Design and Analysis of Posterior Semicircular Canal BPPV Diagnostic Test Based on Physical Simulation

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Abstract

To discuss and analyze how to realize the design of posterior semicircular canal BPPV diagnostic maneuver. First, measure the spatial attitude of the human semicircular canal, establish a BPPV virtual simulation platform, then analyze the key positions of the maneuver, and finally design a new diagnostic maneuver according to the demand, and perform physical simulation verification. The average value of the unit normal vector of the right posterior semicircular plane is $[0.660, 0.702, 0.266]$, after rotate -46.8° around Z axis and 15.4° around Y axis, it parallel to the X axis. After that, when the tilt back angle reaches 70° , the free otoconia in the left utricle will fall into the common crus; when bend forward 53.3° , the unit normal vector of the crista ampullaris plane of the posterior semicircular canal to the XY plane; when bend forward angle reaches 30° , the otoconia slides to the opening of the ampulla; when bend forward angle reaches 70° , the otoconia slides to the bottom of the crista ampullaris. The shallow pitching Yang maneuver is designed as turn head 45° to the one side, bend forward 45° , tilt back 90° , and bend forward 90° . The deep pitching Yang maneuver is designed as bend forward 90° , turn head 45° to one side, tilt back 135° , and bend forward 90° . A new posterior semicircular BPPV diagnostic test is designed to make the induced nystagmus have the characteristics of long latency, reversal, and repeatability, will not cause the inhibitory stimulation of the contralateral superior semicircular canal, and has good operation fault tolerance, which is of great value for clinical and scientific research.

Introduction

Benign paroxysmal positional vertigo (BPPV) is the most common peripheral vestibular disease leading to vertigo in clinics. It is caused by otoconia migration into the semicircular canals. The pathophysiology of this condition has been described by the theories of canalolithiasis (free-floating otoliths in the semicircular canals) and cupulolithiasis (otoconia are directly attached to the cupula), the otoconia directly or indirectly stimulates the ampulla under the action of gravity. The otoconia is more common in the posterior semicircular canal (PSC), followed by lateral semicircular canal (LSC), and rarely seen in the superior semicircular canal (SSC).

In order to determine the specific location of otoconia in the membranous labyrinth, it is necessary to carry out a variety of diagnostic maneuver and observe the characteristics of induced nystagmus.

The rotatory nystagmus induced by Dix Hallpike maneuver can be diagnosed as BPPV of vertical semicircular canal, and horizontal nystagmus induced by roll maneuver can be diagnosed as BPPV of lateral semicircular canal.

Although the Dix Hallpike maneuver is considered as the gold standard for the diagnosis of posterior semicircular canal BPPV, the design of its operation is not perfect, and there are many problems in clinical application.

The characteristics of nystagmus induced by the Dix Hallpike maneuver including latency, limited duration, direction, reversal and fatiguability^[1], which is an important basis to judge whether it is

otolithiasis and the location of the otoconia, but the relevant research is not sufficient^{[2][3]}

The characteristics of nystagmus are affected by the size, quantity, density, location of otoliths and operation of maneuvers, and the intensity and characteristics of nystagmus are inconstant while performing Dix Hallpike maneuver, which will interfere with the diagnosis of BPPV.

Dix Hallpike maneuver may induce a variety of nystagmus. Different locations of otoliths usually have different nystagmus, but the same nystagmus may also be caused by otoliths at different locations. This makes it very difficult to judge the location of otoliths according to the nystagmus characteristics induced by Dix Hallpike maneuver^[2].

For example, the up-beating rotatory nystagmus induced by Dix Hallpike maneuver is often simply judged as the excitatory stimulation of ipsilateral posterior semicircular canal^[3], but the physical simulation experiment shows that it may also be the inhibitory stimulation caused by the detached otoconia in the contralateral utricle fall into the superior semicircular canal^[2].

In addition to judging the involved semicircular canal, it is necessary to further judge the pathogenesis (cupulolithiasis or canalolithiasis) and the specific location of otoconia (long arm side or short arm side), which has important guiding significance for selecting treatment techniques.

Whether the otoliths adhered to the cupula or free-floating in short arm or long arm of posterior semicircular canal, it will cause excitatory stimulation during Dix Hallpike maneuver, which are difficult to distinguish based on the characteristics of nystagmus.

There is no strict scientific basis for determining cupulolithiasis only based on the duration of nystagmus exceeding 1 minute^[3].

