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Functional and imaging anomalies of the vestibular system in motion sickness: a clinical observation study

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Abstract

Objective The aim of this study is to investigate the differences in vestibular organ function tests and the temporal bone computed tomography (CT) findings between healthy individuals and patients with motion sickness (MS), providing a basis for establishing functional and imaging diagnostic criteria for MS.

Method Vestibular organ function tests and temporal bone CT imaging were performed on patients in the MS group ($n=50$) and healthy individuals in the control group ($n=50$). Functional and imaging anomalies of the vestibular organ were identified and their features and patterns were analyzed. Patients with MS were further stratified based on severity to examine whether temporal bone CT findings varied across severity grade, and indexes of diagnostic significance were identified.

Results Comparisons of vestibular function tests revealed significantly lower bilateral vestibular evoked myogenic potential (VEMP) amplitudes in the MS group compared to the control group, with statistical significance ($P<0.05$). The severity of MS demonstrated a positive correlation with reductions in bilateral cervical VEMP (cVEMP) amplitudes ($P<0.05$). Video head impulse test (v-HIT) results indicated statistically significant differences in the gains of the left anterior, right horizontal, and left posterior semicircular canals ($P<0.05$). There were significant differences in the bilateral vestibular caloric test (CT) values ($P<0.05$). In terms of the temporal bone CT findings in the two groups, the detection rate of high jugular bulb combined with sinusitis, poor mastoid pneumatization, diploetic mastoid, or sclerotic mastoid was higher in patients with MS than in the healthy control group. Additionally, the detection rate of temporal bone anomalies in CT scans was significantly higher in the very severe and severe MS groups compared to the mild and moderate MS groups.

Conclusion In this study, we found that patients with MS exhibited functional and structural anomalies in vestibular function and temporal bone CT findings, which were correlated with the severity of MS. These findings suggest that vestibular function tests and temporal bone CT imaging can be used as objective reference indexes for the diagnosis of MS and assessment of its severity.

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Keywords Diploetic mastoid, Motion sickness, Poor mastoid gasification, Sclerotic mastoid, Temporal bone CT, Vestibular function test

Introduction

Motion sickness (MS) is a syndrome characterized by discomfort caused by exposure to irregular motions such as rotation, acceleration, jolting, or shaking and is mainly manifested as dizziness, gastrointestinal distress, and disorientation [1, 2]. Approximately one-third of the world's population is susceptible to MS [3]. With progress and widespread use of modern means of transportation, the incidence of MS has been steadily increasing every year. In addition, the absence of objective criteria for the selection of personnel in specialized fields such as navigation, aviation, and competitive sports underscores the need for research into the pathogenesis of MS and the development of effective and objective diagnostic methods.

The etiology and pathogenesis of MS remain poorly understood, and the diagnosis of MS is primarily symptom-based, lacking definitive functional and imaging diagnostic indexes. Several hypotheses have been proposed to explain the cause of MS, including the sensory conflict hypothesis [4], the neural mismatch hypothesis [5], and the vestibular hypersensitivity hypothesis [6]. Additional theories, such as the endocrine hormone release hypothesis, otolith asymmetry hypothesis, and genetic inheritance hypothesis [5], have also been put forth. Notably, all these hypotheses involve the role of the vestibular organ, a key component of the vestibular system that plays an irreplaceable role in maintaining spatial orientation, postural balance of the body, and automatic nervous regulation [7].

Anatomically, the vestibular system consists of the peripheral and the central vestibular components. The peripheral vestibular system, composed of the vestibular organ and the vestibular nerve, is responsible for the detection and transmission of body motion and positional information. When exposed to an unusual motion environment, the vestibular organ, which initially senses body displacement in the human vestibular system, transmits this information via the vestibular nerve to the vestibular sensory centers, triggering symptoms of motion sickness [8].

Our preliminary clinical observations suggest that anomalies in vestibular organ function and imaging anatomy play a role in the pathophysiology of MS and are associated with treatment efficacy and prognosis. Therefore, this study aims to compare vestibular function test results and temporal bone CT findings between healthy individuals and MS patients to identify distinctive functional and anatomical abnormalities. By establishing functional and imaging-based diagnostic criteria, this research seeks to enhance the accuracy of MS diagnosis, enabling a shift from subjective assessments to objective measures. These findings may also support stratified diagnosis, treatment planning, and prognosis evaluation, as well as provide objective criteria for selecting individuals in specialized professions requiring optimal vestibular function.

Materials and methods

Study participants

A total of 100 individuals who fulfilled the inclusion criteria and voluntarily signed the informed consent form were recruited from the Vertigo Diagnostic and Treatment Center clinic, Yinchuan Hospital of Traditional Chinese Medicine, and from the general population between June 2022 and September 2023. Based on their scores in the modified Motion Sickness Susceptibility Questionnaire (MSSQ), participants were assigned to either the MS group ($n = 50$) or the healthy control group ($n = 50$). All participants underwent an MS induction test, and the severity of MS was determined using the total Graybiel scale score and subsequently graded [9].

MS diagnostic criteria

The diagnostic criteria for MS were based on the *Motion sickness diagnostic criteria: Consensus Document of the Classification Committee of the Bárány Society* [10]. MS was defined as sickness induced by motion stimuli and fulfilling the following criteria (A-D):

A. Motion-induced symptoms: at least one of the following symptoms occur on motion stimulation:

(1) Nausea or gastrointestinal dysfunction
(2) Thermoregulation disturbance (e.g., cold sweats or pallor)
(3) Changes in alertness (e.g., drowsiness, fatigue)
(4) Dizziness or vertigo
(5) Headache or visual fatigue

B. Symptom progression with motion exposure: The above signs or symptoms occur during motion and intensify with prolonged exposure.

C. Symptom resolution after cessation of motion: The signs or symptoms abate following the discontinuation of motion stimuli.

D. Exclusion of alternative causes: The observed signs or symptoms cannot be attributed to other disorders or diseases.

Upon completion of the Motion Sickness Susceptibility Questionnaire (MSSQ) [11, 12], all participants were

assigned into either the MS group or the healthy control group.

