Safety of Ultra-High Field MRI: What are the Specific Risks?

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Abstract There are currently more than 50 ultra-high field (7 T and above) MRI systems installed around the world. The vast majority of these perform studies on humans, whether healthy volunteers, volunteers for clinical research, or actual patients. The increased magnetic field strength potentially raises new safety concerns in the areas of the effects of the static magnetic field itself, increased power deposition due to the higher operating frequency, and acoustic noise. There are currently very different operational modes in different institutions, with policies effectively set by local ethics committees. This article summarizes the current legal and practical status regarding safety of ultra-high field MRI.

Keywords MRI safety · Static magnetic field · Ultra-high field MRI

Introduction

Since the three major commercial MRI vendors (General Electric, Philips and Siemens) started to produce ultra-high field (UHF) MRI scanners for human imaging in circa 2002, the installed-base has increased rapidly, reaching approximately 55 sites with systems of 7 T or above in 2014. This rapid growth in the number of UHF-MRI sites has quickly

led to the development of scanning protocols [1–3] and the required hardware (brain [4–6], cardiac [7, 8], body [9, 10], spine [11, 12], breast [13, 14], and eye [15]) to enable the use of UHF-MRI in both fundamental and clinical research studies as well as in pilot studies for pure clinical use [16–18]. A recent review article provides a comprehensive overview of the current status of high field MRI [19••].

This sharp increase in the use of UHF-MRI has led to important questions regarding the safety of UHF-MRI in general, the legal status of UHF-MRI, and safety concerns when scanning subjects with different types of implants (surgical, dental, etc.) within the body. In this review article, the currently-available literature and the relevant safety policies are discussed. UHF-MRI is defined here as human MRI scanners with a magnetic field strength greater or equal to 7 T. Where appropriate and applicable, clinical field strengths of 1.5 and 3 T are used as a comparative references, but studies on animals at comparable and much higher fields are not discussed. We start by describing the legal status of UHF-MRI in the United States of America (USA), the European Union (EU), and Asia (specifically China and Japan). Subsequently, safety issues concerned with (i) the main magnetic field strength, (ii) projectile forces, (iii) local and global power deposition, and the associated specific absorption rate (SAR), in the subject, and (iv) acoustic noise are reviewed. After these general safety considerations, the subjective experience of UHF participants is described and compared to clinical field strengths. Finally, screening for, and safety of, implants are discussed.

Legal Status

In 2003, the Food and Drug Administration (FDA) in the USA declared that MRI up to 8 T constituted a non-

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significant risk device for adults, children, and infants of 1 month and older; for neonates (defined as infants younger than 1 month) 4 T was declared to be the upper-limit [20•]. The implication of this report is that in the USA approval from the institutional review board (IRB) is required to scan human subjects with UHF-MRI, but it is *not* necessary to apply for an investigational device exemption (IDE) that would require substantially more paperwork. To date only scanners with a maximum field strength of 3 T have received FDA clearance for purely clinical (i.e., with no research element) scanning without the requirement for IRB approval: scanning for purely clinical purposes above 3 T requires IRB approval.

European law, as stated in the general Medical Device Directive (current version Amendment M5—Directive 2007/47/EC of the European Parliament and of the Council of 5 September 2007), requires “safe use of the device”, which needs to be proved by adhering to an accepted international standard. For MRI, this is the International Electrotechnical Commission IEC-60601-2-33 standard and periodic updates thereof. Within this standard, magnetic field strengths of 3 T or less constitute the normal operating mode, field strengths between 3 and 4 T constitute the first level controlled operating mode, and above 4 T the second level controlled operating mode (effectively requiring IRB-approval). Currently, an amendment to increase the first level control operating mode to 8 T is under discussion, but may take significant time before acceptance. Important in this discussion was the publication of the report from the International Commission on Non-Ionizing Radiation Protection (ICNIRP) in 2009 that stated “In conclusion, current information does not indicate any serious health effects resulting from acute exposure to static magnetic fields up to 8 T. It should be noted, however, that such exposures can lead to potentially unpleasant sensory effects such as vertigo during head or body movement” [21]. Guidelines in Asia are similar to those in the EU in that they adhere to the IEC standard.

Biological Effects of the Main Magnetic Field Strength

Interactions between a strong magnetic field and biological tissues can occur due to magnetic induction, magneto-mechanical effects, or electronic interactions [22]. Magnetic induction effects can be subdivided into Lorentz forces and induced currents. Lorentz forces refer to the situation in which a charged particle moves through a static magnetic field, and experiences a force in a direction perpendicular to the motion. Since the Lorentz force is proportional to both the velocity as well as the magnetic field strength, it has been suggested that this force could be significant for blood flow in the aortic arch at UHF [23].

However, extensive measurements of cardiovascular responses in piglets and healthy volunteers at 8 T did not show any clinically significant changes in blood pressure, heart rate, cardiac output, or left ventricular pressure [24]. No clinically significant findings in vital signs were observed in patients with cerebral pathology at 8 T [25]. Finally, when comparing basic cardiovascular parameters as a function of field strength (1.5, 3, 4.5, 6, and 8 T) a significant increase in only the systolic blood pressure was seen (there were no differences in heart rate, respiratory rate, diastolic blood pressure, finger pulse oxygenation levels, core body temperature via an external auditory canal temperature, or fiber optic core body sublingual temperatures). However, the maximum effect (an increase of 3.6 mm Hg at 8 T in systolic blood pressure) was only half that produced by changing postural position [26•], and, therefore, is not considered clinically relevant in most subjects or patients (with a possible exception of e.g., patients with orthostatic hypotension).

