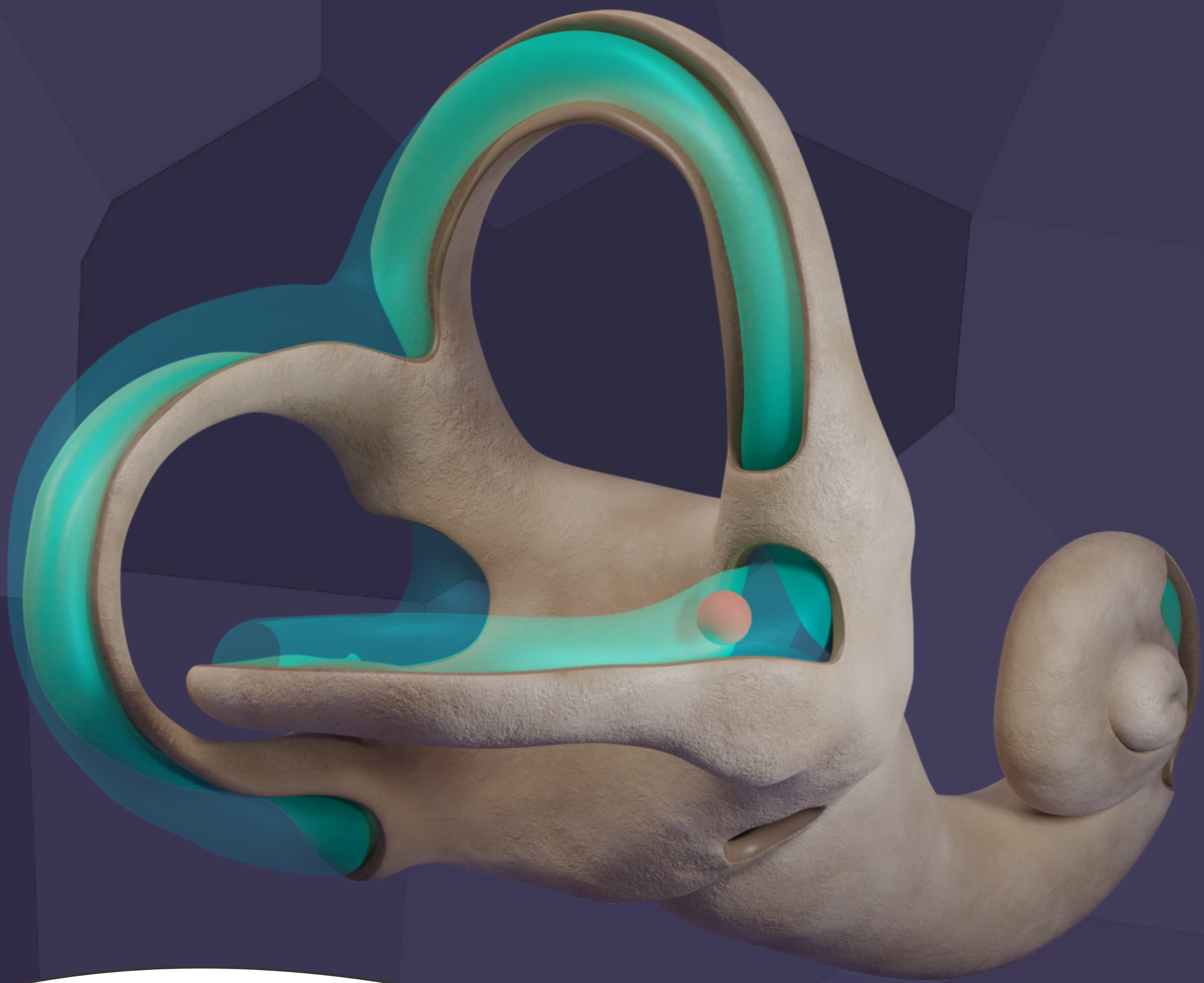
Rolling Ear Stones

Diagnosis and management of Benign Paroxysmal Positional Vertigo with a smartphone application



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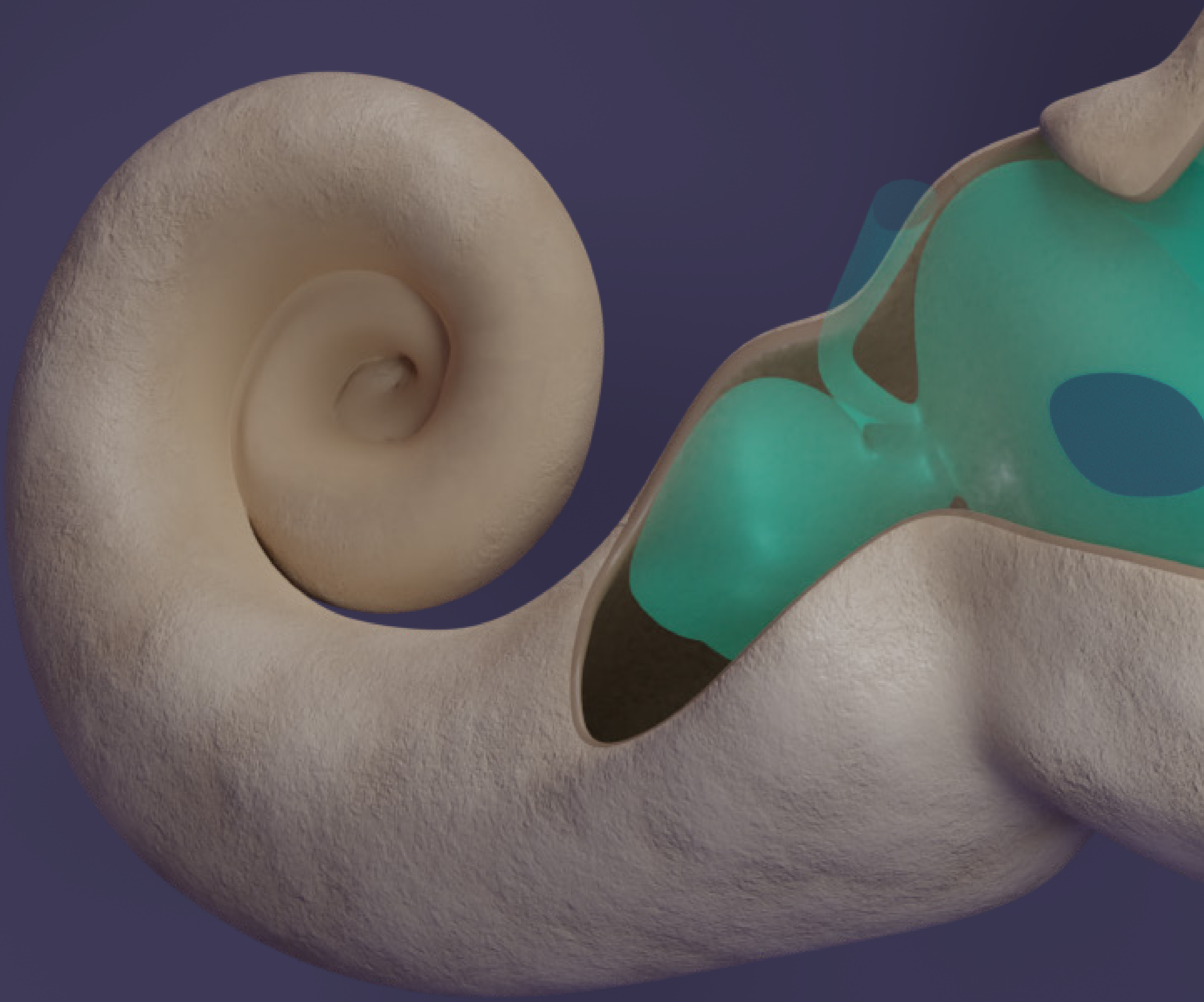
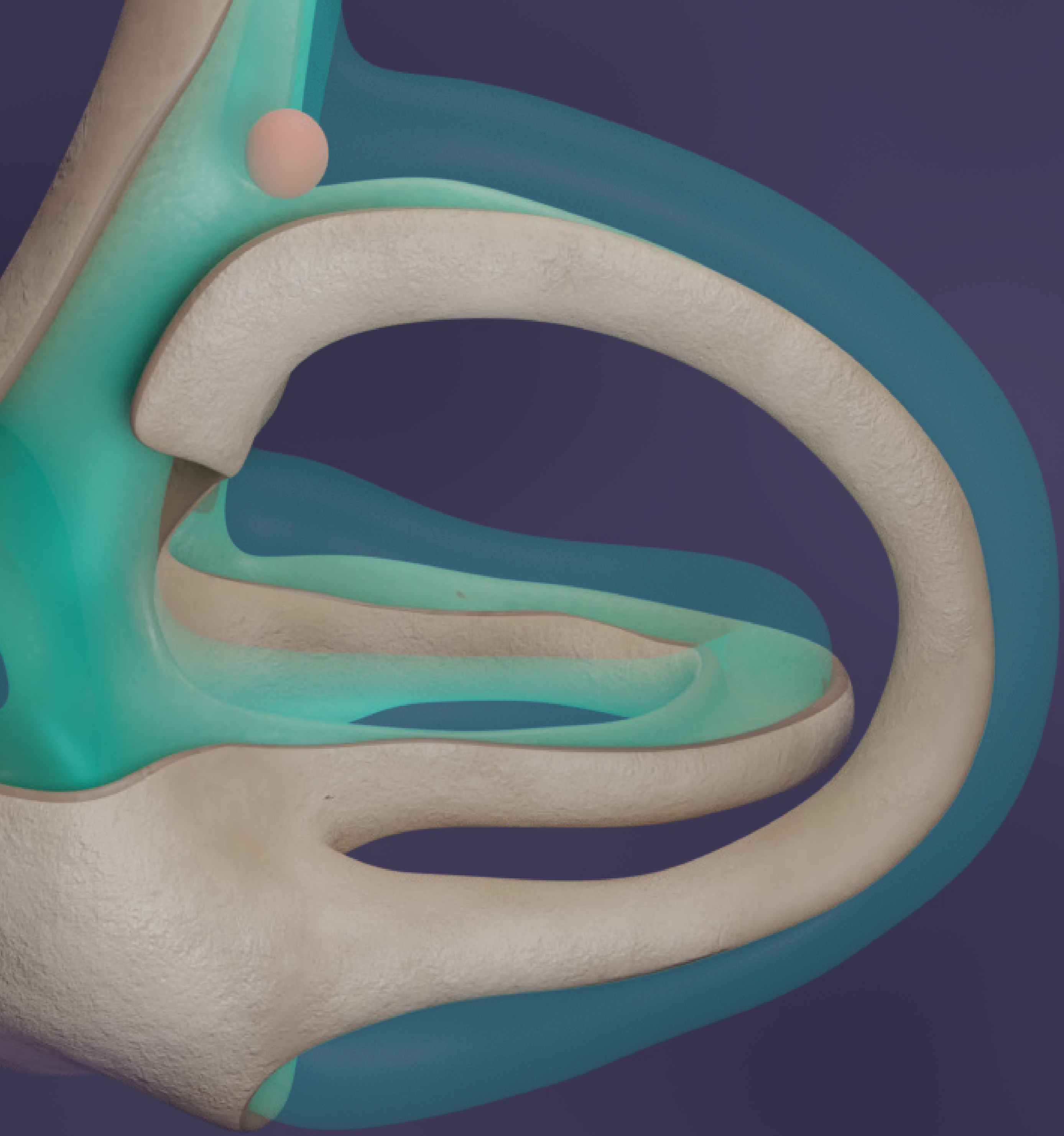


Acknowledgments

This project could have not been possible without my godfather and app programmer's generous efforts and transferable enthusiasm, who taught me how to appreciate the least enjoyable tasks.

I also want to thank my supervisor Dr Caroline Erolin, for her patience, guidance and support through this steep learning year.

Finally, I would like to dedicate this project to my old Medical School at the University of Cyprus and the ENT Department at the General Hospital of Nicosia who taught and trained me and inspired this idea.



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Introduction

Vertigo is the 7th most common cause for a neurological examination in the Emergency Room (Moulin et al., 2003). It is not a condition per say but rather a symptom, which is described as an imaginary sensation of one moving or rotating without an actual force, or of the environment moving around them. It is considered a quite common complaint since along with dizziness, affect 15-20% of adults yearly (Neuhauser, 2016). Its incidence increases with age and female sex. Causes of peripheral vertigo include labyrinthitis, vestibular neuronitis, Meniere's disease, medication and head trauma. The most common cause, however, is Benign Paroxysmal Positional Vertigo.

Benign Paroxysmal Positional Vertigo, or BPPV, stands for sudden and recurrent attacks of vertigo caused by changes in head position. It affects 2,4% of the general population at least once in their lifetime (von Brevern et al., 2007). Symptoms' severity changes during the day. Vertigo is usually worse in the morning and occurs during rapid movements such as sitting up, leaning forward, turning the head, lying down, or rolling in bed. In some cases, it is accompanied by nausea and vomiting (Chang, 2023). The episodes are paroxysmic, lasting less than two minutes, multiple times a day. The symptoms may resolve on their own within days or even weeks (Cleveland Clinic Medical, 2022).