Inclusion criteria

The inclusion criteria were as follows:

(1) Patients who fulfilled the above diagnostic criteria for MS;
(2) Individuals aged between 18 and 60 years, irrespective of sex;
(3) Individuals who were in good physical condition, with normal vision and no history of craniocerebral or psychiatric disorders, with no external ear deformities, and the external auditory canal was unobstructed; and
(4) Participants who agreed to the objectives, methods, and requirements of the study; signed the informed consent form; were able to actively cooperate with all examinations and treatments; and completed the study protocol.

Exclusion criteria

The following were the exclusion criteria:

(1) Patients who did not fulfill the diagnostic criteria for MS;
(2) Patients with a history of ear-related diseases, such as idiopathic sudden deafness, Ménière's disease, vestibular neuritis, positional vertigo, psychogenic vertigo, vertebral artery stenosis, cervical spondylosis, and any other vertigo diseases unrelated to MS;
(3) Patients who had serious underlying conditions such as liver, kidney, or gastrointestinal diseases, as well as psychiatric disorders; and.
(4) Patients with a history of head trauma.

MS induction test and severity grading of MS

An off-vertical axis rotation (OVAR) test, conducted with the SRM-IV BppV vertigo examination system [13] was used to induce symptoms of MS, specifically carsickness. Prior to the start of the research, we conducted homogenization operation training for the test operators. This training aimed to standardize the procedures for each vestibular test, including the proper placement of electrodes in the VEMP tests, the correct administration of stimuli, and the accurate execution of head movements in the v - HIT.

Preparations before the test were as follows:

Participants were instructed to adhere to the following guidelines prior to the test:

(1) Participants were refrained from using anti-motion sickness or sedation medications for one week before the test;
(2) They had to avoid alcohol and/or coffee 24 h prior to the test;
(3) Participants were to be on an empty stomach on the morning of the test.

Test procedure:

Participants were seated and securely fastened in a fully automatic swivel chair, maintaining a forward-facing posture with video eye shields in place. The chair's main axis was tilted by 30°, and the auxiliary axis rotated continuously and uniformly around the vertical axis at a speed of 90°/s while they remained seated. Rotation was maintained until the participant experienced progressively worsening carsickness symptoms to the point of significant discomfort, such as moderate- or severe-grade nausea, or a maximum rotation time of 5 min was reached. The rotation was then stopped, and the participant was returned to a stationary sitting position.

After the test, participants completed the Graybiel scale for rating motion sickness symptoms and signs [9], and the severity of their MS was classified as follows: no symptom: 0 points; mild MS: 1–3 points; moderate MS: 4 points; severe MS: 5–6 points; very severe MS: 7 points. Evaluation was done after performing a motion sickness provocation test (An off-vertical axis rotation (OVAR) test) with a scale of 7 signs and symptoms of motion sickness including nausea syndrome, skin colour, cold sweating, salivation, drowsiness, pain and central nervous system. Those who experienced motion sickness reactions were scored on each item according to the observation scale, and the severity of motion sickness was assessed and graded based on the cumulative total score.

The results from the MSSQ and the Graybiel MS rating scale were consistent in differentiating the MS and healthy control groups.

Temporal bone CT test

All participants underwent temporal bone CT using a 64-slice spiral CT scanner. Participants were placed in a supine position, keeping the head and oropharynx stationary during the scan. The scanned area covered the region from the superciliary arch to the area below the mastoid, with the superior Reid's base line (RBL) serving as the axial reference line. The temporal bone CT scanning parameters were as follows: slice collimation: 2*0.6 mm; field of view (FOV): 250 mm*250 mm; matrix resolution: 512*512; slice thickness: 0.6 mm; pitch: 0.8, and reconstitution interval: 0.4 mm.

All participants underwent plain scanning, tomography, and three-dimensional reconstruction to assess the anatomical features of the temporal bone.

Vestibular function tests

Ocular vestibular evoked myogenic potential (oVEMP) test

Participants were tested in a supine position, with the recording electrodes placed 1 cm below each eyelid, the ground electrode positioned between the eyebrows, and the reference electrode placed at the median mandibular position. Stimulation parameters were as follows: stimulus: short pure tome; stimulation intensity: 100 dBnHL, frequency: 5 Hz, number of stimulus repetitions: 60; and sound was transmitted via insert earphones.

Test procedure: During the test, participants were instructed to gaze at a fixed point located 25° above the horizontal plane without blinking until the sound stimulus stopped.

Waveform analysis: After superimposing 60 stimuli, the resulting waveform was analyzed. A negative peak (N1) typically appeared at ~ 10 ms, followed by a positive peak (P1) at ~ 15 ms, under normal conditions. Amplitudes of P1 and N1 were measured, with normal values defined as amplitude ≥ 2 μV.

Cervical vestibular evoked myogenic potential (cVEMP) test

Following the completion of the oVEMP test, participants remained in the supine position with electrodes transferred to different positions; specifically, the recording electrodes were positioned at the center of the bellies of bilateral sternocleidomastoid (SCM) muscles; the ground electrode was placed right between the eyebrows; and the reference electrode was placed in the suprasternal fossa. Stimulation parameters were as follows: stimulus: short pure tone; stimulation intensity: 105 dBnHL; frequency: 5 Hz; number of stimulus repetitions: 60; and the sound was transmitted via insert earphones.

Test procedure: During the sound stimulation, participants were instructed to raise their heads and focus their gaze on their toes, ensuring contraction of the SCM muscles. The contraction was maintained until the sound stopped.

Waveform analysis: After 60 superimposed stimuli, a negative peak was typically observed at ~ 23 ms under normal conditions, which was recorded as N1; a positive peak was typically observed at ~ 13 ms, which was recorded as P1. Amplitudes of P1 and N1 were measured, and the results were considered normal if the amplitude of the response was ≥ 50 μV. The cVEMP is mainly used to record the electromyographic activity of the sternocleidomastoid muscle to reflect the functional status of the inferior vestibular nerve, mainly the saccule and the inferior vestibular nerve, and abnormal cVEMP results suggest that the saccule function is impaired. The main function of the saccule is to sense the state of movement during vertical linear acceleration (e.g., up and down motion) or changes in gravity, and to transmit information to the central nervous system to help regulate balance. When the saccule function is impaired, the perception of vertical acceleration is abnormal, which may lead to sensory conflicts, thus inducing motion sickness, and may lead to increased sensitivity of the vestibular system, which may increase the susceptibility to motion sickness. cVEMP amplitude is positively correlated with the severity of MS, because a lower increase in cVEMP indicates a poorer functioning of the saccule, and poorer perception of vertical acceleration, and therefore a more severe motion sickness. Therefore, cVEMP amplitude is positively correlated with the severity of MS.

