Published in final edited form as:
Ann N Y Acad Sci. 2015 April ; 1343(1): 69–79. doi:10.1111/nyas.12702.

Vestibular stimulation by magnetic fields

Bryan K. Ward[1], **Dale C. Roberts**[2], **Charles C. Della Santina**[1,3], **John P. Carey**[1], and **David S. Zee**[1,2,4,5]

[1]Department of Otolaryngology, Johns Hopkins University School of Medicine, Baltimore, Maryland [2]Department of Neurology, Johns Hopkins University School of Medicine, Baltimore, Maryland [3]Department of Biomedical Engineering, Johns Hopkins University School of Medicine, Baltimore, Maryland [4]Department of Neuroscience, Johns Hopkins University School of Medicine, Baltimore, Maryland [5]Department of Ophthalmology, Johns Hopkins University School of Medicine, Baltimore, Maryland

Abstract

Individuals working next to strong static magnetic fields occasionally report disorientation and vertigo. With the increasing strength of magnetic fields used for magnetic resonance imaging (MRI) studies, these reports have become more common. It was recently learned that humans, mice and zebrafish all demonstrate behaviors consistent with constant peripheral vestibular stimulation while inside a strong, static magnetic field. The proposed mechanism for this effect involves a Lorentz force resulting from the interaction of a strong static magnetic field with naturally occurring ionic currents flowing through the inner ear endolymph into vestibular hair cells. The resulting force within the endolymph is strong enough to displace the lateral semicircular canal cupula, inducing vertigo and the horizontal nystagmus seen in normal mice and in humans. This review explores the evidence for interactions of magnetic fields with the vestibular system.

Keywords

Magnetic; vestibular; Lorentz

Dizziness in the presence of strong static magnetic fields

There have been many reports of transient dizziness or vertigo in patients, research subjects and other individuals working around magnetic resonance imaging (MRI) scanners.[1-3] These sensations occur more commonly in those exposed to higher strength magnetic fields.[4-7] Prompted by these reports, researchers have measured physiological correlates, using outcomes such as visual tracking tasks,[8] postural assessments[7, 9, 10] and neurocognitive instruments[11] administered just outside the MRI scanner. While results of these studies have

---

Correspondence: Bryan K. Ward, M.D., Johns Hopkins University School of Medicine, 601 N. Caroline St., 6th Floor, Baltimore, MD 21287-0910. bward15@jhmi.edu.

Conflicts of interest: The authors declare no competing financial interests.

supported effects of strong magnetic fields on posture and attention, they have been inconsistent across subjects and studies.

New measurable behaviors inside strong magnetic fields suggestive of direct inner ear stimulation are clarifying our understanding of the interactions between magnetic fields and the labyrinth and leading to fundamental new ways of stimulating the vestibular system. This review will explore current knowledge of how magnetic fields interact with the vestibular system in humans and other animals and propose a mechanism that explains the dizziness humans experience near strong static magnetic fields.

Effects of magnetic fields on eye movements

Activity of hair cells and primary afferent neurons in the inner ear labyrinth is tightly linked to eye movements via the vestibulo-ocular reflex; by studying eye movements, one can infer, quantify and interpret perturbations to the vestibular system.[12] Building upon earlier suggestions that dizziness near magnetic fields may be related to the vestibular system, Patel et al. first studied eye movements using electronystagmography (ENG) in a group of technicians who had been working near a 9.4 T magnet.[13] Testing was performed over the course of a few months; however, subjects were examined away from the magnet. They found nonspecific, inconsistent changes on these tests that were within the range of variation of ENG testing for normal subjects. Though no relationships were identified in those experiments, they were an attempt to link eye movements to the sensations of dizziness experienced by those near strong static magnetic fields. Subsequently, in experimental animals, more evidence appeared to suggest an effect of magnetic fields on the labyrinth.[14]

In 2009, Vincenzo Marcelli *et al.*, studying the effects of a caloric (cold water) stimulus on the brain using functional MRI (fMRI), noted that while examining his subjects' eye movements in darkness, there was a slow drift of the eyes in some of his subjects while they lay inside the 1.5 T magnetic field, even prior to administering a caloric stimulus to the ear.[15] A critical pre-requisite to their observation was elimination of any visual cues, as visual fixation mechanisms suppress the nystagmus of a stimulus to the peripheral vestibular system. Marcelli *et al*. speculated that this unexpected finding was due to effects of the strong static magnetic fields on the labyrinth itself.

The finding of Marcelli *et al*. prompted Roberts *et al*. to study eye movements in normal humans exposed to a stronger (7 T) static magnetic field[16]. With elimination of visual fixation and recording the movements of the eyes with infrared video techniques it was found that: (1) all normal human subjects tested had horizontal nystagmus while lying in the strong static magnetic field (Fig. 1); (2) the direction of nystagmus reversed with extreme head pitch and with direction of entry (feet first versus head first) into the magnet bore; (3) the effect persisted throughout the time in the magnetic field and did not depend on motion into or out of the field (Fig. 2); (4) the effect scaled with the intensity of the magnetic field; and (5) the effect was absent in patients with bilateral peripheral vestibular loss. It is important to note that these effects depended on the static magnetic field alone and not on radiofrequency energy pulses used when taking images, as no images were taken during the experiments. Examining the pattern of eye movements showed that a functioning labyrinth was essential for this phenomenon, and provided a clear behavioral correlate that could be manipulated while exploring the mechanism.

Proposed mechanisms for interactions between magnetic fields and the labyrinth

Several hypotheses had been proposed to explain the vertigo and dizziness humans experience in MRI machines. These ideas consider the unique physical environment of the labyrinth and ways in which strong magnetic fields acting on this environment might influence the vestibular end organs. For instance, some fish species have otolith organs containing ferromagnetic particles[17, 18]. If ferromagnetic particles such as iron were present in the appropriate arrangement within the mammalian inner ear, they would be strongly affected by the magnetic field of an MRI machine. Ferromagnetic material, however, has not been reported in the mammalian labyrinth. Glover et al. suggested three candidate mechanisms for human magnetic vestibular stimulation: (1) forces due to differences in diamagnetic susceptibility between the otolithic membrane or cupula and their surrounding material when inside a magnetic field, (2) induced electrical currents (i.e., Faraday's law of electromagnetic induction), and (3) motion-induced magneto-hydrodynamic (MHD) effects within the labyrinthine fluids[10]. To account for the newly observed eye movement findings of normal human subjects in an MRI scanner (Fig. 1), however, Roberts et al. proposed that Lorentz forces (static magneto-hydrodynamic forces) were the likely mechanism[16].