BPPV's pathophysiology is closely linked to the anatomy of the semicircular canals of the inner ear. The three semicircular canals are positioned in the three perpendicular planes and connect to the utricle containing otoconia (crystals serving in balance). One of the two arms of the canals dilates creating the ampulla. Inside the ampulla, there is the rotation organ or crista ampullaris which contains hair cells acting as mechanoreceptors. This means that they

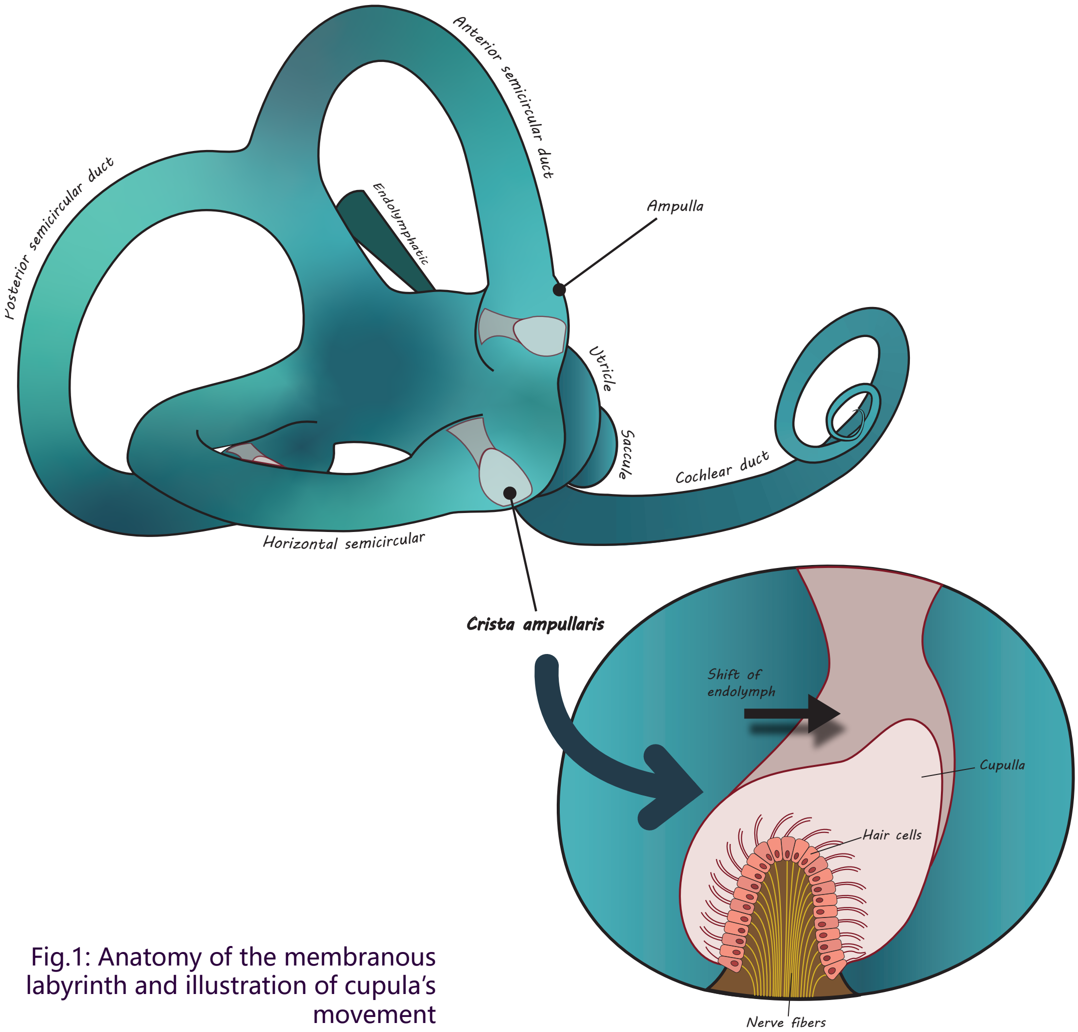


Fig.1: Anatomy of the membranous labyrinth and illustration of cupula's movement

can transmit signals to nerve fibers connected to them when the detect mechanical distortion. Attached to the crista ampullaris is the cupula, a gelatinous mass which moves along with the fluid inside the inner ear (endolymph) when the head changes position. Hair cells follow the cupula's movement and get distorted based on the direction of the shift of the endolymph. Excitation of the hair cells, and by extension the nerve fibers, happens only when this shift is towards a specific for each canal direction. On the opposite ear, the same head movement is translated into the opposite result. Thus, only signals from one of the vestibular nerves are transmitted to the brain (Palmeri and Kumar, 2022).

BPPV is caused by the dislodgment of otoconia into the semicircular canals (Canalithiasis) or cupules (Cupulithiasis) through the end of the canal without an ampulla, and therefore the barrier-acting cupula. When the head is still, there are no symptoms, but when movement occurs, the otoconia shift inside the endolymph causing an imbalance of signals submitted from the crista ampullaris to the vestibular nerves which results in vertigo (Palmeri and Kumar, 2022).

Young patients with BPPV are likely to have a history of head trauma, including head injury or inner ear surgery, which might have caused anatomical alters that allow the dislodgment of the stones. Vestibular neuritis, Meniere's disease and degeneration of the peripheral end organ can also be a cause of BPPV for older patients (Chang, 2023). Most of the cases, however, have no identifiable cause and therefore are considered idiopathic.

Diagnosis is based on nystagmus direction during specific head maneuvers to locate the affected side of the ear and the type of semicircular canal. Nystagmus is an involuntary movement of the eyes, characterized by a slow and fast phase. All of the diagnostic tests were created to exacerbate the otolith's movement in the canals which causes an excitation of the vestibulocochlear (XIII) nerve accompanied by a false eye movement. The central nervous systen tries to correct that movement by quickly redirecting the eyes in the opposite direction. As a result, nystagmus is observed. Nystagmus is characterized by the global direction of the fast corrective phase and the type of movement. So, it can be right/ left, horizontal / vertical / torsional (spinning)

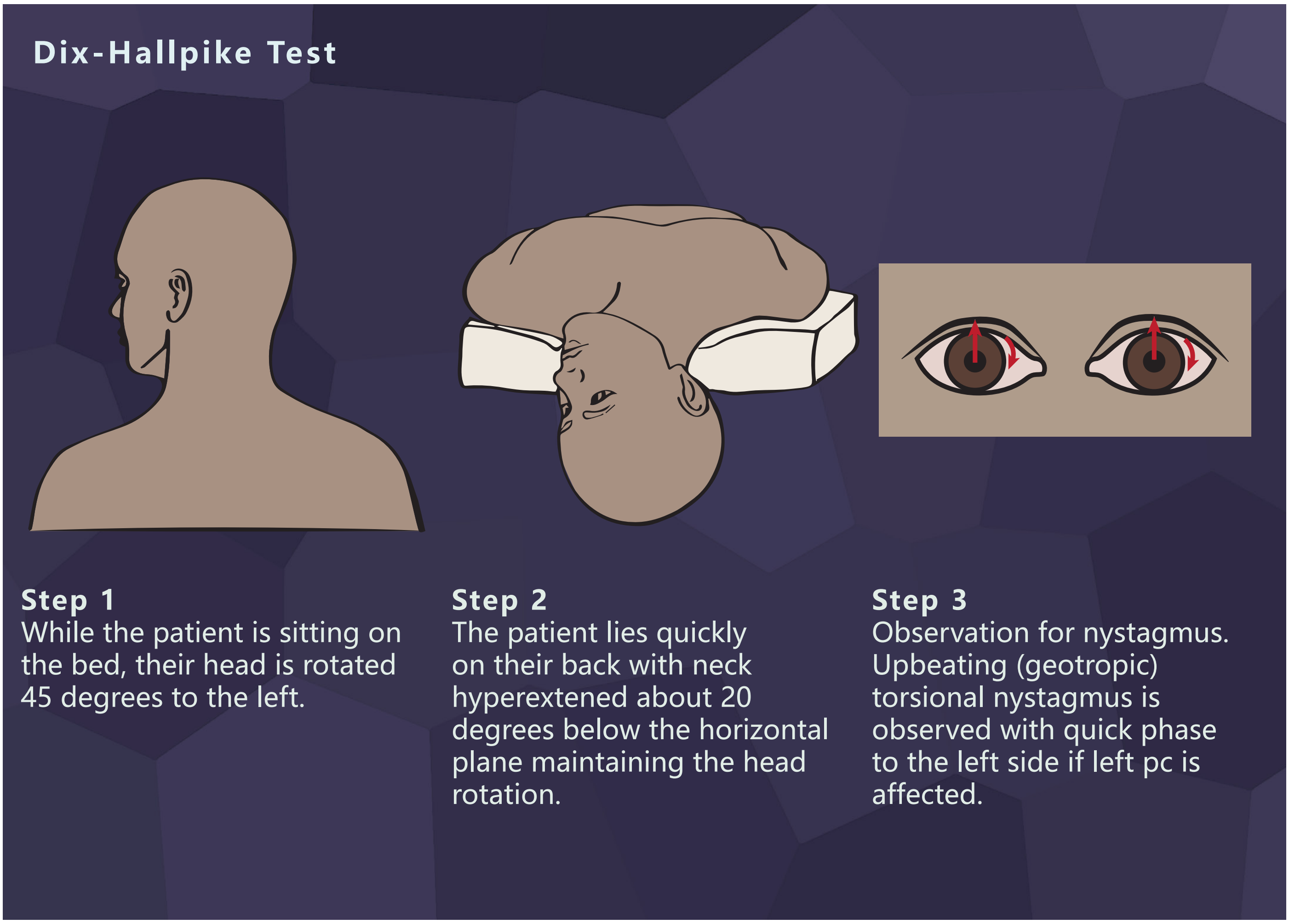


Fig.2: Left Dix-Hallpike Test (Left pc-BPPV) and nystagmus

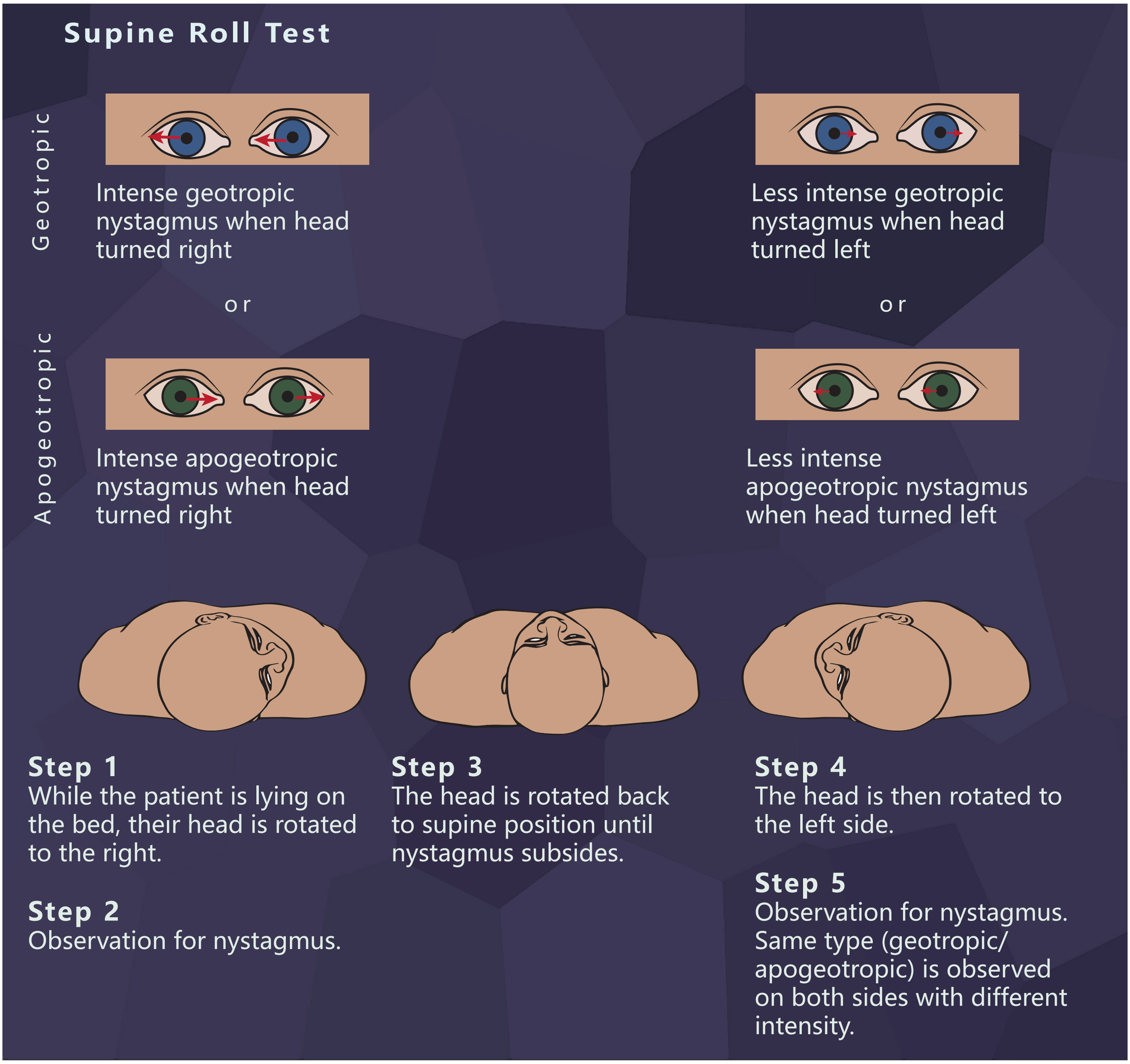


Fig.3: Supine Roll Test description and types of nystagmus when right horizontal canal is affected

and specifically for the diagnostic tests in BPPV geotropic / apogeotropic if beating towards the ground or ceiling (Parnes LS, Agrawal SK, 2003).