Video head impulse test (v-HIT)

The video head impulse test (v-HIT) was performed with the v-HIT tester, following these steps:

Participants were seated on a chair one meter away from a visual target. Eye shields equipped with built-in video eye tracking cameras and speed sensors were worn and securely adjusted to expose their eyeballs completely. The tester stood behind the participants and controlled the direction and movement of the participant's head.

Testing procedure: The tester performed side-to-side head thrusts to measure the vestibulo-ocular reflex (VOR) gain of the left and right horizontal semicircular canals and the gain asymmetry.

For the left head turn procedure, the participant's head was turned 45° to the left with their eyes focusing on the visual target. The tester thrust the head forward and down on a sagittal plane to measure the VOR gain of the right anterior semicircular canal and the corresponding gain asymmetry. The tester then thrust the head backward and up to measure the VOR gain of the left posterior semicircular canal and the corresponding gain asymmetry.

For the right head turn procedure, the participant's head was turned 45° to the right with their eyes focusing on the visual target. The tester thrust the head forward and down on a sagittal plane to measure the VOR gain of the left anterior semicircular canal and the corresponding gain asymmetry. Then the tester thrust the head backward and up to measure the VOR gain of the right posterior semicircular canal and the corresponding gain asymmetry.

A minimum of 15 standard head thrusts was required for each measurement. Non-standard head thrusts were automatically detected and deleted by the system.

VOR gain was recorded for each semicircular canal. The values were normal if the gain was ≥ 0.7 [14].

Caloric test

The caloric test was conducted as follows to assess the functionality of the horizontal semicircular canals via the vestibular system's response to thermal stimulation: The participants were made to lay flat on the examining

couch with a pillow placed under their head, elevating the head by 30° to position the horizontal semicircular canal vertically. An electronystagmography (ENG) device was affixed to the participant's head to monitor eye movements. A light screen was used to block visual input, ensuring that the field of vision was restricted. The participants were instructed to keep their eyes open and focus straight ahead without moving their eyeballs during the test.

Testing procedure: Air was directed into the external auditory canal for 60 s, with care taken to accurately target the eardrum. Cool air (24 °C) and hot air (48 °C) were delivered. The air was injected first into the left external auditory canal and then the right external auditory canal, and cold air was injected before the hot air in both ears. The responses to the cool and hot air stimulation were recorded. The results were interpreted as normal when the sum of unilateral responses to hot and cold air stimulation (hot + cold value) was ≥ 12.

Statistical analysis

All collected data were verified and analyzed using the SPSS 26.0 statistical software. The participants in this study were categorized into two groups: the MS group and the healthy control group. Categorical data were compared using the χ^2 test or independent sample t-test; quantitative data in a non-normal distribution were statistically described using the mean ($\bar{x}$) ± standard deviation (s) and the t-test was used for comparisons between groups. Within-group data in an approximately normal distribution exhibiting homogeneity of variance were compared pairwise using one-way repeated measures analysis of variance (ANOVA). A P value < 0.05 indicated statistically significant differences.

Table 1 Comparison of temporal bone CT findings between the healthy control and MS groups

CT finding	Healthy control group	MS group	Total
No obvious abnormality in temporal bone CT	25	17	42
Sinusitis	8	6	14
High jugular bulb	11	6	17
Sigmoid sinus preposition	3	4	7
Submucous cyst of maxillary sinus	3	7	10
High jugular bulb + Sinusitis	0	6	6
Abnormal mastoid development	0	4	4
Total	50	50	100
χ^2	15.634		
p	0.008		

Results

Comparison of general data

A total of 100 eligible participants were included in this study, with no dropouts. They were divided into the MS group (n = 50) and the healthy control group (n = 50). The MS group consisted of 37 females (74%) and 13 males, aged 19–59 years, with a mean age of 34.94 ± 12.48 years. The healthy control group consisted of 33 females (66%) and 17 males, aged 23–60 years, with a mean age of 37.42 ± 12.91 years.

Statistical analysis suggested that the two groups were comparable in terms of gender (χ^2 = 0.762, P = 0.383) and age (t = 0.977, P = 0.331).

Temporal bone CT findings

Comparison of temporal bone CT findings between the two groups

Temporal bone CT findings showed no obvious abnormality in the temporal bone structure, sinusitis, high jugular bulb, sigmoid sinus preposition, or submucous cyst of the maxillary sinus in either group. However, the detection rate of conditions such as high jugular bulb combined with sinusitis, poor mastoid pneumatization, diploetic mastoid, or sclerotic mastoid was higher in patients with MS than in the healthy control group.

Comparison of temporal bone CT findings between the two groups showed statistical significance, with χ^2 = 15.634 and P = 0.008, suggesting that the temporal bone CT findings differ significantly between the two groups (Table 1).

The comparison of temporal bone CT findings between the two groups is shown in Figs. 1, 2, and 3.

Association between temporal bone CT findings and MS severity

The temporal bone CT results revealed that the detection rates of poor mastoid pneumatization, diploetic mastoid, and sclerotic mastoid were significantly higher in MS patients (who were divided into the severe MS and the very severe MS groups based on MS severity) than in the healthy control group, as shown in Figs. 2 and 3, and 4. There was a significant association between temporal bone CT findings and the severity of MS, with χ^2 = 35.566 and P = 0.008 (Table 2), suggesting that the temporal bone CT anomalies are related to the severity of MS.

