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Three-dimensional Simulations of Six Treatment Maneuvers of Horizontal Canal BPPV Canalithiasis

Evaluating theoretical efficacy of BPPV maneuvers

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Abstract

Background and Objectives

Horizontal canal BPPV is the second most common variant of BPPV after posterior canal BPPV.Various liberatory maneuvers are recommended for the treatment of horizontal canal BPPV

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canalithiasis (hc-BPPV-ca). The aim of this study was to show how 3D dynamic simulation models visualize the movement of the clot of otoconia within the canal for a better understanding of the theoretical efficacy.

Methods

Based on reconstructed MRI images and fluid dynamics, a 3D dynamic simulation model (as a function of time) was developed and applied. Thereby six treatment maneuvers for hc-BPPV-ca were simulated: two types of the roll maneuver (the original 270° and the modified 360°) as well as two Gufoni and Zuma maneuvers (for geotropic and apogeotropic nystagmus).

Results

The simulations showed that the 360° roll maneuver and Zuma maneuver are effective treatment options for hc-BPPV-ca for debris in all locations within the canal. However, the original 270° roll maneuver will not be effective if the clot is in the ampullary arm of the horizontal canal. The Gufoni maneuver for geotropic hc-BPPV-ca is effective, whereas for apogeotropic hc-BPPV-ca there is a risk of treatment failure due to insufficient repositioning of the debris.

Conclusions

The 3D simulations for movement of the otoconia clots can be used to test the mechanism of action and the theoretical efficacy of existing maneuvers for the different BPPV variants. For hc-BPPV-ca, the modified 360° roll maneuver and Zuma maneuver are theoretically efficient for all subtypes, whereas Gufoni maneuver is effective for geotropic nystagmus only.

Key words – BPPV, horizontal canal, simulator, maneuvers, canalithiasis

Abbreviations:

BPPV: Benign Paroxysmal Positional Vertigo

hc- horizontal canal

ca: canalithiasis

scc: semicircular canal

Introduction

BPPV is one of the commonest causes of vertigo. This mechanical inner ear disorder affects posterior canal most commonly followed by horizontal canal. Several different maneuvers have been elaborated over two decades for the treatment of horizontal canal BPPV canalithiasis (hc-BPPV-ca) (1). The most commonly used liberatory maneuvers include the roll maneuver (2), the Gufoni maneuver (3), forced prolonged position (4), and the Zuma maneuvers (5). In canalithiasis, the free-floating otoconial debris move due to gravitational and, in some of the maneuvers, also inertial forces causing cupular deflection during head movement. Based on the orientation of the canal during these maneuvers and the underlying biomechanics, each maneuver theoretically has its advantages and disadvantages, and their efficacy has been compared in studies (6,7,8). Even the combination of two maneuvers has been recommended, e.g., performing the roll maneuver in the clinic and subsequently the forced prolonged positioning as a home exercise (9,10). However, as several maneuvers have been described and recommended, one might infer that not all of them work perfectly or that one might be superior to another (10,11).

To clarify the precise mechanism of the different treatment maneuvers for hc-BPPV-ca, the debris movement of these maneuvers in 3D was simulated, based on a software we recently developed (12,13); in the roll maneuver the effect of orientation of the horizontal canal relative to gravity was also evaluated. Further, the impact of several possible otolith locations within the horizontal canal (Fig 1) was also examined. The ampullary and non-ampullary arms of the horizontal canal are illustrated in Fig 2.

Many two-dimensional illustrations are already available to help the clinician in understanding the initial and final location of the debris at each step of a liberatory maneuver (6,14,15). However, 2D images are limited because they demonstrate the findings only from one angle. This means that there is a need for a simulation that can give a clearer picture of the movement of the debris during each step of the maneuver and facilitate visualization from different angles (12,13). It is important to note that we did not perform simple animations, but rather true simulation of the debris movement based on the biophysics of BPPV. The resultant simulation depends, among other things, on basic assumptions regarding the debris size and distribution, the endolymph viscosity and the canal geometry.

