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Magnetic-Field-Induced Vertigo: A Theoretical and Experimental Investigation

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Vertigo-like sensations or apparent perception of movement are reported by some subjects and operators in and around high field whole body magnetic resonance body scanners. Induced currents (which modulate the firing rate of the vestibular hair cell), magneto-hydrodynamics (MDH), and tissue magnetic susceptibility differences have all been proposed as possible mechanisms for this effect. In this article, we examine the theory underlying each of these mechanisms and explore resulting predictions. Experimental evidence is summarised in the following findings: 30% of subjects display a postural sway response at a field-gradient product of 1 T^2m^{-1}; a determining factor for experience of vertigo is the total unipolar integrated field change over a period greater than 1 s; the perception of dizziness is not necessarily related to a high value of the rate of change of magnetic field; eight of ten subjects reported sensations ranging from mild to severe when exposed to a magnetic field change of the order of 4.7 T in 1.9 s; no subjects reported any response when exposed to 50 ms pulses of dB/dt of 2 Ts^{-1} amplitude. The experimental evidence supports the hypothesis that magnetic-field related vertigo results from both magnetic susceptibility differences between vestibular organs and surrounding fluid, and induced currents acting on the vestibular hair cells. Both mechanisms are consistent with theoretical predictions. Bioelectromagnetics 28:349–361, 2007. © 2007 Wiley-Liss, Inc.

Key words: magnetic resonance imaging; safety; vestibular system; induced current; magnetic susceptibility

INTRODUCTION

Progress in magnet technology for magnetic resonance imaging (MRI) has allowed a gradual increase in the static field strength of whole body installations. The clinical standard is now becoming 3 T, and whole-body scanners operating at 7 T and above are now available. With the increasing field strength comes an increase in shielding to allow convenient siting and hence higher fringe field gradients. It is quite common for users of high-field ($\geq$2 T) MRI scanners to experience disorientation or the subtle perception of movement when working close to or within the bore tube of the magnet. We shall use the term magnetic-field-induced vertigo (MFIV) to refer to this effect. In most cases, MFIV is temporary, ceasing when the subject moves away from the magnet. In more severe cases, perhaps related to longer exposure, or the execution of a more complex task within the bore tube, nausea may accompany the sensation of vertigo. The nausea can then last for an hour or more in a similar manner to motion sickness. There is also anecdotal evidence that operators adapt to MFIV, either by unconsciously adjusting their behavior near the magnet, or by an adaptation process. The advice usually given is to move slowly in the vicinity of the magnet to mitigate MFIV, and manufacturers of scanners ensure that the patient's bed travels into the magnet slowly to keep the peak rate of change of field to less than 1 Ts^{-1}. The main type of apparent motion reported by subjects being moved slowly into our 7 T scanner is a feeling of rotation. These sensations generally occur when the gradient of the field, the gradient-field product, or the gradient-velocity product experienced by the subject's head are high, and hence are not present with the head stationary and at iso-center (i.e., during

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imaging). Some people report a particular direction of apparent movement when standing close to the magnet even when stationary. At present, the mechanism for this perceived apparent movement is unknown, and in particular it is not clear whether sensory or direct neuronal stimulation is the most likely cause. On a practical note, an understanding of the mechanisms and parameters involved in MFIV will ensure that accurate advice can be given to operators wishing to avoid such sensations. In addition, information can be given to patients regarding likely effects.

Balance is known to be a very complex neurological function involving a range of sensors and responses [Kornhuber, 1974a,b; Baloh and Honrubia, 2001]. Confounds or perturbations of perception and actual movement contribute to the feeling of motion sickness [Probst and Schmidt, 1998]. Normal movements of the human head are detected in the vestibular system. Rotational velocity and acceleration of the head are detected by three semi-circular canals, which are orthogonal toroids of conducting fluid (endolymph). A single semi-circular canal is shown schematically in Figure 1A. Each semi-circular canal contains a deflection sensitive cupula (housed in the ampulla) which is closely coupled to the inertial moment of the fluid. The semi-circular canals are joined at the utricle, which is coupled to the saccule and the cochlea (inner ear). The maculae are contained within the utricle and saccule and detect lateral and vertical accelerations. The otolithic membrane forms a plate composed of a gel matrix which supports otoconia (composed of the aragonite form of calcium carbonate) (Fig. 1B). The otolithic membrane effectively forms a mass on a spring whose deflection is sensed by hair cells. Each of the two maculae detect movement of the plate in two orthogonal directions each, and hence the two organs are capable of detecting linear accelerations along all three cartesian axes. The hair cells are linear transducers which sense the movements of the cupula and otolithic membrane, and have a finite firing rate at zero deflection of the associated membrane of about 30 Hz in humans. Movement in one direction increases the rate of firing and conversely, movement in the opposite direction reduces the rate of firing.

There are a number of literature reviews covering bio-effects of electricity and magnetism which look specifically at the range of fields generated in MRI including effects of the static magnetic field and time-varying magnetic-field gradients [Lovsund et al., 1979; Schenck et al., 1983; Schenck, 1992, 2000; Kangarlu and Robitaille, 2000; Baloh and Honrubia, 2001; Liu et al., 2002, 2003a,b; Chakeres and de Vocht, 2005; Feychting, 2005; Gowland, 2005; Schenck, 2005]. However, very little work has been carried out in the very low (.1–10 Hz) frequency range. Schenck has proposed magneto-hydrodynamics (MHD) as a candidate mechanism for MFIV and carried out some rudimentary calculations of the magnitude of the effect [Schenck, 1992]. He also raised the possible involvement of diamagnetic anisotropy and induced current mechanisms, but did not discuss the relative magnitudes of these effects compared to MHD. With the advent of whole-body magnets of 7 or 8 T field strength, vertigo related effects are now more noticeable and affect a wider number of people. It should now therefore be easier to investigate the origins of MFIV.

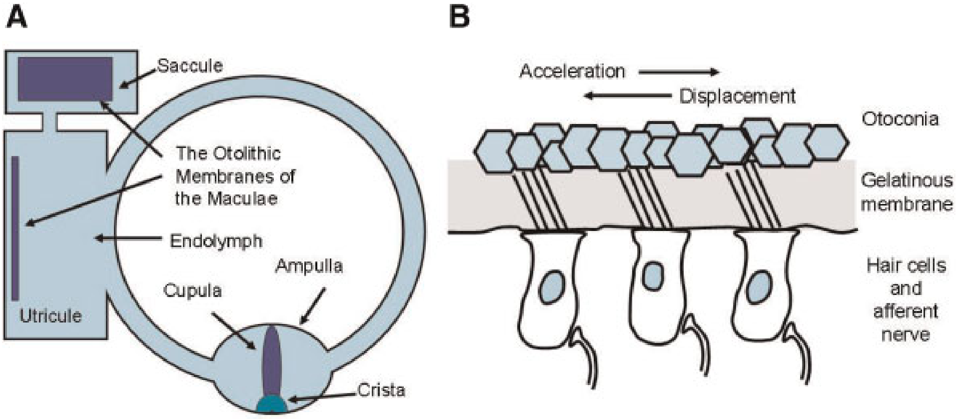

Fig. 1. **A**: A single semi-circular canal showing the gelatinous cupula housed in the ampulla. The relative positions of the utricle and saccule containing the two maculae is also shown. **B**: The otolithic membrane, which comprises calcium carbonate otoconia imbedded in a gel matrix is shown in more detail. Stereocillia, which sense the displacement of the otoconia are imbedded in the gel. Hair cells fire at a rate determined by the displacement of the stereocilla. Hair cells in the crista perform a similar function for sensing the position of the cupula. [The color figure for this article is available online at www.interscience.wiley.com.]