Vestibular function tests

Comparison of VEMP levels between the two groups

The oVEMP and cVEMP amplitudes from the VEMP tests in the healthy control and MS groups were analyzed as non-normally distributed measurement data and compared between the two groups using the non-parametric rank sum test. The results showed that the differences between the two groups in amplitudes of oVEMP and

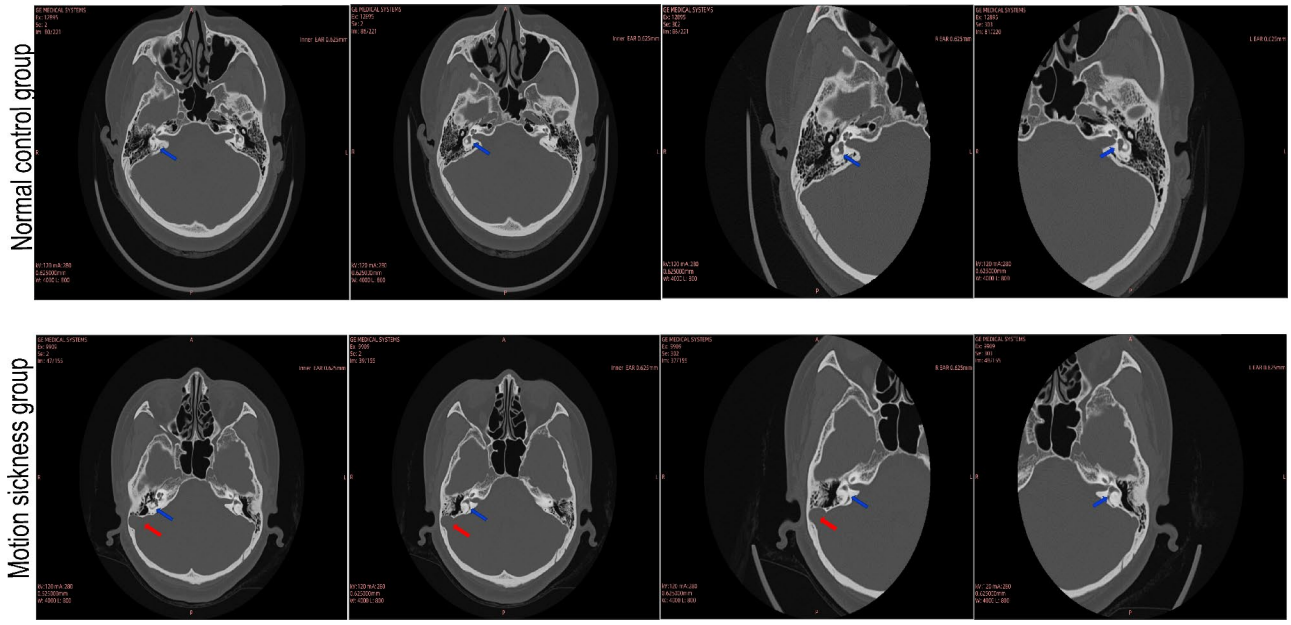

Fig. 1 Comparison of temporal bone CT findings between the two groups (sigmoid sinus preposition + poor mastoid pneumatization) Note: As can be seen from the above figure, the temporal bone CT findings in the healthy control group revealed a predominantly hollow mastoid structure, characterized by numerous transparent, well-defined, and evenly distributed air cells arranged in a honeycomb pattern. In contrast, the MS group displayed a smaller mastoid with fewer air cells, suggesting poor mastoid pneumatization in patients with MS. Additionally, a comparison of findings in the two groups showed that the anterior edge of the sulcus for the sigmoid sinus was approximately 10–14 mm from the posterior wall of the external auditory canal in the healthy control group, while this distance was reduced to less than 10 mm in the MS group, suggesting the presence of sigmoid sinus preposition in patients with MS. Blue arrows indicate the location of vestibular organs and red arrows indicate the location of various structural abnormalities

