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Magnetic Vestibular Stimulation (MVS). A research tool with possible implementation in rehabilitation of stroke-affected athletes – a review

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1. Abstract

Background: People often experience vertigo and other co-occurring effects caused by the action of a strong magnetic field, such as those found in the MRI generator. This effect is a result of vestibular stimulation of the inner ear, the mechanism being a magnetohydrodynamic force (Lorentz force) which is generated by the interaction between normal ionic currents in the endolymph of the inner ear and the strong magnetic fields of the static MRI devices. The result of the induction is magnetic vestibular stimulation (MVS).
Aim of the study: This study aims to present potential of MVS in research of vestibular function, hemispatial neglect syndrome (HNS) and rehabilitation.
Materials and Methods: PubMed and Google Scholar were searched using keywords including “magnetic vestibular stimulation”, “hemispatial neglect syndrome”, “caloric vestibular stimulation”, “galvanic vestibular stimulation”, “rehabilitation” in different combinations.
Materials and Methods: PubMed and Google Scholar were searched using keywords including “magnetic vestibular stimulation”, “hemispatial neglect syndrome”, “caloric

vestibular stimulation", "galvanic vestibular stimulation", "rehabilitation" in different combinations.

Results: Several studies have been conducted using MVS, bringing new light to set-point adaptation of vestibular system. Moreover, MVS can induce spatial attention bias similar to HNS for at least one hour during session.

Conclusions: MVS is a novel tool with many possibilities in e.g. vestibular research. Apart from research, it may have great potential in rehabilitation of patients with HNS – which could be beneficial also for athletes affected by stroke.

Keywords: magnetic vestibular stimulation (MVS), vestibulo-ocular reflex (VOR), vertigo, Lorentz force, nystagmus, hemispatial neglect syndrome (HNS).

2. Introduction

Magnetic vestibular stimulation (MVS) is an effect which is caused by a magnetic field. The magnetic field affects the fluid that is present inside the labyrinth. The mechanisms generate the magnetic field that depends on the movement in magnetic field with large spatial gradients. It has been observed that the magnetic field affects the endolymph in the labyrinth, generates Lorentz force that is responsible for the occurrence of vertigo. Vertigo does not necessarily depend on the movement or gradient of magnetic field. Lorentz force move through the hair cells of the utricle, maintaining their resting potential. They act perpendicularly to both the direction of the magnetic field and the direction of the electric current flow. They cause pressure and then the endolymph moves in the labyrinth, just like with head movements. The magnetic field generate Lorentz force that acts on the charged particle that carries the electric current. It is hypothesized that in the inner ear the Lorentz force, induced by both a strong static magnetic field and by an electric current enter the hair cells of the utricle, create a force that acts on the endolymph above the utricle cells then causes deflection of the semicircular canal cup and consequently the observable nystagmus. The essence of magnetic vestibular stimulation is that the structures of the labyrinth that are stimulated by Lorentz force are the superior and lateral semicircular canals, while the utricle is the main source of the conducted electric current. In the mechanism of MVS, there is a relative contribution of the semicircular canal cups and otolith spots to the electric current flow that generate the Lorentz force, in particular whether the electric current that enters the crest cells of the semicircular canal is capable of generating a Lorentz force sufficient to displace its cup. It is also believed that the macula utricle, both because of its close proximity to the cupulae of the superior and lateral semicircular canals and because of its greater number of hair cells and therefore greater electrical conductivity is primarily responsible for generating the force that causes cupula displacement. Vertigo had been seen for many years in patients exposed to magnetic field, but it was not until Marcelli et al. documented the phenomenon after their observations showed that the studied relationship was correct. They had been studying the effect of caloric vestibular input on the brain using functional MRI. They have observed slow eye drift in some patients' eyes while they lay in a nonirradiated space in a low-intensity magnetic field, before ear irrigation or any MRI scans were taken. They speculated that the unexpected nystagmus in the MRI machine was caused by the effect of strong static magnetic field on the labyrinth alone. To make these observations, necessary was the elimination of visual fixation mechanisms that normally suppress unwanted nystagmus that is induced by imbalanced labyrinthine input signals. By eliminating visual fixation and relying on the principles of physical examination, Marcelli et al. observed a direct effect of strong magnetic field on the vestibular system. [1]

The observation lead by Marcelli et al. was the first objective manifestation of vestibular imbalance in humans examined by high-power MRI in the history of MVS studies. Previous animal experiments that had been investigating the effects of strong magnetic field on body posture suggested that the entire cause of these phenomena was stimulation of the labyrinth in the inner ear, but there was not enough evidence to explain the mechanism. At that time, eye movements that had been studied in humans exposed due to a strong magnetic field. [2]

The effects of magnetic field on the vestibular system of mice had been also studied. In both humans and mice, magnetic field induce head movements, including circular movements, inhibit rising, and mediate the acquisition of conditioned taste aversion. Vestibular responses suggest that high magnetic field affects the inner ear. Loss of inner ear labyrinth function abolishes MF responses in both mice and humans, suggesting that the inner ear is the site of MF effects. [3] Further research is needed to fully elucidate the issues described above.