Depending on the canal affected, posterior (pc) or lateral (lc), Dix-Hallpike or the supine roll test are used for diagnosis (Fig.2-3). Canalithiasis in the anterior canal is a rare occurrence and is diagnosed with the Dix-Hallpike test or the deep hanging head test (Yacovino, D.A., Hain, T.C. & Gualtieri, F 2009).

Based on the diagnosis, a canalith repositioning procedure (CRP) takes place, to put the otoconia back into the utricle with the help of gravitational forces. More specifically, pc-BPPV requires the Epley manoeuvre whilst lc-BPPV is treated with the Barbecue roll manoeuvre and a-BPPV is usually managed with reverse Epley or Yacovino manoeuvre (Parnes and Agrawal, 2003; Audiology and hearing therapy department of the Royal South Hants Hospital, 2024). Although, a 3D simulation study suggests that reverse Epley is not effective for anterior canalithiasis and proposes a modified Yacovino manoeuvre instead (Bhandari A, Bhandari R, Kingma H,et al 2021). The main objective of these manoeuvres is to turn the semicircular canals in the most optimal position for the otolith to move inside the endolymph and be repositioned into the utricle, fixing BPPV symptoms.

During the head manoeuvres, adverse effects might occur which a physician ought to know and warn the patient about, before performing them. Even though exacerbation of vertigo is

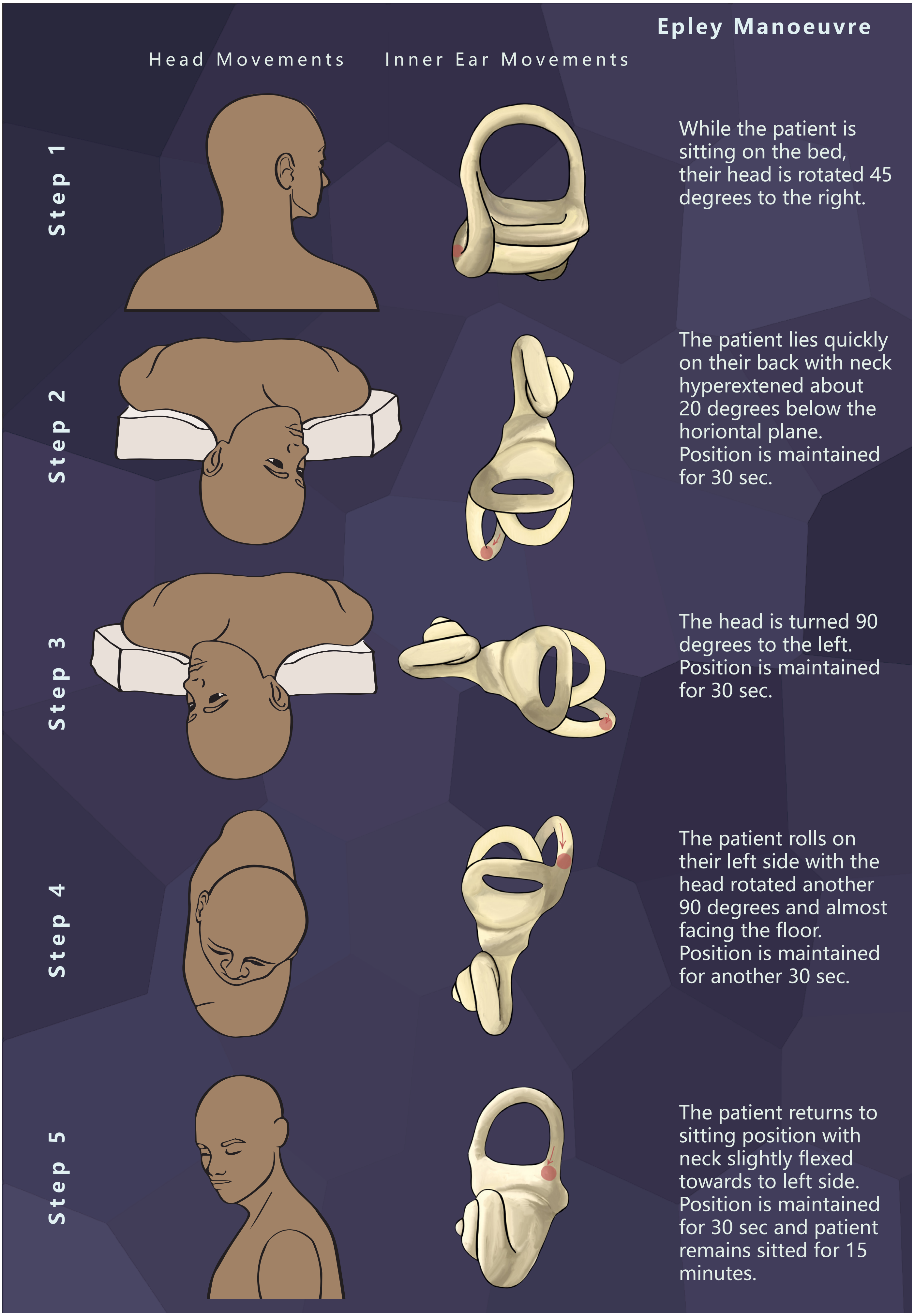
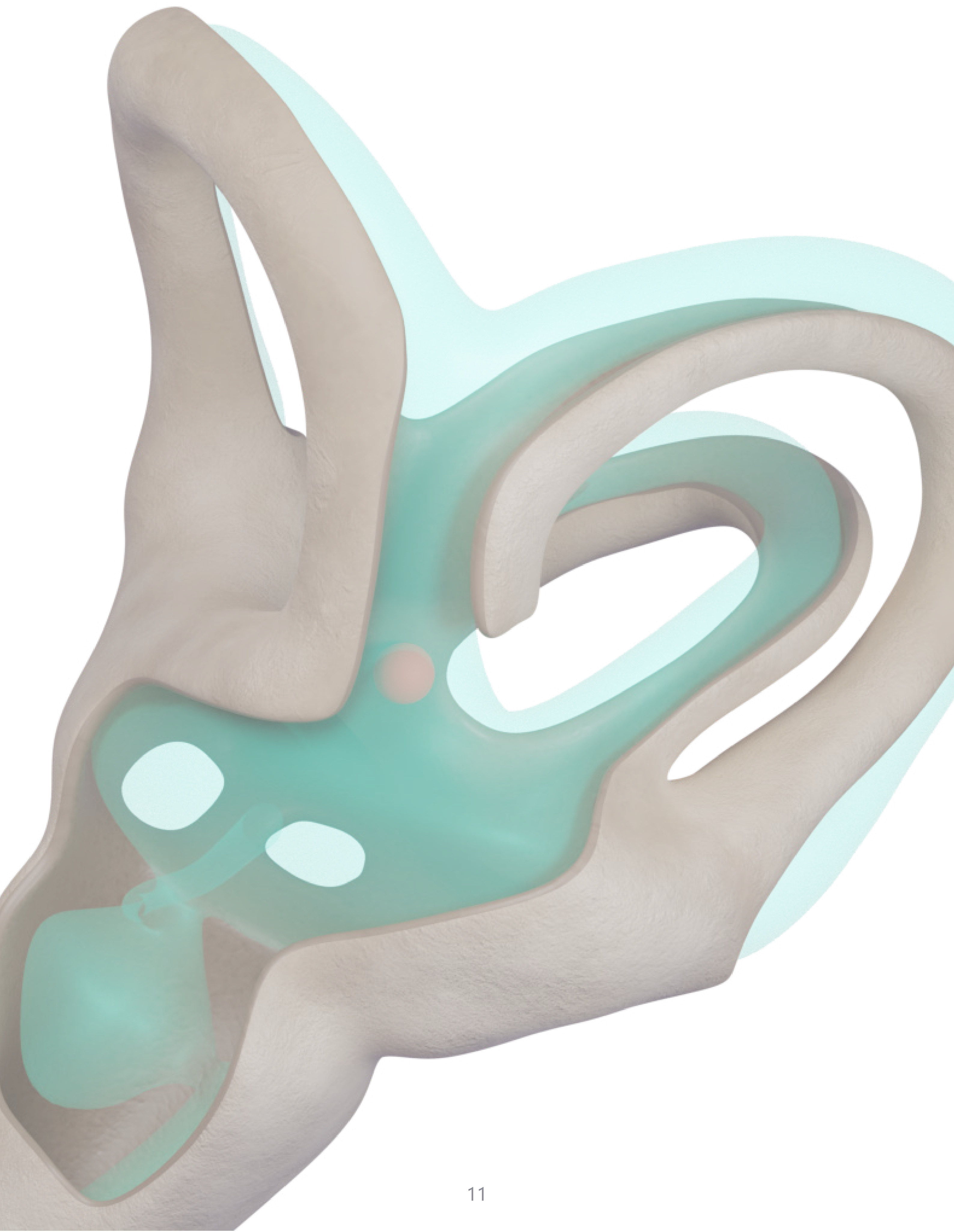


Fig.4: Right Epley Manoeuvre and ear position (Nguyen CT, Basso M., 2022)

expected, some patients might develop nausea or even vomit. Imbalance might also be present after the procedure. Finally, if the CRP is not performed correctly, it is possible for an otolith to be repositioned from the posterior canal into the anterior or lateral, highlighting the need for adequate technique (Palmeri and Kumar ,2022).

Other management options for BPPV involve vestibular suppressing medication and the surgical procedures of neurectomy or posterior canal occlusion in refractory cases (Corvera and García de la Cruz 2017).



Literature Review

Home treatment and Vestibular rehabilitation

BPPV is perceived to have a negative impact on people's quality of life. This is more prevalent in women with the highest difficulties being the sense of depression attributed to the disease, and the exacerbation of symptoms when turning over in bed (Muñoz et al., 2019). In countries other than the UK, BPPV may also have a significant cost for the patients, who require multiple visits to the doctor's office (Kim and Kim, 2017). For example, in the US an individual's health care expenses is US$2,684.74 on average, in Spain it is 364 Euros and in South Korea the cost is estimated at US$180 on average for each BPPV attack. As a result, patients can benefit from reducing medical costs by learning to perform modified CRMs at home as long as they have no contraindications such as neck/back disease, vascular conditions and retinal detachment (Home Epley Maneuver, 2021).

When it comes to home-based canalith repositioning manoeuvres, studies seem to agree on their effectiveness (Ranju et al.,2022) and even superiority to single office-based CRP (Piromchai et al., 2019). Specifically for the most common type of BPPV, pc-BPPV, illustrated guides to performing the manoeuvres three times a day, showed fewer residual symptoms and more effectiveness than single everyday office treatment (Gan et al., 2021). Up to 50% of the patients will suffer from recurrent attacks of BPPV which may last up to two weeks (Sfakianaki et al., 2021). A study conducted in Seoul in 2017 observed that only 24% of the recurrent cases were due to displacement of the otoconia in the same canal and on the same side, thus, questioning the effectiveness of a self-treatment guide at home without another consultation (Kim and Kim, 2017). However, the non-canal-specific vestibular rehabilitation exercises may be used as home treatment instead.

Vestibular rehabilitation (VR) consists of eye, head and body movements repeated three times a day aiming to "advance the natural process of vestibular compensation" after acute or chronic vestibular disease (Xie, 2021). It is not specific to BPPV but can be offered in multiple non-progressive peripheral vestibulopathies which affect a patient's balance.