An attenuation of the nystagmus is often observed when the Dix Hallpike maneuver is repeated. This is known as fatigue and considered to be one of the nystagmus characteristics of BPPV, but it may also affect the diagnosis and efficacy judgment^[4].

Latency is also considered to be an important feature of BPPV nystagmus, but the latency period would range from 5 to 20 seconds, or even more or less^{[3][5]}.

It is necessary to redesign the posterior semicircular diagnostic maneuver to locate the specific location of the otoconia according to the characteristics of induced nystagmus.

Based on BPPV simulation model and semicircular canal spatial attitude mathematical model, this study discusses and analyzes how to realize the design of posterior semicircular canal BPPV diagnostic maneuver.

Result

1. Rotate the posterior semicircular canal to parallel to the sagittal plane

The average value of the unit normal vector of the right posterior semicircular plane (VP) is $[0.660, 0.702, 0.266]^T$.

Rotate VP around coordinate axis to be parallel to X axis (normal vector of sagittal plane) includes the following steps:

1) First step, rotate to XY plane (horizontal plane) or XZ plane (coronal plane), with two options;

the surrounding axis can be the X axis or another axis, with two options; the direction of rotation around the coordinate axis can be clockwise or counterclockwise, with two options;

2) Second step, rotate to the X axis in the coordinate plane (XY plane or XZ plane). There are two options: counterclockwise and clockwise.

There are 16 rotation schemes in total, as shown below (the first 8 rotated to the XY plane, and the last 8 rotated to the XZ plane) (Table 1):

Table 1
schemes to rotate the posterior semicircular canal parallel to the
sagittal plane

schemes	first step(axis:angle°)	second step(axis:angle°)
1	X: -20.7	Z: -48.7
2	X: 159.3	Z: 48.7
3	Y: 21.9	Z: -44.6
4	Y: -158.1	Z: -135.4
5	X: -20.7	Z: 131.3
6	X: 159.3	Z: -131.3
7	Y: 21.9	Z: 135.4
8	Y: -158.1	Z: 44.6
9	X: 69.3	Y: 48.7
10	X: -110.7	Y: -48.7
11	Z: -46.8	Y: 15.4
12	Z: 133.2	Y: 164.6
13	X: 69.3	Y: -131.3
14	X: -110.7	Y: 131.3
15	Z: -46.8	Y: -164.6
16	Z: 133.2	Y: -15.4

In clinical practice, it is customary that each rotation angle should not exceed 90 °. There are four feasible rotation schemes: rotate – 46.8 ° around X axis and – 48.7 ° around Z axis; rotate 21.9 ° around Y axis and – 44.6 ° around Z axis; rotate 69.3 ° around X axis and 48.7 ° around Y axis; rotate – 46.8 ° around Z axis and 15.4 ° around Y axis.

It is difficult to rotate the head in strict accordance with the world coordinate system. You can rotate according to the local coordinate system of the head, but the rotation order should be opposite.

2.null plane of crista ampullaris of right posterior semicircular canal

The normal vector of the crista ampullaris plane of the right posterior semicircular canal(VC) is [0.721, -0.081, -0.688].

Based on the four feasible rotation schemes selected above, the forward inclination angle to rotating the unit normal vector of the crista ampullaris plane of the posterior semicircular canal to the XY plane are 53.3°, 69.1°, 39.3° and 129.3° respectively. (Table 2)

Table 2
rotation scheme for key position of the maneuver for the right posterior semicircular canal

Rotate_to_Sagittal_plane	NP_Angle	Crus_Angle	Ampulla_Angle	Crista_Angle
Z: -46.8 Y: 15.4	-53.3°	70°	-30	-70
Y: 21.9 Z: -44.6	-69.1°	54.2	-45.8	-85.8
X: -20.7 Z: -48.7	-39.3	84	-16	-56
X: 69.3 Y: 48.7	-129.3	-6	-106	-146
Rotate_to_Sagittal_plane = Rotate the PSC to parallel to the sagittal plane; NP_Angle = null plane for right PSC; Crus_Angle = the maximum value of the pitching angle at which the otoconia in the contralateral utricle does not fall into the common crus of the vertical canal; Ampulla_Angle = the minimum pitch angle at which the otolith slides to the opening of the ampulla; Crista_Angle = the minimum pitch angle at which the otolith sliding to the bottom of the crista ampullaris				

3. the maximum value of the pitching angle at which the otoconia in the contralateral utricle does not fall into the common crus of the vertical canal

After rotate - 46.8 ° around Z axis and 15.4 ° around Y axis, when the tilt back angle reaches 70 °, the free otoconia in the left utricle will fall into the common crus.

