Mechanisms for vertigo experienced by subjects in a high field environment: Hypotheses and Experiments

P. M. Glover[1], P. A. Gowland[1], R. W. Bowtell[1], I. Cavin[1]

[1]Sir Peter Mansfield Magnetic Resonance Centre, University of Nottingham, Nottingham, NG7 2RD, United Kingdom

Introduction

Movement of the human head is detected in the vestibular system, which consists of three approximately orthogonal toroids of conducting fluid, each containing a pressure sensitive cupula. These organs detect angular accelerations of the head. The maculae of the vestibular system are the organs which detect lateral and vertical accelerations, and are composed of a gel matrix which supports otoliths (aragonite form of calcium carbonate) [1]. The otoliths effectively form a mass on a spring whose deflection is sensed by hair cells. It is possible to postulate a number of mechanisms for the induction of vertigo during exposure to large magnetic fields. These include: magneto hydrodynamic effects within the vestibular fluids (**MHD**); galvanic vestibular stimulation of hair cells due to induced currents (**GVS**); forces due to magnetic **susceptibility** differences between maculae and surrounding material. In this work we present theoretical predictions together with experimental evidence for and against each of these mechanisms.

Hypotheses

MHD: These effects have previously been proposed as the main cause of vertigo in large magnetic fields [2]. Careful examination of MHD theory does not however support this explanation. Consider a cylinder of fluid having conductivity σ, length l, and radius a is moving axially at velocity v in an axial magnetic field gradient G, then the pressure on the end surface of the cylinder is given by $\pi G^2 a^2 l v \sigma / 8$. Comparing this value to inertially-induced pressure changes during movement suggests that movement in the field gradient leads to a perceived acceleration of $\pi G^2 a^2 v \sigma / 8\rho$ where ρ is the fluid density. In the case of the vestibular system (a = 0.1mm, σ = 1Sm^{-1} and ρ = 1000kgm^{-3}), for very high velocities (v = 10 ms^{-1}) and magnetic field gradients (G = 10Tm^{-1}) this is only equivalent to 10^{-6} of the gravitational acceleration (g). The expression given in Ref. [2] for the pressure changes induced in a toroid due to motion in a strong magnetic field appears to assume angular rotation about the toroid diameter rather than its axis. The former geometry would not produce a deflection of the cupula within the fluid. Calculation of the effect of rotation about the toroid axis gives a smaller pressure change than that calculated in Ref. [2] which is significantly less than the 5 mPa threshold [3] for perception.

GVS: Hair cells form linear deflection transduction sensors and respond to the displacement of the cupulae and the maculae. The hair cell has a static firing rate at zero displacement; deflection causes a change in firing rate which the brain interprets as movement [4]. 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 therefore likely to be lower than the accepted thresholds for peripheral nerve stimulation. Unfortunately, it is difficult to derive a direct relationship between the rate of change of magnetic field (dB/dt) experienced and the perceived acceleration because of the complicated nature of the signal transduction. In addition, the pattern of induced electric fields is likely to depend on the fine structure of the inner ear which it is difficult to simulate with currently available numerical modelling software. However, direct currents applied via vestibular (10μA [4]) or mastoid electrodes (1mA [5]) have been shown to modulate the firing rate of the vestibular hair cells. A simple analysis using modelling of induced [6] and directly applied [7] currents indicates that dB/dt values of 1Ts^{-1} could induce current densities similar to those occurring when 1mA is applied to the mastoid.

Susceptibility: Comparing the magnetically induced force on an otolith, which depends on the susceptibility difference between otolith and fluid, Δχ, and the product of the field and (axial) gradient *B x G*, together with the buoyancy force, yields a perceived axial acceleration of $-\Delta\chi BG / \mu_0 \Delta\rho$, where Δρ is the difference in otolith and fluid density. Assuming a value for *B x G* of 46 T^{2}m^{-1} (which occurs just 30cm inside the bore of a 7 T magnet) and taking literature values of Δχ and Δρ [8], this mechanism would produce a perceived acceleration of 0.01 g (~ 10 times the perception limit for lateral accelerations [1]). The 'levitation' effect due to the bulk diamagnetic susceptibility of the body could also be as high as 0.03g in some regions at the end of the bore of a 7T magnet [9].

Experimental

To explore the relationship between perceived dizziness and magnetic field exposure, six subjects were asked to carry out a series of simple balance, head movement, hand-eye coordination and phantom loading tasks around a 7T whole-body magnet. During the balance tests the subjects were asked to minimise angular rotations of their head. Their movements were video-recorded, while dB/dt was simultaneously recorded using a purpose-built 3-axis logger [10]. The data were used to correlate reported dizziness with the type of movements and induced dB/dt. In order to study the effect of large dB/dt in the absence of subject movement and without forces due to *B x G* effects, a 26 cm inner diameter solenoid, which is capable of delivering single and multiple dB/dt impulses at up to 5Ts^{-1} for 50ms to a static subject has been constructed. The self-reported sensory effects of various stimulations (pulses or 2.5 Hz sinusoid) with this coil were recorded in a separate experiment (well away from large static magnetic fields).

Results

Very large dB/dt values (up to 20Ts^{-1}) could be recorded during movements in and around the 7 T magnet. Some spontaneous movements (e.g. nodding whilst saying 'yes') generated values exceeding 3Ts^{-1} when standing in a field of 1-2T. However even high values (>10Ts^{-1}) of dB/dt did not necessarily correlate with reported vertigo. Some subjects reported imbalance when their head was in a high *B x G* product region, but their movements only induced dB/dt < 1Ts^{-1} (and corresponded to low angular velocity of the head). One subject reported feeling of movement at *B x G* ≈ 5T^{2}m^{-1} (outside magnet bore) whilst being perfectly still. It was observed that off-axis or non-symmetric movements were most likely to generate dizziness. The solenoidal head coil experiments produced no reports of perceived movement (although magnetophosphenes were reported in all subjects at dB/dt ≥ 1.5Ts^{-1}).

Discussion

Re-analysis of MHD theory suggests that it is unlikely that MHD can explain the perception of vertigo during exposure to large magnetic fields. Furthermore there is no evidence that head rotations (around an axis perpendicular to the field) are needed to cause vertigo as would be predicted by MHD theory. In contrast, analysis of the forces due to otolith susceptibility indicates that perceivable effects of several times threshold may occur close to high field magnets. We propose that at magnet field strengths above 3T, it is the otolith susceptibility mechanism that is dominant. In this study even large values of dB/dt do not necessarily induce vertigo. Whilst experimental evidence does not rule out a dB/dt mechanism, experimentally this may be due to the maximum change in B (400 mT) available with the solenoid coil, and hence may explain the inability to induce any perception of movement. A more sensitive force-plate recording instrument will be used in future measurements to explore any sub-conscious effects on balance using both pulses and low frequency sinusoidal stimuli.

References

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