BPPV patients sometimes return to the office after CRP with postural instability. Physical therapy in the form of vestibular rehabilitation tries to improve this symptom through exercises like the Cawthorne-Cooksey. These include three levels of exercises for the eyes, head and torso. The first level consists of horizontal and vertical eye movements and focusing on approaching object in sitting or lying position. The second step is bending the head forward and backwards and then turning it from side to side. The second level takes place in sitting position. After repeating the exercises in the first level, the patient is asked to shrug and rotate the shoulders and bend to pick objects from the floor. If the patient can tolerate the exercises, they then move on to level number three. This level focuses on torso movements, like changing from sitting to standing position and circling in between. Although, many different variations exist, for the purpose of this project the patient leaflet from NHS St George's Hospital was referenced (Department of Audiovestibular Medicine St. George's Hospital, 2019).

Multiple studies which compared VR and CRP were studied in 2017 leading to the conclusion that both together have a "synergic effect" in BPPV symptoms improvement (Bressi et al., 2017). VR is also a suitable alternative home treatment for those with contraindications and when used can reduce the uptake and therefore side effects of anti-vertigo drugs (Van Vugt et al., 2017).

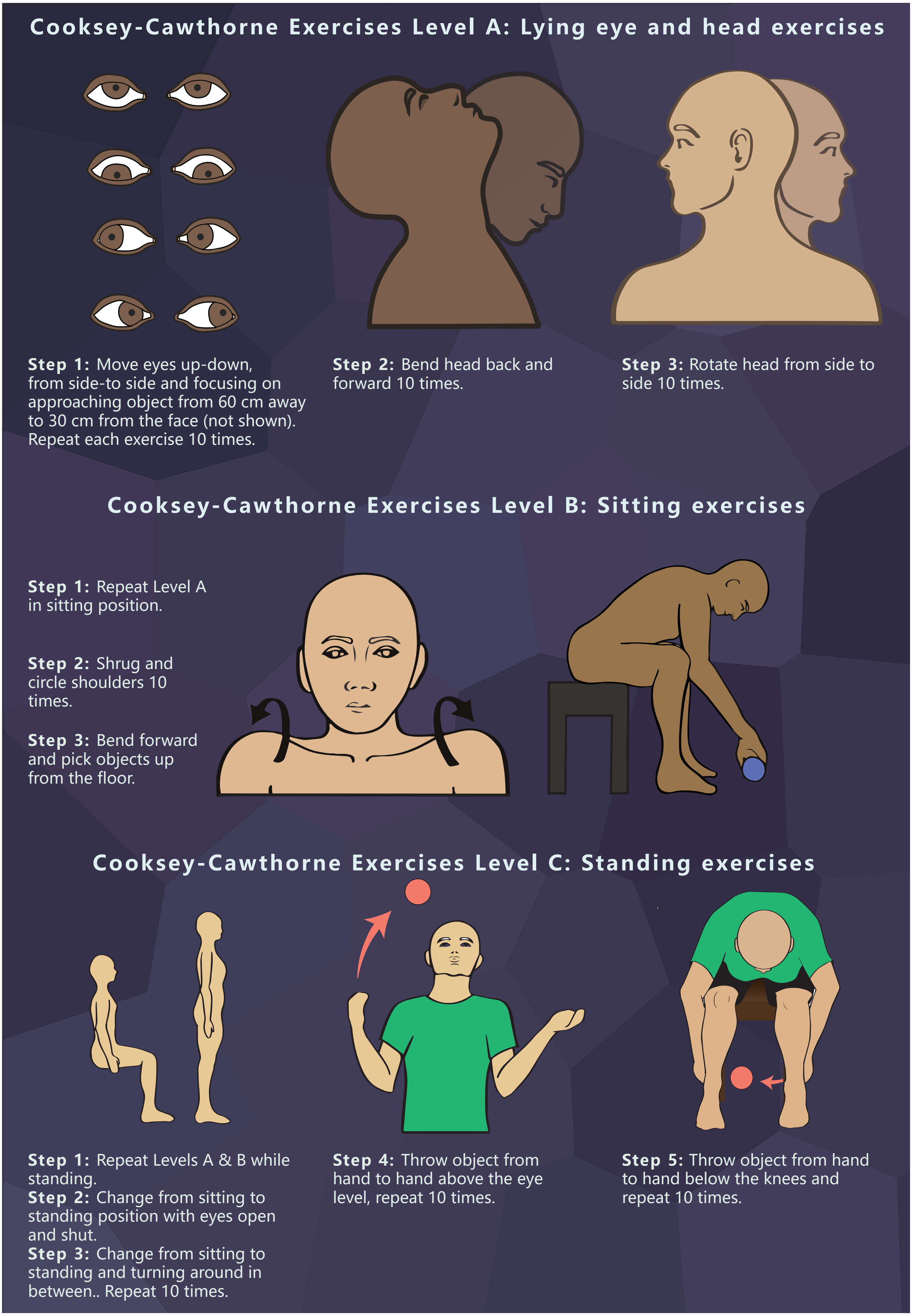


Fig.5: Cooksey - Cawthorne Exercises

Physical device-assisted home treatment

It is undeniable that VR and CRP are effective in BPPV treatment. The question raised, however, is whether health specialists and patients can perform them accurately. Ear, Nose and Throat specialist, Dr Bromwich, admits from experience that Epley manoeuvre, "while easy to perform, is somewhat difficult for patients to remember correctly" (Bromwich et al., 2010). Interestingly, neither family medicine resident doctors in the US seem to be well practiced in the manoeuvre, with less than 20% performing it properly (Beyea et al., 2008), (Bromwich et al., 2010). Therefore, Bromwich tried to address the problem by creating DizzyFix, "a wearable guidance tool" of transparent tubes filled with fluid and a colored particle, "designed to simulate the otoconia found in the inner ear" (Fig.6). The device has shown excellent results in multiple clinical trials, initially for home treatment of BPPV assessment and later of the canalith repositioning technique shown by resident doctors (Bromwich and Parnes, 2008) (Beyea et al., 2008).

Fig.6: DizzyFIX worn on patient's head and assisted by physician.

Other scientists, who recognize the challenges of illustrated home exercises, have developed a Virtual Reality (VR) model for patient training (Tabanfar et al., 2018). This particular model allowed patients to perform a step-to-step Epley manoeuvre by following a moving target through a VR headset. The results proved that VR assisted manoeuvres were performed more accurately than those after following an instructional handout.

Home treatment of BPPV seems to remain an intriguing subject of research, since currently, a clinical trial's results are expected, which will compare the effectiveness of 2D versus 3D Virtual Reality game training for BPPV (Özdil, 2024).

Software Review

In an attempt to present all CRP training media available for health practitioners or patients, this author searched for existing smartphone applications available for Android devices in the UK and found three available in total. Two of them were free to download aiming at home exercises to treat BPPV, while the third one was designed for health professionals to help with diagnosis and treatment manoeuvres in BPPV as well as diagnosed patients.

In summary, the first application called "BPPV Treatment" with more than 1K downloads was designed by MediaVents Hanariks and although easy to navigate and simple to use, had minimal interactive component and only one illustration about the Brandt-Daroff manoeuvre (MediaVents Hindriks, 2020) (Fig.7).

The second application was called "Epley Manoeuvre for BPPV" and had the same popularity as the previous one (Tatsuaki, 2019). It was less structured in the matter of number of pages, and instructions of the app's use. However, it was focused on its goal, as advertised by the name, to directly display the Epley Manoeuvre. Like the previous app, 2D illustrations were used, but unlike the other, they were displaying the back view of the patient (Fig.8). This made the manoeuvre more compatible for the user, who is encouraged to perform along with the instructions. Furthermore, the manoeuvres were explained by a combination of text and sound with a countdown for each position. This feature along with the option to choose the affected side of the ear made the app very engaging and easy to use. Finally, the creator, Tatsuaki Kuroda, took the app a step further by making it available in Japanese as well as English.

The final app was published by Paul Burston based on the Clinical Guidelines for BPPV updated by the American Academy of Otolaryngology- Head and Neck Foundation in 2017 and is available for purchase (Burston, 2023). To begin with , the app includes instructions of use, safety precautions, diagnostic tests, and a treatment guide for all forms of BPPV including Epley, BBQ Roll, Gufoni 1 and 2 manoeuvres, and quick head turns. In contrast to the others, it used 3D models of a patient and inner ear to make teaching more engaging (Fig.9). Like the previous app it has the accessible feature of sound description. Moreover, it makes diagnosis extremely interactive by suggesting the appropriate repositioning manoeuvre based on the user's choice about the direction of nystagmus. Overall, this app is extremely well rounded and detailed. However, although not intended, it likely appeals more to the specific target group of ENT specialists, so it is no surprise that it has resulted in about one hundred downloads so far.

After collecting information for the several types of software available, this author reached to the following personal conclusions. When it came to the artwork, 3D models, were preferred, as they managed to engage the user and make the head movements more comprehensible. The most appropriate view seemed to be the one from the back of the head, both for patients to perform by themselves but also for health professionals who position patients similarly in the office. Finally, what distinguished an app from another was its user-friendly interface, which offered multiple options for customization and user preference.

Comparison of physical device, VR and smartphone applications

When it comes to comparing all types of methods available for CRP training, although the wearable devices are proven effective, smartphone apps are likely more convenient for the majority of people. The wearable physical device and VR headsets are supported with research findings, which the smartphone apps currently are not. However, the first two choices were less cost effective than the apps, some of which are even free. Furthermore, physical devices ("DizzyFIX" or VR headset) require to be worn which might feel uncomfortable during acute BPPV symptoms, whilst apps need only be held in the hand. Moreover, although Dr Bromwich's device is available to order online, smartphone apps are faster and easier to acquire. Nevertheless, without any visible target, it cannot be guaranteed that the public can perform the head manoeuvres efficiently at home, making the physical devices superior to the apps in that aspect. As a result, each method has its strengths and limitations, suggesting that an ideal solution might integrate the best features of all three approaches.

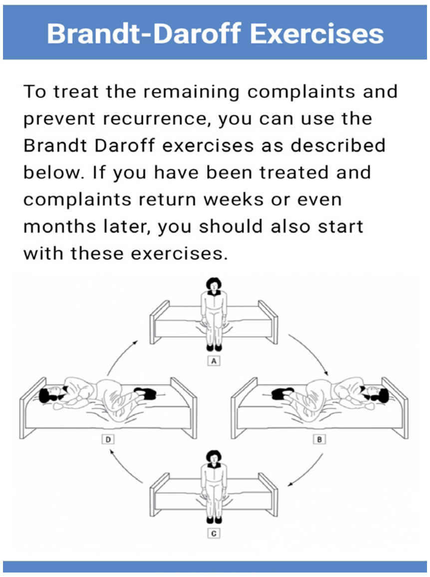


Fig.7: Screenshot of the application "BPPV Treatment" in use

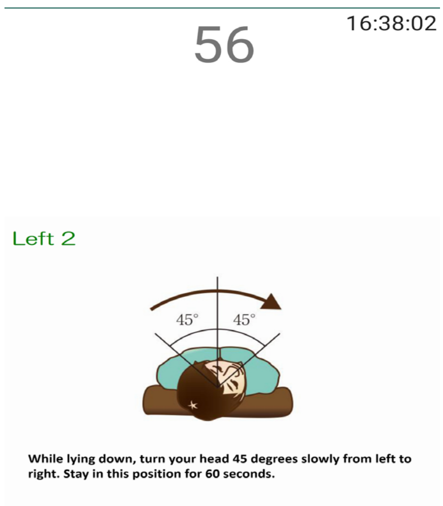


Fig.8: Screenshot of the application "Epley Manoeuvre for BPPV" in use

Fig.9: Screenshot of the application "BPPV Relief" in use

Purpose of the project

This project had two main goals. Firstly, it aimed to help health professionals gain a deep understanding of the anatomical positioning of the stones in the inner ear, when performing CRP, to help better their technique and hopefully future recollection of the manoeuvres. Furthermore, it aimed to provide more convenient and engaging practical opportunities, so medics, and more specifically medical students, could learn at their own pace.

Secondly, the project aimed to create an affordable and practical tool for the public who suffer from BPPV to use as home exercises by providing instructions for vestibular rehabilitation as well as semicircular canal-specific manoeuvres. Moreover, the project aimed to introduce a visible goal for patients performing CRP on their own, considering the literature review proving that real-time, visible targets work better than non-interactive instructions.

Choosing the media

To achieve the goals, different options were explored before choosing the final method of execution. Initially, there was an idea for an interactive 3D printed model of the inner ear, filled with fluid and potential to position stones in the posterior semicircular canal. The model would have been equipped with handles so medical students could move it around 360 degrees in space and reposition the stones back into place. This model was originally going to be used as a self-proposed brief for the Clinical Skills Department of University of Dundee's Medical School. However, it came with a lot of challenges such as finding transparent 3d printing material, waterproofing it, cost of labor and time. Therefore, it was soon abandoned.