It is worth considering each proposed mechanism, as more than one may contribute to stimulation of the labyrinth, depending upon the species-specific inner ear anatomy, the strength of the magnetic field, or head movements in the field. Table 1 shows four hypothesized mechanisms for human magnetic vestibular stimulation. The first (diamagnetic susceptibility) does not require motion in the magnetic field, but requires high field strength. The effects of diamagnetic susceptibility (DS) are similar to the familiar attractive forces between magnets and ferromagnetic objects like iron, except that a magnet weakly repels diamagnetic materials, instead of strongly attracting them. DS effects are typically orders of magnitude smaller than ferromagnetic and hence go unnoticed in daily life. But a strong MRI magnetic field potentially provides an environment where DS effects could become important.

DS translation (repulsive) forces can act on the calcium carbonate of the otoconial end organs, but this can only occur when there is a magnetic field gradient. In the case of an MRI machine this would have to be away from the homogenous portion of the field at the center of the bore since only torque (rotation) forces can occur in a homogenous magnetic field. It is important to note that the conditions for DS do not depend on the polarity of the magnetic field. The magnetic fields of MRI machines have a north-south axis. In humans, the direction of nystagmus changes with head orientation with respect to the magnetic field axis, such that in our 7 T magnet head-first entry produced *right-beating* (i.e., leftward slow-phase) nystagmus and feet-first entry produced *left-beating* (i.e., rightward slow-phase) nystagmus.[16, 19] Head-first entry into the *back* of the MRI bore also produced left-beating nystagmus, suggesting the mechanism producing nystagmus is sensitive to magnetic field polarity. This characteristic rules out DS as being primarily responsible for the observed MRI-associated nystagmus in humans.

The next two mechanisms—*motion-induced* MHD and electromagnetic induction—require head motion inside a strong magnetic field. Motion-induced MHD could occur during head rotation in the constant, homogenous field inside the bore. Currents induced in the inner ear by motion of the head can create their own magnetic fields that interact with the MRI magnetic field to cause forces in the endolymph. In our experiments, however, when nystagmus was observed the head was stationary inside the magnet bore and therefore motion-induced MHD cannot account for the nystagmus. Electromagnetic induction requires movement and is proportional to the change in magnetic field over time (dB/dt). While models support the possibility of induced current sufficient for vestibular stimulation,[20] if electromagnetic induction were responsible for the nystagmus, we would have expected to see a nystagmus that peaks during movement of the subject on the table into the bore and rapidly decays after movement ceases. Instead, we see the nystagmus velocity rises to a maximum at the end of the movement of the table (well after peak dB/dt), and then decreases very slowly (over many seconds to minutes).[16, 21] Moving quickly into and out of the magnet bore does not produce a reversal of nystagmus on exiting the bore, as might be expected from changing the polarity of the induced stimulation. Thus, electromagnetic induction does not appear to explain the magnetic-field induced nystagmus.

The Lorentz force explains magnetic vestibular stimulation in humans

The Lorentz force requires a current flowing through a conductor (or conductive fluid) and a high magnetic field strength, but does not require movement in the magnetic field. When a current passes through an ion-rich fluid within a magnetic field, a force (i.e. a Lorentz force) occurs in the fluid, the direction of which is orthogonal to the current and magnetic field vectors (Fig. 3). The labyrinth is unique in the human body, containing the components for both generation and detection of a Lorentz force. The resting discharge of vestibular afferent neurons is supported by a constant mechanoelectrical transduction current that flows through the transduction channels of vestibular hair cells via ion-rich endolymphatic fluid.[22] When this system is introduced into a strong magnetic field, the magnetic field's interaction with the current flow generates a Lorentz force that acts on the endolymph. The labyrinth also contains shear sensors in the sensory epithelia of the semicircular canals and otoconial end organs.

In the presence of a strong magnetic field such as a 7 T magnet, the normal ionic currents present in endolymph produce sufficient force within vestibular organs to displace the inner ear force sensors, accounting for the observed nystagmus in humans.[16, 23, 24] We hypothesize that current flowing into the utricle primarily generates the force that is producing nystagmus in humans. The utricle contains approximately 33,000 hair cells, whereas each semicircular canal ampulla contains approximately 7,000 hair cells. Therefore, the highest current density would be expected to be in the endolymph over the utricle, immediately adjacent to the lateral semicircular canal cupula. In humans with intact vestibular function, a predominantly horizontal nystagmus is observed, indicating stimulation of the lateral semicircular canals.[16, 19] In those with only unilateral vestibular function, eye movement patterns additionally suggest differential stimulation of the nearby functioning superior semicircular canal cupula (a vertical component appears) in a pattern that is not apparent in the bilaterally-intact individual, because induced forces balance each other out.[19] Although other inner ear end organs such as the saccule and even the cochlea can generate a Lorentz force in a strong magnetic field, there are no accompanying sensors sensitive to static displacement to transduce the effects of such Lorentz forces into the pattern of nystagmus that we have observed.