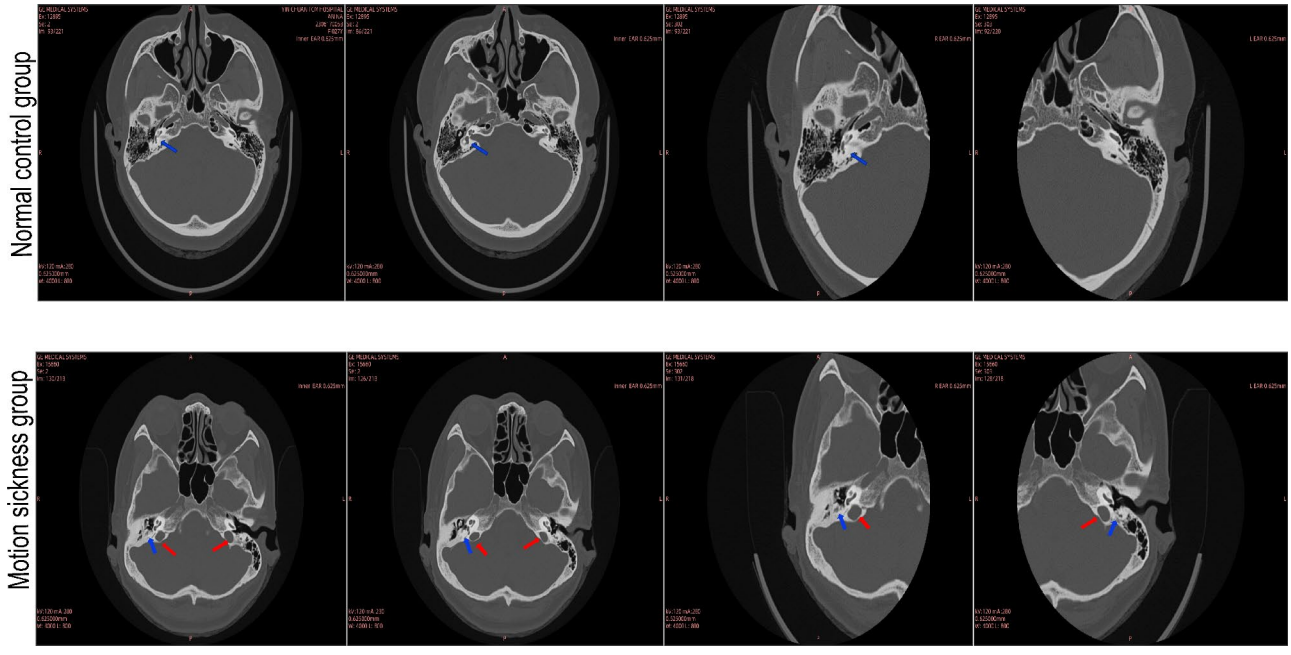

Fig. 2 Comparison of temporal bone CT images between groups (high jugular bulb + diploetic mastoid). Note: As can be seen from the above figure, the temporal bone CT findings in the healthy control group revealed a predominantly hollow mastoid, with numerous transparent, clear, and well-spaced air cells arranged in a honeycomb pattern. In contrast, the MS group displayed a smaller and thicker mastoid structure resembling the diploe of the skull, with only a few transparent and clear air cells, indicating the presence of diploetic mastoid. Furthermore, a comparison of findings between the two groups showed that in the MS group, the jugular bulb extended beyond the lower edge of the cochlear basal turn, whereas in the healthy control group, the jugular bulb remained below this level. These observations from the temporal bone CT findings of the MS group are indicative of a high jugular bulb. Blue arrows indicate the location of vestibular organs and red arrows indicate the location of various structural abnormalities

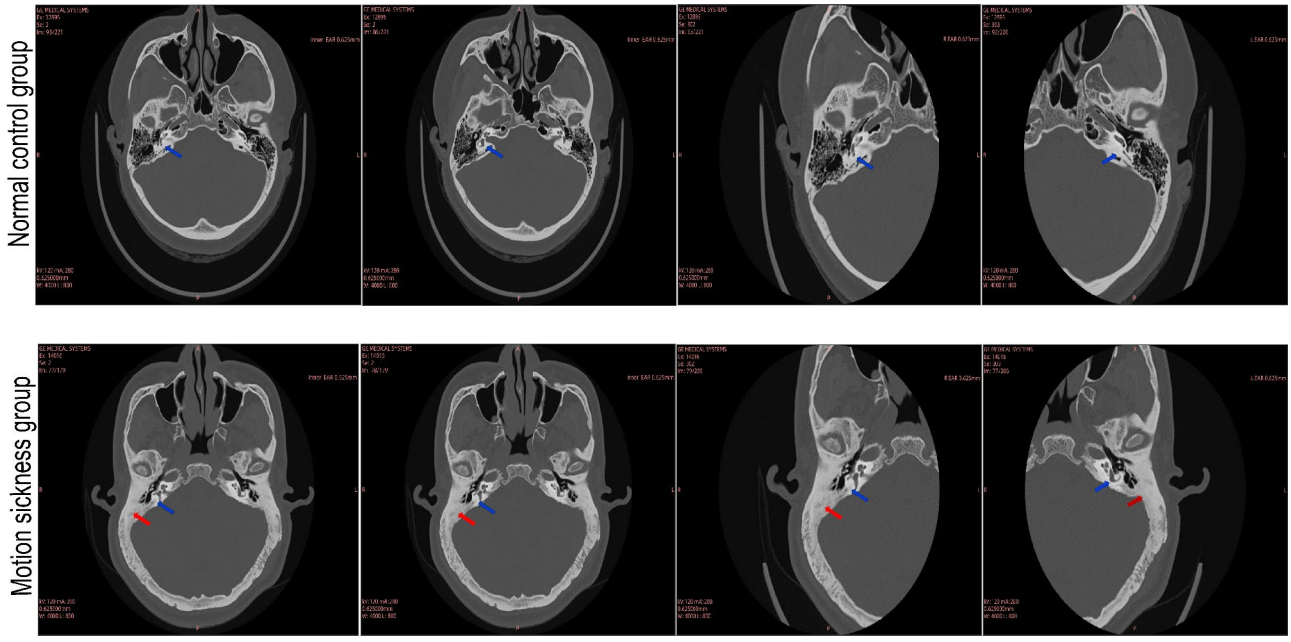

Fig. 3 Comparison of temporal bone CT images between the two groups (abnormal mastoid development). Note: As can be seen from the above figure, the temporal bone CT findings in the healthy control group revealed a predominantly hollow mastoid, with numerous transparent, clear, and well-spaced air cells arranged in a honeycomb pattern. The temporal bone CT findings of the MS group revealed a dense, sclerotic, and thick mastoid without visible air cells. These temporal bone CT findings in the MS group are indicative of abnormal mastoid development. Blue arrows indicate the location of vestibular organs and red arrows indicate the location of various structural abnormalities