It is possible to postulate a number of mechanisms for the induction of vertigo during exposure to strong magnetic fields. These include: induced galvanic vestibular stimulation (iGVS) or direct nerve stimulation; MHD effects within the vestibular fluids; and forces due to diamagnetic susceptibility (DS) differences between the otolithic membrane or cupula and surrounding material when in a magnetic field. In this article, we present a critical review of these three possible electromagnetic interactions with the vestibular system. A number of experiments and observations are reported in an attempt to identify the principal interaction mechanism.

THEORY

In this section, we present theoretical analysis and prediction of the magnetic-field characteristics, including the spatial and temporal rate of change, needed to cause MFIV via each of the mechanisms listed above.

Induced Galvanic Vestibular Stimulation (iGVS)

Vestibular hair cells form linear deflection transduction sensors and have an electrophysiological response to the mechanical displacement of the cupulae and the maculae. The hair cell has a high firing rate at zero displacement of the hairs; deflection then causes a change in firing rate which the brain interprets as movement [Baloh and Honrubia, 2001]. Changes in the electric field across the cell will also modulate the firing rate, giving a false perception of movement. The current densities required to elicit an effect are likely to be lower than the accepted thresholds for direct or peripheral nerve stimulation (PNS). Goldberg [Goldberg et al., 1984] and Watson [Watson and Colebatch, 1998] show that application of a direct current in and around the vestibular system can modulate the firing rate of the afferent nerve of the hair cell, and it has also been shown that currents of the order of 1 mA flowing for 1 s across the head can elicit a sway [Fitzpatrick and Day, 2004]. Fitzpatrick and Day postulate that, as this period is much longer than the time constants related to nerve cell stimulation, it can be assumed that the MFIV mechanism is different to that causing PNS [McRobbie and Foster, 1984]. Fitzpatrick and Day describe in detail how the polarity of the GVS potentials are related to the perception of motion. They show experimentally and theoretically that bipolar stimulation with bilateral electrodes leads to a perception of roll or tilt of the head. They conclude that a current of 1 mA flowing through the mastoid electrode could cause a perilymphatic current of 1μA. This GVS effect has been used to generate a stimulus for an fMRI study of the brain's response to the perception of vertigo [Stephan et al., 2005]. Thomas [Thomas et al., 2001] reports that high frequency episodes of whole-body exposure to switched magnetic fields of 200 μT amplitude and rate of change of .7 Ts^{-1} generates a marked response in a subject's center of pressure (COP) movements on a force-plate. Switched magnetic fields at a much lower magnitude than is usually associated with trans-cranial magneto stimulation (TMS) have also been shown to have an effect on the mood of subjects in scanners [Rohan et al., 2004]. In these two examples the exact mechanism of interaction has not been determined, and the frequencies employed are higher than those explored in this article.

Simple calculations for a cylinder of material of conductivity equal to 1 Sm^{-1} subjected to an axial rate of change of magnetic field of 4 Ts^{-1} gives a current density of 100 mAm^{-2} at a radius of 5 cm. Unfortunately, the human head has a complex geometry and an hetrogeneous conductivity, and we have to rely on numerical methods to estimate the values of current density induced by simple movements. Liu and Crozier have calculated current densities induced in brain tissue during movements in the magnetic field of an MR scanner [Liu et al., 2003b; Crozier and Liu, 2005]. Crozier estimates that in the stray field of a 7 T magnet, the peak current density induced in the whole body moving at a velocity of .8 ms^{-1} could be .48 Am^{-2}, the value needed for PNS. However, the results are quoted as average and/or maximum values and cannot help us determine the proportion of current flowing through the vestibular system. It is difficult to determine the exact spatial distribution of induced electric fields in an individual's inner ear with numerical modeling methods because of the very high spatial resolution required, together with the low frequency excitation required. Information about the magnitude of current density in the inner ear needed to induce vertigo-like effects can be inferred from the results of GVS studies, but again it is not straightforward to relate the internal induced current to the currents applied to the mastoids. By extrapolating from calculations related to Electro-Convulsive Therapy (ECT) [Nadeem et al., 2003] we predict that 1 mA applied to the cranium above the temporal lobe might generate a typical current density of the order of 100 mAm^{-2} in brain tissue near to the inner ear. Transcranial direct current stimulation (tDCS) uses similar current strengths to those used in GVS and current densities of 100 mAm^{-2} in the brain are assumed [Nitsche et al., 2003, 2004]. If such currents cause a perilymphatic current of 1 μA to flow, which will have an effect on the vestibular hair cells, then from simple calculations or scaling of the numerical modeling values obtained by Crozier, we propose that a human head exposed to a rate of change of field equivalent to 4 Ts^{-1} could elicit a response. For example, the peak current density, J_φ, induced in a cylinder of radius, R, conductivity, σ, with an applied rate of change of axial magnetic field, $\mathrm{d}B_z/\mathrm{d}t$, is $J_\varphi = {}^1\!/\!_2\sigma R\,\mathrm{d}B_z/\mathrm{d}t$. Taking $R = 5$ cm, $\sigma = 1$ Sm^{-1}, and $\mathrm{d}B_z/\mathrm{d}t = 4$ Ts^{-1} gives $J_\varphi = 100$ mAm^{-2}. Hence, we may conclude that it is possible that movements in gradients or rotations in homogeneous fields could be perceived as an unrelated experience of movement due to iGVS. As the firing rate of the human vestibular hair cell is in the region of 30 Hz, low-level current stimuli should be present for a period greater than several cycles or else the effect will be averaged. For stimulus frequencies greater than 30 Hz, it is likely that direct stimulation of the nerve cells similar to PNS would be dominant. The vestibular system does respond very quickly to abrupt and large changes in acceleration, but it is unlikely that the currents induced by movement around high-field MR scanners could elicit such a response. The GVS response is sensitive to current polarity, so it is also likely that effects due to iGVS would be sensitive to the polarity of any induced currents.