Perception of self-motion in strong static magnetic fields

Subjects who have reported vertigo in a magnetic field usually report that the sense of self-motion subsides with duration of exposure.[4] In experiments conducted in darkness in 7 T magnetic fields, subjects' perceptions of self-rotation lasted on average less than one minute,[16, 25] despite persistent nystagmus over tens of minutes in the static magnetic field of the MRI.[21, 25] The direction of self-motion was sometimes difficult to describe. Surprisingly, the perceived axis of rotation inside the magnetic field often did not align with the axis of the observed eye movements, with the majority of subjects perceiving rotation about an Earth-vertical axis while supine.[25] For example, despite developing robust nystagmus in the plane of the horizontal canals (i.e., approximately around the axis of the magnet, which is earth-horizontal) while supine in the 7 T MRI bore, a common perception is of lying on a playground roundabout (merry-go-round) with the axis of rotation perpendicular to the Earth's surface at the navel. These inconsistencies in perception may relate to stimulation of other parts of the labyrinth (for example, the anterior semicircular canal), as well as the inherent ambiguity from the circumstance of lying supine in the MRI bore. The artificial stimulation of the lateral semicircular canals suggests the body is rotating around its yaw axis, while the lack of stimulation of the otolith (by a rotating gravity vector) suggests that the body is not rotating. Finally, similar to the reversal phase of nystagmus upon exiting the magnetic field, the perception of rotation also reverses upon exit, a common finding in human optokinetic[26] and rotation studies.[27, 28] This suggests there has been a central adaptation to both the nystagmus and the perception of rotation inside the magnetic field.[16, 21, 25]

Animal models of magnetic vestibular stimulation

Developing animal models of magnetic vestibular stimulation is another way to explore mechanism and accelerate the development of practical applications. One notable advantage to animal models is improved accessibility to powerful magnetic fields. Nuclear magnetic resonance (NMR) chemical analysis has relied upon increasingly higher static magnetic field strength for characterization of molecular structure, with dramatic improvements in resolution of proton resonance over the last several decades.[4] The magnetic fields of NMR scanners are similar to MRI scanners, but tend to have greater field strength and smaller bore size. For practical reasons, these scanners have been convenient for small animal experiments exploring the effects of strong magnetic fields, as they are less costly and more widely available than medical scanners.

Using a strong NMR scanner, Houpt *et al*. performed pioneering studies evaluating the impact of strong static magnetic fields on the vestibular system. Rats and mice were initially noted to circle after exposure to 7 T and 14 T magnetic fields, and the direction of circling behavior depended upon orientation of the magnetic field.[29-31] Expression of the transcription factor c-Fos, a marker of neuronal activation, was increased in the medial vestibular nuclei and nucleus prepositus hypoglossi after exposure.[32] Additional studies suggested an intact labyrinth was critical for these behavioral responses,[14, 31, 33] that responses depended on static magnetic field and not the field gradient,[34] that effects scaled with magnetic field strength,[29] and that after-effects were present only after prolonged exposures.[35] Most recently, mice exposed to strong magnetic fields at different pitch angles demonstrated null positions, i.e., where no circling or c-Fos activation was observed,[36] consistent with our human data demonstrating null positions where no nystagmus is observed.[16] Interestingly, Houpt *et al*. also demonstrated habituation with repeat exposures[37] and evidence of vestibulo-colic reflexes inside the static magnetic field,[38] findings not yet explored in human studies. In sum, the results of the studies by Houpt *et al*. support a Lorentz force hypothesis, suggesting that a similar mechanism to that described in humans may be present in mice and rats as well.

Recently, we placed mice in a 4.7 T static Earth-horizontal magnetic field and demonstrated a horizontal nystagmus, similar to humans in that it changed direction depending on the orientation of the animal in the magnetic field, but also with significantly higher nystagmus velocities.[39, 40] Geometric scaling may contribute to the higher nystagmus velocities observed in mice. Oman and Young show that for a simplified semicircular canal model, pressure on the canal cupula due to head acceleration is given by (omitting constants) $\boldsymbol{P_{rotation} = \alpha r^2 R^2/c^2}$, where α is head angular acceleration, $\mathbf{r}$, and $\boldsymbol{R}$, are the linear radii dimensions of the canal, and c is the linear radius of the cupula.[23] If the linear dimensions are all scaled down proportionally, then for a smaller canal (such as in a mouse) the pressure on the canal cupula due to head acceleration will scale down by the *second* power of this proportion. The Lorentz force, however, scales down with the *first* power of the labyrinth linear dimensions, since $\mathbf{P_{Lorentz}} = \boldsymbol{h\,J\,B/c^2}$, where $\mathbf{h}$ is the linear distance above the utricle, $\mathbf{J}$ is the current into the utricle, and $\mathbf{B}$ is the magnetic field (Fig. 2B).[16] Since the current $\mathbf{J}$ is directly related to the number of hair cells, which is in turn related to $\mathbf{u^2}$, the utricle area, then overall the equation shows a first power relation to the labyrinth linear dimensions. This means that for a given magnetic field strength, animals with smaller semicircular canal diameters experience a Lorentz force that is equivalent to larger natural head angular accelerations, producing a stronger nystagmus response. Thus, the characteristics of the nystagmus and behaviors induced in rodents in strong magnetic fields support the Lorentz force mechanism.

Magnetoreception

Researchers studying magnetoreception—the sense by which animals detect magnetic field direction to guide movements—continue to debate the mechanism of transduction for this response. Magnetoreception requires a sensor sensitive enough to detect the Earth's magnetic field (3.1×10^{-5} T), a magnetic field orders of magnitude weaker than those experienced by humans or other animals in MRI scanners. Wu and Dickman recently showed that the labyrinth may be involved in magnetoreception, providing evidence that vestibular nuclei of homing pigeons are involved in the detection of magnetic fields similar to Earth's and that this finding depends on intact vestibular end organs.[41, 42]

Interestingly, multiple studies in recent years have shown that mammals are sensitive to weak static magnetic fields.[43] Mole rats demonstrate goal-directed magnetic orientation,[44, 45] while other mammalian species as diverse as hamsters,[46] bats,[47] red foxes,[48] dogs,[49] cattle, and deer[50] show preferential magnetic field alignment. Laboratory mice can learn nest building in magnetic coordinates[51] and use magnetic field cues to solve a water maze,[52] suggesting the ability to detect magnetic field polarity. Experimental results in mole rats and bats also indicate a magnetic sense with polarity sensitivity,[47, 51-53] a characteristic consistent with either biogenic magnetite-based sensor (i.e., a ferromagnetic particle) or a Lorentz force mechanism. Whether the observations in the above studies represent an unrecognized function of the labyrinth or another mechanism of transduction[54] requires further study. Our finding of differential geometric scaling of the Lorentz force with semicircular canal size may boost the gain of an otherwise weak signal from Earth's magnetic field.