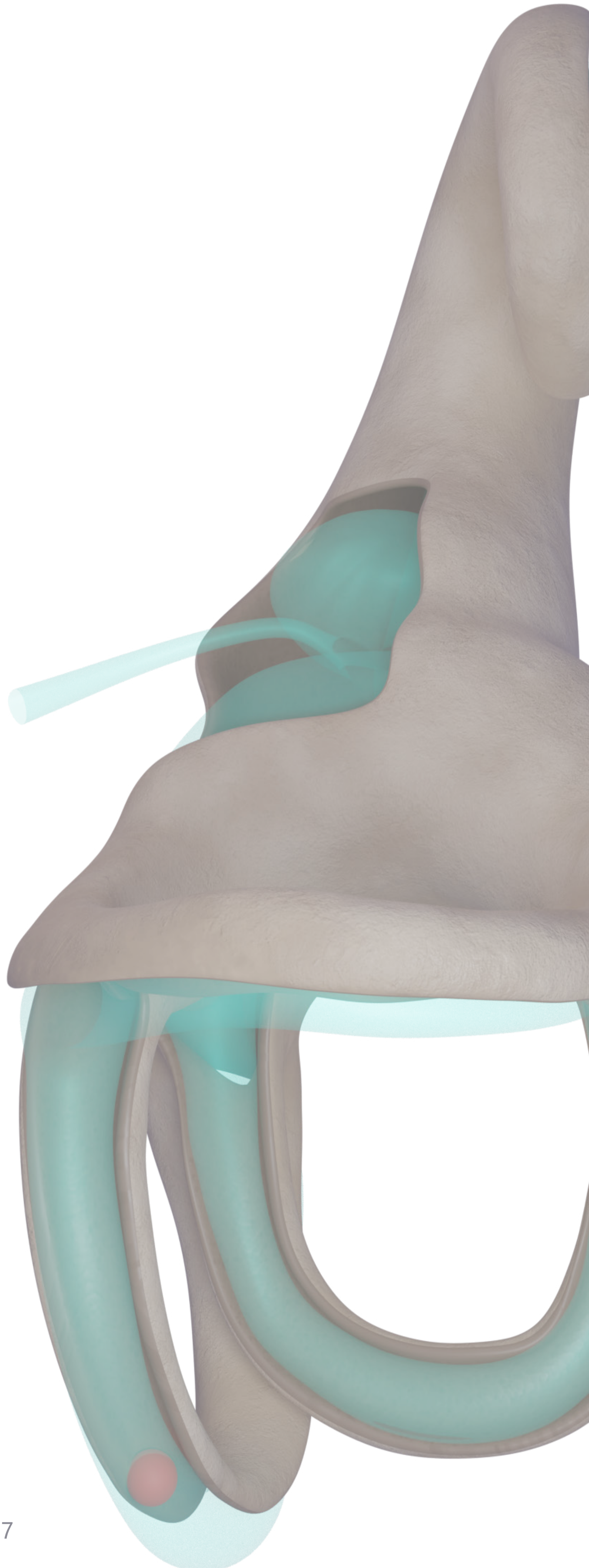
The second idea involved creating the same model with virtual reality prospects. Nevertheless, practical issues about public accessibility to VR goggles during the Masters exhibition show and practicality of use by the Clinical Skills Department and individual patients lead to the search for a more efficient method.

After reaching out to software developer, Hellenic Programs, and pitching the concept of the previous ideas, they proposed to create a smartphone application with an embedded ear simulation. Users would be able to manually rotate a 3D ear model on their screens, while watching otoliths move inside the canals because of gravity. Instructions for the therapeutic manoeuvres would be provided at the same time for the users to simulate on the model.

This idea could serve health professionals to practice their clinical skills by performing the Epley or Barbecue Manoeuvres on the 3D ear. It might not have been practical for patients to use while performing the manoeuvres, like this project was aiming for. Nevertheless, the ear simulation would help them visualize the otoliths in a real-time movement and hopefully help better their recollection of CRP steps. In the end, both audiences would benefit from this interactive feature. Apart from the intriguing ear simulation, the application would include information about the disease, animated instructions for BPPV diagnostic tests and canalith repositioning manoeuvres as well as animated exercises for vestibular rehabilitation.

Creating this smartphone app would address issues such as the user's access to special equipment and the safety precautions and technical challenges of the physical model. Moreover, the collaboration of people proficient in their fields allowed an efficient management of time without optioning for unforeseen difficulties regarding unfamiliar development aspects of the project. Finally, an app had the extreme benefit of wide availability, so the audience was extended from just health professionals originally to the public as well by planning for two different user versions.

The application idea was reintroduced to the Clinical Skills Department, who appeared positive about using it once completed. They even involved an Ear, Nose, and Throat specialist to provide input throughout the process. Therefore, this author undertook the planning and wireframing of the app, the production of 3D models, animations, texts, voiceovers, app logo and colour palette, whilst the software developer took over the ear simulation, app development and the making of a promotional video.



Methods

Wireframing

Before advancing to the 3D modelling, the web-based design tool, Figma, was used to create a wireframing for the app. Aiming to be more specific with the audience, two versions of the app were originally planned: one directed to healthcare professionals and one for the home treatment of BPPV. The main difference in wireframing was the exclusion of the unneeded diagnostic tests in the second version of the app and the inclusion of the Cooksey-Cawthorne exercises. The rest of the screens remained similar to each other. The main menu would give options for learning more information about the app, BPPV itself, the canalith repositioning manoeuvres and the practise of CRP with the 3D ear simulation. Furthermore, information about the disease was adjusted to each version based on the audience, simplifying the information for the non-medical users. Wireframing helped plan the number of models and animations which were divided into steps with appropriate written instructions and timings. It also served in the effective transfer of the design idea to the software developer and later communication.

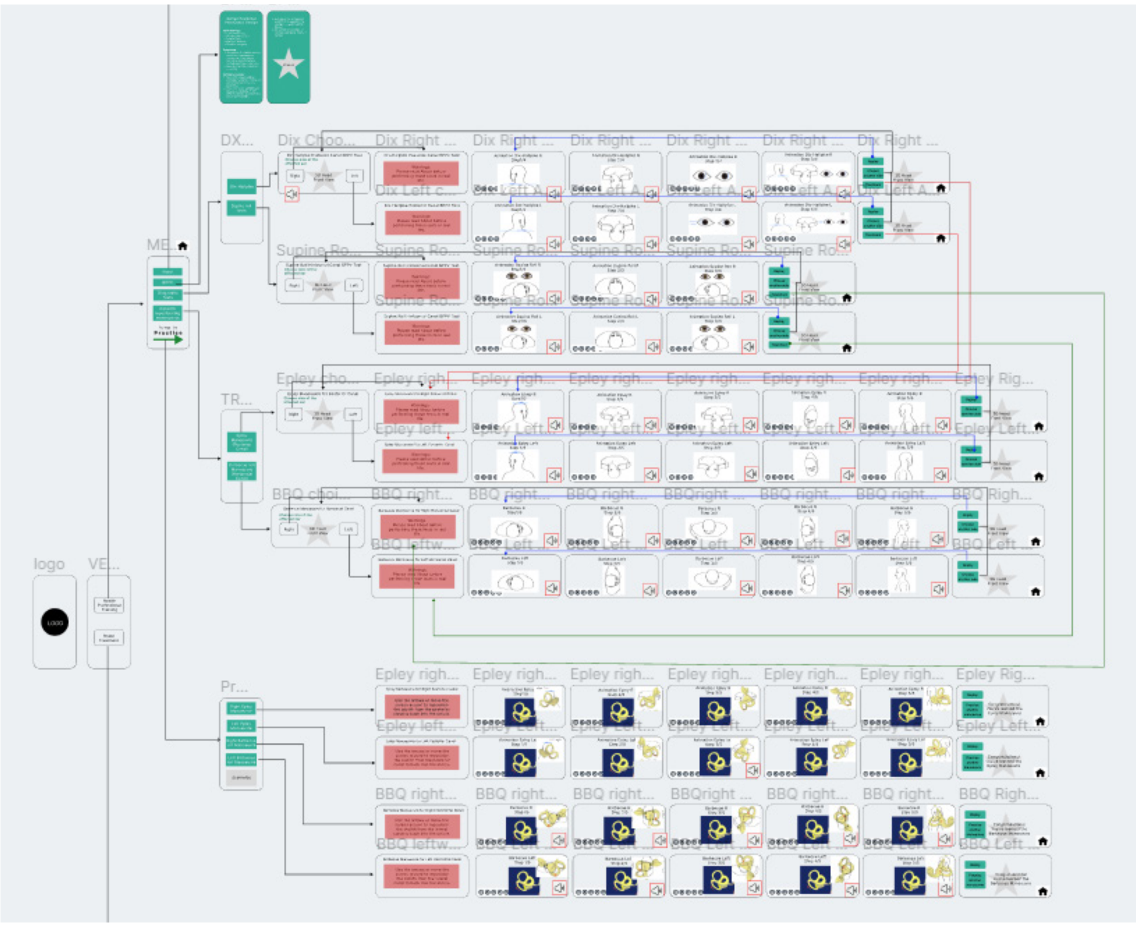


Fig.10: Part of the wireframing for the Health Professionals' version of the app.
From left to right: First screen of opening the application shows the logo which fades into choosing a version between "Health Professionals" and "Home Treatment". The first choice brings the user to the main menu with the choices of "About the app", "BPPV information" "Diagnostic Tests", "Canalith Repositioning Manoeuvres" and "Practise in 3D".
"About the app" includes information about the dissertation and creators. "BPPV information" gives a synopsis of the disease. Choosing the "Diagnostic Tests" opens up another menu for the user to choose between "Dix-Hallpike" and "Supine Roll Test" (tests for the anterior canal were not planned). Both options then require the selection of right or left side. All four selections lead to step-by-step diagnostic animations. Similarly, choosing the "Canalith Repositioning Manoeuvres" gives a choice between the "Epley" or "Barbecue" and after that, the choice of affected side. Choosing the "Practise in 3D" gives the option for performing any CRM left or right to a 3D ear with written instructions.

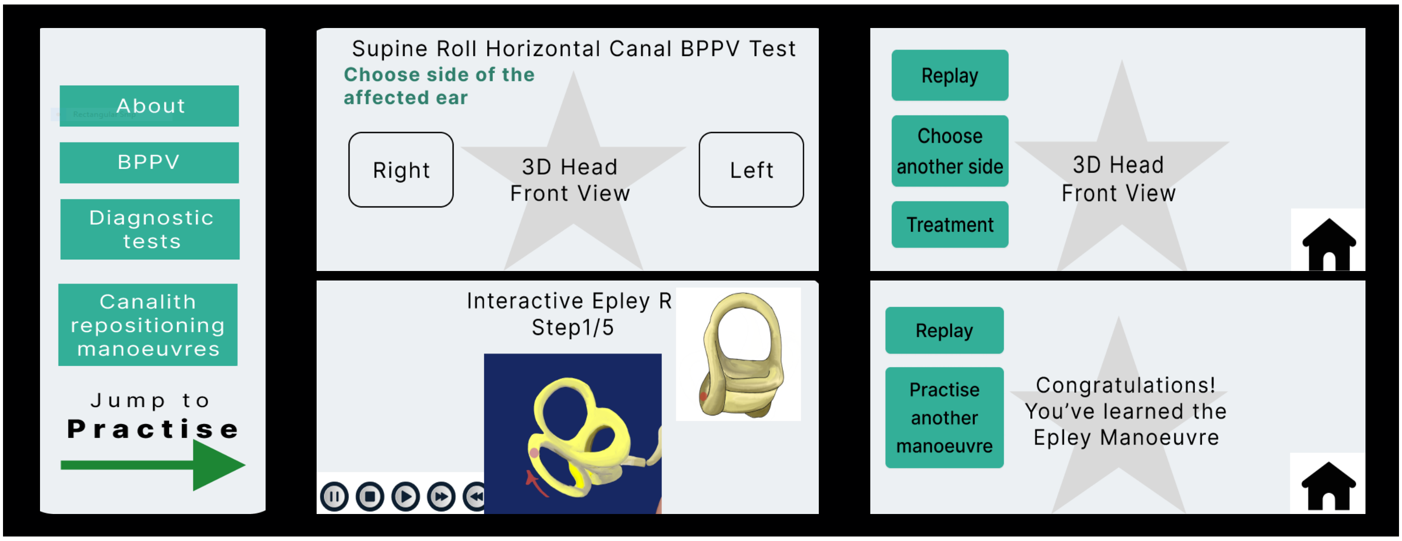


Fig.11: Screenshots of the wireframing for the Health Professionals' version of the app.
Left vertical screen: Main Menu
Left upper horizontal screen: Choosing side of affected ear for Supine Roll Test animation
Right upper horizontal screen: Screen upon completion of Supine Roll Test animation
Left lower horizontal screen: "Practise in 3D" Simulation of right Epley manoeuvre on 3D ear. Visual Instructions on the right upper corner.
Right lower horizontal screen: Completion of 3D simulation with congratulatory message.

