRI room), can take up to one hour. This extended time of course needs to be added to the total treatment time. Considering the duration of treatment (patients may need to lay 2–3 hours or more on the dedicated treating table), this is certainly an important factor, especially from the patient's perspective and the potential risk of deep venous thrombosis from lying in a supine position for extended times, even if this is substantially mitigated by the avoidance of sedative medications and by the use of compression stockings. The quality of the MRI sequences obtained during the procedure and at the end of the treatment using the dedicated coil allowed us to plan the first MRI follow-up (using the standard GE eight-channel head coil) 48 hours after the treatment, just before discharging the patient. The only negative aspect of using the dedicated coil could be with more demanding MRI pulse sequences (i.e. diffusion, perfusion and functional imaging). On the flip side, none of these sequences is useful to identify important neuroradiological findings in the targeted area during the treatment.

Even if further insights and extended studies are required, the possibility of integrating a tcMRgFUS system with a 1.5T scanner seems to offer more advantages than disadvantages. The number of costly 3T units, even though in constant growth, is still far from the widespread 1.5T unit installations. At present, 1.5T units are still completely adequate for most MRI examinations acquired for clinical diagnostic and research purposes. Moreover, most of the medical devices used to monitor vital parameters and most of the patients' implants are still waiting to be certified for 3T MRI units.[30] A magnet operating at 3T offers a higher SNR for both structural imaging and real-time thermometry but also suffers from higher susceptibility artifacts due to any metal component (such as the helmet itself or the stereotactic frame) and dielectric artifacts from the water used to ensure an optimal transducer-to-head coupling. This could severely influence imaging quality compared to 1.5T units. One limitation of this technical note is that it was not possible to make a straight comparison with a 3T system. As a matter of fact, to our knowledge this dedicated coil for 1.5T scanners is still not available for 3T tcMRgFUS systems (although some 3T sites are using different coils wrapped around the outside of the transducer[21] or dedicated self-developed coils). After the first treatment of a patient with a functional neurological disorder using a tcMRgFUS system integrated with a 1.5T MRI unit in 2015,[31] in the following 3 years, the number of total tcMRgFUS installations has increased more than 10-fold, with more than 1000 patients already treated worldwide.[32] The results obtained at our centre using a tcMRgFUS system with a 1.5T unit led us to conclude there will be a greater spread of this promising, emerging technology even in centres that are not equipped with 3T systems, resulting in increased patient accessibility to this treatment option. This will be even more so as health regulatory systems begin to include this procedure among the current reimbursable options, extending this treatment option further. Otherwise the necessary investment (in terms of equipment costs and qualified personnel) for sites that approach this new technology will always be the largest challenge, especially out of the academic world.

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Conflict of interest

The authors declared relationships with the following companies: InSightec Ltd., Tirat Carmel, Israel (product vendor; however, this study was not sponsored by the company nor did the authors received any funds from the company). Paul Wragg is an InSightec employee.

Ethical approval

The institutional review board approved this study (Comitato Etico Palermo 1: verbale no. 04/2018 – 11/04/2018).

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Appendix 1

SNR measurements

The SNR is one of the most commonly used parameters to obtain an objective description of image quality in MRI, and is therefore used for image evaluation, radiofrequency coil comparison and quality assurance. Several methods to determine the SNR of magnetic resonance images have been described in the literature.[33,34] We measured the SNR using the approach proposed by the National Electrical Manufacturers Association (NEMA).[35] In this approach, two identical images of a homogeneous phantom are acquired with minimal time separation between the acquisitions. The images are then subtracted, and the SNR is taken to be:

$$\mathrm{SNR}_{\mathrm{NEMA}} = \frac{\sqrt{2}\overline{S}}{\sigma} \tag{1}$$

where $\overline{S}$ is the mean signal in a region of interest (ROI) containing at least 75% of the phantom area defined in either of the two original images, and σ is the standard deviation from the same ROI in the resulting subtracted image. The medical image processing, analysis, and visualisation (MIPAV; https://mipav.cit.nih.gov/) software was used to calculate the SNR following the NEMA approach.

The SNR measurements were performed with both coils on the three orthogonal planes using the same pulse sequence parameters used for treatments. To report a more detailed analysis of our system/set-up, the number of excitations (NEX) was changed between cycles of MRI acquisitions for each plane. The phantom used for these tests is InSightec's daily quality assurance gel phantom (the one commonly used to ensure proper function of the ExAblate system before each treatment) (Figure 4(a and b).

On all tests we performed, as can be seen from Table 2, the dedicated surface coil allowed acquisitions with a significant gain in SNR values compared to the body radiofrequency coil. These results confirm the great potential of tcMRgFUS systems integrated with 1.5T magnets when a dedicated surface flexible coil is used.

Table 2. SNR calculation results.

		SNR (gain)		
Coil	NEX	Sagittal plane	Coronal plane	Axial plane
Body RF	1	6.6	3.7	2.5
2-ch FUS		21.8 (3.31)	22.6 (6.11)	27.5 (10.91)
Body RF	4	13.6	7.0	5.1
2-ch FUS		44.5 (3.27)	40.6 (5.77)	51.5 (10.20)
Body RF	6	16.7	9.3	6.0
2-ch FUS		56.9 (3.41)	58.8 (6.30)	67.3 (11.14)

NEX: number of excitations; SNR: signal-to-noise ratio; RF: radiofrequency; FUS: focused ultrasound. The ratio values of the two-channel FUS coil SNR to the body RF coil SNR are reported in brackets.

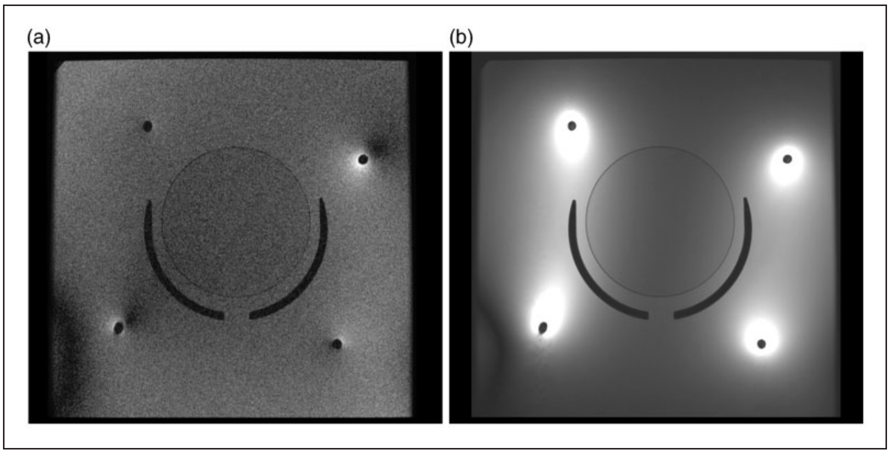

Figure 4. Example of the magnetic resonance imaging (MRI) scans used for signal-to-noise ratio measurements at 1.5T using a daily quality assurance gel phantom set-up. Axial scans acquired with the MRI body radiofrequency coil (a) and with the dedicated two-channel FUS-Head coil (b). Scan parameters reported in Table 1; images from acquisitions with four averages are shown.