MRI scanner safety

Human MRI scanners are considered safe, so long as one adheres to appropriate guidelines with respect to metal and noise exposure, and use of intravenous contrast agents. The United States Food and Drug Administration qualifies MRI scanners up to 8 T as posing non-significant risk.[55] In medical practice, over 27 million MRI scans occur annually in the United States,[56] the majority of which use 1.5 T and 3 T MRI scanners. While studies with long-term follow-up after exposure to high strength magnetic fields are lacking, no short-term adverse effects have been observed in fields of strength up to 8 T.[57] A few research participants, however, have reported nausea, vertigo, and vomited after being in an 8 T MRI scanner.[58] Perhaps the most common vestibular side effect of having an MRI scan is benign paroxysmal positional vertigo (BPPV), which is caused by detached otoconia either free floating in the endolymph or attached to the cupula of the posterior semicircular canal.[59] This syndrome can be provoked after a long period of lying flat, and is not related to the MRI apparatus per se.[60]

Altered sensations are common in people entering strong magnetic fields. In addition to vertigo and nausea, a metallic taste, concentration difficulties, and transient perceptions of flashes of light called *phosphenes* are reported.[3-5, 61] During one of our experiments inside the 7 T MRI, a research participant noted rhythmic flashes in his peripheral vision that occurred with each beat of nystagmus, and he was concerned a smoke detector had been activated. While such sensory effects may be alarming to the unprepared, there is no evidence suggesting these sensations are harmful.

It is important to remember that the Lorentz force of magnetic vestibular stimulation scales with magnetic field strength.[16] We thus expect more individuals will experience self-motion in stronger magnetic fields. This hypothesis is corroborated by reports of workers exposed to magnetic fields of different intensity.[4, 5, 7] Currently, the most powerful scanners for humans have static field strengths of 9.4 T, and human scanners up to 11.7 T are in production.[62] For such scanners, the scaling effect of magnetic vestibular stimulation should be considered, as the pursuit of better image resolution and decreased time to acquire images requires increased magnetic field strengths,[63] which may lead to increased reports of odd or uncomfortable sensations by individuals undergoing scans.

Future directions

A Lorentz force mechanism as the cause of human dizziness near and within MRI machines has potential applications for areas of neuroscience and human disease. While the mechanism may contribute to magnetoreception (as described above), it may also prove useful in developing a high throughput assay of vestibular function in, for example, zebrafish[64] or for clinical diagnosis of human vestibular disease, as the side and intralabyrinth site of vestibular injury might be differentiated on the basis of the pattern of eye movements observed in strong magnetic fields.[19]

Furthermore, despite the fact that a person's perception of vertigo and motion disappears as they remain inside the scanner, the nystagmus—and thus the vestibular stimulus—persists the entire time a subject is lying in the MRI scanner. This method of constant stimulation provides a novel approach to investigate vestibular physiology, and vestibular adaptation in particular. By applying a constant force to the vestibular endorgans, magnetic vestibular stimulation is a fundamentally new way to stimulate the vestibular system, delivering a force to the semicircular canal cupulae akin to a constant acceleration, while the subject is lying still[21]. Such experiments can be performed for prolonged periods with little discomfort to the participant, and provide a unique way to study the time course and degree to which mechanisms in the brain can adapt to and suppress an unnatural and unwanted sustained nystagmus. Furthermore, magnetic vestibular stimulation can be used to identify structures within the brain associated with vestibular activation per se in darkness, as well as its suppression by pursuit and fixation mechanisms in the light. As a novel experimental method, magnetic vestibular stimulation may produce new insights in vestibular physiology[65] and vestibular perception.

Finally, stimulation of the labyrinth by magnetic fields has implications for functional MRI studies of all types (including resting state studies[66, 66]), as artifacts may be induced by the inevitable labyrinthine excitation by MRI machines (unless the subject just happens to be at the null position). The pattern of stimulation depends on magnetic field orientation relative to the labyrinth, and the polarization can vary by MRI scanner manufacturer.[67] We were initially puzzled by why the nystagmus observed by our Italian colleagues was in the opposite direction from that observed in our magnets. It was later discovered that the two magnet manufacturers had polarized the magnets differently. And the Lorentz force hypothesis (i.e., by the right-hand rule) depends on orientation of the magnetic field vector.

Acknowledgments

This work was made possible by R21DC011919 and salary support for BW from NIDCD T32DC0000027. We would like to especially thank contributors to the Vestibular NeuroEngineering Lab Research Fund, the Lloyd B. Minor Vestibular Research Fund, and the support of the Lott and Cinquegrana families.