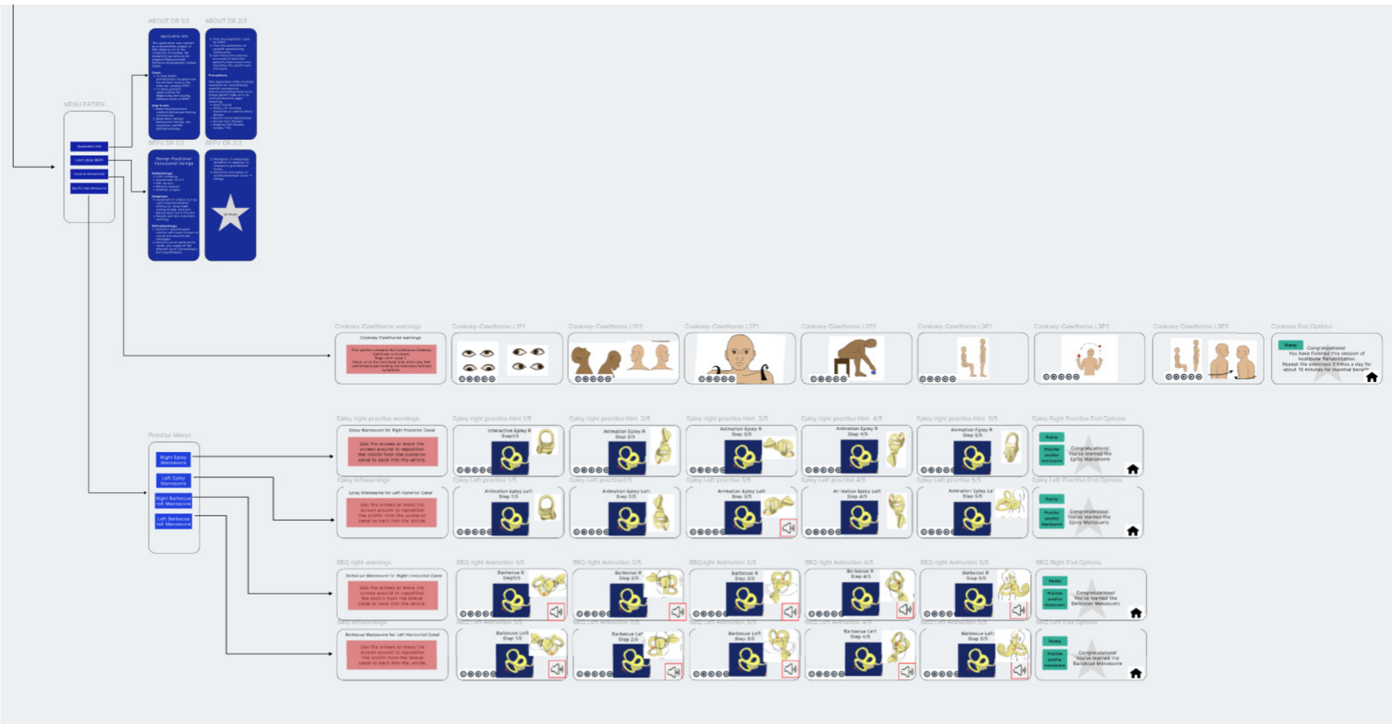


Fig.12: Wireframing for the "Home Treatment" version of the app.
Left vertical screen: Main Menu with options of "About the app", "About BPPV", "Vestibular Rehabilitation" and "Practise in 3D "
From top to bottom row: Screenshots of information about the application 's development., screnshots with information about the disease adjusted for non-health professionals. The third row shows a Cooksey Cawthorne 3D animation broken down into steps. The final four rows show the ear simulation for Epley and Brabecue manoeuvres, like in the health professionals' version.

3D Modelling

The first model that was created was the inner ear using the 3D modelling software Blender 3.6. After referencing anatomical atlases, three digital images of the right inner ear were created in Sketchbook 6.0.7 to visualize the organ in medial, lateral and superior views (Lane & Witte, 2010) (Netter, 2023). Those images were then positioned as reference images in Blender to serve as a guide for box modelling (Fig.13). The semicircular bony canals were created from individual cubes using extruding and spinning techniques. They were later joined together to create the vestibule (Fig. 14). The cochlea was made by adjusting the height and turns of a “spiral nurbs path” using the reference pictures. The path was then given some depth to look like a tube, which was then converted to mesh, joined with the rest of the bony labyrinth and given some subdivisions to smooth out the edges (Fig. 15). The challenging part was the joining of the interfacing vertices of the cochlea, to reproduce the cojoined outside surface of the bone while maintaining the inside diaphragms (Fig.16). It was a tedious and long process but made the final result quite realistic.

The membranous labyrinth was created similarly to the bony labyrinth. Instead of duplicating the latter, scaling it down and positioning it inside the bone as the membranous part, box modelling was preferred (Fig.17). This way, no adjustments to the length of the membranous canals were needed, nor was the cochlear duct merged at places together, like the bony part.

After the cochlear duct was modelled inside the bone, some faces on the lateral surface of the 1st cochlear turn were deleted to reveal the duct. Around the duct, some bony vertices were connected to divide the inside of the bone into the scala media (cochlear duct), the scala vestibuli and the scala tympani (Fig.18). Faces were also deleted from other sites of the bone to create the oval and round windows, and partially reveal the semicircular ducts, saccule and utricle. The bone was then given a “Solidify” modifier for some thickness on the edges.

After that, three material IDs were created for the model (outside surface, inside surface and spongy bone between them) and hand-picked faces were attributed to each of them (Fig.19).

When the model was completed, UV unwrapping had to take place before texturing, which took about one week and a lot of trial and error at marking the unwrapping seams.

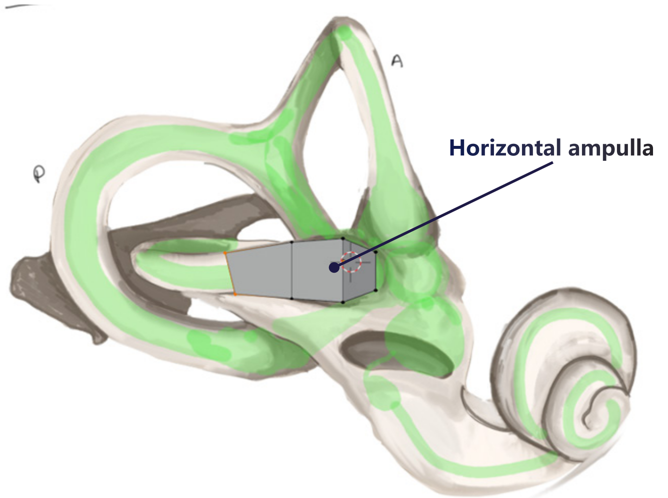


Fig. 13: Reference picture of lateral view of the inner ear at the background and early stages of box modeling of the horizontal canal. A cube was scaled and positioned in front of the image to match the horizontal ampulla which was then extruded posterio-medially.

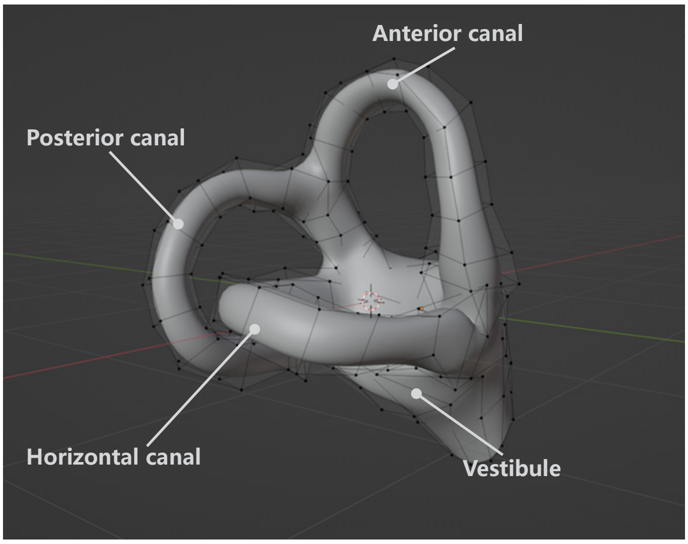


Fig.14: The bony semicircular canals and vestibule in Edit mode. Two levels of subdivision have smoothed the original sharp edges.

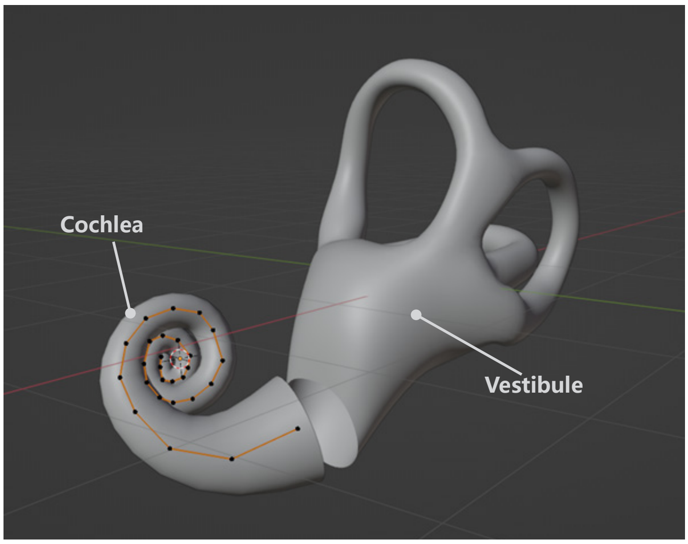


Fig.15: Creating the cochlea. The nurbs path on the left with increased depth is positioned close to the vestibule before connecting the objects.

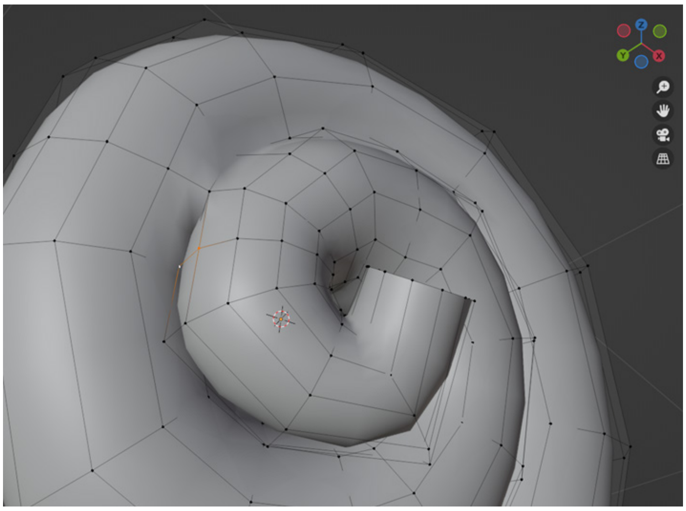


Fig.16: Merging overlapping vertices of cochlea to create a homogenous outer surface without compromising the inner curves.

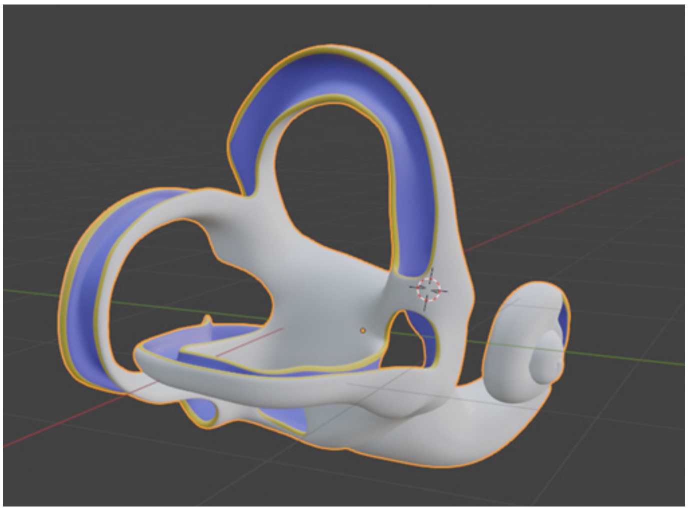


Fig.19: Attributing material IDs to faces of the bony labyrinth. In white is the outer surface of the bone, in yellow is the spongy bone and in blue is the inside of the bone.

