7T & Higher-Human Safety the Path to the Clinic Adoption

Jaane Rauschenberg, PhD

Medical Physics in Radiology, German Cancer Research Center, Heidelberg, Germany

Introduction

In 1998, the first 8-Tesla whole body MRI system was installed for research purposes [1]. By the end of 2010, more than 20 ultra-high field systems, i.e. MR systems above 3T, for human imaging will be in operation, mainly 7T MR scanners. These fast developments lead to increased safety concerns regarding potential risks and health effects associated with the use of MRI. The purpose of this lecture is to identify potential hazards for volunteers, patients, as well as for MR personnel in the environment of ultra-high field MR systems. Additionally, possible solutions are pointed out to avoid or at least to decrease these risk factors.

Three types of fields are responsible for potential hazards during MRI procedures: The high static magnetic field B_0 generating the macroscopic nuclear magnetization, the alternating magnetic gradient fields G for spatial encoding of the MR signal, and the radiofrequency (RF) electromagnetic fields B1 for excitation and preparation of the spin system. After a short description of the safety regulations and operation modes, the three types of fields are discussed regarding to safety, especially for ultra-high field MRI.

Operation Modes

Two comprehensive reviews by international commissions form the base of exposure limits. The International Electrotechnical Commission (IEC) published the international MR Safety Standard (IEC 60601-2-33) [2] and the International Commission for Non-Ionizing Radiation Protection (ICNIRP) issued safety recommendations for occupational exposure and patients [3, 4]. To reflect the existing uncertainty about harmful effects of magnetic and electromagnetic fields and to offer the necessary flexibility for the development and clinical evaluation of new MR technologies, both safety regulations give exposure limits for three different modes of operation for patients:

a) Normal operating mode: Routine MR examinations that do not cause physiological stress to patients.

b) Controlled (first) operating mode: Specific MR examinations outside the normal operating range where discomfort and/or physiological stress to some patients may occur. Therefore, a clinical decision must be taken to balance such effects against foreseen benefits and exposure must be carried out under medical supervision.

c) Experimental (second) operating mode: Experimental MR procedures with exposure levels outside the controlled operating range. In view of the potential risks for patients and volunteers, special ethical approval and adequate medical supervision is required.

Static Magnetic Field

The static magnetic field interacts with the human body at the molecular, cellular, tissue, and organ level [5]. If the body is moved through the spatially variable magnetic field, e.g., head movement of the MR personnel during patient preparation at the bore end, electric currents induced in the body. Regarding side effects, this might be the most important difference compared to lower-field magnets [6, 7], as induced currents inside the body depend on dB/dt. Currents may also occur due to flowing blood [8, 9].

During the recent years, several studies have been published concerning health effects of MR workers and patients on the exposure to strong static magnetic fields beyond 4 Tesla. Chakeres et al could not detect any significant effects of vital sign parameters like heart rate, respiratory rate, diastolic blood pressures, finger pulse oxygenation levels, and core body temperature at 8 T [10]. The only physiological parameter that was significantly changed was the systolic blood pressure. This is consistent with a hemodynamic compensatory mechanism to counteract the drag on blood flow exerted by magneto-hydrodynamic forces [11]. Some volunteers and patients exposed to static magnetic fields above 1.5 T experienced sensations of dizziness, vertigo, and nausea [7, 10, 12-15]. Such effects are thought to be consistent with magneto-hydrodynamic effects on the endolymph of the vestibular apparatus [15]. The often reported metallic taste in the mouth, which occurs during approach to the magnet, is not related to dental fillings; instead, the taste sensation comes from liberation of protons due to currents across the tongue caused by temporally changing magnetic fields [16, 17]. Moreover, some volunteers and patients reported on magnetophosphenes occurring during rapid eye movement in a field of at least 2 T, which may be attributable to weak electric fields induced by movements of the eye, resulting in an excitation of structures in the retina [6, 14].

All these side effects might be increased in the environment of an ultra-high field system. To reduce the magnetic-field induced electric currents it is cautioned that patients should be moved slowly into the magnet bore. MR personnel should not move fast in the stray field of the magnet, although due to the long bore of ultra-high field machines the magnetic field strength close to the bore end is not that different than for 3 T MR systems (e.g. at the laser cross position of a 7T System B_0 = 2.0 T , and at same position of a 3T MR System B_0 =1.24 T). The threshold for motion-induced vertigo has been estimated to be around 1 T/s for durations greater than 1 s [18]; avoiding these sensations is likely to afford protection against other effects of induced electric fields and currents that arise as a consequence of motion in a strong static magnetic field. Some 7T MR systems are equipped with an automatic patient table that reduces the velocity while the head is moved through the highest magnetic field gradient (close to the bore end of the magnet). However, for this technique the head position must be known.