References

1. Kangarlu A, et al. Cognitive, cardiac, and physiological safety studies in ultra high field magnetic resonance imaging. Magnetic resonance imaging. 1999; 17:1407–1416. [PubMed: 10609989]
2. Chakeres DW, Bornstein R, Kangarlu A. Randomized comparison of cognitive function in humans at 0 and 8 Tesla. Journal of magnetic resonance imaging: JMRI. 2003; 18:342–345. [PubMed: 12938130]
3. de Vocht F, et al. Exposure, health complaints and cognitive performance among employees of an MRI scanners manufacturing department. Journal of magnetic resonance imaging: JMRI. 2006; 23:197–204. [PubMed: 16374876]
4. Schenck JF, et al. Human exposure to 4.0-Tesla magnetic fields in a whole-body scanner. Medical physics. 1992; 19:1089–1098. [PubMed: 1518472]
5. Schaap K, et al. Occupational exposure of healthcare and research staff to static magnetic stray fields from 1.5-7 Tesla MRI scanners is associated with reporting of transient symptoms. Occupational and environmental medicine. 2014
6. Heilmaier C, et al. A large - scale study on subjective perception of discomfort during 7 and 1.5 T MRI examinations. Bioelectromagnetics. 2011; 32:610–619. [PubMed: 21598286]
7. Theysohn JM, et al. Vestibular effects of a 7 Tesla MRI examination compared to 1.5 T and 0 T in healthy volunteers. PloS one. 2014; 9:e92104. [PubMed: 24658179]
8. de Vocht F, et al. Cognitive effects of head-movements in stray fields generated by a 7 Tesla whole-body MRI magnet. Bioelectromagnetics. 2007; 28:247–255. [PubMed: 17290435]
9. van Nierop LE, et al. MRI-related static magnetic stray fields and postural body sway: a double-blind randomized crossover study. Magnetic resonance in medicine: official journal of the Society of Magnetic Resonance in Medicine/Society of Magnetic Resonance in Medicine. 2013; 70:232–240.
10. Glover PM, et al. Magnetic-field-induced vertigo: a theoretical and experimental investigation. Bioelectromagnetics. 2007; 28:349–361. [PubMed: 17427890]
11. van Nierop LE, et al. Does assessment of personal exposure matter during experimental neurocognitive testing in MRI-related magnetic fields? Magnetic resonance in medicine: official journal of the Society of Magnetic Resonance in Medicine/Society of Magnetic Resonance in Medicine. 2014
12. Leigh, RJ.; Z, DS. The Neurology of Eye Movements. 5. Oxford University Press; New York: 2015.
13. Patel M, et al. Pilot study investigating the effect of the static magnetic field from a 9.4-T MRI on the vestibular system. J Occup Environ Med. 2008; 50:576–583. [PubMed: 18469627]
14. Cason AM, et al. Labyrinthectomy abolishes the behavioral and neural response of rats to a high-strength static magnetic field. Physiol Behav. 2009; 97:36–43. [PubMed: 19419674]
15. Marcelli V, et al. Spatio-temporal pattern of vestibular information processing after brief caloric stimulation. Eur J Radiol. 2009; 70:312–316. [PubMed: 18342473]
16. Roberts DC, et al. MRI Magnetic Field Stimulates Rotational Sensors of the Brain. Curr Biol. 2011
17. O'Leary DP, et al. Magnets in guitarfish vestibular receptors. Experientia. 1981; 37:86–88. [PubMed: 7202681]
18. Vilches-Troya J, Dunn RF, O'Leary DP. Relationship of the vestibular hair cells to magnetic particles in the otolith of the guitarfish sacculus. J Comp Neurol. 1984; 226:489–494. [PubMed: 6611358]
19. Ward BK, et al. Magnetic vestibular stimulation in subjects with unilateral labyrinthine disorders. Front neurology. 2014; 5:28.
20. Laakso I, Kannala S, Jokela K. Computational dosimetry of induced electric fields during realistic movements in the vicinity of a 3 T MRI scanner. Phys Med Biol. 2013; 58:2625–2640. [PubMed: 23552657]
21. Glover PM, et al. A dynamic model of the eye nystagmus response to high magnetic fields. Phys Med Biol. 2014; 59:631–645. [PubMed: 24434733]

22. Horwitz GC, Risner-Janiczek JR, Holt JR. Mechanotransduction and hyperpolarization-activated currents contribute to spontaneous activity in mouse vestibular ganglion neurons. The Journal of general physiology. 2014; 143:481–497. [PubMed: 24638995]
23. Oman CM, Young LR. The physiological range of pressure difference and cupula deflections in the human semicircular canal. Theoretical considerations. Acta Otolaryngol. 1972; 74:324–331. [PubMed: 4639724]
24. Antunes A, et al. Magnetic field effects on the vestibular system: calculation of the pressure on the cupula due to ionic current-induced Lorentz force. Phys Med Biol. 2012; 57:4477–4487. [PubMed: 22722424]
25. Mian OS, et al. On the vertigo due to static magnetic fields. PloS one. 2013; 8:e78748. [PubMed: 24205304]
26. Brandt T, Dichgans J, Buchle W. Motion habituation: inverted self-motion perception and optokinetic after-nystagmus. Exp Brain Res. 1974; 21:337–352. [PubMed: 4442493]
27. Guedry FE, Lauver LS. Vestibular Reactions during Prolonged Constant Angular Acceleration. Journal of Applied Physiology. 1961; 16:215–&.
28. St George RJ, Day BL, Fitzpatrick RC. Adaptation of vestibular signals for self-motion perception. J Physiol-London. 2011; 589:843–853. [PubMed: 20937715]
29. Houpt TA, et al. Behavioral effects of high-strength static magnetic fields on rats. J Neurosci. 2003; 23:1498–1505. [PubMed: 12598638]
30. Lockwood DR, et al. Behavioral effects of static high magnetic fields on unrestrained and restrained mice. Physiol Behav. 2003; 78:635–640. [PubMed: 12782218]
31. Houpt TA, Houpt CE. Circular swimming in mice after exposure to a high magnetic field. Physiol Behav. 2010; 100:284–290. [PubMed: 20206191]
32. Snyder DJ, et al. c-Fos induction in visceral and vestibular nuclei of the rat brain stem by a 9.4 T magnetic field. Neuroreport. 2000; 11:2681–2685. [PubMed: 10976943]
33. Houpt TA, et al. Rats avoid high magnetic fields: dependence on an intact vestibular system. Physiol Behav. 2007; 92:741–747. [PubMed: 17585969]
34. Houpt TA, et al. Evidence for a cephalic site of action of high magnetic fields on the behavioral responses of rats. Physiol Behav. 2007; 92:665–674. [PubMed: 17568635]
35. Houpt TA, et al. Behavioral effects on rats of motion within a high static magnetic field. Physiol Behav. 2011; 102:338–346. [PubMed: 21118699]
36. Houpt TA, et al. Orientation within a high magnetic field determines swimming direction and laterality of c-Fos induction in mice. American journal of physiology Regulatory, integrative and comparative physiology. 2013
37. Houpt TA, et al. Repeated exposure attenuates the behavioral response of rats to static high magnetic fields. Physiol Behav. 2010; 99:500–508. [PubMed: 20045422]
38. Houpt TA, et al. Head tilt in rats during exposure to a high magnetic field. Physiol Behav. 2012; 105:388–393. [PubMed: 21903121]
39. Ward BK, R D, Carey JP, Zee DS, Della Santina CC. Magnetic Field-induced Nystagmus in Mice. Barany Society Proceedings. 2012 abstract.
40. Ward BK, R D, Swarthout L, Zee DS, Carey JP, Della Santina CC. Magnetic Field-induced Eye Movements in Mice. ARO Proceedings. 2013 abstract.
41. Wu LQ, Dickman JD. Magnetoreception in an avian brain in part mediated by inner ear lagena. Curr Biol. 2011; 21:418–423. [PubMed: 21353559]
42. Wu LQ, Dickman JD. Neural correlates of a magnetic sense. Science. 2012; 336:1054–1057. [PubMed: 22539554]
43. Begall S, et al. Magnetic alignment in mammals and other animals. Mamm Biol. 2013; 78:10–20.
44. Kimchi T, Etienne AS, Terkel J. A subterranean mammal uses the magnetic compass for path integration. Proc Natl Acad Sci U S A. 2004; 101:1105–1109. [PubMed: 14732687]
45. Oliveriusova L, et al. Magnetic compass orientation in two strictly subterranean rodents: learned or species-specific innate directional preference? J Exp Biol. 2012; 215:3649–3654. [PubMed: 22855619]