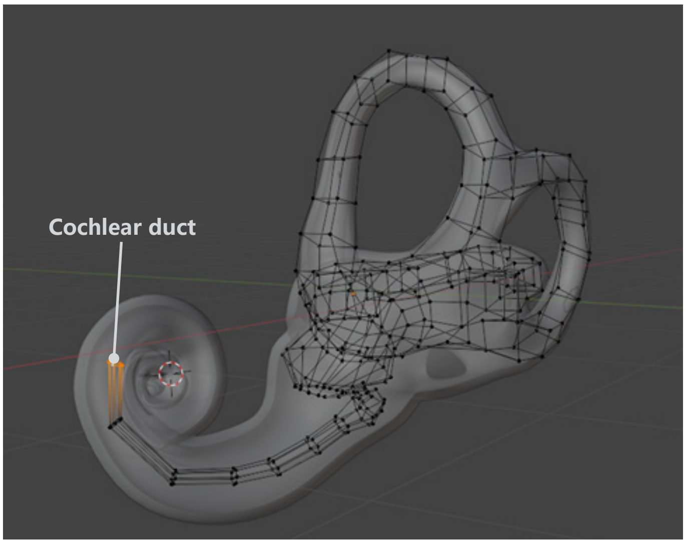


Fig.17: Membranous labyrinth in Edit Mode inside the bony labyrinth. The cochlear duct is extruded to follow the spiral shape of the cohlea.

Before adding textures, the model was assessed for anatomical accuracy by a CAHID lecturer in anatomy. This resulted in the repositioning of the round window, some adjustments in the transverse diameter of the cochlea and the partial creation of the endolymphatic duct.

Texturing was done in Adobe 3D Substance Painter 8.3.1. The outside surface was created using the existing bone material in Adobe's collection with a lighter colour. On top of that, a layer of greyish elevated cement was painted with the homonymous brush. For the inner surface, a modified version of the "Monster Tongue" material with the removal of some harsh elements and a deep brown colour was used. The spongy bony ID was textured with a spongy whitish brush. The membranous labyrinth was textured using a transparent material by adjusting a glass texture and using alpha blend material preview

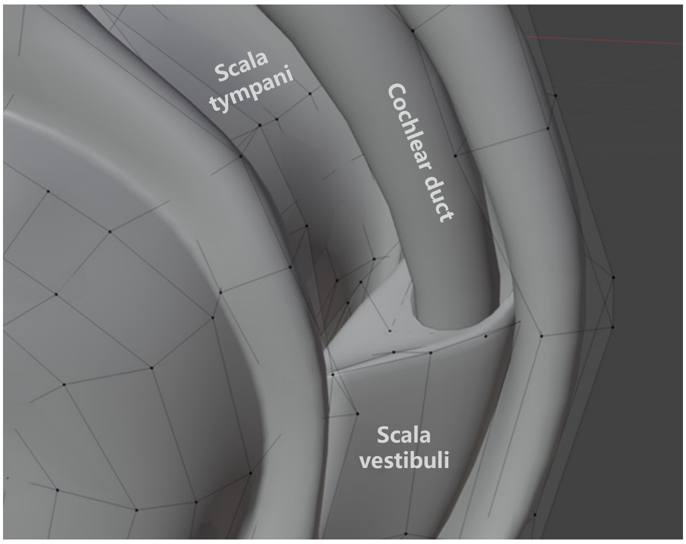


Fig.18: Connection of vertices inside the bony labyrinth to surround the cochlear duct and divide the rest of the canal into the scala vestibuli and scala tympani.

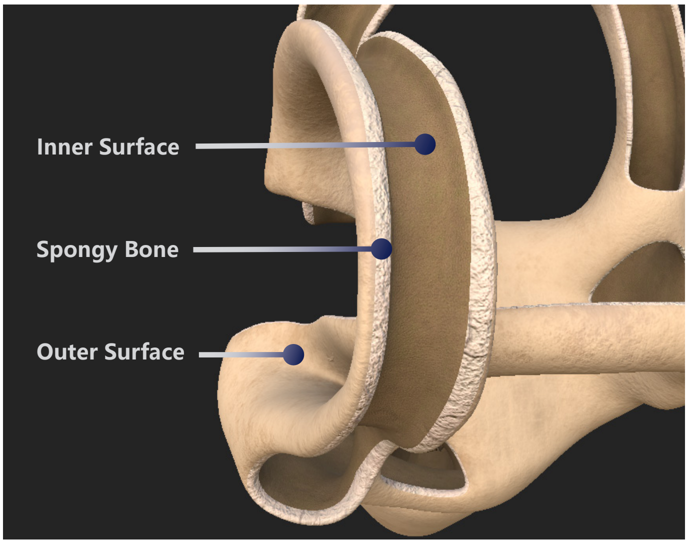


Fig.20: Bony labyrinth textured

in Blender.

For the planned CRP animations, it was decided to modify existing ZBrush human models and create three diverse patients. Using the woman model by Tsvetomir Georgiev, found in Maxon ZBrush 2023.1.1 lightbox, two female patients were created: a young black woman and an elderly white woman (Fig. 21-22). “Transpose” tool was used to adjust the height, shoulder, and neck levels as well as other body parts such as thighs, breasts and abdomen. Using the same creator’s male model, an Asian middle-aged man was created as well (Fig. 23). Finally, the models were textured using Polypaint and Alpha brushes. Hair was not created for any of the models, in order to keep them as simple as possible for the public to understand the ears’ position during the animations. Eyes were also created for each of them using simple 3D spheres and

Fig.21: Black Female

Fig.22: Elderly Woman

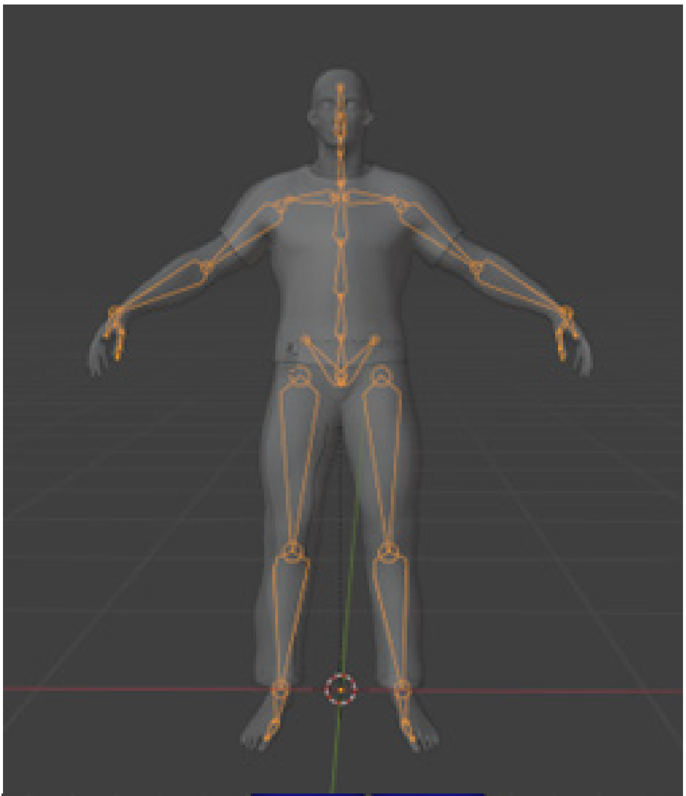
Fig.23: Asian Male

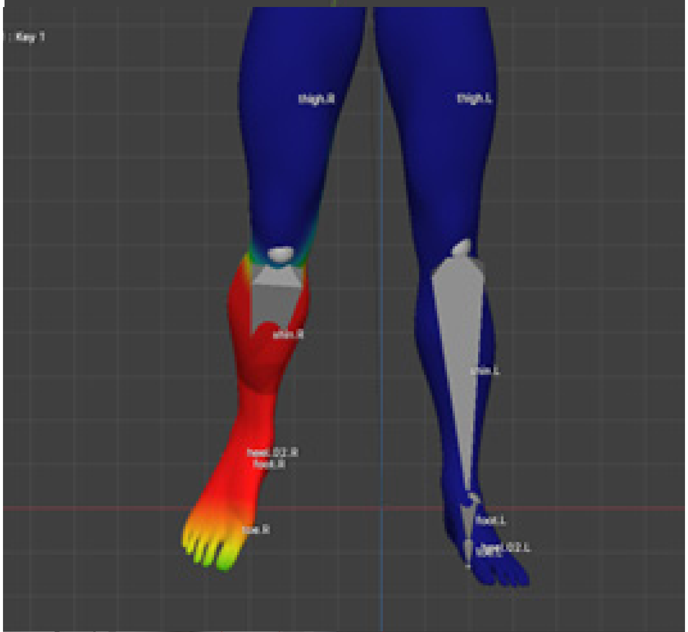
projecting realistic common-rights iris pictures on them. Feedback from the NHS ENT fellow suggested the changing of the original brown eye colours to lighter ones due to nystagmus being challenging to capture and comprehend in darker tones. Therefore, the two models chosen for the nystagmus animations were given a light blue and green iris colours.

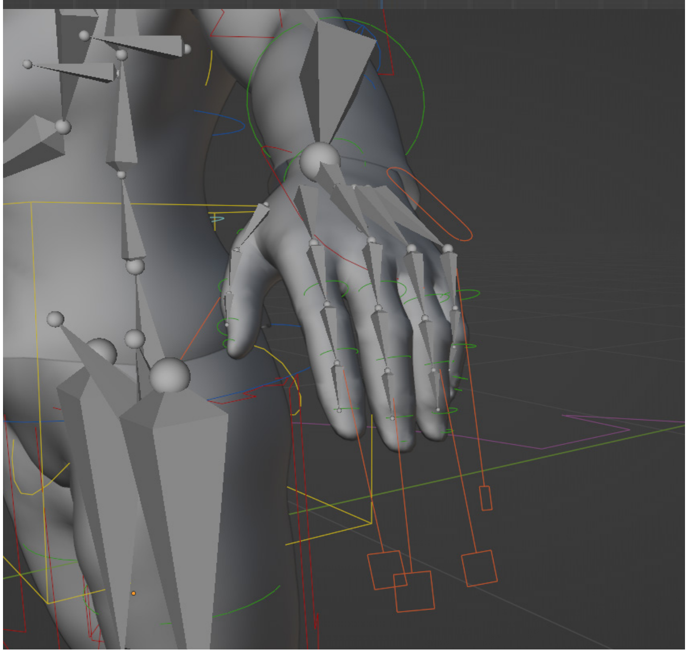
For the clothes, a simple mask selection was used in ZBrush, where the masked region was extracted, the inside surface was deleted and then remeshed to simplify. In Blender the sewing technique served the purpose of making a simple maxi dress as well.

Rigging

The human models were then imported into Blender to rig. A “human meta-rig” was added and adjusted in scale to match the model’s height. After that, each bone was repositioned inside the human model to simulate a skeleton (Fig.24). Due to inexperience some challenges in rig generation arose. These were addressed by practical solutions suggested by fellow animation students including the reduction of the polycount for the models and the automatic rig generation, which worked brilliantly. In some cases, there was a further need for manual manipulation of the effect each bone had on the human model. This was attained through weight painting on the model with a brush (Fig.25) Rigging was done four times in total, once for each of the models, and another one with finger rigging for more fine movements for the elderly woman (Fig.26).







From top to bottom
Fig.24: Human meta-rig adjusted to model’s height and joint locations.
Fig.25: Weight painting the effect of right shin bone on the model’s surface. The rig is seen to cause the right knee to flex when shin is rotated backwards. Red corresponds to the area with greater effect , yellow corresponds to a medium effect and blue are the areas where the bone has no effect.
Fig.26: Rigged elderly woman’s fingers. When the orange squares are moved the whole finger moves along. The green circles around each phalanx flex or extend the individual joints.

Creating the scene

Finally, a simple doctor's office scene was created in Blender using box modelling. This included a medical couch from online references, a door, a window, floor, walls and a poster with a rendered original picture of the inner ear (Fig.27). Most of the objects were given plain colours with roughness and metallic elements adjustments, while others, like the floor, were given premade textures from an online 3D library. The same room with some box-modelled armchairs and hanging paintings was also used for the home environment when rendering the Cooksey-Cawthorne exercises (Fig.28).

Fig.27: Doctor's Office Scene

Fig.28: Home Scene

Animating

Before animating the characters, they needed to be attributed to the tests. The Black female was randomly chosen for the Dix-Hallpike test and subsequently for the Epley manoeuvre while the Asian male was chosen for the Supine Roll test and the Barbecue Roll manoeuvre. However, the white elder woman was animated for the Cooksey-Cawthorne exercises intentionally. Like mentioned before, vestibular rehabilitation can be used as a substitute to CRP when contraindications don't allow their performance. Since these conditions tend to have a higher incidence in the elderly, the model of the elderly woman model fitted the profile for VR best.