Neurobehavioral effects caused by the exposure to static magnetic fields have been studied. Eye–hand coordination and a near-visual contrast sensitivity were found to be slightly declined at 1.5 T [19], whereas a small negative effect on short-term memory was noted at 8

T [20]. A more recent study could not detect any neurobehavioral effect at 3T; here, the results of a cognitive test battery were compared to a control experiment without magnetic field [21]. In a new study from 2010 no significant effect on cognitive function at 1.5 T and 7 T could be found [22].

Long-term effects of exposure to static magnetic fields are difficult to assess. Until now, after over 100 million examinations worldwide, of which more than one thousand examinations were conducted at 4, 7 or 8T, no indications for any lasting health effects on humans have been observed, except for avoidable incidences related to inadvertent introduction of metallic objects within the magnetic field (i.e., ferromagnetic objects turning into projectiles [23, 24]).

Several guidelines and recommendations were proposed concerning the exposition during the stay and during the movement within the vicinity of the MR magnet for both MR workers and patients. In Europe, the static magnetic field guideline for MR workers is based on the ICNIRP guideline from 1998 [3]. From this, occupational exposure is limited to 2 Tesla for head and trunk, and 5 Tesla for limbs. European guidelines for patients are based on the International Electrotechnical Commission (IEC) [2] and divide the limits in above described three operation modes. In the normal mode patients can be exposed to fields up to 3 T, in the first (controlled) mode, patients can be exposed up to 4 T. For MRI examinations within the second (experimental) mode (>4 T) significant risks cannot be excluded. In the US, the non-significant risk status was extended for clinical fields up to 8 T by the Food and Drug Association already in July 2003 [3].

According to present knowledge, it is not expected that exposure of human subjects to static magnetic fields of 7 T implies a specific risk of damage or disease, as far as known contraindications are observed.

Gradients: Peripheral Nerve Stimulations and Noise

The gradient system produces weak magnetic fields which are superimposed on the static magnetic field. Gradient fields are switched on and off at acoustic frequencies of up to 10 kHz, and electric currents within the body are induced. In 7T systems, gradient performance is identical to modern 1.5 and 3T systems, as all systems are made to observe the IEC 60601-2-33 guidelines [2] for switching gradients.

However, the acoustic noise associated with an MR examination is produced through the interaction of the gradient system with the static magnetic field due to Lorentz forces, and the acoustic noise level of ultrahigh-field systems is therefore expected to increase. However, with worst case protocols at a 7T Magnetom Siemens MR System sound pressure levels up to 112 dB are generated, which is similar to those of a 1.5 T Siemens MR System [25]. The low sound pressure level of this 7T MR system results from additional technical measures to reduce acoustic noise.

Radiofrequency

RF electromagnetic pulses for spin excitation will deposit energy in the tissue in the form of heat. Particularly, the dependence of RF power deposition on the Larmor frequency (or B_0 field strength) has been a topic of research over the last 30 years. For ultra-high field whole body MR systems accurately predicting the RF power absorption has become essential to classify the potential clinical practicality of these systems as well as future ones. The RF wave length in tissue λ_{tiss} decreases with B_0 which results for protons in $\lambda_{tiss} \approx 11$ cm at 7T (for comparison: $\lambda_{tiss} \approx 52$ cm at 1.5T and $\lambda_{tiss} \approx 26$ cm at 3T). The reduced wave length leads to constructive interferences of standing waves within the body and thus produces inhomogeneous RF excitation [26]. Beside the resulting inhomogeneities in image signal and contrast a main problem is the inhomogeneous distribution of RF power deposition. Therefore, the critical health concern is not only associated with RF power deposition in the whole head/body, but with the rise in local temperatures. In practice, one of the important safety concerns is the RF "hot spots"' produced by the rise in specific absorption rate (SAR). In addition, coupling of the RF pulse energy with local receive-only coils and other medical devices further raises the risk of heating. Also of increasing concern is the potential RF heating during MRI in patients with medical implants.