Magneto-Hydrodynamics (MHD)

MHD describes the flow of conducting fluids in electromagnetic fields. Here we use the term MHD to describe the forces on a moving conducting fluid due to the effect of the magnetic field on currents induced in the fluid. MHD effects become important when these forces are similar in magnitude to the viscous and inertial forces in the fluid. The relative magnitudes of these effects are characterised by the 'Magnetic Reynolds number', R_m, [Ferraro and Plumpton, 1966]. For vestibular structures on a scale of a few millimeters and fluid conductivities of order unity, R_m is of order 10^{-9}, so that MHD effects are unlikely to be of any relevance. It is possible that MHD effects are significant for blood flowing within much larger arteries, having a high velocity of the order 1 ms^{-1} and at magnetic fields above 7 T [Kangarlu and Robitaille, 2000].

Let us now consider the geometry of the vestibular, semi-circular canals in more detail. Each semi-circular canal can be modelled as a toroid having an overall radius b (approximately 3 mm) and an internal radius a (.17 mm). Two possible configurations for motion of the toroid relative to the field that may result in a net pressure being induced are shown in Figure 2. Schenck [Schenck, 1992] has previously considered the geometry shown in Figure 2A in which there is angular rotation about the toroid diameter in a perpendicular magnetic field. MHD effects due to this motion would not naturally produce a deflection of the cupula within the fluid as the force is radial, and resultant torque on the loop would not induce a net pressure gradient around the tube. However, Schenck assumes that this radial force is transmitted perfectly to the cupula of an orthogonal canal, and goes on to compare the resulting pressure with the value of the minimum perceived pressure on the cupula (13 μPa) determined by Oman [Oman and Young, 1972]. However, this comparison is not relevant for a number of reasons. First, the pressure should be calculated in the larger diameter ampulla rather than the smaller diameter semi-circular canal. This gives rise to a reduction in pressure by a factor of 16 because of the 16 times larger cross-sectional area of the ampulla compared to the canal. Dividing the pressure given by Schenck by 16 (9.4 μPa) gives an effective cupula pressure below the minimum perceived value. Second, examination of the whole vestibular system in detail shows that perfect coupling of forces is highly unlikely for most angular rotations of the head. In most pairs of canals the transmitted radial force would exert itself on both sides of an adjacent cupula almost equally resulting in only a small net pressure. For most natural rotations of the head at least two (usually all three) of the canals will experience inertial pressures. The MHD explanation of MFIV as resulting from MHD effects consequently demands that the cupula senses a small perturbation effect at or near the limit of its sensitivity whilst the head is rotating and accelerating rapidly.

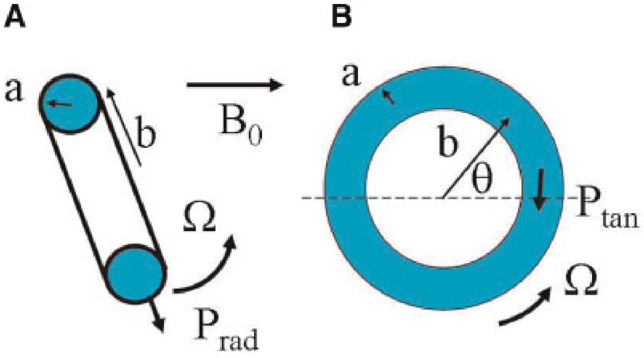

Fig. 2. Geometry used for calculation of pressure on cupula due to angular velocity of semi-circular canal. **A**: The geometry assumed for the derivation by Schenck, and (**B**) the geometry for the derivation in this work. The direction of B_0 is common to both diagrams. [The color figure for this article is available online at www.interscience.wiley.com.]

We may now consider the geometry shown in Figure 2B, where the toroid rotates about its axis with the magnetic field in the plane of the toroid. In this situation, the induced pressure acts directly on the cupula of the toroid. For this arrangement, the pressure on the cupula may be determined by integrating the pressure generated on elements around the toroid due to the changing components of the magnetic field to give,

$P = \pi B_0^2 a^2 \sigma\Omega/8$, where Ω is angular velocity of the toroid. A derivation of this expression is given in appendix A of the accompanying supplementary material. For $B_0 = 7$ T, $\sigma = 1$ Sm^{-1}, and $\Omega = 10$ rads^{-1} this would give a pressure of 5.5 μPa, which when divided by the ratio of the cross-sectional areas of the ampulla and canal gives a value that is very much smaller than the minimum pressure needed for perception. Other types of motion of the toroid may yield a finite pressure, but these are even lower than those calculated above.

Diamagnetic Susceptibility

All materials possess a magnetic susceptibility due to the electronic configuration of the atoms and molecules of the material. Weakly interacting materials are classified as either paramagnetic or diamagnetic depending on the sign of the magnetic susceptibility. The small, but finite energy of interaction between the induced magnetic dipoles of the material and the imposed magnetic field can give rise to a net force or torque. In the following section the forces on the otolithic membrane and the cupula are calculated for magnetic fields in the vicinity of a 7 T whole-body magnet.

In an inhomogeneous magnetic field the force on an object is given by considering the spatial rate of change of the product of the magnetic moment and magnetic field [Ueno and Iwasaka, 1994]. Such effects have been used to levitate small objects [Catherall et al., 2005] and the Gouy method for determining magnetic susceptibility is based on this effect. In an inhomogeneous magnetic field an otoconia (Fig. 1B) is subjected to such a force, which creates a deflection of the otolithic membrane and that can be directly compared to the force, and hence the deflection, caused by acceleration of the head. Thus the apparent acceleration, **a**, perceived by the subject in an inhomogeneous magnetic field, B, is given by,

$$\mathbf{a} = -\frac{(\chi_o - \chi_f)\nabla(B^2)}{2(\rho_o - \rho_f)\mu_0}$$

where ρ_o and ρ_f are the density of the otoconia and fluid, respectively, χ_o the susceptibility of the otoconia, χ_f the susceptibility of the fluid, and $\bigtriangledown(B^2)$ is the gradient of the square of the magnetic field. A derivation of this expression is given in appendix B of the accompanying supplementary material. For the aragonite form of calcite, χ_o is -14.1×10^{-6} and ρ_o is 2900 kgm^{-3} [Lide, 2006]. The fluid surrounding the otoconia (145 mM KCl for endolymph) may be assumed to have the density of water and a susceptibility of -8.97×10^{-6} [Lide, 2006]. There is no evidence found in the literature to indicate that (in humans) the magnetic properties of the otolithic membrane are affected by