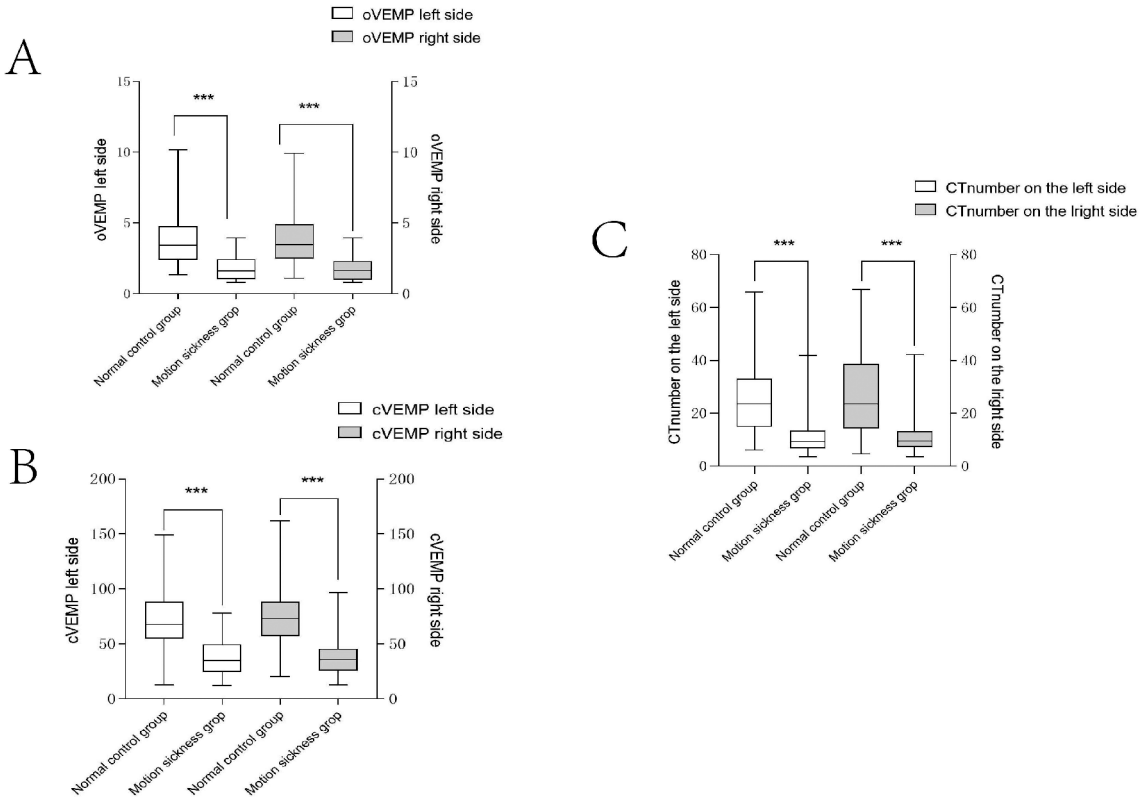

Fig. 4 (**A**) Box plot of the comparison of oVEMP between the two groups; (**B**) Box plot of the comparison of cVEMP between the two groups; (**C**) Box plot of the comparison of bilateral caloric test values between the two groups

Table 2 Comparison of temporal bone CT findings as per severity of MS in the MS group

		Temporal bone CT findings						
		No obvious abnormality in bilateral temporal bone CT	Sinusitis	High jugular bulb + Sinusitis	High jugular bulb	Sigmoid sinus preposition	Submucous cyst of maxillary sinus	Abnormal mastoid development
Severity	Very severe	0	0	1	0	1	1	3
	Severe	2	3	2	2	1	0	1
	Moderate	8	2	3	1	0	3	0
	Mild	7	1	0	3	2	3	0
	χ^2	35.566						
	p	0.008						

Table 3 Comparison of oVEMP and cVEMP amplitudes between the healthy control and MS groups

Group	OVEMP		CVEMP	
	Left	Right	Left	Right
Healthy control group	3.42(2.42,4.77)	3.47(2.48,4.92)	67.83(54.83,88.26)	73.11(56.75,88.10)
MS group	1.60(1.03,2.45)	1.64(0.99,2.32)	34.62(24.34,49.36)	35.63(25.56,45.39)
t value	-5.964	-6.891	-6.811	-6.894
P value	< 0.001	< 0.001	< 0.001	< 0.001

Table 4 Comparison of v-HIT gains between the healthy control and MS groups

Group	Left anterior	Right anterior	Right horizontal	Left posterior	Right posterior	Left horizontal
Healthy control group	0.95 ± 0.12	0.93 ± 0.11	1.11 ± 0.21	0.95 ± 0.15	0.89 ± 0.13	0.96(0.88,1.13)
MS group	0.88 ± 0.10	0.91 ± 0.11	0.93 ± 0.15	0.88 ± 0.12	0.87 ± 0.10	0.94(0.85,1.01)
t/z value	2.846	1.222	5.062	2.519	0.741	-1.107
P value	0.005	0.225	< 0.001	0.013	0.461	0.268

Table 5 Comparison of bilateral CT values between the healthy control and MS groups

	Vestibular caloric test	
	Left hot + left cold	Right hot + right cold
Healthy control group	23.48(14.86,32.98)	23.49(14.24,38.57)
MS group	9.23(6.69,13.43)	9.41(7.20,13.09)
Z value	-6.294	-5.281
P value	< 0.001	< 0.001

Table 6 Comparison of cVEMP amplitude as per severity of MS in the MS group

	cVEMP	
	Left	Right
Mild	55.07(37.27,61.68)	53.95(35.25,64.80)
Moderate	42.61(30.44,46.57)	34.51(25.10,37.83)
Severe	29.02(23.98,32.61)	35.63(16.43,45.35)
Very severe	20.77(12.57,22.33)	23.24(16.24,37.19)
H value	25.391	15.010

cVEMP were statistically significant ($P < 0.05$) (Table 3; Figs. 4A and B).

Comparison of v-HIT gains in the two groups

The v-HIT gains (left anterior, right anterior, right horizontal, left posterior, and right posterior) were analyzed using the independent sample t-test to compare the healthy control and the MS groups. Differences between the two groups in v-HIT gains (left anterior, right horizontal, and left posterior) were statistically significant ($P < 0.05$), while differences in the v-HIT gains (right anterior and right posterior) were not significant ($P > 0.05$) (Table 4). The differences in left horizontal v-HIT gains between the two groups were compared using the non-parametric rank sum test, and the results showed that there was no significant difference between the groups in left horizontal v-HIT gains ($P > 0.05$) (Table 4).

Comparison of bilateral CT values between the two groups

The bilateral CT values in the healthy control and the MS groups were non-normally distributed measurement data, and between-group comparisons were made using the non-parametric rank sum test. The results showed that the differences in bilateral CT values between the two groups were statistically significant ($P < 0.05$) (Table 5; Fig. 4C).

Comparison of amplitude of VEMP, v-HIT gains (left anterior, right horizontal, left posterior), and bilateral CT values with MS severity

The relationship between vestibular function test data and the severity of MS within the MS group was analyzed using the Kruskal–Wallis test and one-way ANOVA. The results showed a significant association between the bilateral cVEMP amplitude and the severity of MS

($P < 0.05$) (Table 6). However, there was no significant relationship between the bilateral oVEMP amplitude, v-HIT gains (left anterior, right horizontal, left posterior), or bilateral CT values with MS severity in the MS group ($P > 0.05$).

Discussion

In our statistical analysis, we first compared the general data of the two groups, including gender and age. The results showed that there were no significant differences in gender and age between the MS group and the healthy control group. This indicates that these two factors did not significantly affect the baseline characteristics of the two groups. Regarding comorbidities, we excluded patients with serious underlying conditions such as liver, kidney, or gastrointestinal diseases, as well as psychiatric disorders, through the exclusion criteria. Although we did not adjust for these factors in a statistical model, the use of strict inclusion and exclusion criteria helped to minimize the potential confounding effects.