The IEC or FDA limits for tissue energy deposition should be respected similar to lower-field systems. However, SAR scales quadratically with the magnetic field strength [27]. Therefore, at ultra-high field MR systems the SAR related pulse sequence parameters like RF flip angle, TR, number of slices etc., are more restricted than for 3T applications. Especially for high-SAR pulse sequences like fast Spin echo and SSFP sequences or for high-flip angle applications as fat suppression or magnetic transfer pulses the compliance with SAR limits is difficult to archieve. To overcome these problems the variable-rate selective excitation (VERSE) algorithm has been proposed for slice-selective RF pulses [28], which maintains short pulse duration while reducing the SAR. At ultra-high field imaging the VERSE method has been applied for SAR optimization of time-of-flight angiography [29] and in multidimensional parallel transmission pulses [30].In a recent study an acoustic noise optimized VERSE algorithm is presented [31].

Most important is the correct calculation of possible SAR values due to the used RF-transmit coil, sequence parameters, and patient weight. At normal applications the MR systems have SAR monitoring implemented and for ultra-high field scanners a conservative SAR restriction is disposed. Custom-build RF coils, however, need to be assessed concerning SAR, where SAR simulations with human models are required since hot spots cannot be revealed adequately with phantom measurements only [32, 33].

The SAR determination of multidimensional parallel transmission pulses is even more challenging. As mentioned above, MR imaging at field strengths of 3T and higher suffers from RF field inhomogeneities. Therefore, parallel RF transmission was introduced which allows shaping the B1 transmit field in a patient-specific way for slice selective RF excitation [34, 35] as well as multidimensional RF pulses [36]. However, the introduction of parallel transmission requires a thorough revision of the present (single-channel) SAR management concept. Recent studies revealed significant, highly safety-relevant differences between single-channel and multi-channel RF transmission leading to a worldwide search for new, adequate SAR monitoring systems (e.g., [35, 37, 38]). A comprehensive management concept should include SAR estimation prior to the MR scan, RF monitoring where the actually transmitted RF fields is measured during the examination, and in the case that the RF power is rated to be dangerous the scan execution has to be aborted [39]. Moreover, as the problem of B1 inhomogeneity is patient depended, SAR simulations should be performed before each MR examination.

Conclusion

Up to now, no health risks of ultra-high field applications could is reported, as far as known contraindications are observed. Nevertheless, special safety care has to be taken at MR systems with field strength beyond 3T. Awareness of the growing likelihood for side effects to arise at higher fields should be a motivation for physicians to take additional time for patients. It is important not to alarm the subjects, but to give them a reasonable and sensible outlook on possible side effects. As switching gradients are the same as used for modern 3T or 1.5T MR systems, no special safety management is needed for ultra-high field systems. However, as the SAR is related to the RF electromagnetic field and this to the field strength of the MR system, transmitted RF is highly-safety relevant. Especially for new RF coil designs like multidimensional transmit pulses a deliberate SAR management concept is needed. Special care has to be taken for patients with metallic implants, because also non-ferromagnetic devices can lead to hazardous heating due to local SAR increase.

Literature

1. Robitaille, P.M., Abduljalil, A.M., Kangarlu, A., Zhang, X., Yu, Y., Burgess, R., Bair, S., Noa, P., Yang, L., Zhu, H., Palmer, B., Jiang, Z., Chakeres, D.M., and Spigos, D., *Human magnetic resonance imaging at 8 T.* NMR Biomed, 1998. **11**(6): p. 263-5.
2. *Medical Electrical Equipment - Part 2-33: Particular requirements for the basic safety and essential performence of magnetic resonance equipment for medical diagnosis*, in *IEC 60601-2-33*. 2010, International Electrotechnical Commission.
3. *ICNIRP GUIDELINES FOR LIMITING EXPOSURE TO TIME-VARYING ELECTRIC, MAGNETIC, AND ELECTROMAGNETIC FIELDS (UP TO 300 GHz)*. 1998, International Commission on Non-Ionizing Radiation Protection.
4. *ICNIRP STATEMENT ON MEDICAL MAGNETIC RESONANCE (MR) PROCEDURES: PROTECTION OF PATIENTS*. 2004, International Commission on Non-Ionizing Radiation Protection.
5. Kangarlu, A., Baudendistel, K.T., Heverhagen, J.T., and Knopp, M.V., *[Clinical high- and ultrahigh-field MR and its interaction with biological systems].* Radiologe, 2004. **44**(1): p. 19-30.
6. Kangarlu, A. and Robitaille, P.M.L., *Biological effects and health implications in magnetic resonance imaging.* Concepts in Magnetic Resonance, 2000. **12**(5): p. 321-359.
7. Theysohn, J.M., Maderwald, S., Kraff, O., Moenninghoff, C., Ladd, M.E., and Ladd, S.C., *Subjective acceptance of 7 Tesla MRI for human imaging.* MAGMA, 2008. **21**(1-2): p. 63-72.