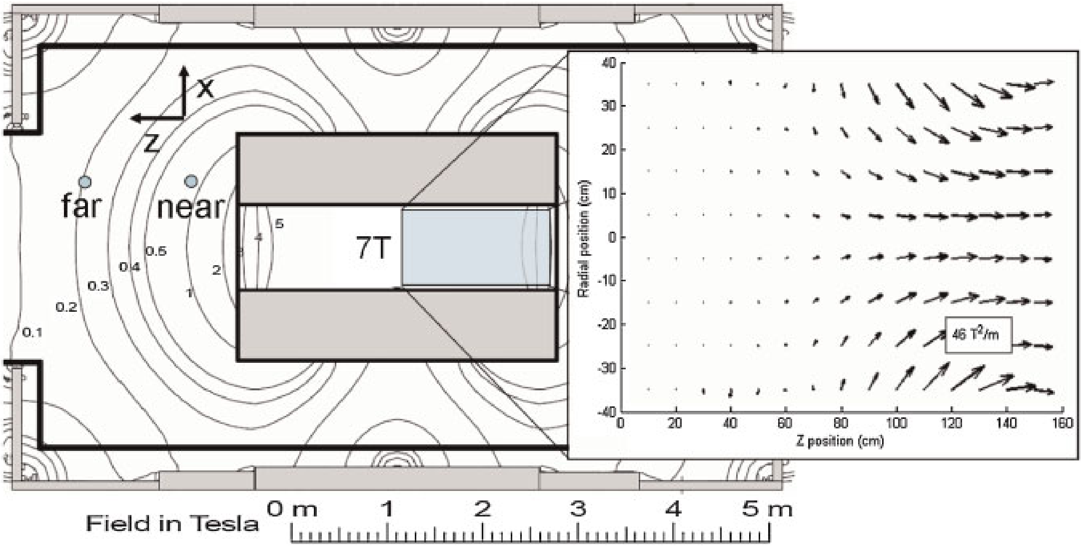

Fig. 3. Showing the field plot of a 7 T 900 mm bore whole body magnet. Axes definitions are shown together with the "near" and "far" locations used in the static-subject static-field experiment. The scale bar indicates overall size of magnet and installation. The inset arrow plot represents the magnitude and direction of the force on a diamagnetic object within the bore of the 7 T magnet. A point where $B \times G$ has a value of 46 T^{2}m^{-1} is shown, which corresponds to an equivalent subject percieved acceleration of 1% of g due to otolithic membrane susceptibility. Distances on the inset graph are from iso-center (z axis) and radially across bore. [The color figure for this article is available online at www.interscience.wiley.com.]

the presence of any trace elements. The magnitude of the vector $\frac{1}{2}\nabla B^2$ can be written as $B \times G$, where G is the gradient of the field. Taking a value of 46 T^2m^{-1} (which occurs at a position just 30 cm inside the bore of a 7 T magnet—see Fig. 3) the susceptibility effect would produce a perceived acceleration of $-.01$ g. This value is of the order of the perception threshold for lateral accelerations. However, there is a large variation in literature values and significant inter-subject variation of these thresholds [Kornhuber, 1974a,b], and the value of $B \times G$ required for perception at minimum threshold may be as low as 4.6T^2m^{-1} (which occurs at a position just outside the bore of a 7 T magnet). The minus sign for the perceived acceleration would indicate that a subject standing in front of the magnet would feel an effective acceleration towards the magnet when facing either towards or away from the magnet.

In the case of the cupula it is not possible to equate the diamagnetic force to a perceived acceleration in the same way for the following reasons. First, we do not know the precise difference in susceptibility between cupula and endolymph. The cupula is a gelatinous membrane and there are no crystalline structures in this body which could lead to anisotropic properties. Second, we do not know the exact difference in density between the cupula and fluid—although a sensible assumption is that the difference is very small. Third, the cupula is viscously coupled to the fluid and the precise process of mechanical deformation due to motion is unknown. If it is assumed that the cupula is like a piston positioned inside a ring of fluid, then assuming that the cupula has a thickness, t, the susceptibility-induced pressure on the cupula is given by $P = \Delta\chi tBG/\mu_0$, where $\Delta\chi$ is the cupula-fluid susceptibility difference. Taking $t = 100$ μm and assuming a 1% difference in cupula-fluid susceptibility then a $B \times G$ product of 1.8 T^2m^{-1} would give a cupula pressure equal to the minimum perceptible value of 13 μPa. This value of $B \times G$ product is not dissimilar to the more certain value derived for the otolithic membrane where fewer assumptions about material characteristics need to be made.

METHODS

It is clear from the preceding section that experiments designed to explore the parameters which govern the perception of vertigo are required. The susceptibility mechanism does not depend on motion and should therefore be perceived by stationary subjects, but should only be noticed in regions where both the gradient and field are high. The iGVS and MHD mechanisms require a combination of motion and a strong magnetic field. In addition, the MHD mechanism requires a high angular velocity of the vestibular system which can only be achieved by rotation of the head. We have designed experiments to try to separate these effects, which are summarised in Table 1. The first class of experiments (termed static-subject changing-field) test the iGVS mechanism by exposing the subject to an impulse of high rate of change magnetic field without the presence of a strong magnetic field component. The second class of experiments (termed static-field moving-subject) tests the MHD and iGVS mechanisms and was carried out in or around the magnet so that the time variation of the field is determined by the subject's movement. A third class (static-field static-subject) test for the presence of the susceptibility mechanism via observation of behavior when subjects are static and positioned in a region where the product of field and field gradient is high. All the experiments and protocols were reviewed and approved by the University of Nottingham Medical School Ethics Committee.

Static Subject Changing Field

This part of the study was designed to explore the effect of single or very low frequency events in which subjects were exposed to a high rate of change of uniform magnetic field with time, without the effects of a static magnetic field. To avoid effects of magnetic-field gradients and movement, a solenoid coil which could accommodate a human head was constructed. The subject was able to stand upright with the head inside a solenoidal electromagnet coil, which was supported by a gantry as shown in Figure 4 and located well away from any magnetic field. The solenoid was formed from 819 turns of insulated copper wire of 5×1.8 mm^2 cross-section arranged as two separate windings. Driving both windings in series gave a magnetic-field efficiency of 2.8 mTA^{-1} and an inductance of 167 mH. The efficiency and dB/dt values were calibrated with a gaussmeter (GM04 Hirst Magnetic Instruments, Falmouth, UK). The required waveform was generated by an in-house built waveform generator controlled by a computer and amplified by a pair of Amcron (Crown, Inc., Elkhart, IN) 7700 power supplies, wired in series, and operated in constant current mode. The maximum magnetic field generated within the coil was 200 mT with a maximum rate of change of up to 5 Ts^{-1}. Typically the coil could generate a single dB/dt event of 2 Ts^{-1} amplitude for 200 ms. The waveforms used are shown in Figure 5. The slow ramp up and down periods were timed to produce a dB/dt which was a factor of 20 times lower than in the impulse. It is not possible to produce a completely unipolar dB/dt or sequences having a high duty cycle without overheating the coil or power supplies. The inner winding of 400 turns could be used on its own to

TABLE 1. For Each Mechanism Discussed a Summary of Conditions and their Magnitudes are Given