Recently, it has been proposed theoretically and supportive experimental evidence has been acquired, that the Lorentz force on the ionic fluid inside the semicircular canals causes vestibular activation leading to nystagmus (a slow involuntary motion of the eye), a feeling of “moving along a curve”/rotation, vertigo, and in the most extreme cases nausea [27••, 28•]. Nystagmus and the perception of rotation persist even after the subject has reached the centre of the scanner and table motion has stopped. Since vestibular activation arises from the interaction between ionic flow and the magnetic field, the fact that the perception persists when lying still in a strong magnetic field is consistent with this explanation, i.e., no motion through the magnetic field is necessary to induce these effects. When the subject is removed from the scanner the opposite direction of nystagmus and perceived curved motion is experienced. After-effects of vestibular activation have been shown to last for at least 2 min after a 30 min exposure to 7 T, as proven by a significant influence on the sway path, and up to 15 min for body axis rotation according to the Unterberger’s stepping test [29]. However, other studies have shown a relation between the occurrence of vertigo and the speed at which the patient enters the magnet through the inhomogeneous magnetic field [30], with a higher speed introducing a higher occurrence. Thus, there appear to be two different effects that are present, one dynamic and one static, and one might hypothesize that the vertigo caused by vestibular effects is enhanced by the co-occurrence of motion. This could be a topic of further study.

The second component of magnetic induction effects is currents induced in static tissue when the body moves through an inhomogeneous magnetic field, as dictated by Faraday’s law of induction. This occurs both for a subject

being placed inside the MRI scanner as well as for MRI technicians who are moving in the vicinity of the UHF scanner. Crozier has shown that even at 4 T the induced currents can be significant in such situations [31]. These induced currents have been linked to various sensations, such as the occurrence of magnetic phosphenes and feelings of vertigo. Phosphenes are stimulations of the optic nerve or the retina, which produce a flashing light sensation in the eyes, but are considered not to be dangerous or long-lasting. Phosphenes can be generated by the stimulation of several different visual areas which are at the low level of anatomical cortical hierarchy. There appears to be an individual threshold level for phosphene generation, with the sizes of the phosphenes increasing as a function of the dB/dt .

Magneto-orientation and magneto-mechanical translations (i.e., reorienting and forces on diamagnetic or paramagnetic materials in the body) are thought to be too small to have a significant effect on human subjects in an UHF-MRI scanner [22, 32•]. Also, the influence of a strong static magnetic field on the rate of chemical reactions due to electron spin interactions on radicals pairs has been suggested, but is not considered to be a significant physiological effect [22, 32•].

A question which is of relevance to many functional MRI studies is whether the result of all of the effects considered above actually alters the ability to perform cognitive tasks inside the magnet. In order to test, this hypothesis cognitive tests have been performed using various tasks at many different field strengths. Since there had been no consistent finding that cognitive tests give different results when the patient is located outside or inside the magnet, the ICNIRP in 2009 stated that “...current information does not indicate any serious health effects resulting from the acute exposure of stationary humans to static magnetic fields up to 8 T”. In 2011, Heijnrich et al. published a meta-analysis of the influence of the magnetic field strength on cognition (including all papers published before August 2010). They concluded that for the visual system only a small but significant effect was present [33], although as the authors pointed out the studies included in the meta-analysis were quite heterogeneous in nature [34]. Thereafter, the same group performed a study in which healthy subjects were randomly tested while stationary in the iso-center of 0 (mock magnet), 1.5, 3, and 7 T MRI scanners, as well as in a dynamic situation produced by moving the patient table in a sinusoidal motion at the location of the steepest gradient of the magnetic field. No significant effects on cognitive function were found at any field strength or condition [35•]. In contrast, studies by the group of De Vocht showed some small but significant effects on attention/concentration and visuospatial orientation when the subject was positioned in

the stray field of a 7 T scanner both when stationary and also after moving their head [36, 37]. Bearing in mind the recent studies, discussed previously, on nystagmus, it would be interesting to investigate whether this could explain the observed cognitive effects in the visuospatial and attention/concentration domain, and to replicate the possible relation between nystagmus and these cognitive effects in a magnetic field free environment during vestibular activation [38].

Physical Effects of the Main Magnetic Field Strength: Projectile Forces

The projectile forces, i.e., the force with which a magnetic object is accelerated toward the region with the highest magnetic field, are proportional to the product of the magnetic field and the spatial magnetic field gradient ($B_0 \cdot dB_0/dx$). This force is much smaller for paramagnetic than for ferromagnetic objects and, therefore, the main concern regards ferromagnetic objects. This suggests that, in addition to the actual magnetic field strength of the scanner, an equally important criterion is whether the magnet is actively or passively shielded. As an example, as shown in Capstick et al. [39] the projectile force close to the bore of the magnet is only slightly higher for a passively shielded 7 T scanner than for an actively shielded 3 T clinical scanner from the same vendor (all modern 3T scanners are currently actively shielded). The current (post ~ 2010) generation of UHF-scanners uses actively shielded 7 T magnets, with the footprint being very similar to that of actively shielded 3 T scanners, implying that similar safety policies as for 3 T MRI scanners can be applied with respect to magnetic objects. However, for 7 T magnets which are not actively shielded, it is even more important that special training is given to all personnel since projectile forces are significant at distances much further from the magnet than for 3 T systems, and even with substantial passive steel shielding, the 5 gauss line is often outside the RF-shielded room.