The extreme value of pitching angle for other three scheme are 54.2 °, 84 ° and - 6 ° respectively. (Table 2)

4. the minimum pitch angle at which the otolith slides to the opening of the ampulla

After rotate - 46.8 ° around Z axis and 15.4 ° around Y axis, when the bend forward angle reaches 30 °, the free otoconia in the lower arm of the ipsilateral posterior semicircular canal slide to the opening of the ampulla.

The minimum value of bend forward angle for other three scheme are 45.8°, 16°, and 106° respectively. (Table 2)

5. the minimum pitch angle at which the otolith sliding to the bottom of the crista ampullaris

After rotate - 46.8 ° around Z axis and 15.4 ° around Y axis, when the bend forward angle reaches 70 °, the free otoconia in the lower arm of the ipsilateral posterior semicircular canal slide to the bottom of the crista ampullaris.

The minimum value of bend forward angle for other three scheme are 85.8°, 56° and 146° respectively. (Table 2)

In clinical practice, manual operation cannot accurately control the rotation angle. At the same time, it is required that the operation should not be too complex, and a certain operation error should be allowed without affecting the therapy effect.

To sum up (Table 2), we set the posterior semicircular canal bppv diagnostic maneuver as follows:

1) Rotate the PSC to the sagittal plane

The plane of PSC does not need to be strictly set parallel to the gravity vector, and a slight deviation will not have too much impact on the otoconia sliding.

The otoconia movement mainly occurs in the lower arm of the posterior semicircular canal, and the main influencing factor is the rotation around the Z axis.

For the convenience of operation and control, and to be consistent with the traditional operation habits, it can be simplified to turn 45 ° to the right.

2) Bend forward to make the starting position of otoconia consistent.

The angle of bend forward should exceed the minimum angle at which the otoconia slides to the opening of the ampulla or the bottom of the crista ampullaris. For easy operation and control, it can be set to reach the prone position.

3) tilt back causes the otoconia in the ipsilateral posterior semicircular canal to move away from the ampulla, but the otoconia in the contralateral utricle does not fall into the common crus.

The pitch angle is less than the angle at which the otolith in the opposite utricle fall into the common crus. For the convenience of operation and control, it can be set to tilt back 45 ° and not more than 70 ° after returning to the sitting position. At this time, the otoconia slides along the lower arm of the posterior semicircular canal, and there is still obvious hydrodynamic effect.

4) bend forward caused the otolith in the ipsilateral posterior semicircular canal to move towards the ampulla, but the crista ampullaris was at the null position.

Because the crista ampullaris is sensitive to the angle, it is required to calculate the rotation angle accurately.

If the preceding steps are first turning 45 ° to the right to make the right posterior semicircular canal parallel to the sagittal plane, then bend 90 ° forward to make the otoconia sliding to the bottom of the crista ampullaris, and finally tilt 135 ° back to causes the otoconia move away from the ampulla, then after those rotations, the normal vector of the crista ampullaris plane of the posterior semicircular canal is $[0.452, 0.086, -0.888]$, which is parallel to the gravity vector after bend forward 95.5 °, that is, bend forward 50.5 ° after sitting up. Unarmed operation can be simplified to sit up and bend forward 45 °.

Observation of otoconia movement caused by Yang maneuver based on physical simulation

The shallow pitching Yang maneuver is designed as turn head 45° to the one side, bend forward 45°, tilt back 90°, and bend forward 90°(Fig. 1). The deep pitching Yang maneuver is designed as bend forward 90°, turn head 45° to one side, tilt back 135°, and bend forward 90°(Fig. 2). The otoconia movement meets the design goal.

Discussion

The knowledge of semicircular canal spatial posture and otolith theory are the basis for our design of BPPV diagnostic test.

In fact, we don't know enough about the spatial posture of semicircular canal, especially the spatial posture of membranous semicircular canal and crista ampullaris.

BPPV simulation model is an important tool to study BPPV^[7]. Its premise is to establish the membrane labyrinth model in standard spatial coordinate system.

We established the BPPV simulation model and further measured and obtained the spatial attitude information of semicircular canal and crista ampullaris, which makes it possible to design the posterior semicircular BPPV diagnostic maneuver according to the predetermined goal.