Mechanism	Dependent conditions	Theoretical order of magnitude for effect	Experiments performed	Typical experimental conditions used	Summary of result and conclusion
iGVS	Applied dB/dt	A dB/dt of order 4 Ts^{-1} is required which may generate induced currents of the order 100 mAm^{-2} in the head for periods exceeding 100 ms.	Static subject changing field	2 Ts^{-1} for period of 100 ms	No detected effect for these parameters.
	Movement through static gradients		Patient bed movements	0.1 ms^{-1} and up to 6 Tm^{-1} (at both ends of magnet)	Yes, perception of rotation. Asymmetry is reported.
	Head rotation in a strong field		Static field moving subject	At 7 T and angular velocities not exceeding 1 rads^{-1}	Yes, for most participants effect is moderate to severe.
MHD	Head rotation in a strong field	Angular velocity of order 10 rads^{-1} and $B \geq 4$ T predicted. Scales as B^2.	Static field moving subject	At 7 T and angular velocities not exceeding 1 rads^{-1}, that is, less than would be predicted to cause significant MHD effects	See above. Subjects perceive effects at velocities an order of magnitude smaller than the predicted threshold for MHD.
DS	Both strong fields and gradients but no subject movement needed	$B \times G \geq 5$ $\mathrm{T}^2\mathrm{m}^{-1}$ may give perceptible effect in some subjects.	Static field static subject	A $B \times G$ of 1 $\mathrm{T}^2\mathrm{m}^{-1}$ was measured where subjects stood near the magnet.	Postural sway modification occurs in some subjects. Some subjects have perception of falling while completely stationary in the stray field

In addition the table shows the experiments conducted and how they relate to the mechanisms to be tested, together with experimental conditions used and summary of measured effect.

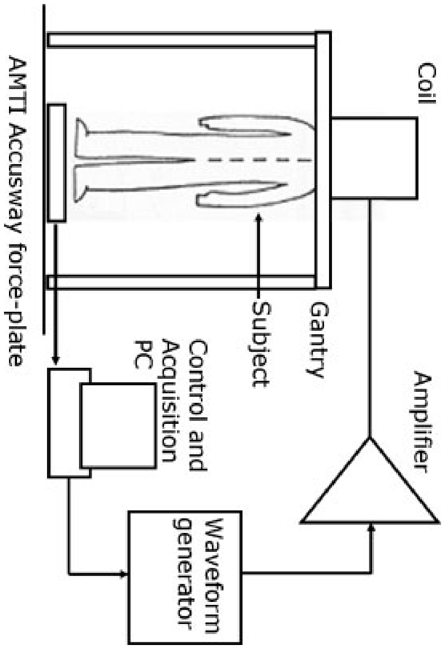

Fig. 4. Apparatus for static-subject changing field experiments showing solenoid coil on gantry, force-plate and control/acquisition computer.

generate higher rates of change of field, but with reduced event duration. Integer numbers of cycles of sinusoidal excitation at low frequency (up to 5 Hz) could also be used.

For these experiments, the subject (with eyes closed) stood on a force-plate (Accusway AMTI, Watertown, MA) which recorded lateral movements and location of the COP during the study. Removable flat blocks and a heavy rubber mat were placed under the force-plate to ensure that the subject's head was in the center of the solenoid. During each trial, six channels of forces (F_x, F_y, F_z) and moments (M_x, M_y, M_z) were recorded. Twelve subjects volunteered for this part of the study (eight males and four females, mean age 26 ± 4 years). Each subject was first allowed to practice standing still on the force-plate with the head in the coil for 1 min without data being saved or stimuli being presented. Four trials, each of 1 min duration, were then used for each of two stimuli: a sinusoidal stimulus of four cycles at 2.5 Hz with a maximum dB/dt of 2 Ts^{-1} and peak magnetic field of 127 mT; and a pulsed stimulus of 50 ms duration at 2 Ts^{-1} giving a peak field of 50 mT (Fig. 5). Each stimulus was repeated eight times at 5 s intervals during the 1 min trial. For two of the trials with each stimulus (picked at random) the current was set to zero. The subject was subsequently asked to identify the trials during which the current was applied. The peak dB/dt used for these studies was set at 2 Ts^{-1} for both single event and sinusoidal waveforms to just avoid magnetophosphenes, which could induce a reaction from the subject and would certainly inform the subject about the presence of the stimulus. Subjects wore ear plugs to mask the very faint audible click from the coil when it was pulsed with current.

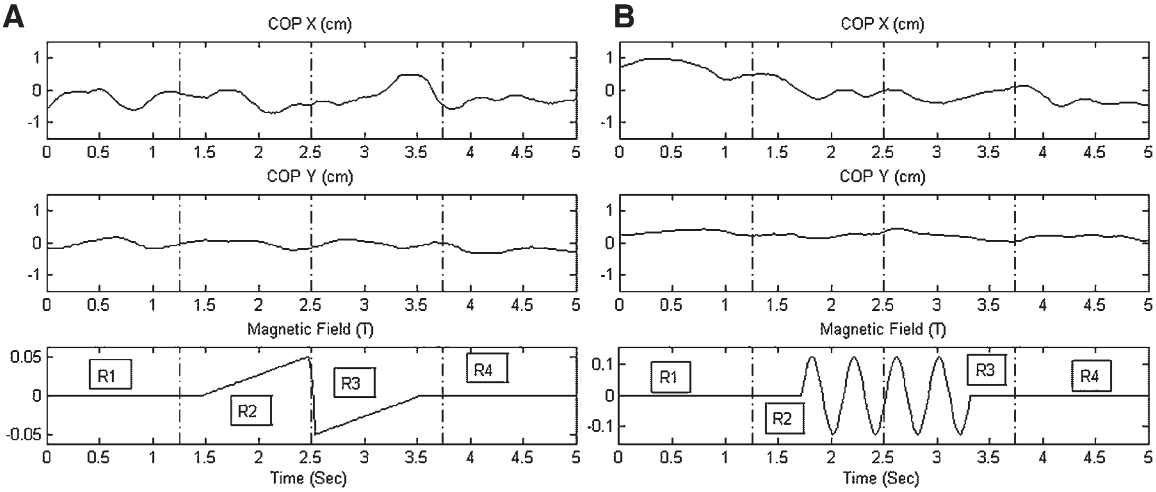

Fig. 5. Typical COP variations are shown for (**A**) pulsed and (**B**) sinusoidal stimulus presentations for static-subject changing-field experiment. The 5 s stimulus period has been divided into four regions defining times before, during and after stimulus delivery. The X and Y COP variation during each of these periods is shown for one subject.

Static Field Moving Subject

The remaining tests were performed in and around a 7 T, 900 mm bore, whole body magnet (Magnex, Abingdon, UK). A field plot of the magnet environment is shown in Figure 3. The magnitude and direction of the force that would be experienced by a diamagnetic object within the bore of the magnet is represented as an arrow plot. A purpose built dB/dt meter consisting of three orthogonal search coils (each of 100 turns and 284.0 mm^2 area) was used to measure and record the emf induced by motion of the head in the magnetic field [Cavin et al., 2006]. The search coil assembly was lightly attached to the side of the head adjacent to the sphenoid bone. Voltages induced were amplified and sampled at 100 Hz by a multi-channel data logger (ADC-11 Pico Technology Ltd., St. Neots, UK and laptop PC). The coils were calibrated using the solenoid coil (described above) driven to generate a known dB/dt.

