SMRT-ISM RM Forum:
Safe Exposure Limits for Staff & Patients
Interactions with the Body
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The main sensory effects usually associated with magnetic resonance imaging are:

1) Peripheral nerve stimulation due to gradient switching,
2) Magnetic field induced vertigo (MVIF) at high fields,
3) Metallic taste in the mouth due to movement in high fields,
4) Magneto-phosphenes due to movement in high fields or switched fields.

Abstract
In this talk the biology of the nerve axon, hair and retinal cells will be discussed. The spatial and temporal nature of a magnetic field induced electric field which can excite or modulate these cells, will be explored. Within these biological and physical contexts the effects listed above may be fully explained. However, exact quantification and prediction of thresholds will depend on subject and scanner dependent factors (for example size of person or their disposition to motion sickness). The MFIV effect may (in addition to the electric field effect) also have a mechanical origin which is due to the relative magnetic susceptibility of the vestibular components.

Magnetic Field Interactions with Matter
Magnetic Susceptibility:
Materials can have a magnetic susceptibility \( \chi \) which is small and either positive (paramagnetism) or negative (diamagnetism). Placed in a strong in-homogeneous magnetic field a diamagnetic material will be subject to a force trying to move it towards a lower field. The force on an object having a difference in susceptibility from the surrounding medium \( \Delta \chi \) is \( F = \Delta \chi r \nabla (B^2) / 2 \mu_0 \), where \( r \) is the object volume. A field-gradient product of 1470 T^2/m would produce a force sufficient to balance the force due to gravity and ‘levitate’ water or biological tissue.

Electric fields induced by movement in a magnetic field:
In a conductive medium the current density \( J \) is given by the electric field \( E \) multiplied by the conductivity \( \sigma \). The general expression for induced electric field may be given by,
\[
E = -\nabla V - \partial A / \partial t - v \times B ,
\]
where \( V \) is a scalar potential and \( A \) is a vector potential such that the magnetic field \( B \) is defined as \( B = \nabla \times A \). For an isolated, rigid body moving at velocity \( v \) in a static magnetic field only the final term is non-zero. In low conductivity biological tissues (\( \sigma \) of order unity) the main magnetic field is not perturbed by the additional magnetic field caused by \( J \). Calculation of the electric fields induced by motion in complex shapes requires numerical computation (4). For a more simple spherical conductor moving in a magnetic field gradient we obtain
\[
J_s = \frac{1}{2} \sigma r \partial B_z / \partial t ,
\]
where \( r \) is the radius and \( \partial B_z / \partial t \) is the resulting rate of change of magnetic field caused by the motion in the gradient. We can estimate the current density induced by a movement producing \( \partial B_z / \partial t = 2 \) T/s in a head to be of the order of 25 mA/m^2.

Magneto-hydrodynamics (MHD):
As the name suggests, this term usually refers to conductive fluid flow and the modification of that flow by the presence of a magnetic field. If the current induced by movement of a conductive medium in a magnetic field is large enough, then the current itself generate a magnetic field which will oppose the main magnetic field. The net force is given by the volume integral \( F = \int (J \times B) / \partial \tau \). For fluid flow this force can be added to the Navier-Stokes’ flow equation. Hence a net increase in pressure can be calculated for a given flow velocity and magnetic field.

How does the physics affect biological systems?

Electrical stimulation of nerves and axons:
Transcranial magneto-stimulation (TMS) uses short pulses of field having a dB/dt of order 1000 T/s. Peripheral nerve stimulation (PNS) can be caused by gradient switching of order 60 T/s for 1 ms (5). A strength – duration curve for the response of nerve tissue (due to electric or switched gradients) may be determined. Hence the electric field needed for nerve stimulation may be estimated at around 6 V/m (6) and increasing with frequency. In the regime of natural movements around magnets (0 – 20 Hz) it is unlikely that direct nerve stimulation occurs. Although natural movements around a 7 T magnet can produce up to 10 T/s the resulting electric fields are still too small for direct nerve stimulation in the human body (4,5). Numerical modelling can determine the strength of the electric fields in tissue due to gradient switching or movement in magnetic fields (7,8).

Magnetophosphenes:
The sensation of flashing lights (phosphenes) can be generated electrically or from temporally changing magnetic fields (9,10). Measurements of current density required for electro-phosphenes indicate that a much lower depolarising potential is required (by about 2 orders of magnitude) as compared to nerve depolarisation (20 mV). This indicates a retinal origin where small electric fields may influence the generation of action potentials in the photo-receptors (11,12). The ability to generate magnetophosphenes is highly frequency dependent with 20 Hz being the frequency where the eye is most sensitive. A rate of field change of 2 T/s for a 50 ms duration will induce magnetophosphenes. Magnetophosphenes can be generated by movements of the head and eyeball in a high field magnet. However, the perception of magnetophosphenes is subjective and dependent on ambient light conditions, blinking etc. The current density induced due to magnetic field changes is of similar magnitude to that required for electro-phosphenes. It is most likely that magnetophosphenes are mediated by an electric current flow through the retina rather than a direct magnetic field effect on the retinal cells.