3. Application in research

In the work written by Jareonsettasin, [4] the vestibulo-ocular reflex is a simple behavior that stabilizes eye position, when the head moves - is used to investigate how tonic activity adapts to a new set point to prevent eye drift when the head is stationary. Set-point adaptation was induced with MVS by placing healthy subjects under 7T MRI for 90 min. MVS is ideal for prolonged vestibular activation because it mimics constant head acceleration and produces sustained nystagmus similar to natural vestibular lesions. Nystagmus is induced by MVS that is decreased slowly but incompletely over multiple time scales. An adaptive hypothesis was proposed that uses a cascade of mathematical integrators to reproduce the response to MVS, including a gradual decrease in nystagmus as the set-point changes over progressively longer periods of time. Set-point adaptation MVS is a biological model with applications in basic neurophysiological research on all types of movements, functional brain imaging, and the treatment of vestibular and higher-level attention disorders by introducing new biases to counteract pathological ones. To study set-point adaptation, it had been decided to use a vestibular model because the unwanted spontaneous nystagmus that occurs with unilateral labyrinthine damage is an intriguing problem for the adaptive networks that adjust set points; they must rebalance centrally to overcome any persistent asymmetric activity originating from the periphery. This nystagmus normally dissipates over time through adaptive processes. Using the effects of magnetic field on the labyrinth of normal humans (magnetohydrodynamic vestibular stimulation (MVS) due to Lorentz force that acts on the fluids in the semicircular canals and push the dome into a new position), a surrogate vestibular lesion was then created to study set-point adaptation. MVS is particularly suitable for studying the set-point adaptation of the vestibulo-ocular reflex (VOR), that are given the currently accepted ideas that MVS simulates a constant head acceleration and induces a continuous nystagmus. Due to the properties of the labyrinth and the central velocity storage mechanism, the slow phase velocity (SPV) which is induced by the constant acceleration increased to a constant value with a time constant of 10–15 s. During sustained MVS, however, after reaching the maximum value, the SPV slowly decays back toward a new but nonzero baseline. The adaptation process, that is inferring that the sustained invariant nystagmus is unnatural and pathological, occurs to eliminate the bias and unwanted eye drift. When the adaptive stimulus is suddenly removed, a side effect with oppositely directed slow phases occurs, revealing the previous adaptation. This work investigated a key aspect of this problem, how the brain adjusts set- points, the levels of activity that provide stable postures at rest and allow us to initiate movements from solid platforms. They have chosen chosen a simple model, the VOR, and a new way of stimulating it, MVS. These data and modeling provide strong evidence that MVS is comparable to a more natural vestibular stimulus, constant head acceleration. Using the unique features of MVS that make it ideal for studying mechanisms that eliminate unwanted deviations in neural activity - set-point adaptation - they show that existing models fail to account for vestibular adaptation timescales ranging from minutes to hours.