Tissue Heating from Transmitted Electromagnetic (EM) Fields

Heat is created in the body by the interaction of the electric field component of the EM field, generated by the transmit coil with the conductive elements (tissue, blood, skin) of the body. The power deposited in the body is quantified in terms of the SAR measured in W/kg. The SAR is proportional to the product of the conductivity and the square of the electric field. The mechanism by which heat is generated is the induction of eddy currents in conductive tissue

according to Faraday's law. Two different SAR measures relevant to clinical MR scanning follow from these, namely local 10 g SAR and the whole body SAR. As the terms suggest the local SAR is defined as the peak SAR value after spatial averaging over any 10 g of tissue, whereas the partial or whole body SAR is spatially averaged over the entire body and can be estimated from the total RF power deposited in the body. At low field the SAR increases as the square of the operating frequency [40]. The same legal SAR-regulations are applicable to UHF-MRI as at lower field strengths. The FDA limits are: whole body average 4 W/kg for 15 min, head/trunk local (1 g tissue) 8 W/kg for 10 min, extremities (1 g tissue) 12 W/kg in 5 min. The IEC has three levels, with all values over a 6 min average: normal (all patients), whole body average 2 W/kg, head/trunk local 10 W/kg, and extremities local 20 W/kg; first level (supervised) 4 W/kg, 10 W/kg, and 20 W/kg, respectively; second level (IRB approval) 4 W/kg, >10 W/kg, and >20 W/kg, respectively. Testing uses an American Standards of Tests and Measurements (ASTM) standard [41]. The assumption when using the phantoms recommended by the ASTM (which mimic the dielectric properties of tissue) is that the spatial distribution of the EM field is well-characterized, which means that the position of the highest electric field, and therefore highest heating, can be predicted and thermal measurements can, therefore, be performed at that location. However, at 7 T the wavelength of the EM fields in the tissue-mimicking materials is ~ 13 cm [42], which means that wave interference occurs inside the phantom which makes prediction of the location of maximum heating much more difficult. Therefore, many high field studies have deviated from the strict guidelines of the ASTM standard, or have attempted to measure the electric fields directly. It should be noted that, despite wave interference effects, many groups have shown that these do not always lead to a higher local relative to global SAR [42, 43]. Taken all these effects into account, it has been shown that the whole body SAR does not show a quadratic relationship, but more closely adheres to a linear increase with field above 3 T [42]. As with lower field strengths, the vendors use a simplified body/head model to estimate the SAR of a particular imaging sequence, given the EM field characteristics of the particular coil being used. There is then, typically, a further factor-of-two safety margin built into the scanning limits.

One of the areas of very active research at high field is the use of transmit array technology, in which the transmit RF coil consists of a number of independent channels, each of which can be separately controlled in terms of the magnitude and phase of the transmit power. These systems have been commercially released for 3 T (dual-transmit from all three major vendors) and are available for up to

eight channels on 7 and 9.4 T systems. The fact that the magnitude and phase of each of the separate channels can be different for each patient makes the process of SAR estimation much more complicated, with potentially higher risk of producing a "hot-spot". This higher risk is caused by the very nature of parallel transmit: tailoring the RF distribution by constructive and destructive interference. As an example, if one or more transmit coils were to malfunction, the local power deposition can be higher than the calculated level due to the absence of an element of destructive interference. The safety considerations of parallel transmit are, however, not an UHF-MRI specific safety issue, but a more generic safety issue [44].

Acoustic Noise

As described by Lorenz' law, currents in the gradient coils impose forces on the conductors due to the presence of the strong magnetic field, thereby leading to physical vibrations. These vibrations are coupled into the magnet structure and are manifested as acoustic noise [45, 46]. Since the forces are proportional to the strength of the magnetic field, one would expect higher noise levels for higher magnetic fields, as indeed has been noted for example in the 0.2–3.0 T range [47]. However, the amount of acoustic noise produced by an MRI scanner depends critically on the engineering of the gradient coil and the imaging sequences used, and this non-linearity is making direct predictions highly non-trivial. In terms of UHF-MRI measurements, echo planar imaging was found to be only slightly louder (105 dB) at the entrance-bore of a 7 T scanner than on a clinical 3 T scanner (103 dB) made by the same manufacturer, although the imaging sequences were not specifically designed to be comparable [39]. Also, a conference abstract showed similar maximum noise levels (112 dB) for sinusoidal EPI acquired at 7 T as on lower field MRI scanners [48]. From a practical point-of-view, a very important difference is that commercial head-coils for 7 T MRI are designed with a multi-channel (32 or 16) array insert which is much more tightly fitting than standard head coils at 3 T, making it impossible to employ double ear protection (ear plugs plus headphones) at 7 T, and one has, therefore, to rely solely on ear plugs. The major disadvantage of the use of ear plugs is that their noise suppression is highly dependent on how well they are inserted, the geometry of the subject's ear canal, and they are also prone to being dislodged during patient handling or scanning. It is, therefore, not surprising that approximately one-third of the participants undergoing a 7 T MRI examination reported acoustic noise as an important distress factor [49].

