Side Effects of High Magnetic Fields

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Target Audience: Scientists and clinicians with an interest in MR safety

Summary: The elevated internal and external static magnetic fields and higher radio frequency of MR scanners operating at high magnetic field raise some special safety risks, which should be considered when operating and installing high field scanners. The side effects of high magnetic fields, particularly magnetic field induced vertigo also need to be taken into account.

Introduction: High field MRI (> 3 T) offers many opportunities in clinical practice and biomedical research. However it also poses some definite risks to patients or volunteers and to staff, including unwanted side effects, which can be minimized by careful management. High field MRI can involve exposing staff and volunteers to static fields greater than the exposure limits that have been recommended by international bodies in order to avoid potential, currently ill-defined hazards to health. The issues requiring special consideration at high field mainly relate to the static magnetic field, although RF heating also becomes a more serious issue.

Static Magnetic Fields: There are a variety of potential mechanisms for interaction between the human body and strong, static or slowly-varying magnetic fields, including those based upon electromagnetic induction, magneto-mechanical effects and electron spin interactions (1-3). However, to date none of these have been shown to have clinically significant, long-term or short-term, deleterious effects at currently accessible field strengths. The International Commission for Non-Ionizing Radiation Protection (ICNIRP) currently suggest a limit of 2 T for occupational exposure to static magnetic fields in general workplaces, although for specific work applications, when the environment is controlled and appropriate work practices are implemented, exposure up to 8 T is acceptable (2). 8 T is also the upper limit suggested by ICNIRP for patient imaging in controlled operating mode, though higher field studies in experimental mode may be carried out under IRB approval with appropriate clinical monitoring (4).

The most significant effect of exposure to high magnetic field is dizziness. This magnetic field induced vertigo (MFIV) (5), results from interaction between the magnetic field, and the vestibular system of the inner ear that is responsible for balance. Suggested causes of this effect (1, 5) include: currents induced in the vestibular system due to movements that change the flux linked by the head (e.g. translation through the region of large field gradient at the end of the magnet or head rotation in the uniform field at the centre of the magnet); forces on structures in the inner ear due to exposure of the heterogeneous distribution of magnetic susceptibility to large gradients in the field magnitude; and magneto-hydrodynamic forces on fluid moving in the inner ear. However it has recently been shown that the most probable cause of MFIV is the Lorentz force on the ionic currents that flow continuously in the endolymph fluid within the semi-circular canals (6). In the presence of a strong field this force produces small deflections of the cupulae, which mimic the effect of natural movement or changes in head pose, thus leading to feelings of vertigo. A signature of MFIV is a pattern of involuntary eye movements (known as nystagmus) which can be detected during exposure to strong magnetic fields. Evidence for the Lorentz force on ionic flow being the cause of MFIV, comes from modelling (7), along with experimental findings, such as the persistence of nystagmus during prolonged exposure to a strong field and changes in the perceived motion and nystagmus with head orientation with respect to the magnetic field (6, 8). Slow adaptation of the vestibular system to continuous input also affects the time-course of MFIV during field exposure (8, 9), potentially explaining why sensations are generally strongest during and immediately after movement into a region of strong field and also can persist after removal of the field following a prolonged exposure (10, 11).

Other, noticeable side effects of movement in high magnetic fields can include the induction of a metallic taste in the mouth and the generation of magnetophosphenes (1). The metallic taste most likely results from ions produced by the voltages induced in the mouth as a result motion-related changes in magnetic flux. In an experimental study, Cavin et al (12) showed that around half of the subjects from a group of 15 perceived a metallic taste when head-shaking at 80 beats per minute within the stray field at the end of a 7T magnet (directed in the anterior/posterior direction) corresponding to a peak rate of change of field of around 2 T/s at the skull surface. Magnetophosphenes result from induced currents at the retinal surface: using a driven head-sized, solenoidal coil, Glover et al. (12) found that magnetophosphenes could be readily generated using a uniform magnetic field varying at 1.5 T/s over a 50 ms period. Such rates of change of field can be produced by rapid head movements inside and close to a 7 T magnet, but subjective perception of magnetophosphenes is strongly affected by the ambient light conditions.