According to the work written by Wyssen, the effects of MVS on nystagmus severity, self-motion perception, and cognitive performance had been studied by exposure to a 7T magnetic field generated by an MRI scanner. Strong magnetic field induces dizziness, balance disorders, and nystagmus, an effect called magnetic vestibular stimulation (MVS). The vestibular system is located in the inner ear and measures the acceleration of the rotational axes (yaw, pitch, roll) via the three semicircular canals and the acceleration along the translational axes (nasal-occipital, interaural, and vertical head) via the macula, utricle, and saccule. The occurrence of MVS can be explained by the interaction of ionic current-induced Lorentz force that acts on the dome of the semicircular canals of the vestibular system. MVS gets more increased with more increasing magnetic field strength. Stimulation is caused by two different components. First of all, moving the participant into the borehole creates a dynamic magnetic field that induces Lorentz force that acts on the dome of the semicircular canals. Secondly, the static magnetic field of the MRI scanner, in which the participants lay still during the experiment, also induces a constant Lorentz force. Thus, in all experiments including using MRI scanners, the participant's vestibular system is continuously stimulated by a static magnetic field. Nystagmus is elicited by movement as well as by static rest in a strong magnetic field. The forces associates with movement cause a strong nystagmus that disappears after a few minutes. Nystagmus which is elicited in static magnetic field is weaker and gradually decreases with time but does not disappear completely during exposure. The direction of nystagmus depends on the polarity of the magnetic field and reverses upon withdrawal from the magnetic field. MVS acts mainly on the horizontal and superior semicircular canals, causing reflex eye movements, i.e., mainly horizontal and torsional nystagmus and, to a lesser extent, vertical nystagmus. In another group of patients with vestibular disorders, no nystagmus has been observed, and in still other group of patients, more pronounced vertical nystagmus components have been observed. Because nystagmus is involuntary, it is a well-suited measure of vestibular stimulation strength. Nystagmus can be suppressed by visual fixation; therefore, eye movements must be assessed in complete darkness. Self-motion perceptions were most often described as rotations in roll and, to a lesser extent, in the yaw and pitch planes. While nystagmus persists throughout the exposure, self-motion perception usually disappears after 1 to 3 min. The constant portion of MVS allows for prolonged vestibular input that is not accompanied by conscious perception of self-motion. Moving or moving in strong magnetic field affects cognitive performance. One study found that MVS can potentially lead to symptoms of derealization due to the false perception of self-motion. However, studies investigating the effect of static rest in magnetic field have not shown conclusive results on neuropsychological tasks, except for repeated impairment of visual accuracy. Interestingly, the strength of MVS can be modulated by changing the head position, thereby changing the orientation of the vestibular organs with respect to the magnetic field direction. The MVS effect can be reduced in most subjects by tilting the head forward toward the body (from chin to chest). In this way, changing the head position in the tilt axis allows for a comparison of the measurable MVS effects at different stimulation strengths. In this procedure, the strength of MVS was manipulated in participants by comparing measurements between two head positions. In the condition that should elicit stronger MVS, the participant lay supine in the scanner with the Reid plane orientation approximately vertical to the Earth (supine position). In the condition that should elicit weaker MVS, the participant's head was tilted approximately 30° forward (tilted position). Theoretically, it is possible to compare the supine position with a baseline position in which nystagmus does not occur. However, the required tilt for the baseline position is different for each participant and is time-consuming, as it requires several instances of changing positions and moving the participant in and out of the scanner to test the differences in the adopted body positions. [5]

In summary, there are many theories about MVS, produced as a consequence of the MVS effect which generates Lorentz force, and the influence of Lorentz force on the occurrence of vertigo symptoms, but further research is needed to thoroughly explain the phenomena we describe.

4. Interference of MVS with fMRI findings

As useful as it could be in vestibular research, existence of MVS could induce bias in interpretation of fMRI data. Discovery of MVS implies existence of possible artifacts in functional magnetic resonance imaging (fMRI) – MVS takes place in static magnetic field, and so it is present through the whole time the subject lies in MRI scanner. Boegle et al. [6, 7] found areas influenced by MVS in fMRI scans, associated with vestibular and ocular motor function, as well as with visual resting-state network. The strongest activation of these areas occurs in ones “the nearest” to the vestibule, while the effect slowly fades closer to central processing areas. It is likely caused by the fact that vestibular stimuli are processed in a hierarchical, multileveled manner.

Moreover, stimulation of areas affected by MVS seems to increase with strength of magnetic field, which means experiments conducted in higher field strengths (>3T) are more susceptible to interference from MVS. [6, 7] Due to the nature of Lorentz force, it is also possible to manipulate effects of MVS by tilting the subject's head. In most patients, symptoms of MVS lessen with head tilted towards the chest. This way a null position can be found, in which nystagmus completely stops. [8] Theoretically, this phenomenon could be used to reduce effects of MVS on fMRI findings. However, the angle of null position varies greatly between subjects due to anatomical differences, making practical application rather problematic. Experiment protocols would have to include repeating checking for nystagmus and repositioning the patient’s head, while not every study is suited for that.