Subject Experience of UHF-MRI

Several groups have studied the subjective perception of comfort/discomfort and sensory experiences of their volunteers and patients by means of post-exam questionnaires [49, 50, 51, 52]. In our institute, the most important effects were dizziness when moving into the scanner (34 % of 101 healthy subjects), scanner noise (33 %), dizziness moving out of the scanner (30 %), dizziness during scanning (14 %), and metallic taste (11 %) [49]. These findings are similar to studies co-ordinated by the high field group in Essen, Germany [51, 52]. In these latter studies, from a total number of 573 subjects, only 10 % of the subjects rated at least one source of discomfort with a score of 8 or higher on a 10 point scale ranging from 0 = not unpleasant at all (or no sensations) to 10 = very unpleasant/unbearable (very strong sensation). The long scan duration (on average 72 min) was the main reason for discomfort, with vertigo and the requirement to lie completely still noted as other sources of discomfort. In 166 patients, a parallel questionnaire was filled in after a 1.5 T examination. The main differences between experiences at the two field strengths arose from the longer exam duration, the higher acoustic noise, the lower room temperature, and reduced contact with the operator (due to lack of clinical experience of the operator). It should be noted that none of these effects are intrinsic to high field imaging per se: many institutions limit the total scanning time to 1 h, the same as for a 3T scan, and have experienced technicians running the systems. Regarding specific sensations, the main differences were the more severe experience of vertigo at 7T as well as feelings of nausea, headache, fear, unreality, and experiences of sweat attacks, light flashes, and tachycardia. However, the average score for these sensations, except for the vertigo, was very low (0.5 or smaller on the 10 point scale).

Taken together, these data suggest that besides issues related specifically to a research as compared to clinical-setting and operation (long examination times, long time lying still, poor operator communication), the most prominent side-effect of UHF-MRI is increased dizziness, probably caused by vestibular effects as discussed previously. In general, UHF-MRI is very well tolerated as, for example, evidenced by only 3 % of the subjects rating a 7 T examination overall as unpleasant [49].

Safety of Implants

An informal survey among the UHF sites present at the ISMRM ultra-high field MRI workshop in Noordwijk in 2013 showed a wide variation in local policies at 7 T for scanning subjects with implants. Several sites relied on information from the MRI safety website (<http://www.mrisafety.com>), the official site of the Institute for Magnetic Resonance Safety, Education, and Research. As of March 2014, however, this site had only tested three objects at 7 T: two contrast agent delivery systems and a human-implantable microchip, all labelled Conditional 5. Some sites required proper testing according to the ASTM guidelines, whereas others relied on their local testing procedures. The ASTM guidelines include testing procedures for displacement force, torque, RF heating, and the influence on image quality [53, 54]. Whereas the first two testing procedures are rather straightforward, as outlined earlier positioning of the implant at the worst case location for RF-heating testing is much more challenging at UHF than for lower fields, due to the substantially increased non-uniformity and asymmetric nature of the EM fields in conducting samples, i.e., how does one verify that the location of maximum heating is actually being probed? It has been suggested that EM-simulations should first be performed in order to obtain a good indication of the worst case situation, before actual measurements are performed [55]. In general, one has to be very careful with implants whose dimensions are close to one-half wavelength, as for lower fields [56].

Although at quite a few UHF-sites the profile of scanned subjects is restricted to 20–30 year old healthy subjects, as is for example the case for sites focusing on normal cognition or technical development, an increasing number of sites are also including older subjects as well as patients (see e.g. [50]). Even in the younger population some implants are highly prevalent, for example dental retainer wires (local experience showed that approximately 25–50 % of the potential volunteers in this age range have such a retainer wire in place). Both simulations as well as phantom experiments of these wires showed that the maximum temperature rise is less than 1.6 °C even when using five times the allowed SAR level [57]. No adverse effects have been observed after more than 20 volunteers with dental retainer wires have undergone head 7 T scans. The authors conclude, therefore, that “Overall our simulations and supporting experiments suggest that volunteers and patients with dental wires can be scanned on a 7T system without the risk of enhanced SAR”. However, it should be noted that this study focused on the practical safety issues without adhering strictly to the ASTM guidelines.

When scanning older subjects and patients, one of the more frequently seen implants are cardiac stents. Unfortunately, there are relatively few data available on the displacement force or torque although one ISMRM-abstract tested twenty stents and recorded a maximum deflection angle of 33°, which is smaller than the gravitational force [58]. Potential heating due to RF deposition has been investigated by Santoro et al. who showed a temperature rise around 3 °C near the tip of the stent for a 60 min scan at a SAR-level three times higher than the IEC

guidelines. The authors conclude "... if IEC guidelines for local/global SAR are followed, the extra RF heating induced in myocardial tissue by stents may not be significant versus the baseline heating induced by the energy deposited by a tailored cardiac transmit RF coil at 7.0 T, ...". However, in practice more than one cardiac stent is frequently implanted and the quoted study did not show whether combinations of more than one stent can also be considered safe. Of course, this is a challenging question, since the exact positioning of the stents with respect to each other and occurrence of partial overlap as well as difference in total length, provides a very large parameter space to investigate.