Methodology

A 3D model of the inner ear based on reconstructed MRI images of the temporal bone was used for the orientation of the semicircular canals. The 3D image of the inner ear was extracted from DICOM files of MRI images. The orientation of the canals in the head and the angles between the canals were in accordance with the various studies reported (16,17,18). The simulation was created on Unity 3D software. A humanoid was animated within Autodesk Maya with precise angulations for the maneuvers. The head of the humanoid was linked to the semicircular canal in such a way that any head movement causes reciprocal movement of the canals. A thin tube was inserted into the center of each canal. Otoconial debris in the form of a crystal was put inside the canal. The diameter of the tube was 1.5 mm and the crystal size used was 0.7 mm. 35N linear drag and 0.05 angular drag were applied to the fluid. The time taken for the particle to move at each step of the maneuver was accelerated in all simulations presented here to make it more user-friendly.

We are aware that our simulations and underlying physics model cannot precisely represent the in vivo movement of the otoconia in the SCC of an individual patient because there are ~~too~~ many variables among patients. For example, the pressure difference on both sides of the cupula of the crista ampullaris due to the debris movement is related to the exact volume, number and location of the otolith particles in the membranous labyrinth (11).

Results

The following maneuvers were studied with the simulator: the two roll maneuvers (2), the Gufoni maneuver (3), and the two Zuma maneuvers (4).

Roll Maneuver: two types – non-ampullary versus ampullary arm

The initial roll maneuver for hc-BPPV-ca (2,19) was described as a 270° roll of the head and body in 90° steps starting with the patient in supine position. In the simulation, the head is raised by 30° to make the horizontal canal vertical with respect to gravity (20). The maneuver uses gravity to move the debris through the canal and brings it in the direction of the utricle. In the next step, the subject is turned 90° to the healthy side, followed by moving into the prone position and then turning another 90° to turn to the affected side. This maneuver works when debris is present in the *non-ampullary* arm of the horizontal canal. **Simulation 1** demonstrates the movement of the debris present in the non-ampullary arm of horizontal canal by the roll maneuver (speed accelerated for clarity). The debris present in this position would cause geotropic nystagmus on the supine roll test. The video of the simulation is available in the supplementary file.

Simulation 1: Roll Maneuver for Debris in the Non-Ampullary Arm

The simulations show that the 270° roll maneuver is effective in repositioning debris in the horizontal canal only if it is near enough to the utricular opening. If the debris is closer to the ampulla, the debris will move from the ampullary to the non-ampullary arm, but not to the utricle leading to treatment failure. This is illustrated in **Simulation 2.** The video of the simulation is available in the supplementary file.

Simulation 2: 270° Roll Maneuver – Failed Repositioning

A modified roll maneuver (21,23) was recommended for the treatment of hc-BPPV-ca of both ampullary and non-ampullary arms along with hc-cupulolithiasis by adding a step to the above-described procedure by first turning the head 90° relative to gravity to the affected side first. This followed by a return to the central supine position and then following up with the steps previously described in the roll maneuver enables debris present in any position in the horizontal canal to move towards the utricle.

Simulation 3 shows the debris movement in each step of hc-BPPV when the debris is present in the ampullary arm close to the cupula in which apogeotropic nystagmus occurs. The video of the simulation is available in the supplementary file.

Simulation 3: Modified Roll Maneuver for Debris in the Ampullary Arm

The practical clinical implications of these three simulations show which maneuver would theoretically be the most effective. It can be seen that by turning the head to the affected side relative to gravity and performing the roll maneuver as a 360° rotation, this maneuver would be effective in treating BPPV with debris in any position in the horizontal canal. Therefore, the modified roll maneuver (21) is recommended for the treatment.

Gufoni Maneuver

This maneuver is used to treat the geotropic form of hc-BPPV. The otoconial debris in the non-ampullary arm is repositioned using centrifugal force due to a rapid deceleration and by the gravitational force (24). When the patient is moved into the side-lying position on the healthy side, the debris moves from the non-ampullary arm of the horizontal canal towards the utricle. By turning the head so that the nose points downwards, the repositioned debris cannot re-enter into the canal. Then the patient is brought back to the sitting position. This is demonstrated in **Simulation 4**. The video of the simulation is available in the supplementary file.

Simulation 4: Gufoni Maneuver

When the otolith debris is found floating near the ampulla, the resultant canalithiasis will produce *apo*geotropic nystagmus on the supine roll test. When the Gufoni maneuver is to be performed for particles present in the ampullary arm of the horizontal canal, it has to be started from the affected side. The patient is moved into the side-lying position on the affected side to allow the debris to move from the ampullary arm of the horizontal canal to the most dependent position. In the next step when the nose is turned up, the debris moves to the non-ampullary arm of the horizontal canal. The patient is finally brought back to the upright sitting position. However, the simulator shows that there is a chance that the debris does *not* reach the utricle and may fall back into the canal. This will result in failure of the maneuver, which is demonstrated in **Simulation 5.** The video of the simulation is available in the supplementary file.