Varying position of inner ear structures between individual subjects appear to be an important factor that could interfere with fMRI data, along with other less influential characteristics (e.g. right- or left-handedness, age). Boegle in 2020 [9] proposed a subject-specific proxy – pMVS – a regressor that allows mathematical correction of variance in acquired fMRI data. For this proxy to be calculated, an additional image of temporal bone in 3D constructive interference in steady-state (3D-CISS) sequence is needed in order to confirm position of horizontal semicircular canal in magnetic field. In another study [5] this position was assessed with a magnetometer attached to the subject's head in combination with 3D-CISS scan. This allowed to determine the orientation of inner ear’s structures during the phase of experiment when no scans were taken. That study was a presentation of an experimental setup without fMRI, therefore it didn't use pMVS. Nevertheless, combining pMVS, 3D-CISS images, and the method involving a magnetometer (when needed) could make a convenient tool when addressing anatomical differences in fMRI studies.

To conclude, interference of MVS with fMRI seems to be an important factor, which should be considered when planning studies on areas affected by MVS. Nonetheless, existence of MVS shouldn't be perceived as an obstacle, but rather as an opportunity. If used with thorough understanding, it could become a powerful tool in research.

5. MVS and hemispatial neglect syndrome (HNS)

MVS appears to have great potential in studies on spatial neglect. HNS is a cognitive disorder found in patients with unilateral brain injury, occurring e.g. after a stroke. This may be concerning for sports community, as stroke can occur in athletes, with higher incidence in sports as e.g. American football. [10] The lesion causes a shift in frame of reference in the horizontal plane, most commonly to the right side. [11] These patients are unable to respond to or report stimuli coming from contralesional side, they also fail to initiate or complete movement in or toward contralesional side. [12] Thus, patients with lesions in the right hemisphere "neglect" the left side of their body and space, and reverse phenomenon happens in patients with injured left hemisphere. Moreover, they have difficulties manipulating, reporting, or producing information stored mentally, as well as keeping the body posture or gaze centered – instead, they deviate toward the ipsilesional side. This condition can severely interfere with basic self-care activities (e.g. patients omit the left side of the body while dressing), reading, or even eating (e.g. patients may eat only food placed on the right side of the plate). [10] What may have dangerous consequences, HNS affects maintaining postural balance and navigating (e.g. patients fail to avoid furniture or walls). Therefore, it puts them at risk of falls, injuries, and being struck by a vehicle while crossing the street. Many patients suffer from anosognosia – they are unaware of their own deficits or their results, which discourages them from seeking treatment. Approximately one-third of stroke survivors present HNS during acute stage. This fact is concerning, as HNS is associated with poor long-term recovery. HNS can last for a number of years after a stroke. It occurs more commonly in patients with right-sided brain injury. [13] One of the most widely recognized batteries of tests used in the diagnosis of HNS is Behavioral Inattention Test (BIT), divided into two subtests: Conventional and Behavioral. The BIT Conventional subtest contains 6 items: line crossing, letter cancellation, star cancellation, figure and shape copying, line bisection, and representational drawing. The BIT Behavioral subtest contains 9 items: picture scanning, phone dialing, menu reading, article reading, telling and setting the time, coin sorting, address and sentence copying, map navigation, and card sorting. [14] Some studies use a classic cut-off score, while others diagnose HNS when patients present abnormal left-right asymmetry in at least one of the tests.

It has been known for years that caloric vestibular stimulation (CVS), as well as galvanic vestibular stimulation (GVS) are capable of inducing an effect mimicking HNS in healthy subjects, known also as spatial attention bias. [15, 16] CVS consists of irrigating subject's ear with cold or warm water. Sudden change of endolymph temperature in semicircular canals causes convection currents to form, which results in vestibular stimulation. Apart from that, cooling of vestibular nerves increases, while warming decreases their firing rates. [17] During GVS two electrodes are placed on subject's mastoid processes – one anode and one cathode. The stimulus is a controlled electrical current, usually at levels of ~1 mA.[18] However, it was recently discovered that during MVS spatial attention bias is not only possible to induce, but also to sustain for at least 1 hour. Furthermore, its intensity does not present adaptive decline overtime. [19] This characteristic is distinct from the ability of MVS to induce nystagmus, which decreases in intensity with continued stimulation, although it does not disappear completely. Additionally, upon leaving magnetic field, both spatial attention bias and nystagmus had aftereffects in the opposite direction. Nonetheless, they were no longer statistically detectable 7 minutes after leaving MRI bore. Such long simulation of spatial neglect opens up new possibilities in the research of this disorder. It could, among other things, allow for conducting more tests during a single experiment, while being a more comfortable solution for subjects.