Firstly, the existing diagnostic tests for PSC BPPV are reviewed and analyzed.

Dix and Hallpike described in detail all clinical manifestations of BPPV, introduced that specific manipulation can stimulate vertigo symptoms and nystagmus, which is still used today and named Dix Hallpike maneuver^[1].

When Dix and Hallpike designed the Dix Hallpike maneuver, they did not fully understand the pathophysiology of BPPV, so they did not realize that the Dix Hallpike maneuver induced otolith in PSC move away from the ampulla.

Although the Dix Hallpike maneuver is still the standard maneuver for the diagnosis of PSC BPPV, the scientificity of its design is worth discussing.

There are some modified Dix Hallpike maneuver, such as mini Dix Hallpike maneuver^[8], side-lying maneuver^[9] and half Dix-Hallpike maneuver^[10].

Compared with the classic Dix Hallpike maneuver, these methods mainly have a smaller head tilt angle, which is not much different in essence.

It is generally believed that Dix Hallpike maneuver is used to diagnose PSC-BPPV and ASC-BPPV, but in fact, Dix Hallpike maneuver can also induce vertigo in 39% of LSC-BPPV patients^[11], which makes it difficult to analyze the positive results of Dix Hallpike maneuver, and correct judgment can be made in combination with the characteristics of nystagmus.

The nystagmus characteristics of BPPV include latency, direction of nystagmus, duration, reversal, and fatigability^{[1][3][7]}.

Usually, the upbeating rotatory nystagmus induced by Dix Hallpike test is judged as ipsilateral posterior semicircular canal excitatory stimulation, which is recognized as ipsilateral posterior semicircular canal BPPV. However, in theory, it may also be inhibitory stimulation of the contralateral superior semicircular canal. Moreover, the physical simulation experiment shows that during the Dix Hallpike test, the otoconia in the contralateral utricle will fall into the superior semicircular canal, causing inhibitory stimulation^[2].

By optimizing the diagnostic test and controlling the angle range of head tilt back, so that the free otoconia in the contralateral utricle will not fall into the superior semicircular canal, the interpretation of upbeating rotatory nystagmus can be simplified as the excitatory stimulation of the ipsilateral posterior semicircular canal.

Although fatigue is considered an important feature of BPPV, it is not recommended to repeat Dix Hallpike action to demonstrate fatigability, because it unnecessarily subjects patients to repeated vertigo symptoms, which is discomforting^[3].

More importantly, the nystagmus induced by repeated diagnostic tests may be inconsistent due to the fatigability, it will interfere with the diagnosis and treatment of BPPV^[12].

The intuitive explanation for the fatigability is that repeated operation turns large otoliths into small otoliths, but this is inconsistent with the research results of otolith hydrodynamics.

Roselli's research shows that the lower arm of the posterior semicircular canal is straight, repeated diagnostic tests will move the otoconia away from the ampulla and reduce the nystagmus^[13].

Theoretically, if the starting position of otoconia movement is consistent, the nystagmus induced by repeated diagnostic test should also be consistent.

This inspires us that if the diagnosis test is improved to keep the starting position of otolith movement consistent, fatigue can be eliminated.

By bending forward, the otoconia scattered in the lower arm of the posterior semicircular canal slide down to the opening of the ampulla under the action of gravity, so that the starting position of the otolith movement in the repeated diagnostic test can be consistent.

In Dix Hallpike test, nystagmus occurs after lying flat for a moment, which is called latency period, and it is an important feature of BPPV nystagmus.

The cause of delayed nystagmus is that the otoconia moves in the ampulla with weak hydrodynamic effect, and the obvious hydrodynamic effect appears only after entering the narrow semicircular canal.

Because the position of the otoconia in the ampulla is not fixed, the latency period is unstable and has a large range of variation, some of them even have no obvious latency period, which will weaken the diagnostic significance of the latency period for BPPV^[3].

Through the forward bending motion, the scattered otoconia in the lower arm of the posterior semicircular canal slide down to the bottom of the crista ampullaris under the action of gravity, which can not only make the starting position of otolith movement in the repeated diagnostic test consistent, but also keep the time of the latency period consistent, so as to strengthen the diagnostic significance of the latency period for BPPV.