Simulation 5: Gufoni Maneuver for Apogeotropic Nystagmus

Zuma Maneuvers

This maneuver was proposed to treat apogeotropic hc-BPPV which can occur when the debris is in the ampullary arm of the horizontal canal (as canalithiasis) or attached to the cupula (cupulolithiasis) on the canal or utricular side (22,23). The maneuver uses the endolymph inertia and gravitational force acting on the particle to bring the debris back into the utricle.

The simulation shows that by moving the subject into the side-lying position on the affected side in the first step, brisk deceleration and inertia can detach the otoconia from the cupula (if attached to the canal side). Upward turning of the head in the second step aims to facilitate the movement of the detached otoconia through the canal. By moving the subject to the dorsal decubitus followed by turning the head by 90° toward the unaffected side, the otoconia are brought closer to the utricle. The patient's head is bent ~~tilted slightly~~ forward, followed by a slow return of the patient to the sitting position. The aim of this is to prevent the particles from moving back into the horizontal canal (25). This is demonstrated in **Simulation 6.** The video of the simulation is available in the supplementary file.

Simulation 6: Zuma Maneuver

Modified Zuma Maneuver

The modified Zuma maneuver is recommended for treatment of geotropic hc-BPPV. It is a modification of the original Zuma maneuver (6). The simulation shows that by turning the head 45° towards the unaffected side in the first step and then moving the subject into the side-lying position on the affected side in the next step, the horizontal canal is brought to the vertical plane. The otolith debris moves away from the ampulla into the non-ampullary arm of the canal due to the gravity. Turning the head 90° towards the unaffected side takes the debris further away, towards the utricle. Tilting the head forward in the final step prevents the debris form reentering the canal. This is demonstrated in **Simulation 7.** The video of the simulation is available in the supplementary file.

Simulation 7: Modified Zuma Maneuver

Simulation 8 shows that the Zuma maneuver is an effective treatment option for debris present in the non-ampullary arm. Thus, we found further evidence that the Zuma maneuver can be used for hc-BPPV-ca affecting both ampullary and non-ampullary arms. The video of the simulation is available in the supplementary file.

Simulation 8: Zuma Maneuver for debris in the Non-Ampullary Arm

Discussion

Different liberatory maneuvers use different mechanisms of action, head positions and head movements. The simulations provide the viewer with a three-dimensional visualization of the head movement and how this movement influences semicircular canal orientation and finally the movement of the otolith debris.

Roll maneuvers - The roll maneuvers depend on the gravitational force to move the debris through different positions out of the canal. The simulator shows that if the otoconial debris is present in the ampullary arm of horizontal canal, the 270° roll maneuver will not be able to liberate the debris; it will work only for removal of the debris from the non-ampullary arm. In contrast, the 360° roll maneuver will be able to accomplish the repositioning of debris present in all positions of the canal, in both the ampullary and non-ampullary arms. This brings us to the conclusion that the modified roll maneuver with 360° rotation is a better maneuver for hc-BPPV-ca irrespective the precise location of the debris (25).

Gufoni maneuvers - Their mechanism of action is based on centrifugal and gravitational forces. The simulator shows that the Gufoni maneuver is effective for geotropic hc-BPPV with debris in the non-ampullary arm of the horizontal canal. The modified Gufoni for apogeotropic hc-BPPV with the debris in the ampullary arm may possibly lead to a failure because theoretically it is not able to move the otolith debris completely out of the canal (24). It can convert an apogeotropic nystagmus into a geotropic nystagmus by bringing the debris from the ampullary arm to the non-ampullary arm. The simulations bring us to the conclusion that the Gufoni maneuver is effective for hc-BPPV-ca in the non-ampullary arm while the modified Gufoni may fail in treatment of hc-BPPV-ca in the ampullary arm. Therefore, it is recommended that after the modified Gufoni maneuver, an additional maneuver in the form of a Gufoni maneuver for geotropic nystagmus or a roll maneuver is required to complete the repositioning. The simulation also shows that the Zuma maneuver, which adds an additional 90^0 rotation to the modified Gufoni maneuver, makes it an effective treatment option.