The group of Vanderbilt tested 28 different implants and objects ranging from aneurysm clips and biopsy tissue markers to an armor-piercing bullet! Nine of the 28 objects showed a deflection angle of greater than 45°, which according to the ASTM guidelines could pose a safety risk. Among these nine objects, several are actually considered conditionally safe or even MR safe at 3T. Using the argument that the UHF-MRI scanners do not have a body-coil, the authors only tested the RF heating for brain implants which would be located inside the head-coil. The temperature rise did not exceed the 1 °C during 18.5 min of scanning at 100 % of the allowed SAR.

Besides these studies, other published articles describe safety studies of aneurysm clips [59], implants for ear-nose-throat surgery [60], upper eye implants [61], cranial fixation plates [62], an EEG-cap [63], intraocular lenses [64], actuators [65], ballistic objects [66], and extracranial neurosurgical implants [67].

Conclusion

During more than a decade of experience with UHF-MRI, no severe adverse effects have been reported and all studies on subjective acceptance of UHF-MRI have shown good acceptance both by normal volunteers as well as patients. The only important side-effect that is frequently reported is vertigo resulting in the most extreme cases in nausea. Until a few years ago, this was mainly attributed to rapid patient table-motion through an inhomogeneous magnetic field, but the latest studies have indicated that a more plausible cause is vestibular activation due to Lorentz forces on ion currents in the semicircular loops. These forces can also cause involuntary eye motion, i.e., nystagmus. Taking all these observations into account, the conclusion is that UHF-MRI is, safety-wise, highly comparable to clinical systems at 3 or 1.5 T. However, the legal status of UHF-MRI as well as official documentation is currently lagging well behind the lower field strengths. Acceptance of the amendment to the IEC standards to increase the first level

control operating mode to 8 T would open up the possibility of CE-marking of UHF-MRI scanners, as well as formal FDA approval for clinical scanning. Although not changing many applications at UHF-MRI in practice, because scientific experiments with normal volunteers as well as patients would still require IRB approval, it would ease the way for diagnostic clinical use of UHF-MRI. Due to the lack of formal approval of UHF-MRI scanners, in many countries it is troublesome or indeed impossible to obtain financial reimbursement for clinical UHF-MRI scans, even in situations in which UHF-MRI would enhance diagnosis compared to 3T MRI alone. Of course, the vendors of UHF-MRI would still need to do the formal application for FDA-approval and CE-marking even after the potential change by the IEC to approve use of UHF-MRI in the first level control operating mode.

Currently, the main problem for deciding whether to scan subjects with implants is the lack of exchange of results of safety tests performed at the different UHF sites. Although several sites publish some findings of their safety tests, many more implants have been tested completely or partially in the different institutes than have not been published in official journals. This lack of publication as well as the scatter of the few published studies throughout diverse journals, can probably be explained by the necessary time-investment to publish these results and the lack of interest in accepting publications of safety testing on a single implant by the different journals. There is also disagreement as to how valid the ASTM testing method established for 3 T and 1.5 T is for 7 T studies, and how it should be adapted to recognize the very different EM properties of tissue at higher fields. In general, it is agreed that careful simulations of the electric fields encountered at the anatomical location of the implant should guide the phantom experiments [55]. Simulations should be performed in a wide variation of body compositions and dimensions to be able to discern the worst case scenario. Some guidelines on the how to perform these simulations as well as how to provide convincing evidence that in a phantom experiment a realistic worst case scenario has truly been tested would be very helpful. Overall, a general repository of test results, for example hosted by the International Society for Magnetic Resonance in Medicine, would represent a big step forward in promoting clinical use of UHF-MRI.

Compliance with Ethics Guidelines

Conflict of Interest Dr. Matthias J. P. van Osch and Dr. Andrew G. Webb each declare no potential conflicts of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been highlighted as:

- Of importance
- Of major importance

1. Moenninghoff C, Maderwald S, Theysohn JM, Kraff O, Ladd ME, El HN, van de Nes J, Forsting M, Wanke I. Imaging of adult astrocytic brain tumours with 7 T MRI: preliminary results. *Eur Radiol.* 2010;20(3):704–13.
2. Lupo JM, Chuang CF, Chang SM, Barani IJ, Jimenez B, Hess CP, Nelson SJ. 7-Tesla susceptibility-weighted imaging to assess the effects of radiotherapy on normal-appearing brain in patients with glioma. *Int J Radiat Oncol Biol Phys.* 2012;82(3):e493–500.
3. Visser F, Zwanenburg JJ, Hoogduin JM, Luijten PR. High-resolution magnetization-prepared 3D-FLAIR imaging at 7.0 Tesla. *Magn Reson Med.* 2010;64(1):194–202.
4. Petridou N, Italiaander M, van de Bank BL, Siero JC, Luijten PR, Klomp DW. Pushing the limits of high-resolution functional MRI using a simple high-density multi-element coil design. *NMR Biomed.* 2013;26(1):65–73.
5. Adriany G, Van de Moortele PF, Wiesinger F, Moeller S, Strupp JP, Andersen P, Snyder C, Zhang X, Chen W, Pruessmann KP, Boesiger P, Vaughan T, Ugurbil K. Transmit and receive transmission line arrays for 7 Tesla parallel imaging. *Magn Reson Med.* 2005;53(2):434–45.
6. Shajan G, Kozlov M, Hoffmann J, Turner R, Scheffler K, Pohmann R. A 16-channel dual-row transmit array in combination with a 31-element receive array for human brain imaging at 9.4 T. *Magn Reson Med.* 2013;71(2):870–9.
7. Snyder CJ, DelaBarre L, Metzger GJ, Van de Moortele PF, Akgun C, Ugurbil K, Vaughan JT. Initial results of cardiac imaging at 7 Tesla. *Magn Reson Med.* 2009;61(3):517–24.
8. Graessl A, Renz W, Hezel F, Dieringer MA, Winter L, Oezderdem C, Rieger J, Kellman P, Santoro D, Lindel TD, Frauenrath T, Pfeiffer H, Niendorf T. Modular 32-channel transceiver coil array for cardiac MRI at 7.0T. *Magn Reson Med.* 2013;72(1):276–90.
9. Umutlu L, Maderwald S, Kinner S, Kraff O, Bitz AK, Orzada S, Johst S, Wrede K, Forsting M, Ladd ME, Lauenstein TC, Quick HH. First-pass contrast-enhanced renal MRA at 7 Tesla: initial results. *Eur Radiol.* 2013;23(4):1059–66.
10. Raaijmakers AJ, Ipek O, Klomp DW, Possanzini C, Harvey PR, Legendijk JJ, van den Berg CA. Design of a radiative surface coil array element at 7 T: the single-side adapted dipole antenna. *Magn Reson Med.* 2011;66(5):1488–97.
11. 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):734–40.
12. Vossen M, Teeuwisse W, Reijnders M, Collins CM, Smith NB, Webb AG. A radiofrequency coil configuration for imaging the human vertebral column at 7 T. *J Magn Reson.* 2011;208(2):291–7.
13. McDougall MP, Cheshkov S, Rispoli J, Malloy C, Dimitrov I, Wright SM. Quadrature transmit coil for breast imaging at 7 Tesla using forced current excitation for improved homogeneity. *J Magn Reson Imaging.* 2014. doi:10.1002/jmri.24473.
14. van de Bank BL, Voogt IJ, Italiaander M, Stehouwer BL, Boer VO, Luijten PR, Klomp DW. Ultra high spatial and temporal resolution breast imaging at 7T. *NMR Biomed.* 2012;26(4):367–75.
15. Beenakker JW, van Rijn GA, Luyten GP, Webb AG. High-resolution MRI of uveal melanoma using a microcoil phased array at 7 T. *NMR Biomed.* 2013;26(12):1864–9.
16. Van der Kolk AG, Hendrikse J, Zwanenburg JJ, Visser F, Luijten PR. Clinical applications of 7 T MRI in the brain. *Eur J Radiol.* 2013;82(5):708–18.
17. Moser E, Stahlberg F, Ladd ME, Trattnig S. 7-T MR—from research to clinical applications? *NMR Biomed.* 2012;25(5):695–716.
18. Versluis MJ, van der Grond J, van Buchem MA, van Zijl P, Webb AG. High-field imaging of neurodegenerative diseases. *Neuroimaging Clin N Am.* 2012;22(2):159–71.
19. •• Kraff O, Fischer A, Nagel AM, Moenninghoff C, Ladd ME. MRI at 7 Tesla and above: demonstrated and potential capabilities. *J Magn Reson Imaging.* 2014. doi:10.1002/jmri.24573. *Excellent review of the current status of ultra-high field MRI both regarding technical challenges and solutions as well as clinical applications.*
20. • U.S. Department of Health and Human Services, Food and Drug Administration, Center for Devices and Radiological Health. Criteria for significant risk investigations of magnetic resonance diagnostic devices. 2003. <http://www.fda.gov/downloads/MedicalDevices/DeviceRegulationandGuidance/GuidanceDocuments/UCM072688.pdf>. Accessed April 2014. *Basic document stating that MRI up to 8 Tesla is considered a non-significantly risk device for human subjects older than 1 month.*
21. International Commission on Non-Ionizing Radiation Protection. Amendment to the ICNIRP Statement on medical magnetic resonance (MR) procedures: protection of patients. *Health Phys.* 2009;97(3):259–61.
22. International Commission on Non-Ionizing Radiation Protection. Guidelines on limits of exposure to static magnetic fields. *Health Phys.* 2009;96(4):504–14.
23. Kinouchi Y, Yamaguchi H, Tenforde TS. Theoretical analysis of magnetic field interactions with aortic blood flow. *Bioelectromagnetics.* 1996;17(1):21–32.
24. Kangarlou A, Burgess RE, Zhu H, Nakayama T, Hamlin RL, Abduljalil AM, Robitaille PM. Cognitive, cardiac, and physiological safety studies in ultra high field magnetic resonance imaging. *Magn Reson Imaging.* 1999;17(10):1407–16.
25. Yang M, Christoforidis G, Abduljali A, Beversdorf D. Vital signs investigation in subjects undergoing MR imaging at 8T. *AJNR Am J Neuroradiol.* 2006;27(4):922–8.
26. • Chakeres DW, Kangarlou A, Boudoulas H, Young DC. Effect of static magnetic field exposure of up to 8 Tesla on sequential human vital sign measurements. *J Magn Reson Imaging.* 2003;18(3):346–52. *Study of vital signals over a wide range of magnetic field strengths (8, 6, 4.5, 3, and 1.5 Tesla). The only statistically significant effect of magnetic field strength was observed with systolic blood pressure, although this effect was of comparable magnitude as observed during a postural change.*
27. •• Roberts DC, Marcelli V, Gillen JS, Carey JP, Della Santina CC, Zee DS. MRI magnetic field stimulates rotational sensors of the brain. *Curr Biol.* 2011;21(19):1635–40. *First study to suggest that interactions between ionic currents in the endolymph of the vestibular labyrinth and the static magnetic field result in vestibular activation causing nystagmus.*
28. • Mian OS, Li Y, Antunes A, Glover PM, Day BL. On the vertigo due to static magnetic fields. *PLoS One.* 2013;8(10):e78748. *Many different experiments to further explore the occurrence of nystagmus and vertigo during UHF-MRI examinations after the seminal paper of Roberts et al (27) that proposed ionic currents in semi-circular loops as the cause of vestibular activation.*
29. Theysohn JM, Kraff O, Eilers K, Andrade D, Gerwig M, Timmann D, Schmitt F, Ladd ME, Ladd SC, Bitz AK. Vestibular effects of a 7 Tesla MRI examination compared to 1.5 T and 0 T in healthy volunteers. *PLoS One.* 2014;9(3):e92104.