8. Tenforde, T.S., *Biological interactions and potential health effects of extremely-low-frequency magnetic fields from power lines and other common sources.* Annu Rev Public Health, 1992. **13**: p. 173-96.

9. Tenforde, T.S., *Magnetically induced electric fields and currents in the circulatory system.* Prog Biophys Mol Biol, 2005. **87**(2-3): p. 279-88.

10. Chakeres, D.W., Kangarlu, A., Boudoulas, H., and Young, D.C., *Effect of static magnetic field exposure of up to 8 Tesla on sequential human vital sign measurements.* J Magn Reson Imaging, 2003. **18**(3): p. 346-52.

11. Chakeres, D.W. and de Vocht, F., *Static magnetic field effects on human subjects related to magnetic resonance imaging systems.* Prog Biophys Mol Biol, 2005. **87**(2-3): p. 255-65.

12. Kangarlu, A., Burgess, R.E., Zhu, H., Nakayama, T., Hamlin, R.L., Abduljalil, A.M., and Robitaille, P.M., *Cognitive, cardiac, and physiological safety studies in ultra high field magnetic resonance imaging.* Magn Reson Imaging, 1999. **17**(10): p. 1407-16.

13. Schenck, J.F., *Safety of strong, static magnetic fields.* J Magn Reson Imaging, 2000. **12**(1): p. 2-19.

14. Schenck, J.F., *Physical interactions of static magnetic fields with living tissues.* Prog Biophys Mol Biol, 2005. **87**(2-3): p. 185-204.

15. Glover, P.M., Cavin, I., Qian, W., Bowtell, R., and Gowland, P.A., *Magnetic-field-induced vertigo: a theoretical and experimental investigation.* Bioelectromagnetics, 2007. **28**(5): p. 349-61.

16. Stillman, J.A., Morton, R.P., and Goldsmith, D., *Automated electrogustometry: a new paradigm for the estimation of taste detection thresholds.* Clin Otolaryngol Allied Sci, 2000. **25**(2): p. 120-5.

17. Cavin, I.D., Glover, P.M., Bowtell, R.W., and Gowland, P.A., *Thresholds for perceiving metallic taste at high magnetic field.* J Magn Reson Imaging, 2007. **26**(5): p. 1357-61.

18. *AMENDMENT TO THE ICNIRP "STATEMENT ON MEDICAL MAGNETIC RESONANCE (MR) PROCEDURES: PROTECTION OF PATIENTS"*. 2009, The International Commission on Non-Ionizing Radiation Protection.

19. de Vocht, F., van-Wendel-de-Joode, B., Engels, H., and Kromhout, H., *Neurobehavioral effects among subjects exposed to high static and gradient magnetic fields from a 1.5 Tesla magnetic resonance imaging system--a case-crossover pilot study.* Magn Reson Med, 2003. **50**(4): p. 670-4.

20. Chakeres, D.W., Bornstein, R., and Kangarlu, A., *Randomized comparison of cognitive function in humans at 0 and 8 Tesla.* J Magn Reson Imaging, 2003. **18**(3): p. 342-5.

21. Lepsien, J., Müller, K., Cramon, D.Y.v., and Möller, H.E., *Effects of a High Static Magnetic Field on (Higher) Cognitive Functions.* Proc. Intl. Soc. Mag. Reson. Med., 2010. **19**: p. 782.

22. Schlamann, M., Voigt, M.A., Maderwald, S., Bitz, A.K., Kraff, O., Ladd, S.C., Ladd, M.E., Forsting, M., and Wilhelm, H., *Exposure to high-field MRI does not affect cognitive function.* J Magn Reson Imaging, 2010. **31**(5): p. 1061-6.