6. Application in rehabilitation of HNS

Many methods of HNS rehabilitation have been developed. Apart from pharmacological therapy, some of these methods include, but are not limited to: 1) prism adaptation therapy, 2) visual scanning training, 3) limb activation, 4) dynamic auditory stimulation, 5) eye patching, 6) various forms of vestibular stimulation [20, 11] (See Tab. 1.)

Method of HNS rehabilitation	Brief summary
Prism adaptation therapy	Wearing prisms that shift the entire visual field of each eye to the right side. During sessions, patients make repeated goal-directed hand and arm movements toward a visual target. Visual shift causes a rightward movement error, which upon repetition is eliminated via adaptation. [21]
Visual scanning training	Exercises with visual cues (e.g. red line, scanning board) on contralesional side. Aims to enhance visual exploration [22]
Limb activation	Encouraging movement with limb located in contralesional space. The limb serves as active cueing device. [22]
Dynamic auditory stimulation	Presenting stereo sound moving from the ipsilesional to the contralesional side. Reasonable effect in the short term. [23]
Eye patching	Wearing glasses containing an ipsilesional monocular patch or ipsilesional half-field patches. Aims to block input to the contralesional superior colliculus, which inhibits leftward orienting mediated by the right superior colliculus. [11, 22]
Vestibular stimulation	Various methods, including CVS. Produces an attentional bias which may compensate the preexisting attention bias toward the ipsilesional side. [11]

Tab. 1.: Some of non-pharmacological methods of HNS rehabilitation along with their brief explanations. HNS – hemispatial neglect syndrome, CVS – caloric vestibular stimulation.

In addition to inducing spatial attention bias in healthy subjects, vestibular stimulation in general is able to reduce the effects of spatial neglect in stroke patients. Although researchers agree on the short-term effect during vestibular stimulation itself, its application in the treatment of patients is not that obvious. For years, research has been conducted in this area regarding the use of CVS and GVS [24, 25], but data on this topic is still poorly systematized and sometimes even contradictory. For example, it was reported that just one session of GVS reduces spatial neglect, and the effects are visible even 4 weeks after treatment. [26] On the other hand, Nakamura in 2015 [25] observed that the total charge of GVS correlates with effectiveness. In 2024, a systematic review was published, according to which the effects of GVS and sham GVS are similar, and CVS is more likely to be effective. [27] Further research is still needed on these two methods of vestibular stimulation. It would be beneficial to include e.g. *a priori* calculations to ensure adequate sample sizes, longer follow-up observation and acknowledging time since stroke in statistical analysis. MVS, as the youngest of stimulation methods, is even less researched in terms of rehabilitation of spatial neglect. For now, its potential in this matter is assessed by analogy with CVS. [28] Given similarities in their principles, this is a logical solution. After all, both of these methods rely on fluid motion of the semicircular canals pressing on their cupulae, although CVS accomplishes this via convection currents, while MVS via the Lorentz force. The crucial difference, however, is the time of stimulation that MVS makes possible. Spatial attention bias can be maintained for at least an hour during a single MVS session, whereas CVS effects disappear quite quickly. Due to such a large difference, one could assume that MVS could have even greater potential in HNS rehabilitation than CVS. Nonetheless, it is not advised to jump to conclusions – all VS methods need extensive research first. First, one must properly prove which methods work and in which protocol, and only then could we compare them with one another.

7. Conclusions

MVS is a novel method of vestibular stimulation, occurring in static magnetic field affecting patients inside MRI scanners. MVS is caused by Lorentz force, pushing endolymph of semicircular canals against their cupulae. Since its relatively recent discovery, it has been used in a number of studies regarding e.g. vestibular function and HNS. MVS appears to interfere with fMRI data in areas linked to vestibular, ocular motor function and visual resting-state network. Furthermore, influence of MVS on fMRI scans is altered by anatomical differences between subjects, although this can be reduced with usage of mathematical regressors or deliberate design of experimental protocol. It was newly reported that MVS causes spatial attention bias possible to maintain for at least one hour without decline. This fresh discovery opens new options in research and rehabilitation of HNS, which could be beneficial for sports community, as athletes can be exposed to increased risk of stroke.

8. Disclosure

8.1. Author's contribution

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supervision – Anna Hanslik, Tomasz Olszanecki
project administration – Agnieszka Walczak, Monika Olszanecka
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8.4. Informed Consent Statement

Not applicable.

8.5. **Data Availability Statement**

The authors confirm that the data supporting the findings of this study are available within the article's bibliography.

8.6. **Acknowledgments**

Not applicable.

8.7. **Conflict of Interest Statement**

Authors declare no conflict of interests.

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