Analysis of temporal bone CT findings

Comparison of temporal bone CT findings between healthy individuals and patients with MS revealed statistically significant differences. Findings such as poor mastoid pneumatization, diploetic mastoid, and sclerotic mastoid were detected more often in patients with MS, and this finding was consistent with earlier research indicating that inadequate temporal bone pneumatization could affect the vestibular aqueduct and contribute to vertigo [15]. These results suggest that poor mastoid pneumatization may serve as an anatomical and pathological basis for vertigo.

While isolated anomalies in the temporal bone exert minimal effects on MS, the combination of conditions such as high jugular bulb and sinusitis notably increases MS risk. This supports the hypothesis that MS arises from interactions between multiple systems, such as the vestibular, auditory, and visual systems. Visual stimuli—closely anatomically linked to the vestibular system—are a known trigger for MS [16]. It has been demonstrated that individuals with vestibular dysfunction may not experience MS in a specific environment or condition but can develop MS symptoms when exposed to visual stimulation. For instance, Paillard et al. [17] reported an exacerbation of symptoms among patients with MS in environments with unpleasant odors such as gasoline. Liu et al., [18] in their study on the effects of different odors in a mouse model of MS, found that certain aromas, including ginger essential oil, orange peel essential oil, and vinegar, could reduce MS symptoms in mice.

Poor mastoid pneumatization, diploetic mastoid, and other CT - detected abnormalities may disrupt the normal physiological environment around the vestibular organ. The abnormal structure can lead to altered pressure distribution in the inner ear, affecting the circulation of endolymph and perilymph. This, in turn, may interfere with the normal function of the vestibular receptors, making individuals more susceptible to MS. For example, a reduced number of mastoid air cells in poor mastoid pneumatization may limit the ability of the inner ear to regulate pressure changes during motion, increasing the likelihood of sensory conflicts that trigger MS symptoms. In our study, statistically significant associations were identified between temporal bone CT findings and the severity of MS. The detection rates of poor mastoid pneumatization, diploetic mastoid, and sclerotic mastoid among patients in the very severe MS and severe MS groups were significantly higher compared to the moderate MS and mild MS groups. This may be attributable to compromised airflow and ventilatory disorders in individuals with hypoplastic or diploetic mastoid air cells, rendering them more susceptible to MS when subjected to motion stimuli like shaking or jolting in vehicles.

These results suggest that smaller mastoid air cells are associated with increased MS severity, highlighting the potential of using temporal bone CT imaging as an objective diagnostic tool for MS.

Utility of temporal bone CT imaging in the vestibular organ

MS affects the daily activities of affected individuals, particularly in terms of travel, high-altitude work, and aerospace or navigation undertakings, with its incidence increasing annually. The vestibular system, responsible for motion sensing and information processing, plays a major role in the triggering of MS symptoms [19]. Nevertheless, the diagnosis of MS remains primarily symptom-based and is mainly based on experiences reported by the patient, which can lack objectivity to some extent.

Preliminary clinical experience suggests that temporal bone CT tests can aid in the diagnosis of MS. The temporal bone, an irregularly shaped structure at the junction of posterior and middle cranial fossae, houses the middle ear, inner ear, vestibular receptor, and other vital structures [20]. The temporal bone begins to develop air content after birth, reaching adult levels by adolescence. Physiologically, the temporal bone serves various functions such as receiving sound, producing resonance, storing gas, reducing the weight of the skull, preventing external trauma, and protecting the sensitive structures of the inner ear from external temperature fluctuations. The air content in the temporal bone is closely related to the occurrence and prognosis of inflammation [21].

From preliminary clinical findings, temporal bone CT findings in patients with MS commonly include poor mastoid pneumatization, high jugular bulb, and sinusitis. In this study, the aim was to provide an imaging basis for diagnosing MS by exploring the relationship between MS

and these temporal bone abnormalities. High-resolution CT of the temporal bone plays a key role in aiding structural analysis, causative diagnosis, and treatment follow-up, making it an essential tool for patients with MS.

Role of vestibular function tests in the diagnosis and treatment of MS

The vestibular function tests incorporated in this study included the oVEMP test, cVEMP test, v-HIT, and the caloric test.

The vestibular organ, or the "bony labyrinth," located in the inner ear comprises the cochlea, three pairs of mutually perpendicular semicircular canals, a pair of saccules, and a pair of utricles. This intricate system functions as the body's receptor for detecting motion states and the spatial position of the head. When the body undergoes rotational or variable rectilinear motion, changes in velocity (including both acceleration and deceleration) cause lymphatic flow within the labyrinth, which in turn generates electrical signals. The nerve impulses caused by these electrical signals are transmitted to the brain via the vestibular branch of the eighth pair of cranial nerves, leading to corresponding reflexes and symptoms [22].

Saccules and utricles detect linear accelerations, including vertical and horizontal movements, and the three pairs of semicircular canals detect rotational accelerations. Structurally, the semicircular canals are interconnected tubes approximately 0.4 mm in diameter. Each canal has an enlarged section called the ampulla, which contains the ampullary crest. The crest houses hair cells, which serve as receptors for the vestibular organ. Due to its anatomical precision and functional uniqueness, the vestibular organ can accurately identify the spatial position and motion direction of the head at any given time. This makes vestibular function tests essential in diagnosing and understanding the pathophysiology of MS.

In the caloric test, hot and cold water are used to stimulate the lymphatic flow, inducing nystagmus. The functioning of the bilateral horizontal semicircular canals is evaluated by analyzing the direction and time of the nystagmus. However, only the functioning of horizontal semicircular canals at low frequencies can be assessed [23].

The v-HIT, an advanced method based on the head thrust test, provides a comprehensive evaluation of the functioning of the semicircular canals based on measuring the gain—the ratio eye movement velocity to head movement velocity—and identifies catch-up saccades (CS). It allows for the quantitative assessment of all six semicircular canals [23].

The cVEMP, which originates from the saccule, is mainly used to evaluate the vestibulo-collic reflex (VCR). This reflects the functional status of the inferior vestibular components, including the saccules and inferior vestibular nerve afferent pathway.

The oVEMP, originating from the utricle, is used to evaluate the function of the vestibulo-ocular reflex (VOR). It indicates the functional status of the superior vestibular components, including the utricles and the superior vestibular nerve afferent pathway [24].