Ten volunteers were recruited to take part in this experiment (six males and four females, mean age 28 ± 6 years). Subjects were asked to lie in a prone position on the patient bed with head towards the magnet. They were introduced into the magnet at a normal bed velocity of .1 ms^{-1} giving peak dB/dt values of about 1 Ts^{-1} and their experiences were recorded. The subject was moved so that the head reached the homogeneous (zero gradient) part of the magnet. They were then asked to slowly nod (long axis of head rotated from z to y axis direction), and then rotate their heads axially (around both z and y axis directions) with a period of between 4 and 12 s timed by an audio cue. Movements were executed for approximately 30 s followed by a 1 min rest period. These movements were then repeated at low field (<.5 T) with the subject away from the magnet to confirm that they felt no sensation of dizziness when performing these movements normally. Responses were graded on a simple three point scale which was: none (no discernable effect); mild (notice an effect); and severe (uncomfortable or unpleasant effect).

Two subjects from the above cohort who could discern a specific direction of apparent motion whilst being moved into the magnet were placed on a temporary bed arrangement at the rear of the magnet and the experiment repeated. By considering the subject movement relative to the magnet bore entrance, then, if the response was predominantly due to iGVS the direction of apparent motion would be reversed as the induced current direction would be reversed in the subject's frame of reference. However, the effect of magnetic susceptibility would not reverse when comparing similar positions at either end of the magnet, as the net diamagnetic force on an object is symmetrical about the center plane of the magnet.

Static Field Static Subject

A number of users of the 7 T have reported a feeling of movement and falling when standing stationary near the magnet. To evaluate this effect, 10 subjects (6 males and 4 females, mean age 30 ± 9 years) were positioned at two different locations: one near to the magnet where $B \sim .8$ T and $B \times G \sim 1.0$ T^{2}m^{-1}, and one 1 m further away from the magnet where $B \sim 0.2$ T and $B \times G \sim .06$ T^{2}m^{-1}. In this test dB/dt =

0 Ts^{-1} or is vanishingly small as movement is only a few millimeters over several seconds. Subjects were asked to stand still for 1 min prior to the start of the experiment. This period was used to calibrate the displacement measurements and to measure the magnetic field. The subjects were asked to fix their gaze on a point on the wall 3 m away. Fixed markers were placed on the subject's head to track the subject's forward sway using a video camera placed side-on to subjects. At each position the subject closed their eyes for 20 s and then opened them for 20 s for three cycles directed by an auditory cue. An indicator light was also illuminated behind the subject to provide a visual indication of the cue within the video record.

RESULTS

Static Subject Changing Field

Although not the subject of this article it is useful to note that magneto-phosphenes (perceived flashes) were routinely reported when subjects were exposed to dB/dt values of 1.5 Ts^{-1} for 50 ms at low light levels. The threshold values described here are consistent with previously reported values, although the latter are for sinusoidal waveforms in the frequency range of 10–50 Hz [Lovsund et al., 1979, 1980a,b; Silny, 1984; Kangarlu and Robitaille, 2000]. The threshold of perception was found to increase to about 2 Ts^{-1} in dark conditions or if subjects shut their eyes. The seemingly anomalous slight rise in the threshold under dark conditions has not been previously reported in the literature. No subject reported either an audio click or magneto-phosphenes during the balance tests or was able to identify when the stimulus was being presented any better than would be achieved by a random guess. No subject reported any feelings of vertigo or sensation of movement during the study. The root mean square deviation of the COP from the mean position during each trial was calculated for each subject for each of the three stimulus conditions (a) none, (b) pulsed, and (c) sinusoidal. No trend was observed related to the presence of an applied field and no sensation of sway was reported by the subjects. To reduce the effect of any long term drift in COP we explored the possibility that any sway is correlated with the stimulus. Figure 5 shows an excerpt from a typical trial during stimulus presentation. To evaluate the effect of dB/dt on volunteers' balance within an experiment, the 5 s time period was divided into four parts: pre-stimulus, early and late periods during stimulus, and post-stimulus (marked as R1, R2, R3, and R4, respectively, on Fig. 5). Differences in size of movement during these 1.25 s intervals were evaluated. The RMS COP movement during each of these periods showed no correlation with the stimulus. While there are clearly inter-subject differences there is no significance at any level for the hypothesis that the movement is related to the applied stimulus. In addition, no cross-correlations could be found in the raw data (either forces or moments) any more significant than $P = .3$ (based on a single sided t-test comparing mean cross-correlations during stimulation and no stimulation). Single events in which higher dB/dt values of up to 5 Ts^{-1} for 40 ms were applied to a few individuals, who again reported no apparent movement or feeling of vertigo, but did report an obvious magneto-phosphene flash.

Static Field Moving Subject

Seven out of ten subjects felt a magnetic field induced sensation of movement that was inconsistent with the direction of motion of the bed when being pushed into the magnet. Two of the seven indicated that the sensation was severe. The total integrated change in field during the movement into the magnet was measured to be of order 6 T over a time period of between 6 and 10 s with peak dB/dt values of order 1 Ts^{-1}. When the two subjects who could identify a particular direction of apparent motion when being pushed into the bore were pushed into the opposite end of the magnet the apparent direction of motion was reversed. Taking one particular subject as an example, when lying supine on the bed at the north (normal) end of the magnet the feeling was one of tipping backwards, and at the south end (rear) the feeling was one of tipping forwards. At either end of the magnet, if the subject turned over to a prone position then the apparent motion direction was reversed (i.e., to an observer, the direction of reported apparent movement stayed the same). This observation is consistent with the pattern of current flow as experienced by the subject being reversed when entering the magnet from the opposite end.

The head movements executed by the subjects at the center of the magnet corresponded to measured maximum angular velocities of less than 1.5 $rads^{-1}$. The reported mild to severe sensations of MFIV were well above any minimum threshold with two subjects reporting a feeling of nausea very soon after the start of the test. The peak recorded values of dB/dt were not particularly high, lying in the range of 1.5–6 Ts^{-1} but had a duration lying between 6 and 2 s. Nine out of 10 subjects reported either mild or severe MFIV effects at some point in the experiment, with 2 subjects withdrawing part way through the tests due to severe nausea. Generally higher values of field change were recorded when executing nodding or horizontal motion rather than axial rotations. It was observed that the subject's axial rotation was not precisely aligned with the main field axial direction. Eight out of the 10 subjects reported a feeling of dizziness immediately after the end of the test, which persisted for some time (anecdotal reports of between 10 and 30 min) even though they had not reported severe responses during head motion. The data for field change over the period of a movement (integration time) for all subjects is shown in the inset detail of (Fig. 6). The data for all subjects are plotted to show mild, severe, and no reported effect for all requested movements. Values are clustered because the subjects were asked to perform the same tasks. The average of all the mild responses gives a field change of 4.7 T in a time of 1.9 s. The average of the d*B*/d*t* values is 2.8 Ts^{-1}. The measurement error in any particular integration was typically ±10% for both time and field values.