Zuma maneuvers - Zuma maneuvers utilize gravity along with inertia for debris mobilization. The modified Zuma maneuver is effective for repositioning of the otoliths present in the non-ampullary arm. With the simulator, it is evident that the original Zuma maneuver is useful in repositioning otoliths in all positions in the horizontal canal, in both the ampullary and non-ampullary arm. We can thus conclude that the original Zuma maneuver works effectively in hc-BPPV-ca and no modifications are required.

Timing

For an effective repositioning, it is important for the particle to reach the lowest position of the canal at the end of each step of the maneuver, as was also shown in studies on posterior canal BPPV (26,27). If the next step is performed before the particle reaches the desired position, the maneuver may fail. The simulation emphasizes the importance of waiting between the steps to allow gravity to take the debris to the most dependent position. To our knowledge, there is no hard evidence currently available that indicates what the minimum time interval between the different positions must be. We currently wait at least 45 seconds between two successive movements and also wait until the induced nystagmus has disappeared completely (by exception, the nystagmus decreases in amplitude and velocity but might be persistent).

Finally, it is important to note that in our simulations, the time taken for the particle to move at each step of the maneuver has been accelerated to make it more user-friendly.

Limitations

Our study is based on the orientation obtained from reconstructed MRI images. Currently, the major limitation of this simulator is that the orientation of the semicircular canals vary from patient to patient and hence it does not entirely represent the situation in every individual patient. We are also aware that the natural variations in the orientation and morphology have a substantial impact on the validity of the extrapolation to the individual patient and may explain why the maneuvers need more time or fail in some patients. This indicates that one should switch maneuvers if a patient does not respond. The simulations present ideal planes and angulations. Restrictions in patient mobility may not allow these ideal parameters and effect the final outcome of the maneuver. Despite the inherent limitations, we feel that simulators are an effective way of understanding BPPV and therapeutic maneuvers for BPPV treatment.

Conclusion

The simulator provides a useful tool for the clinician to understand the orientation of the head, semicircular canals and debris in different positions in the canals in a three-dimensional space. The simulator helps us to understand the movement of the otoconia with respect to the movement of the head, which improves our understanding of the optimum plane and angulation required to get the best results.

Our study shows that the modified roll maneuver and Zuma maneuver are effective treatment options for canalithiasis of the horizontal canal in all positions in the canal. The Gufoni maneuver works well when the otolith debris is in the non-ampullary arm of the horizontal canal. The simulator showed that the Gufoni maneuver for apogeotropic nystagmus may be inadequate for repositioning and there are higher chances of treatment failure.

This simulator can also be used for teaching and research purposes to help to modify existing maneuvers to make them more effective and to develop new maneuvers.

Finally, we encourage a clinical validation of our theoretical results, i.e., randomized controlled clinical trials directly comparing the efficacy of the various maneuvers discussed here.

Conflict of interest

M. Strupp is Joint Chief Editor of the Journal of Neurology, Editor in Chief of Frontiers of Neuro-otology and Section Editor of F1000. He has received speaker's honoraria from Abbott, Auris Medical, Biogen, Eisai, Grünenthal, GSK, Henning Pharma, Interacoustics, J&J, MSD, Otometrics, Pierre-Fabre, TEVA, UCB, and Viatris. He is a shareholder and investor of IntraBio. He distributes "M-glasses" and "Positional vertigo App". He acts as a consultant for Abbott, AurisMedical, Heel, IntraBio and Sensorion.

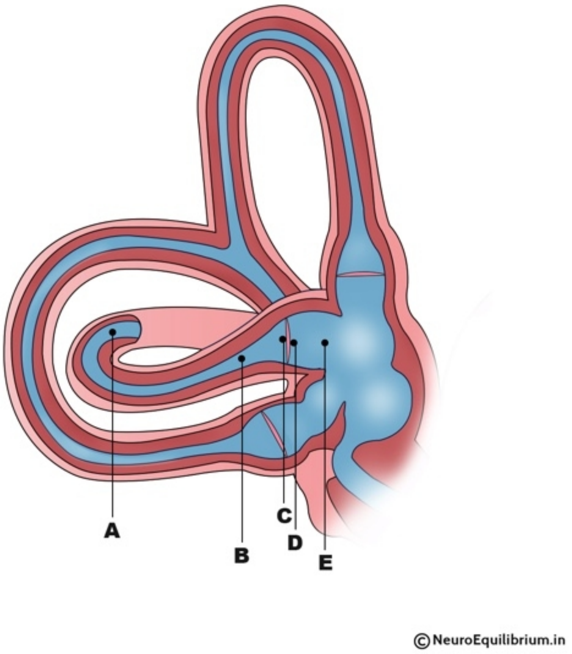
Rajneesh Bhandari is Director NeuroEquilibrium Diagnostic Systems Private Limited, India.