30. Fulton SC, Horovitz SG, Duyn J. Comparative study of patient comfort at 7T and 3T MRI. *Proceedings of the SMRT* 2006.
31. Crozier S, Liu F. Numerical evaluation of the fields induced by body motion in or near high-field MRI scanners. *Prog Biophys Mol Biol*. 2005;87(2–3):267–78.
32. • Schenck JF. Physical interactions of static magnetic fields with living tissues. *Prog Biophys Mol Biol*. 2005;87(2–3):185–04. *Good review article concerning the physical interactions of static magnetic field with living tissues.*
33. Heinrich A, Szostek A, Nees F, Meyer P, Semmler W, Flor H. Effects of static magnetic fields on cognition, vital signs, and sensory perception: a meta-analysis. *J Magn Reson Imaging*. 2011;34(4):758–63.
34. de Vocht F, Stevens T, Kromhout H. Comment on: effects of static magnetic fields on cognition, vital signs, and sensory perception: a meta-analysis. *J Magn Reson Imaging*. 2012;35(1):235–6.
35. • Heinrich A, Szostek A, Meyer P, Nees F, Rauschenberg J, Grobner J, Gilles M, Paslakis G, Deuschle M, Semmler W, Flor H. Cognition and sensation in very high static magnetic fields: a randomized case-crossover study with different field strengths. *Radiology*. 2013;266(1):236–45. *Detailed study on the effect of high magnetic field and magnetic field gradients on cognition.*
36. van Nierop LE, Slottje P, van Zandvoort MJ, de Vocht F, Kromhout H. Effects of magnetic stray fields from a 7 Tesla MRI scanner on neurocognition: a double-blind randomised crossover study. *Occup Environ Med*. 2012;69(10):759–66.
37. de Vocht F, Glover P, Engels H, Kromhout H. Pooled analyses of effects on visual and visuomotor performance from exposure to magnetic stray fields from MRI scanners: application of the Bayesian framework. *J Magn Reson Imaging*. 2007;26(5):1255–60.
38. Tabak S, Collewyn H. Human vestibulo-ocular responses to rapid, helmet-driven head movements. *Exp Brain Res*. 1994;102(2):367–78.
39. Capstick M, McRobbie D, Hand J, Christ A, Kuhn S, Mild H, Cabot E, Li Y, Melzer A, Papadaki A, Pruessmann KP, Quest R, Rea M, Ryf S, Oberle M, Kuster N. An investigation into occupational exposure to electromagnetic fields for personnel working with and around medical magnetic resonance imaging equipment. 2008. <https://www.myesr.org/html/img/pool/VT2007017FinalReportv04.pdf>. Accessed April 2014.
40. Bottomley PA. Turning up the heat on MRI. *J Am Coll Radiol*. 2008;5(7):853–5.
41. ASTM International. Measurement of radio frequency induced heating on or near passive implants during magnetic resonance imaging. West Conshohocken: ASTM International; 2011.
42. Collins CM, Smith MB. Signal-to-noise ratio and absorbed power as functions of main magnetic field strength, and definition of 90 degrees RF pulse for the head in the birdcage coil. *Magn Reson Med*. 2001;45(4):684–91.
43. Gandhi OP, Chen XB. Specific absorption rates and induced current densities for an anatomy-based model of the human for exposure to time-varying magnetic fields of MRI. *Magn Reson Med*. 1999;41(4):816–23.
44. Vernickel P, Roschmann P, Findeklee C, Ludeke KM, Leussler C, Overweg J, Katscher U, Grasslin I, Schunemann K. Eight-channel transmit/receive body MRI coil at 3T. *Magn Reson Med*. 2007;58(2):381–9.
45. Edelstein WA, Hedeem RA, Mallozzi RP, El-Hamamsy SA, Ackermann RA, Havens TJ. Making MRI quieter. *Magn Reson Imaging*. 2002;20(2):155–63.
46. Hedeem RA, Edelstein WA. Characterization and prediction of gradient acoustic noise in MR imagers. *Magn Reson Med*. 1997;37(1):7–10.
47. Price DL, De Wilde JP, Papadaki AM, Curran JS, Kitney RI. Investigation of acoustic noise on 15 MRI scanners from 0.2 T to 3 T. *J Magn Reson Imaging*. 2001;13(2):288–93.