Static Field Static Subject

Measurements of the forward displacement of the head for each subject were taken from the video file with a sampling interval of 1.6 s (50 frames). The averaged response over three cycles of 20 s with eyes closed followed by 20 s with eyes open for subject 4 is shown in Figure 7. The mean displacement of the head between eyes open and eyes closed states when the subject stood close to the magnet was compared with the mean displacement when the subject was positioned further from the magnet. The mean differences together with the standard error in the means are shown in Figure 8. Three out of the 10 subjects tested exhibited significant mean displacement forward sway in the near position (1.0 T^2m^{-1}) compared to the far position (.06 T^2m^{-1}) ($P < .05$ using two sided t-test). Two other subjects (7 and 9) showed a marked increase in the amount of sway when positioned close to the magnet—reflected in the larger SEM values. Two subjects (4 and 9) perceived the presence of the magnetic field as a feeling of "falling" when standing stationary near the magnet.

DISCUSSION

Table 1 contains a summary of the experimental results and general conclusions discussed in this section. MHD effects have previously been proposed as the main cause of vertigo in strong magnetic fields. However, the large difference in the magnitudes of the magnetic and inertial forces seems to preclude such an

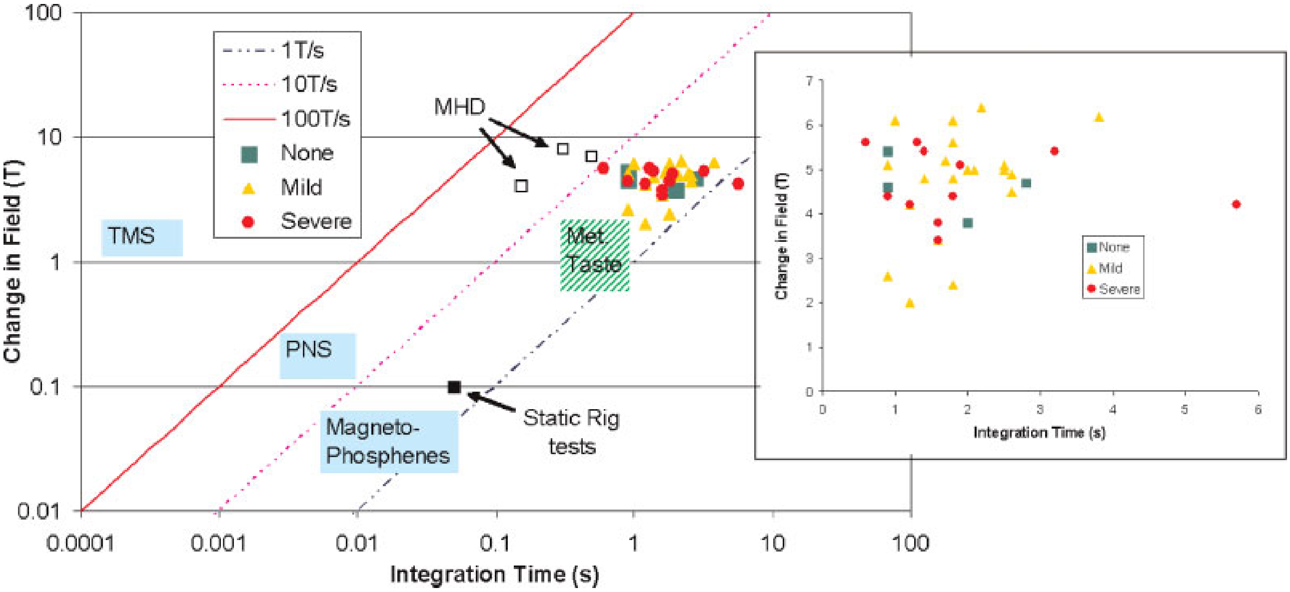

Fig. 6. Summary of effects of exposure to excursions of magnetic field over particular integration times for static-field moving-subject experiment. The inset graph shows measured values of field change for integration times taken from the recordings of d*B*/d*t* during movement of the subject at the iso-center of the 7 T magnet. The subject response grades are shown separately as None (squares), Mild (triangles), and Severe (circles). Note that linear scales have been used and error bars have been omitted for clarity. Uncertainty in any one measurement is typically of the order of ±10%. In the main graph, iso-contours for various values of d*B*/d*t* are shown. Approximate operating regions of particular phenomena are given as a guide. The expected location of any possible minimum MHD effect is shown for calculations based on a 4 and 7 T magnetic field. [The color figure for this article is available online at www.interscience.wiley.com.]

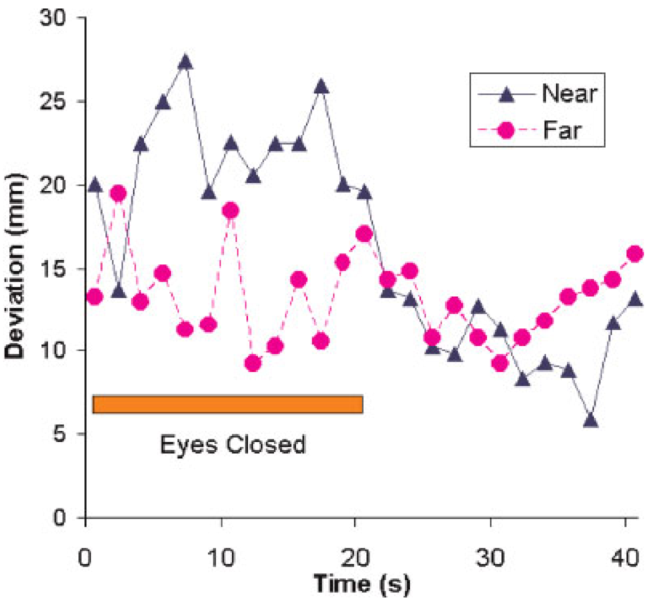

Fig. 7. Static-field static-subject experiment: average time course (three cycles) of movements for subject 4 while standing close to and far away from magnet during 20 s eye closed and 20 s eyes open period. The period of eye closure is shown by the bar. [The color figure for this article is available online at www.interscience.wiley.com.]

explanation for MFIV. This is also consistent with the fact that perception of MFIV does not require the execution of high angular velocity movements of the head.

The perception of "falling" or the postural sway modification for subjects standing stationary close to the magnet is likely to result from a susceptibility-related effect as it is the only one of the three possible mechanisms which does not require a temporal rate of change of magnetic field. The direction of gaze and head orientation could modify the sway direction slightly and two subjects twisted slightly on closing their eyes. This is similar behavior to that seen in GVS experiments [Fitzpatrick and Day, 2004] and supports the suggestion that the mechanism underlying the magnetic field induced sway operates via the vestibular system.