46. Deutschlander ME, et al. Learned magnetic compass orientation by the Siberian hamster, Phodopus sungorus. Anim Behav. 2003; 65:779–786.
47. Wang YN, et al. Bats respond to polarity of a magnetic field. P R Soc B. 2007; 274:2901–2905.
48. Cerveny J, et al. Directional preference may enhance hunting accuracy in foraging foxes. Biol Letters. 2011; 7:355–357.
49. Hart V, et al. Dogs are sensitive to small variations of the Earth's magnetic field. Front Zool. 2013; 10
50. Begall S, et al. Magnetic alignment in grazing and resting cattle and deer. P Natl Acad Sci USA. 2008; 105:13451–13455.
51. Muheim R, et al. Magnetic compass orientation in C57BL/6J mice. Learn Behav. 2006; 34:366–373. [PubMed: 17330527]
52. Phillips JB, et al. Rapid Learning of Magnetic Compass Direction by C57BL/6 Mice in a 4-Armed ‘Plus’ Water Maze. PloS one. 2013; 8
53. Marhold S, Wiltschko W, Burda H. A magnetic polarity compass for direction finding in a subterranean mammal. Naturwissenschaften. 1997; 84:421–423.
54. Johnsen S, Lohmann KJ. The physics and neurobiology of magnetoreception. Nat Rev Neurosci. 2005; 6:703–712. [PubMed: 16100517]
55. U.S. Department of Health and Human Services, Food and Drug Administration, Center for Devices and Radiological Health, Guidance for Industry and FDA Staff. Criteria for Significant Risk Investigations of Magnetic Resonance Diagnostic Devices. Jun 20.2014
56. Lafortune, G.; De Looper, M.; Balestat, G. Health at a glance 2009: OECD indicators. OECD Publishing; Paris: 2009.
57. van Osch MJ, Webb AG. Safety of Ultra-High Field MRI: What are the Specific Risks? Current Radiology Reports. 2014; 2:1–8.
58. Yang M, et al. Vital signs investigation in subjects undergoing MR imaging at 8T. AJNR Am J Neuroradiol. 2006; 27:922–928. [PubMed: 16611792]
59. Kim JS, Zee DS. Clinical practice. Benign paroxysmal positional vertigo. N Engl J Med. 2014; 370:1138–1147. [PubMed: 24645946]
60. Baloh RW, Honrubia V, Jacobson K. Benign positional vertigo: clinical and oculographic features in 240 cases. Neurology. 1987; 37:371–378. [PubMed: 3822129]
61. Vaughan T, et al. 9.4T human MRI: preliminary results. Magnetic resonance in medicine: official journal of the Society of Magnetic Resonance in Medicine/Society of Magnetic Resonance in Medicine. 2006; 56:1274–1282.
62. Vedrine P, et al. Manufacturing of the Iseult/INUMAC Whole Body 11.7 T MRI Magnet. Ieee T Appl Supercon. 2014; 24
63. Schaap K, et al. Inventory of MRI applications and workers exposed to MRI-related electromagnetic fields in the Netherlands. Eur J Radiol. 2013; 82:2279–2285. [PubMed: 24055183]
64. Ward BK, et al. Strong Static Magnetic Fields Elicit Swimming Behaviors Consistent with Direct Vestibular Stimulation in Adult Zebrafish. PloS one. 2014; 9:e92109. [PubMed: 24647586]
65. Shaikh AG. A trail of artificial vestibular stimulation: electricity, heat, and magnet. J Neurophysiol. 2012; 108:1–4. [PubMed: 22457451]
66. Scholvinck ML, et al. Neural basis of global resting-state fMRI activity. Proc Natl Acad Sci U S A. 2010; 107:10238–10243. [PubMed: 20439733]
67. Straumann D, Bockisch CJ. Neurophysiology: vertigo in MRI machines. Curr Biol. 2011; 21:R806–807. [PubMed: 21996500]

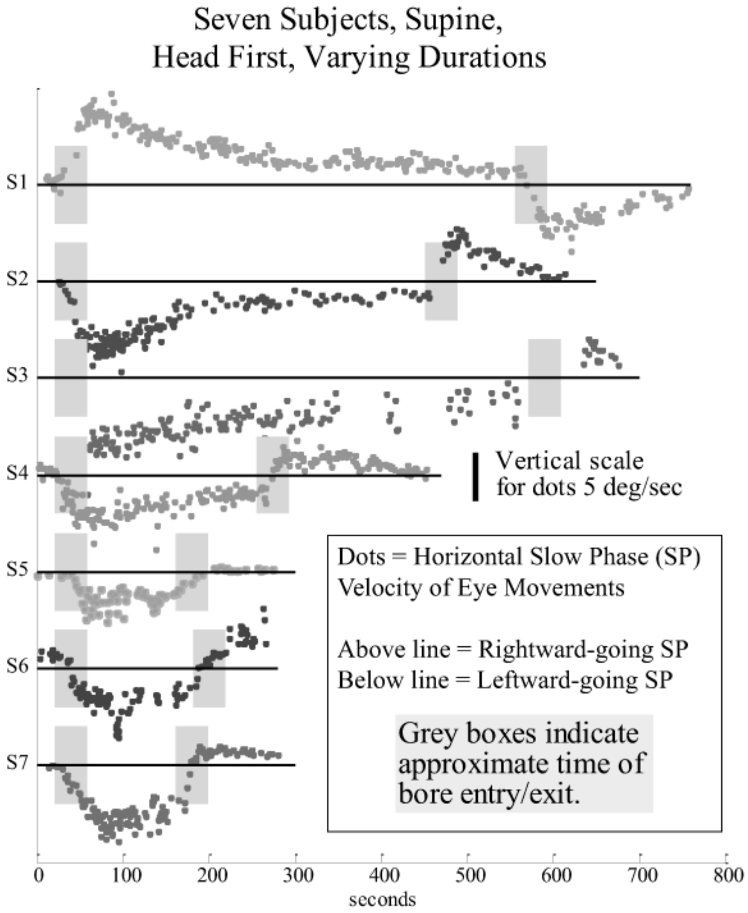

Figure 1.