There is no effective method to distinguish the BPPV subtypes such as cupulolithiasis, short arm type canalolithiasis and long arm side canalolithiasis. All those types induced excitatory stimulation while performing the Dix-Hallpike maneuver.

The differential diagnosis can be made through the following steps:

Continue with the above operation, after sitting up, bend 45 degrees to make the crista ampullaris parallel to the gravity vector, and the otoconia in the long arm side moves towards the ampulla for a long distance, and reverse nystagmus occurs; while the otoconia in the short arm side or adherent to cupula have no obvious hydrodynamic effect.

Furthermore, if you increase the bend forward angle to more than 120 degrees, the otoconia in the short arm side will fall into the utricle, and the nystagmus disappears after repeated diagnostic test, and the short arm type canalolithiasis can be distinguished^[2].

Traditionally, cupulolithiasis are distinguished by the duration of nystagmus. It is considered that the duration of nystagmus more than 1 minute is cupulolithiasis^[3], but it may also be short arm type canalolithiasis.

Previous studies have analyzed nystagmus through deep learning method to locate otoliths, but the instability of nystagmus characteristics induced by Dix Hallpike test and the inaccuracy of interpretation label will seriously affect the effectiveness of deep learning model^[14].

There is an urgent need to design a new posterior semicircular canal BPPV diagnostic test to overcome the above-mentioned shortcomings.

The shape of the semicircular canal is complex, and its rotation in three-dimensional space is particularly complicated. Although turning the plane's rotation problem into the plane's normal vector rotation problem is conducive to calculation and understanding, its rotation schemes are diverse, and it is difficult to accurately implement the angle in freehand operation.

It can be found that when the posterior semicircular canal is rotated to the sagittal plane, the otolith movement of the diagnostic test mainly occurs in the lower arm of the posterior semicircular canal. The most important rotational movement is rotation around the Z axis, and subsequent movements around the Y axis will not cause too much influence on the sliding of the otoconia.

According to the traditional custom, in order to facilitate operation and control, it is feasible to simplify the operation as rotation 45 ° to the right to rotate the right posterior semicircular canal parallel to the sagittal plane.

Forward bending makes the starting position of otoconia consistent, and the fault tolerance is very good. 30 ° forward bend is enough for the otoconia to slide to the opening of the ampulla, and 70 ° forward bend is enough for the otoconia to slide to the bottom of the crista ampullaris.

For easy operation and control, it can be set to reach the prone position. If conditions restrict the operation, it can be set to bend forward 45°.

Leaning back to induce the otoconia move away from the ampulla is the most critical step of the diagnostic test, but it is required that the free otoliths in the contralateral utricle will not fall into the common crus to enhance the specificity of the diagnostic test.

In order to facilitate operation and control, it can be set to return to the sitting position and then lean back 45°,but not more than 70° is effective. At this time, the otoconia slides down the lower arm of the posterior semicircular canal, which still has obvious hydrodynamic effects.

The backward angle has a large range of variation, and the fault tolerance is strong.

After returning to the sitting position, continue to bend forward to make the otoliths in the ipsilateral posterior semicircular canal move toward the ampulla, but the crista ampullaris is at the null point.

At this time, there was reverse nystagmus for otoconia in the long arm side, there was no obvious nystagmus for otoconia in short arm side or otoconia adherent to cupula.

Since the crista ampullaris is more sensitive to angle, the forward angle must be accurately calculated. It is necessary to bend forward 50.5° after returning to the sitting position, which can be simplified as bend forward 45°.

A new posterior semicircular BPPV diagnostic test is designed to make the induced nystagmus have the characteristics of long latency, reversal and repeatability, will not cause the inhibitory stimulation of the

contralateral superior semicircular canal, and has good operation fault tolerance, which is of great value for clinical and scientific research.

Methods

Measurement of human semicircular canal spatial attitude

Fifty-five bone labyrinth models were segmented from inner ear MRI data, which was applied with a Siemens 1.5T superconducting magnetic resonance system and 3D constructive interference steady-state sequence (3D-CISS) (TR: 6.0 ms, TE: 2.7 ms, FOV: 135 mm×18 mm, matrix: 256×102, thickness: 0.7 mm) [2].

First obtaining the centerline of each semicircular canal, then calculate the normal vectors of the semicircular canal plane, and finally obtain the average unit normal vector of each semicircular canal plane^[6].

The membrane labyrinth models were segmented of micro-CT examination data^[15].