These tests provide complementary insights into the intricate functioning of the vestibular system, facilitating the diagnosis and understanding of vestibular disorders like MS.

The sensory conflict hypothesis and neural mismatch hypothesis are generally adopted in current studies on the pathogenesis of MS. The sensory conflict hypothesis, the cornerstone of research on the pathogenesis of MS, considers MS as arising from a conflict between the vestibular, proprioceptive, and visual inputs processed by the brain under external stimuli [25]. Building on this, the neural mismatch hypothesis attributes MS to a discrepancy between the visual, proprioceptive, and vestibular sensory inputs transmitted to the brain and the brain's anticipated "internal model" of motion [5]. Although additional hypotheses have emerged based on these two theories, none can fully explain the pathogenesis of MS. There is little doubt, however, that the vestibular system plays a crucial role. Therefore, vestibular function testing is instrumental in not only evaluating therapeutic efficacy but also in providing an objective basis for diagnosing MS.

Analysis of data from the vestibular function tests in this study revealed that the amplitudes of oVEMP and cVEMP, v-HIT gains (left anterior, right horizontal, left posterior), and caloric test values of patients with MS were significantly lower than those in the healthy control group. Notably, the amplitude of cVEMP was correlated with the severity of MS. These findings indicate that patients with MS exhibit distinct vestibular function deficits compared to healthy individuals, with impaired vestibular organ function being a characteristic feature. This is consistent with prevailing hypotheses in current research, which propose that vestibular dysfunction is a primary factor in the pathogenesis of MS [6]. The development of motion sickness is not the result of a single vestibular organ dysfunction, and a comprehensive assessment of saccadic and canal function in combination with a variety of vestibular function tests (v-HIT, hot/cold test, VEMP) is required. The significant differences in left anterior, right horizontal, and left posterior gain values in this study suggest that some patients with motion sickness may have only unilateral or specific semicircular canal function abnormalities. This is related to individual differences, and no clear significant correlation between left and right sides was found; asymmetry of left and right hemicircular canal function may influence

susceptibility to motion sickness in some individuals. However, there is still a lack of large-scale studies demonstrating that the left and right hemicrania can directly influence the development of motion sickness, and not all patients with abnormal hemicranial function will develop motion sickness due to individual variability in compensatory capacity and central adaptive mechanisms.

It is important to note that the vestibular system consists of a peripheral part and a central part. Specifically, the peripheral part refers to the semicircular canals, ellipsoid sacs, and globus pallidus, and the central part refers to the vestibular nerves, the vestibular nuclei of the brainstem, the cerebellum, the cerebral cortex, and connecting pathways. The development of motion sickness is mainly closely related to the peripheral vestibular organs. The vestibular examination involved in this study, in which VEMP assessed the function of elliptical capsule and saccule, v-HIT assessed the high-frequency vestibular function of the six semicircular canals, and hot and cold test detected the low-frequency function of the horizontal semicircular canals. Vestibular dysfunction was determined when v-HIT hemicircular gain was reduced, hot and cold tests were unilaterally or bilaterally attenuated, and oVEMP and/or cVEMP were abnormal, with ≥ 1 of these 3 present, and not all vestibular organs were referred to as hypocompetent until they were simultaneously diminished in function.

Limitations and future research directions

The limitations of this study were as follows: (1) The irregularity of motion sickness attacks is related to the patient's own health and psychological state, which makes the test results have a certain degree of error, but this study reduces this error as much as possible through the motion sickness simulation test. (2) The Graybiel Motion Sickness Rating Scale was chosen as the evaluation index in this study, which is a questionnaire-type scale that is easily affected by patients' subjective factors and is not comprehensive enough. (3) The sample size of this study is small, lacking longitudinal data, and there is a certain error; in future research efforts to expand the sample size can be taken multidisciplinary, multi-regional joint research.

Future studies could build on our findings by exploring the impact of temporal bone abnormalities on MS progression. Long - term follow - up studies could be conducted to observe how changes in temporal bone structure over time relate to the development and worsening of MS symptoms. Additionally, we could investigate other vestibular dysfunctions in MS that were not covered in this study. For example, studying the role of the central vestibular system in MS, including the function of vestibular nuclei in the brainstem and their connections with other brain regions. Research could also focus on the interaction between different vestibular abnormalities and how they contribute to the overall pathophysiology of MS. By addressing these aspects, future studies can further advance our understanding of MS and potentially lead to more effective diagnostic and treatment strategies.

Conclusion

In conclusion, the diagnosis of MS currently relies primarily on symptomatology. The findings of this study demonstrate the close association between MS and the vestibular organ, and the characteristic patterns in temporal bone CT imaging and vestibular functional test findings among patients with MS were identified. These findings offer valuable insights that could contribute to refining the diagnostic criteria for MS by incorporating imaging and vestibular function assessments.

Abbreviations

MS	Motion Sickness
MSSQ	Motion Sickness Susceptibility questionnaire
oVEMP	Ocular vestibular evoked myogenic potential
cVEMP	Cervical vestibular evoked myogenic potential
v-HIT	Video head impulse test
CT	Calorict test
VEMP	Vestibular evoked myogenic potential
VCR	Vestibulo-collic reflex
VOR	Vestibulo-ocular reflex

Author contributions

Ling Chen: Conceptualization, Formal Analysis, Funding acquisition, Writing – original draft, Writing – review & editing. Guo-Hui Li: Conceptualization, Data curation, Writing – review & editing. Li He: Data curation, Formal Analysis, Software, Writing – original draft, Writing – review & editing. Liang-Juan Zhao: Data curation, Software. Na Bao: Data curation, Formal Analysis, Software. All authors read and approved the final draft.

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Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

This study was conducted with approval from the Ethics Committee of North Minzu University and Yinchuan Traditional Chinese Medicine Hospital (Issue: 2021-8-28), registered in International Traditional Medicine Clinical Trial Registry (http://itmctr.ccebtcm.org.cn/zh-CN/UserPlatform/ProjectView?pid=77437c78-f787-484b-bbe6-78e3b975e7ac, No. ITMCTR2024000793, November 11 2024). This study was conducted in accordance with the declaration of Helsinki. Written informed consent was obtained from all participants.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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