Seven normal human subjects (S1-S7) showing nystagmus in a 7 T MRI scanner. There was little or no nystagmus before subjects went into the bore but a robust horizontal nystagmus developed in the bore, which gradually declined. As the subjects came out of the bore, most developed a nystagmus in the other direction. S5, who was in the bore for the shortest period, showed a minimal reversal when brought out of the bore. There was no obvious vertical or torsional component in this group. Seven subjects (six in this figure, and one presented in Figure 2) had a right beating and one subject a left beating nystagmus in the bore with the head nearly flat on the table (S1). Subject 1 has a null position that is further forward than the other subjects. His nystagmus therefore appears to be in the opposite direction, but with head pitched further backward, is in the same direction as the other subjects. The data points shown are obtained from the raw pupil tracking software by marking the endpoints of slow phase movements and computing their average velocity from the slope of the resulting line. Another normal and representative subject, with more detailed quantification, is shown in Figure 2. In these experiments the magnetic field is oriented from the subject's head toward their feet when entering the magnet bore in the standard MRI head-first orientation.

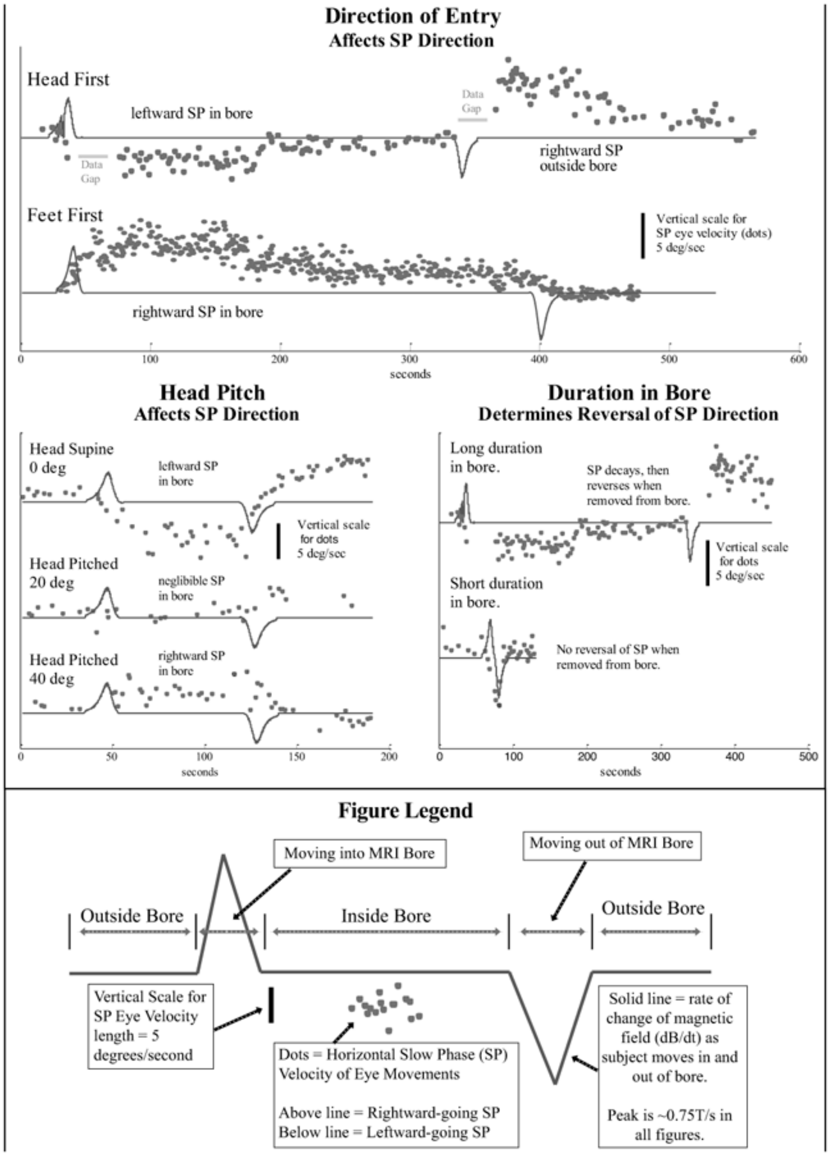

Figure 2.

Effects of different movement patterns and head orientation on magnetic field nystagmus. Data from a single normal human subject. Legend (bottom) shows basic structure for all figures; filled dots show horizontal slow-phase (SP) nystagmus velocity and the solid line shows rate of change in magnetic field near subject's head as he moved into and out of the bore. Key points are identified in the title of each figure. The effects of entry direction, duration in the bore and head orientation imply Lorentz effects (see Table 1).