Flow of electrically conducting fluids in a magnetic field generates Hall voltages which are largest when the flow is perpendicular to applied field. In the case of pulsatile blood flow in the cardio-vascular system, it is the resulting flow-induced voltages which contaminate electro-cardiogaphic measurements made inside an MR scanner (13). These voltages scale with the applied field (14) and at field strengths of more than 40 T might exceed thresholds for electrical stimulation of the heart. It has been suggested that the Lorentz force on the currents flowing through large arteries as a result of the flow-induced potentials might induce measureable effects on blood flow and pressure at fields of order 10 T (15). However Atkinson et al. (16) found no statistically significant changes in vital signs, including systolic and diastolic blood pressure, in a study of 25 human volunteers who were exposed to a 9.4 T static magnetic field.

Cognitive effects of exposure to high field have also been reported in some studies, but the literature in this area is currently contradictory (16-19).

<u>Gradient and RF Fields</u>: The forces experienced by gradient coil windings during MR scanning increase with increasing operating field, potentially leading to the generation of louder acoustic noise in and around high field scanners. Greater attention therefore needs to be paid to acoustic damping and gradient coil mounting in high field scanners in order to avoid side effects of excessive acoustic noise. RF power deposition increases with field strength and at high field the RF power deposition becomes less uniform, leading to local SAR hotspots (20). The reduction of the wavelength of the RF used in high field MRI means that RF interactions with implants and devices must be specifically analysed before they are used in high field scanners. Only a relatively small number of devices have so far been fully tested for use at 7 T (21-23).

<u>Subject Perception</u> The above discussions are supported by recent surveys of subject tolerance of 7T scanning procedures, which generally show that 7 T scanning is well tolerated with dizziness being the most commonly recorded side effect (24-28).

<u>References</u>

1. Schenck JF (2000) Safety of strong, static magnetic fields. *J. Magn. Res. Imag.* 12:2-19.
2. ICNIRP (2009) Guidelines on limits of exposure to static magnetic fields. in *Health Physics*, ed Protection ICoN-IR, pp 504-514.
3. Ziegelberger G & Int Commission N-I (2014) Guidelines for limiting exposure to electric fields induced by movement of the human body in a static magnetic field and by time-varying magnetic fields below 1 Hz. *Health Physics* 106(3):418-425.
4. ICNIRP (2009) Amendment to the ICNIRP "Statement on medical magnetic resonance (MR) procedures: protection of patients.". *Health Physics* 97(3):259-261.
5. Glover PM, Cavin I, Qian W, Bowtell R, & Gowland PA (2007) Magnetic-field-induced vertigo: A theoretical and experimental investigation. *Bioelectromagnetics* 28(5):349-361.
6. Roberts DC*, et al.* (2011) MRI Magnetic Field Stimulates Rotational Sensors of the Brain. *Current Biology* 21(19):1635-1640.