48. Schmitter S, Mueller M, Semmler W, Bock M. Maximum sound pressure levels at 7 Tesla—what's all this fuss about? *Proceedings of the international society for magnetic resonance in medicine* 2014. p.3029.
49. Versluis MJ, Teeuwisse WM, Kan HE, van Buchem MA, Webb AG, van Osch MJ. Subject tolerance of 7 T MRI examinations. *J Magn Reson Imaging*. 2013;38(3):722–5.
50. Rauschenberg J, Nagel AM, Ladd SC, Theysohn JM, Ladd ME, Moller HE, Trampel R, Turner R, Pohmann R, Scheffler K, Brechmann A, Stadler J, Felder J, Shah NJ, Semmler W. Multi-center study of subjective acceptance during magnetic resonance imaging at 7 and 9.4 T. *Invest Radiol*. 2014;49(5):249–59.
51. •• Heilmaier C, Theysohn JM, Maderwald S, Kraff O, Ladd ME, Ladd SC. A large-scale study on subjective perception of discomfort during 7 and 1.5 T MRI examinations. *Bioelectromagnetics*. 2011;32(8):610–19. *Extensive study on subjective perception of 7 Tesla MRI as compared to examinations at 1.5 Tesla.*
52. Theysohn JM, Maderwald S, Kraff O, Moenninghoff C, Ladd ME, Ladd SC. Subjective acceptance of 7 Tesla MRI for human imaging. *MAGMA*. 2008;21(1–2):63–72.
53. Woods TO. Standards for medical devices in MRI: present and future. *J Magn Reson Imaging*. 2007;26(5):1186–9.
54. Clauson D. ASTM standards in action. Promoting the safe use of MRI technology. 2014. <http://www.astm.org/standardization-news/features/promoting-safe-use-of-mri-technology-ma12.html>. Accessed April 2014.
55. Kainz W. MR heating tests of MR critical implants. *J Magn Reson Imaging*. 2007;26(3):450–1.
56. Konings MK, Bartels LW, Smits HF, Bakker CJ. Heating around intravascular guidewires by resonating RF waves. *J Magn Reson Imaging*. 2000;12(1):79–85.
57. Wezel J, Kooij BJ, Webb AG. Assessing the MR compatibility of dental retainer wires at 7 Tesla. *Magn Reson Med*. 2013. doi:10.1002/mrm.25019.
58. Ansems J, Van der Kolk AG, Kroeze H, van den Berg CA, De Borst GJ, Luijten PR, Webb AG, Renema WK, Klomp DW. MR imaging of patients with stents is safe at 7.0 Tesla. *Proceedings of the international society for magnetic resonance in medicine*. 2012. p. 2764.
59. Kangarlu A, Shellock FG. Aneurysm clips: evaluation of magnetic field interactions with an 8.0 T MR system. *J Magn Reson Imaging*. 2000;12(1):107–11.
60. Thelen A, Bauknecht HC, Asbach P, Schrom T. Behavior of metal implants used in ENT surgery in 7 Tesla magnetic resonance imaging. *Eur Arch Otorhinolaryngol*. 2006;263(10):900–5.
61. Schrom T, Thelen A, Asbach P, Bauknecht HC. Effect of 7.0 Tesla MRI on upper eyelid implants. *Ophthalm Plast Reconstr Surg*. 2006;22(6):480–2.
62. Kraff O, Wrede KH, Schoemberg T, Dammann P, Nouredine Y, Orzada S, Ladd ME, Bitz AK. MR safety assessment of potential RF heating from cranial fixation plates at 7 T. *Med Phys*. 2013;40(4):042302.
63. Mullinger K, Brookes M, Stevenson C, Morgan P, Bowtell R. Exploring the feasibility of simultaneous electroencephalography/functional magnetic resonance imaging at 7 T. *Magn Reson Imaging*. 2008;26(7):968–77.
64. van Rijn GA, Mourik JE, Teeuwisse WM, Luyten GP, Webb AG. Magnetic resonance compatibility of intraocular lenses measured at 7 Tesla. *Invest Ophthalmol Vis Sci*. 2012;53(7):3449–53.
65. Lee H, Xu Q, Shellock FG, Bergsneider M, Judy JW. Evaluation of magnetic resonance imaging issues for implantable microfabricated magnetic actuators. *Biomed Microdevices*. 2014;16(1):153–61.
66. Dedini RD, Karacozoff AM, Shellock FG, Xu D, McClellan RT, Pekmezci M. MRI issues for ballistic objects: information obtained at 1.5-, 3- and 7-Tesla. *Spine J*. 2013;13(7):815–22.
67. Sammet CL, Yang X, Wassenaar PA, Bourekas EC, Yuh BA, Shellock F, Sammet S, Knopp MV. RF-related heating assessment of extracranial neurosurgical implants at 7T. *Magn Reson Imaging*. 2013;31(6):1029–34.