23. Colletti, P.M., *Size "H" oxygen cylinder: accidental MR projectile at 1.5 Tesla.* J Magn Reson Imaging, 2004. **19**(1): p. 141-3.

24. Chaljub, G., Kramer, L.A., Johnson, R.F., 3rd, Johnson, R.F., Jr., Singh, H., and Crow, W.N., *Projectile cylinder accidents resulting from the presence of ferromagnetic nitrous oxide or oxygen tanks in the MR suite.* AJR Am J Roentgenol, 2001. **177**(1): p. 27-30.

25. Schmitter, S., Mueller, M., Semmler, W., and Bock, M., *Maximum sound pressure levels at 7 Tesla – what's all this fuss about?* Proc. Intl. Soc. Mag. Reson. Med., 2009. **17**.

26. Hoult, D.I. and Phil, D., *Sensitivity and power deposition in a high-field imaging experiment.* J Magn Reson Imaging, 2000. **12**(1): p. 46-67.

27. Bottomley, P.A. and Edelstein, W.A., *Power deposition in whole-body NMR imaging.* Med Phys, 1981. **8**(4): p. 510-2.

28. Conolly, S., Nishimura, D., Macovski, A., and Glover, G., *Variable-Rate Selective Excitation.* Journal of Magnetic Resonance, 1988. **78**(3): p. 440-458.

29. Schmitter, S., Johst, S., Bock, M., Ugurbil, K., and van de Moortele, P.-F., *Shen J, Chen Z, Yang J. New FOCI pulses with reduced radiofrequency power requirements.* Proc. Intl. Soc. Mag. Reson. Med., 2010. **18**: p. 4424.

30. Setsompop, K., Alagappan, V., Zelinski, A.C., Potthast, A., Fontius, U., Hebrank, F., Schmitt, F., Wald, L.L., and Adalsteinsson, E., *High-flip-angle slice-selective parallel RF transmission with 8 channels at 7 T.* J Magn Reson, 2008. **195**(1): p. 76-84.

31. Schmitter, S. and Bock, M., *Acoustic noise-optimized VERSE pulses.* Magn Reson Med. **64**(5): p. 1446-52.

32. Kraff, O., Bitz, A.K., Kruszona, S., Orzada, S., Schaefer, L.C., Theysohn, J.M., Maderwald, S., Ladd, M.E., and Quick, H.H., *An eight-channel phased array RF coil for spine MR imaging at 7 T.* Invest Radiol, 2009. **44**(11): p. 734-40.

33. Kozlov, M. and Turner, R., *Fast MRI coil analysis based on 3-D electromagnetic and RF circuit co-simulation.* J Magn Reson, 2009. **200**(1): p. 147-52.

34. Ibrahim, T.S., Lee, R., Baertlein, B.A., Kangarlu, A., and Robitaille, P.L., *Application of finite difference time domain method for the design of birdcage RF head coils using multi-port excitations.* Magn Reson Imaging, 2000. **18**(6): p. 733-42.

35. Seifert, F., Wubbeler, G., Junge, S., Ittermann, B., and Rinneberg, H., *Patient safety concept for multichannel transmit coils.* J Magn Reson Imaging, 2007. **26**(5): p. 1315-21.

36. Katscher, U., Bornert, P., Leussler, C., and van den Brink, J.S., *Transmit SENSE.* Magn Reson Med, 2003. **49**(1): p. 144-50.

37. Graesslin, I., Falaggis, K., Biederer, S., Glaesel, D., Vernickel, P., Roeschmann, P., Leussler, C., Thran, A., Zhai, Z., Morich, M., and Katscher, U., *SAR Simulations and Experiments for Parallel Transmission.* Proc. Intl. Soc. Mag. Reson. Med., 2007. **15**: p. 1090.

38. Brote, I., Orzada, S., Kraff, O., Maderwald, S., Quick, H., Yazdanbakhsh, P., Solbach, K., Wicklow, K., Bahr, A., Bolz, T., Ladd, M.E., and Bitz, A.K., *A Multi-Channel SAR Prediction and Online Monitoring System at 7T.* Proc. Intl. Soc. Mag. Reson. Med., 2009. **17**: p. 4788.

39. Graesslin, I., *Monitoring Safety and RF Heating for Parallel Transmission Systems.* ISMRM Workshop on MR Safety: RF Heating of the Human in MRI, 2010.