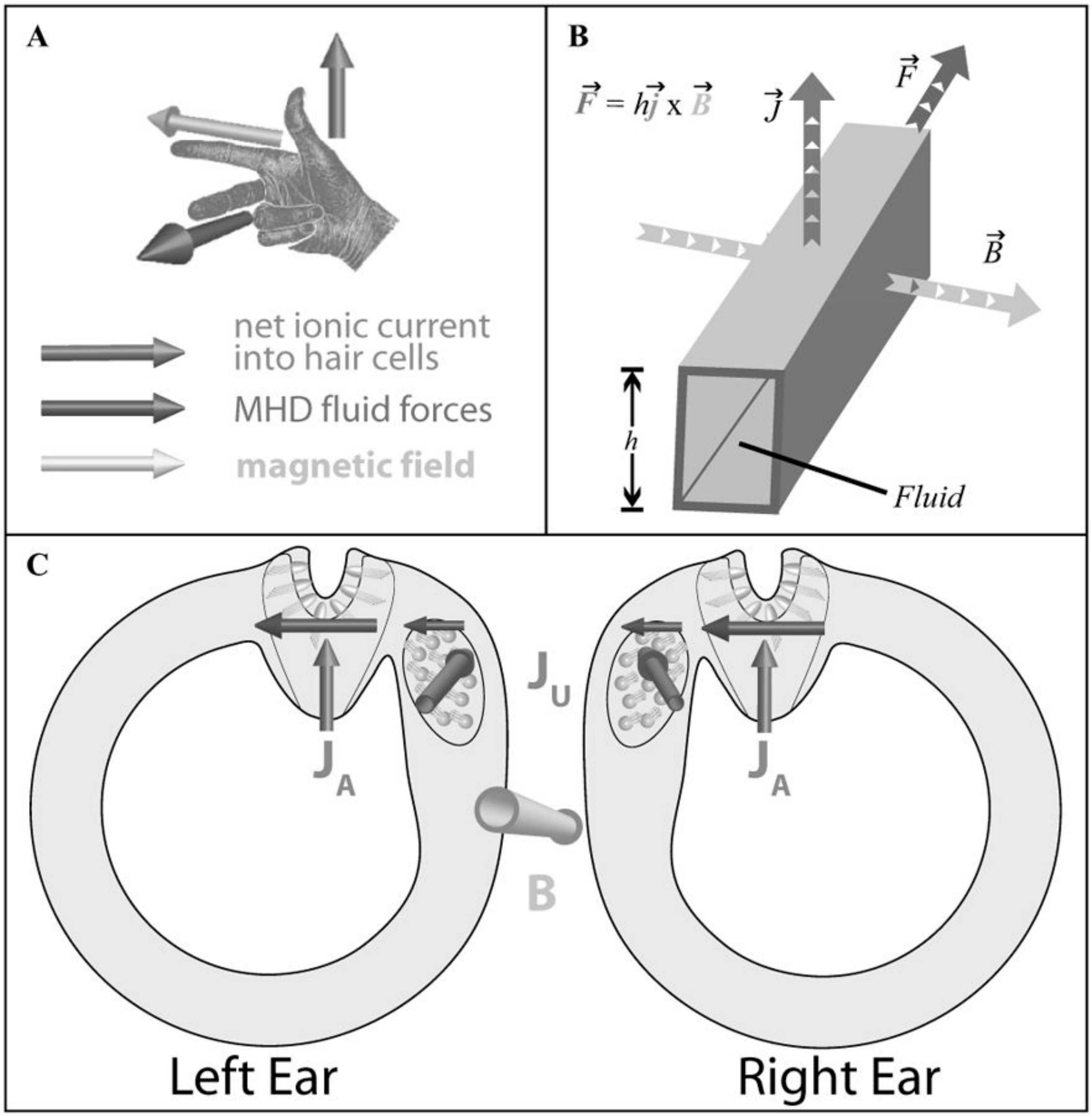

Figure 3.

Hypothesized Lorentz force model involving force vectors. Arrows indicate suspected vectors contributing to the Lorentz force. A) Legend (left) shows right-hand rule relationship among hair cell ionic currents (green), magnetic field (yellow), and resulting Lorentz or MHD fluid force (red). B) Simplified schematic (right) of Lorentz force. **F**, Lorentz force, *h*, height, ***j***, current density, **B**, magnetic field. C) Schematic showing how the inner ear currents from the utricle (J_U) and ampulla (J_A) interact with the magnetic field (B) to generate a force that acts on the horizontal semicircular canal cupulae.

Table 1

Possible mechanisms of human magnetic vestibular stimulation

Physical principle	**Physiological effects**	**Data for/against**
Mechanism 1: (*Static*) **Diamagnetic susceptibility** (**DS**) effects. Materials that are not ferrous or paramagnetic are diamagnetic, and could be acted upon by translational (repulsive) and torque forces in the field gradient outside the bore, and torque-only forces in the bore's homogenous magnetic field.	Translational and torque forces could act on otoconia or other vestibular structures while inside the magnetic field gradient, just outside the magnet bore. Torque forces could act on these structures inside the bore.	Figure 2 shows that direction of entry, and hence magnetic field polarity with respect to the head, does change the nystagmus direction, which argues against static torque forces while inside the bore. Transient effects while moving into the bore could still move diamagnetic material in opposite directions for those two conditions, but would not cause the persistent nystagmus.
Mechanism 2: *(Motion-induced)* **Motion-induced MHD** (Magneto Hydro Dynamic) effects, with motion-induced electric currents. Movement of conductive fluid through a magnetic field induces currents in the fluid and can impede or modify the fluid flow.	Pressure of fluid in semicircular canals could be affected during head rotations, and lead to cupula pressures not related to the head motion, possibly inducing vertigo.	Nystagmus is present without any head rotation, strongly ruling against this effect. Also, Glover[10] shows computations suggesting that this effect may be too small to be perceived.
Mechanism 3: (*Motion-induced)* **Electromagnetic Induction** (dB/dt). Currents induced in body tissue by a changing magnetic field *while moving* into or out of the bore through the magnetic field gradient.	Direct stimulation of neural tissue by motion through the magnetic field.	Human data shows long nystagmus velocity decay times, maximal velocity *after* (not during) peak dB/dt, and no reversal in nystagmus direction with quick movements into and then out of the magnet bore. All these observations argue against dB/dt.
Mechanism 4: (*Static*) **Lorentz force**, with existing static electric current. Static magnetic (***B***) field and electric (***J***) current in a conductive fluid cause flow perpendicular to both ***J*** and ***B*** vectors (i.e., cross product of ***J*** and ***B*** vectors), see Figure 3.	MRI magnetic field combined with natural electric currents in the labyrinth could cause fluid flow or pressure in canals.	Our data are most compatible with this effect. The long duration of nystagmus suggests this type of constant, static effect, with adaptation causing a decrease in response over several minutes and a transient reversal on leaving the field.

Note: "Motion-induced" denotes mechanisms requiring head movement relative to the magnetic field, and "Static" denotes those that do not require head movement. Three mechanisms were previously proposed:[10, 21] diamagnetic susceptibility (DS), motion-induced MHD (magnetohydrodynamics), and electromagnetic induction (dB/dt, for the mathematical notation for "change in magnetic field over time"). Roberts *et al*. added Lorentz forces as a fourth and perhaps most likely mechanism when subjects are stationary and in the homogenous part of the field.[16]