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

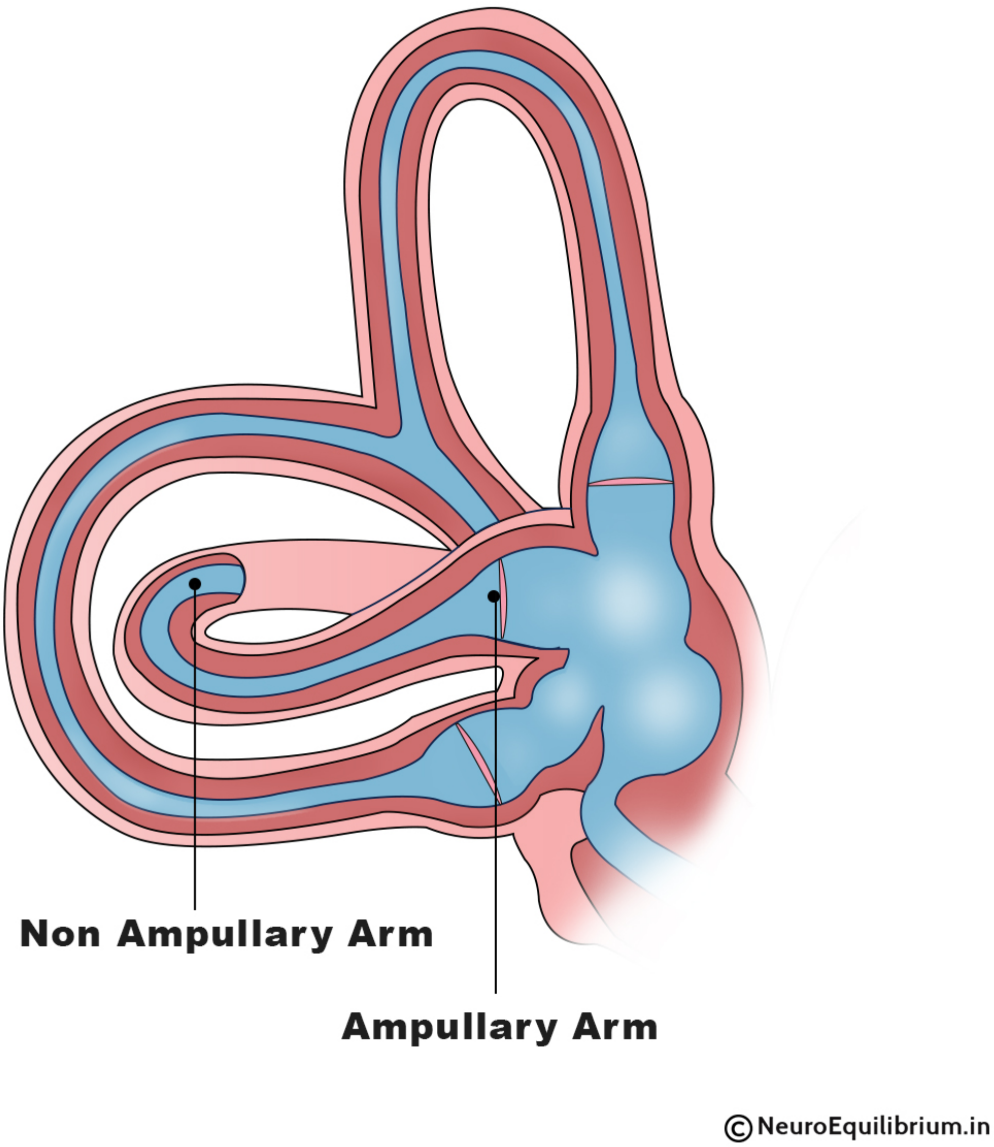
Disclosure: None

Availability of Data and Materials

Data can be shared publicly.



eFigure 1. Different otolith debris positions in horizontal canal BPPV. A) Canalithiasis non-ampullary arm, B) Canalithiasis in the ampullary arm, C) Cupulolithiasis on the canal side, D) Cupulolithiasis on the utricle side, E) Canalithiasis in the short arm (6)



eFigure 2. Anatomy of horizontal canal showing ampullary arm and non-ampullary arm

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