While it is good practice to move slowly in and around magnets it was clear from the $\mathrm{d}B/\mathrm{d}t$ record that high rates of change of field could be generated when subjects were not actually doing one of the tests, but merely standing near the magnet, talking in a relatively animated manner (e.g., nodding head). High peak values of $\mathrm{d}B/\mathrm{d}t$ of between 10 and 20 Ts^{-1} can be generated by fast angular rotations of the head just inside the magnet bore (3–4 T). Peak values exceeding 3 Ts^{-1} can be observed when people are standing in a field of 1 T. However, the experimental results for static subject changing field show that high peak values of $\mathrm{d}B/\mathrm{d}t$ are not enough in themselves to give rise to a sensation of vertigo. Figure 6 summarises the results related to the sensation of iGVS related vertigo. The integrated $\mathrm{d}B/\mathrm{d}t$ (giving a total field change) is plotted against the total integration time. Contours of constant $\mathrm{d}B/\mathrm{d}t$ are indicated. The data points define a region on the graph which shows the values of field change required for induction of a mild or severe sensation of

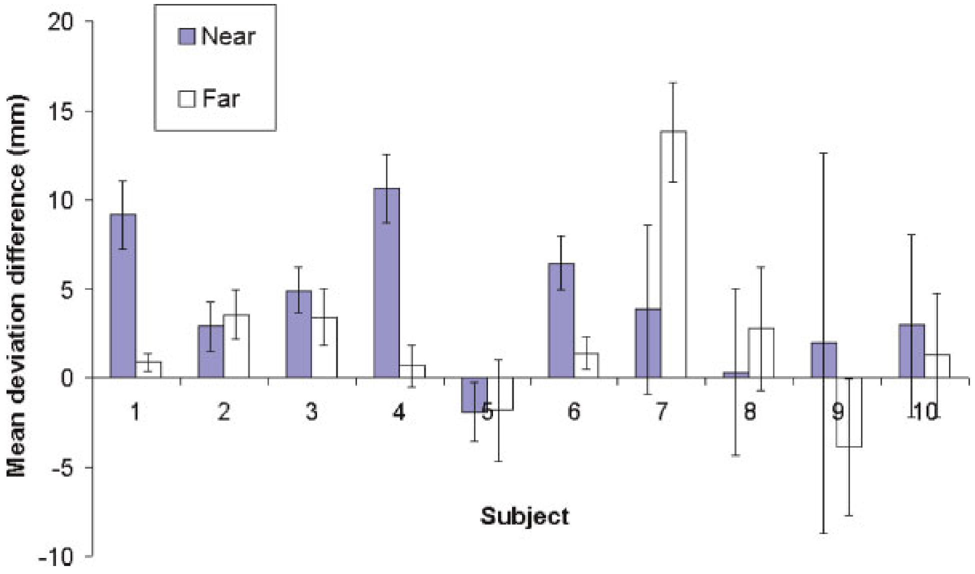

Fig. 8. Static-field static-subject experiment: graph showing mean difference forward displacements between eyes closed and open by subject whilst near and far from magnet. The error bars show the standard error of the means. [The color figure for this article is available online at www.interscience.wiley.com.]

vertigo. The region where effects are perceived could be defined by field changes of 2 T or more and a rate exceeding 1.5 Ts^{-1} for times greater than 1 s. Larger field changes of 4 T or more can also be perceived over longer periods. The approximate regions where other known effects (magneto-phosphenes, metallic taste, or PNS effects) occur are shown in terms of rates of change and integration time. All sensory effects occur at similar values of dB/dt, but the total integration time required for perception is different. Also shown are the points where Schenck predicts that MHD effects might become detectable (two points are for a 4 T magnet and one for a 7 T magnet at 10 and 3.2 $rads^{-1}$ angular velocity, respectively). Very short transients of high dB/dt (such as those produced in the static rig test) are unlikely to induce vertigo until the nerve stimulation thresholds are reached, corresponding to the rates used in TMS for example. Natural movements, even at fields of 7 T would be unlikely to ever generate such high dB/dt values in this frequency range. It might be concluded that the total field change is the dominant parameter governing iGVS. The integrated current density, and hence the amount of charge moving in the tissue, is proportional to the field change. However, this charge is not accumulated in a nerve or cell so it may be purely the total length of stimulus duration that is significant. The long time constants observed in sway measurements are unlikely to be a result of delays in the vestibular sensory apparatus, since the time constants are many times the firing period of the hair cell afferent nerves. Motion sickness occurs for motion occurring at frequencies below 1 Hz. It is likely that time constants in the balance feedback central nervous system are of the order of the inverse of this frequency and hence such low frequency perturbations cause the most disruption.

The practical difficulty of introducing a true sham control when dealing with a large magnet has to be acknowledged. We are unable to switch the field off or provide conditions which truly disguise the location of the subject. In carrying out the experimental work, subjects generally underwent a whole series of tests to identify when a threshold was passed. However, the balance processing functions have adaptation and integration mechanisms with long time constants and so it is possible that a prior trial could have a lasting and opposite effect on subsequent trials. Future experiments aimed at accurate determination of thresholds should include long rest periods. The wide range of inter-subject variation and ability to adapt or deal with the MFIV effects are apparent both in our experiments and in other balance-related research. It would be instructive to combine the subject's sensitivity to MFIV with measurements of the balance functions, and acceleration perception thresholds.

CONCLUSIONS

Forces on the diamagnetic otolithic membrane and/or cupula can explain some of the experiences of subjects in and around high field magnets. In combination with the galvanic stimulation due to sustained magnetic field changes at rates of .5 Ts^{-1} and above, these cause the brain to be presented with a confusing set of stimuli which are interpreted as apparent motion unrelated to actual movement. Evidence of a static field-gradient effect and the similarity of iGVS with GVS findings supports the hypothesis that the transduction mechanism is vestibular in origin—that is, due to either mechanical forces or electrical changes in the afferent nerves—rather than a direct effect on the CNS. The value of $B \times G$ required to give a measurable postural sway response in the most sensitive subjects is around 1 T^2m^{-1}. The work described here demonstrates that a significant effect is measurable in a static field and confirms the existence of a susceptibility related mechanism. It is unlikely that any biological damage can be caused by the susceptibility mechanism as deflections of the cupula or otolithic membrane are only a small fraction of the normal operating range, that is, only accelerations equivalent to a slow elevator at most. It may however be prudent for manufacturers of MR scanners to provide data showing the 1 and/or 5 T^2m^{-1} contours of $B \times G$ so that users could be advised that effects might be perceived inside this volume. Advice to users might be to restrict their overall field change over a period of 1 s to less than 2 T, which would minimise MFIV, although it is quite easy to exceed this threshold accidentally by turning the head in the field.

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