Firstly, the bone labyrinth model obtained from micro CT data segmentation is registered with the previously established standard bone labyrinth model, and then the membranous labyrinth model is synchronously transformed in three-dimensional space, so as to establish the spatial direction of the membranous labyrinth model^[2].

In addition, obtain the plane point coordinates of the crista ampullaris of the membrane semicircular canal model, fit the plane, and calculate its unit normal vector, which is convenient for three-dimensional rotation calculation.

Building BPPV virtual simulation platform

The three-dimensional physical simulation in this study uses the Bullet open source physics engine, and the development environment uses the open-source software Blender (version 2.79 b)^[2].

The membranous labyrinth model was import into Blender software, and otoliths were set everywhere according to the needs of the study.

Enable physics for rigid body, and setting the rigid body type of the semicircular canal models to passive, and the rigid body type of the otoconia to active.

Analysis the key positions of the maneuver

1.Rotate the posterior semicircular canal to make it parallel to the sagittal plane

Calculate the scheme that the unit normal vector of the right posterior semicircular canal is rotated to be parallel to the normal vector of the sagittal plane, i.e., the x-axis.

2. Calculate the null plane of crista ampullaris of the posterior semicircular canal

The position at which crista ampullaris parallel to the gravity vector is called the null plane^[16].

In order to distinguish canalolithiasis from cupulolithiasis, the maneuver was designed to tilted backward or forward to reach the null plane, so as to induce different type of nystagmus between canalolithiasis and cupulolithiasis.

First, calculate the unit normal vector of the crista ampullaris plane of the posterior semicircular canal after the previous rotations, and then calculate the scheme of rotating it to the XY plane (horizontal plane).

3. The maximum value of the pitching angle at which the otoconia in the contralateral utricle does not fall into the common crus of the vertical canal

Because the posterior semicircular canal is rotated to be parallel to the sagittal plane according to different rotation schemes, the final spatial orientation of the posterior semicircular canal is different and needs to be calculated separately.

Since the posterior semicircular canal is parallel to the sagittal plane after rotation, the extreme value of pitch angle of other schemes can be calculated according to the angle difference to the null plane.

Gradually increase the angle, and observe the extreme pitching angle at which the otoconia in the contralateral utricle falls into the common crus.

4. Calculate the minimum pitch angle at which the otolith slides to the opening of the ampulla

To eliminate fatigue, the otoconia moves towards the ampulla through the pitching motion, so that the starting position of the otoconia is the same when it moves away from the ampulla in the next step.

Gradually increase the angle and observe the minimum pitch angle at which the otoconia slides to the opening of the ampulla.

5. Calculate the minimum pitch angle at which the otoconia sliding to the bottom of the crista ampullaris

To make the latency period consistent, the position of otoconia in the ampulla should be consistent.

Gradually increase the angle and observe the minimum pitch angle at which the otoconia slides to the bottom of the crista ampullaris .

Design new diagnostic maneuver

Based on the analysis of the key position of diagnostic maneuver, new diagnostic maneuver is designed according to demand and verified by physical simulation.

Declarations

Author Contributions

XY, QY designed the experiment and wrote the pape, ZL design physical simulation. All authors read and approved the manuscript.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Financial Disclosure

Reports no disclosures

Ethical approval

The study group confirmed that the design and data collection of this retrospective research was performed in accordance with the Helsinki protocol and standard of Good Clinical Practice. Informed consent was not required because this was a retrospective study. All data were anonymized and de-identified before analyses. The study protocol was approved by the Ethics Committee of Wenzhou People's Hospital. The Ethics Committee of Wenzhou People's Hospital determined that the study was exempt from an informed consent requirement since it was a review of existing clinical data with patient identifiers removed.

Data availability

Data files are available on request to the corresponding author.

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Figures

Figure 1

Shallow pitching Yang maneuver A, turn head 45° to the right, otoliths are scattered in the lower arm of the posterior semicircular canal. B, bend forward 45°, otoliths slides to the opening of the ampulla. C, tilt back 90°, otoliths move away from the ampulla. D, bend forward 90°, otoliths move towards the ampulla, but the crista ampullaris was at the null position.

Figure 2

Deep pitching Yang maneuver A, bend forward 90° , otoliths slides to the bottom of the crista ampullaris. B, turn head 45° to the right. C, tilt back 135° , otoliths move away from the ampulla. D, bend forward 90° , otoliths move towards the ampulla, but the crista ampullaris was at the null position.