Metalllic taste:
Users of high field magnets often report a sensation related to an acidic or metallic taste. Again, this sensory effect is most likely to be mediated by an electric current flow through or across the surface of the tongue. Electrogustometry has been used in clinical and research environments where a current stimulator is used to assess the function of the taste buds (13,14). Measurement of the magnetic field changes needed to elicit a taste sensation indicate that a typical rate of change of 2.3 T/s is required (15). Estimating the current density flowing across the tongue due to movements of the head in the magnetic field gives an approximate agreement with the directly applied current density required for taste stimulation. The metallic taste comes from liberation of protons due to currents across the tongue caused by temporally changing magnetic fields (16). There is no evidence that the magnetic field itself causes a taste sensation – movement of the subject is required.

Vertigo:
There are three possible candidates for the sensation of magnetic field induced vertigo (MFIIV). These are current flow due to dB/dt, susceptibility of vestibular structures and magneto-hydrodynamics (MHD) (17-19). In the vestibular system rotational accelerations of the head give rise to a pressure difference across the cupular membrane in the semi-circular canals. Linear accelerations are sensed by the deflection of a flat plate membrane in the utricle and saccule chambers. Both pressure in the canals and deflection of the plates are sensed by hair cells with their cilia embedded in either the cupulae or maculae respectively. The hair cells have the useful property of being a linear - the firing rate of the afferent nerve attached to the hair cell is roughly proportional (plus an offset) to the displacement of the cilia and hence the deflection or pressure. The force due to differences in magnetic susceptibility of the fluid and cupulae/maculae generate a mechanical displacement which would be sensed by the brain as an effective acceleration. The otoliths which make up the utricle and saccule maculae are calcium carbonate crystals which have known susceptibility. For these structures a field gradient product of 46 T m⁻² can be directly equated to a perceived acceleration of 0.1 m/s². This mechanism would imply that a subject would sense
an effective acceleration subject without them moving at all. The sign of the effect would indicate that the perception of acceleration would be towards regions of higher field. For the cupulae the perceived rotational acceleration in a similar magnetic field gradient may be small because the cupulae susceptibility is likely to be close to that of the surrounding fluid. The net pressure due to magneto-hydrodynamic effects can be calculated for given angular accelerations. For a toroid of fluid the pressure generated is mostly radial which does not couple to the cupula in that canal. It will also largely cancel in orthogonal canals. Calculations of the effective pressure would indicate that even for high magnetic fields (> 4T) the effect would only be at the limits of perception for very high angular accelerations such as vigorous shaking of the head (20). Galvanic vestibular stimulation (GVS) and inner vestibule stimulation experiments demonstrate the linearity of hair cell nerve firing and subject response (21,22). Quite small amounts of current can elicit a sway response in a subject. The electric field directly modulates the firing rate of the cell. Hence quite small rotations and movements in the magnetic field can generate electric fields on a par with those needed for the GVS effect. In addition, the total time of applied dB/dt is relevant to the subject’s perception. Of the order of 2 T/s (dB/dt) needs to be maintained for 1 second for subjects to perceive an effect. The sense of the direction of perception of movement reverses if the sense of the current flow around the head reverses. Large peak values of dB/dt are not in themselves enough to induce vertigo (17). Vertigo is perceived by a subject for head rotation velocities and accelerations which are a lot lower than would be required if MHD were to be the major transduction mechanism. The susceptibility mechanism is also a possibility as there are a small number of subjects who claim to be ‘falling’ when standing adjacent to a 7T magnet. This can be measured by monitoring their postural sway whilst they fix their gaze on a spot whilst opening and closing their eyes. Subjects report a sudden onset of the effect near the magnet as would be expected with a gradient times field relationship (17).

As the positions of maximum induced current and susceptibility effects are at their maximum in exactly the same locations of the magnet then it is difficult to separate the two except by polarity of the effect. Rats show circling behaviour and taste aversion after exposure to magnetic fields (23). By removal of the labyrinth the rats are oblivious to the field exposure. The vertigo effect can be confirmed as an action of the magnetic field on the primary transducer – rather than directly on the CNS. It is likely that MFIV is mediated through induced current affecting the hair cells. MHD is the least likely effect and there may also be a susceptibility related effect detectable in some subjects. The animal experiments unfortunately can not confirm the mechanism although the sensitivity to direction of field/presentation would tend to indicate an induced electric field mechanism.

Figure 1: A summary of sensory effects in humans based on change in magnetic field over duration of change to elicit effect. Areas indicated show approximate regions where TMS, PNS and Magnetophosphenes are observed. Experimental data points indicate where the vertigo effect is mild or unpleasant. A region indicating typical changes needed for metallic taste is shown. Calculated data points showing changes needed to elicit an MHD based vertigo effect are significantly above those required for any subject’s experience.
Conclusions

It appears from the evidence that the major sensory effects observed at field strengths less than 8T are mediated through induced electric fields. Electric fields are induced by rotation or translation of the subject in magnetic fields. Magnetic susceptibility of sensory tissues in the vestibular system may also be responsible for a magnetic field effect on humans. MHD is unlikely to have a role in such small structures. No definitive evidence of a direct magnetic effect on the CNS has been reported in humans for field strengths up to 8T.

References