7. Antunes A, Glover PM, Li Y, Mian OS, & Day BL (2012) Magnetic field effects on the vestibular system: calculation of the pressure on the cupula due to ionic current-induced Lorentz force. *Physics in Medicine and Biology* 57(14):4477-4487.
8. Mian OS, Li Y, Antunes A, Glover PM, & Day BL (2013) On the Vertigo Due to Static Magnetic Fields. *Plos One* 8(10).
9. Glover PM, Li Y, Antunes A, Mian OS, & Day BL (2014) A dynamic model of the eye nystagmus response to high magnetic fields. *Physics in Medicine and Biology* 59(3):631-645.
10. van Nierop LE, Slottje P, Kingma H, & Kromhout H (2013) MRI-related static magnetic stray fields and postural body sway: A double-blind randomized crossover study. *Magnetic Resonance in Medicine* 70(1):232-240.
11. Theysohn JM*, et al.* (2014) Vestibular Effects of a 7 Tesla MRI Examination Compared to 1.5 T and 0 T in Healthy Volunteers. *Plos One* 9(3).
12. Cavin ID, Glover PM, Bowtell RW, & Gowland PA (2007) Thresholds for perceiving metallic taste at high magnetic field. *Journal of Magnetic Resonance Imaging* 26(5):1357-1361.
13. Fischer SE, Wickline SA, & Lorenz CH (1999) Novel real-time R-wave detection algorithm based on the vectorcardiogram for accurate gated magnetic resonance acquisitions. *Magnetic Resonance in Medicine* 42(2):361-370.
14. Debener S, Mullinger KJ, Mazy RK, & Bowtell RW (2008) Properties of the ballistocardiogram artefact as revealed by EEG recordings at 1.5, 3 and 7 T static magnetic field strength. *International Journal of Psychophysiology* 67(3):189-199.
15. Kinouchi Y, Yamaguchi H, & Tenforde TS (1996) Theoretical analysis of magnetic field interactions with aortic blood flow. *Bioelectromagnetics* 17(1):21-32.
16. Atkinson IC, Renteria L, Burd H, Pliskin NH, & Thulborn KR (2007) Safety of human MRI at static fields above the FDA ST guideline: Sodium imaging at 9.4T does not affect vital signs or cognitive ability. *Journal of Magnetic Resonance Imaging* 26(5):1222-1227.
17. de Vocht F*, et al.* (2007) Cognitive effects of head-movements in stray fields generated by a 7 Tesla whole-body MRI magnet. *Bioelectromagnetics* 28(4):247-255.
18. de Vocht F, Stevens T, van Wendel-De-Joode B, Engels H, & Kromhout H (2006) Acute neurobehavioral effects of exposure to static magnetic fields: Analyses of exposure-response relations. *Journal of Magnetic Resonance Imaging* 23(3):291-297.
19. Schlamann M*, et al.* (2010) Exposure to High-Field MRI Does Not Affect Cognitive Function. *Journal of Magnetic Resonance Imaging* 31(5):1061-1066.
20. Kangarlu A, Ibrahim TS, & Shellock FG (2005) Effects of coil dimensions and field polarization on RF heating inside a head phantom. *Magnetic Resonance Imaging* 23(1):53-60.
21. Santoro D*, et al.* (2012) Detailing Radio Frequency Heating Induced by Coronary Stents: A 7.0 Tesla Magnetic Resonance Study. *PLoS One* 7(11).
22. van Rijn GA, Mourik JEM, Teeuwisse WM, Luyten GPM, & Webb AG (2012) Magnetic Resonance Compatibility of Intraocular Lenses Measured at 7 Tesla. *Investigative Ophthalmology & Visual Science* 53(7):3449-3453.
23. Wezel J, Kooij BJ, & Webb AG (2014) Assessing the MR Compatibility of Dental Retainer Wires at 7 Tesla. *Magnetic Resonance in Medicine* 72(4):1191-1198.
24. Heilmaier C*, et al.* (2011) A Large-Scale Study on Subjective Perception of Discomfort During 7 and 1.5 T MRI Examinations. *Bioelectromagnetics* 32(8):610-619.
25. Versluis MJ*, et al.* (2013) Subject tolerance of 7 T MRI examinations. *Journal of Magnetic Resonance Imaging* 38(3):722-725.
26. Cosottini M*, et al.* (2014) Short-term side-effects of brain MR examination at 7 T: a single-centre experience. *European Radiology* 24(8):1923-1928.
27. Rauschenberg J*, et al.* (2014) Multicenter Study of Subjective Acceptance During Magnetic Resonance Imaging at 7 and 9.4 T. *Investigative Radiology* 49(5):249-259.
28. Klix S*, et al.* (2015) On the Subjective Acceptance during Cardiovascular Magnetic Resonance Imaging at 7.0 Tesla. *PLoS One* 10(1).