As discussed in the introduction and agreed by the ENT fellow, the animations of the diagnostic tests and canalith repositioning manoeuvres were considered more engaging from the back view of the patients. Therefore, the camera was positioned at the head of the patient's bed (Fig.29). Using the rigged characters, keyframes

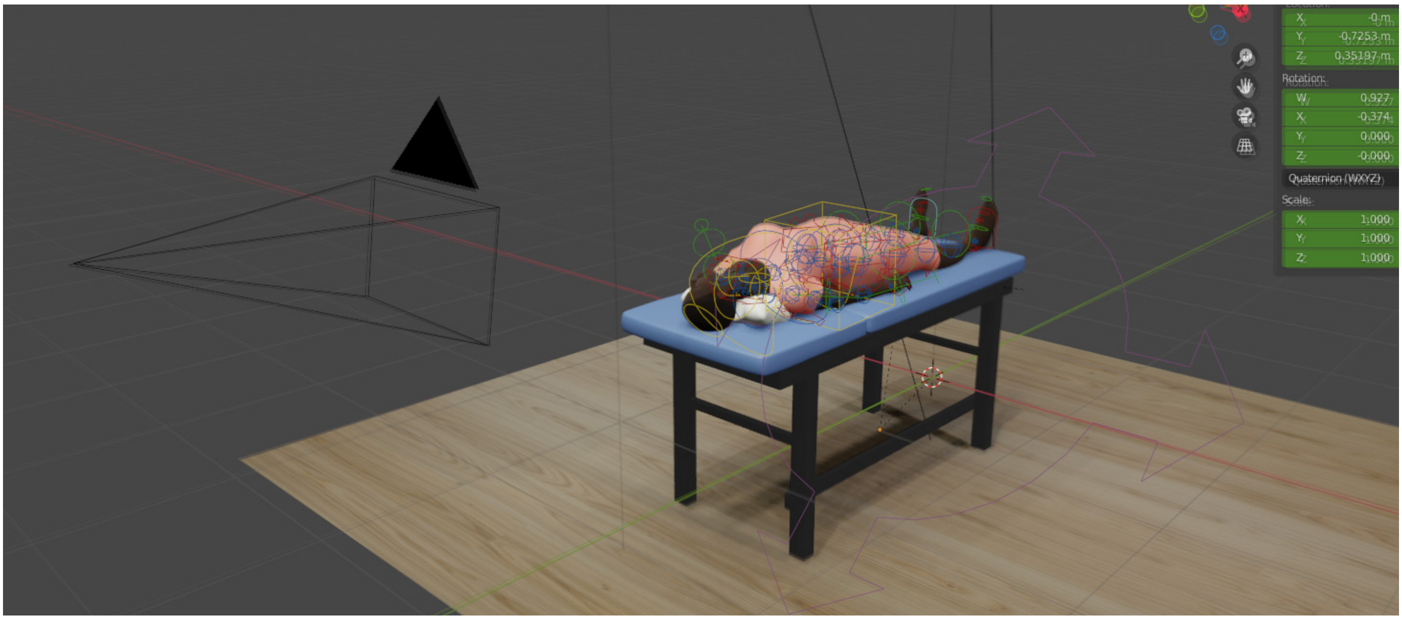


Fig.29: Epley Animation behind the scenes. Camera is positioned at the head of the rigged black female lying on the bed.

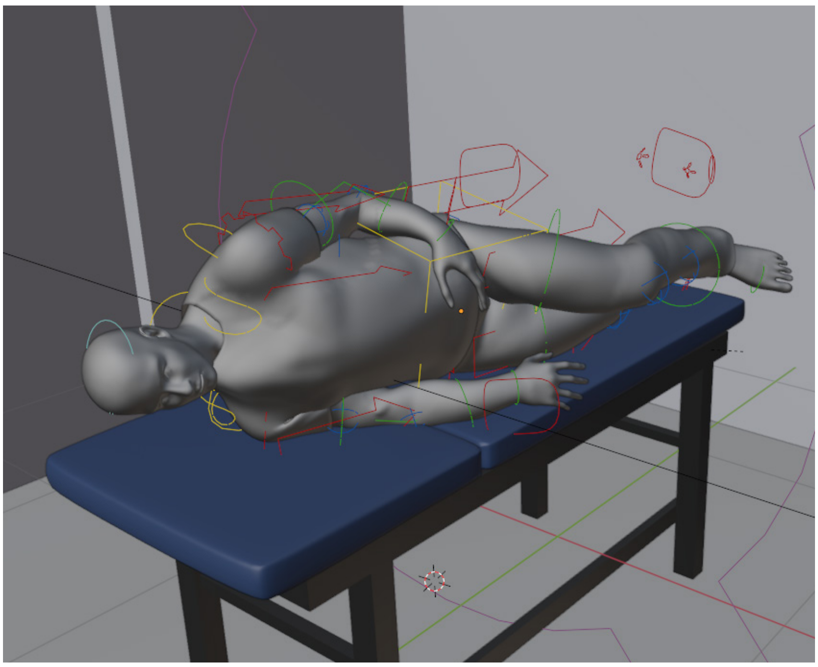


Fig.30: Animating the last step of right Barbecue Roll manoeuvre, when the model is posed trying to get up from lying position and sit on the bed.

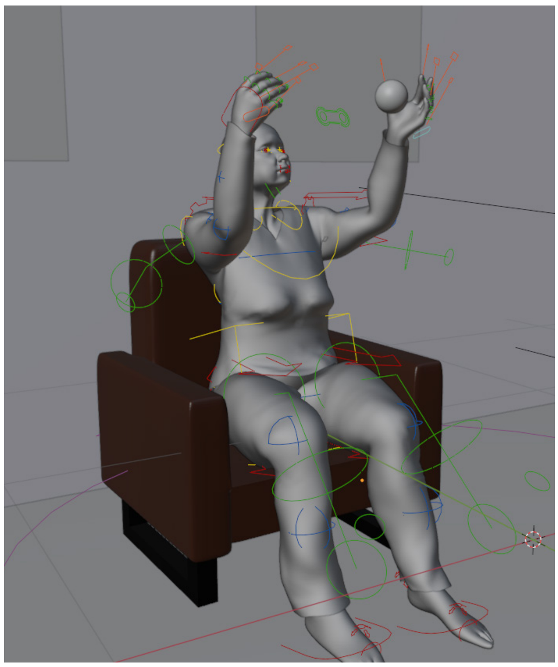


Fig.31: Animating the Cooksey-Cawthorne Level C exercise when the model is throwing a ball from hand to hand above eye level.

were inserted in pose mode for the different stages of the diagnostic tests and canalith repositioning manoeuvres.

The downside of rigging low polycount models in Blender was the loss of mesh detail, which was achieved in ZBrush, such as the eyelid lines. In the animations focusing on the body movement (Dix-Hallpike, Supine Roll, Epley, Barbecue Roll) this was barely noticeable. Nevertheless, if the camera were to zoom in for the nystagmus animations, it would become more obvious. As a result, for the eye animations the high-poly (one million polycount) models were imported in Blender without rigging and only the eyes' location and rotation were animated, to achieve more realistic results (Fig.32).

For the Epley and Barbecue Roll animations of the inner ear both the ear model as well as the otolith's location needed to be considered. Firstly, the ear's rotation was keyframed at the beginning and ending of each step of the manoeuvres at the same timings as the ones used for the human animations. During the time when the ear remained immobile, the parented

Fig 32.: Animating the nystagmus in Dix-Hallpike Test. The model is unrigged, has a high polycount and newly created eyelashes in Blender. The camera focuses on the movement of the eyes.

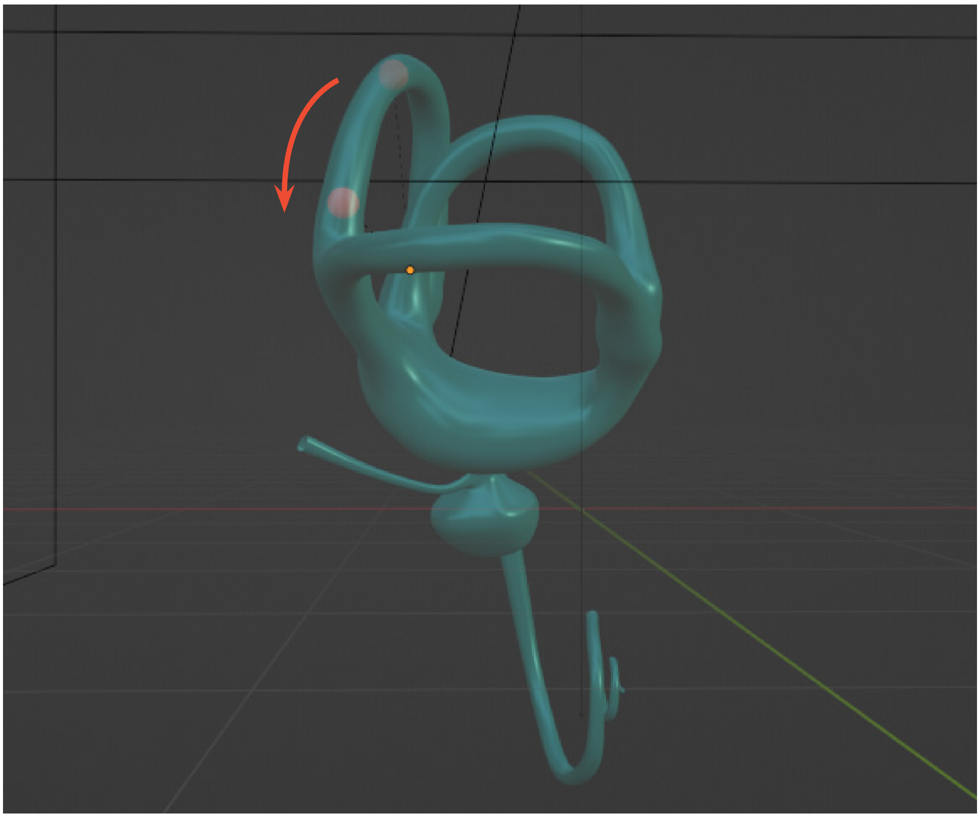


Fig.33: Animating the stone movement inside the ducts. Keyframes for locations were placed at the start and ending location. The red arrow shows the movement of the stone during Step 4 of the left Epley manoeuvre.

otolith's movement was animated (Fig.33). While creating the animations, the focus was on the correct path of the otolith rather than the speed of the movement which could easily be adjusted post rendering.

In total, 18 short animations were rendered in Eevee at 25 fps as mp4 files: Dix-Hallpike, Supine Roll Test, Geotropic horizontal nystagmus left and right, Geotropic Torsional nystagmus, Epley manoeuvre left and right, Barbecue manoeuvre, Inner Ear Animations during Epley and Barbecue and the three levels of Cooksey-Cawthorne exercises in parts. Apart from the last ones, the animations were mirrored to be used in the app for the opposite ear side. Splitting into parts was done by the software developer at a later stage. Finally, using an AI voice, the audible steps for the animations were generated to include in the application, alongside the instructive captions.

Design

When it came to the design of the app, a background image was rendered in Blender, using a simple noise texture node on a purple World colour (Fig.34). The image was then put into Adobe Illustrator v.27.5 where it was textured using a tile pattern (Fig.35). The resulting picture served as a background for the app and the colour picker tool was used to create a palette suiting the 3D ear's colours (Fig.36). In the same software a logo for the app was created (Fig.37). This concluded the individual assets of the app.

Application Development

The programming of the application and ear simulation was done by the collaborator software developer. The simulation of the inner ear was created in Unity after receiving the original file of the 3D ear made in Blender. An otolith was positioned in the horizontal ampulla for the Barbecue Roll manoeuvre and in the posterior ampulla for the Epley manoeuvre. After that, the otolith was given the properties of moving as a rigid body, responding to gravity. The speed of movement was also adjusted, after feedback from the ENT specialist, so it would look like there was resistance in the otolith's movement due to the endolymph. Constraints to movement pass

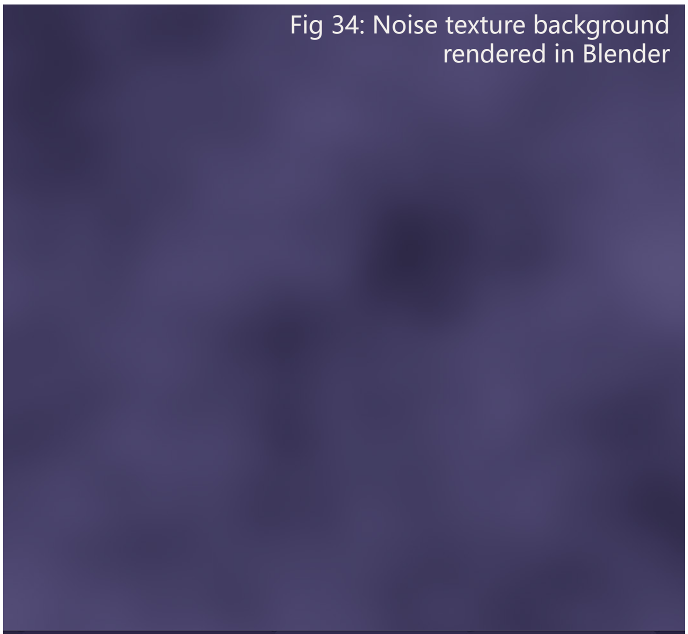


Fig 34: Noise texture background rendered in Blender

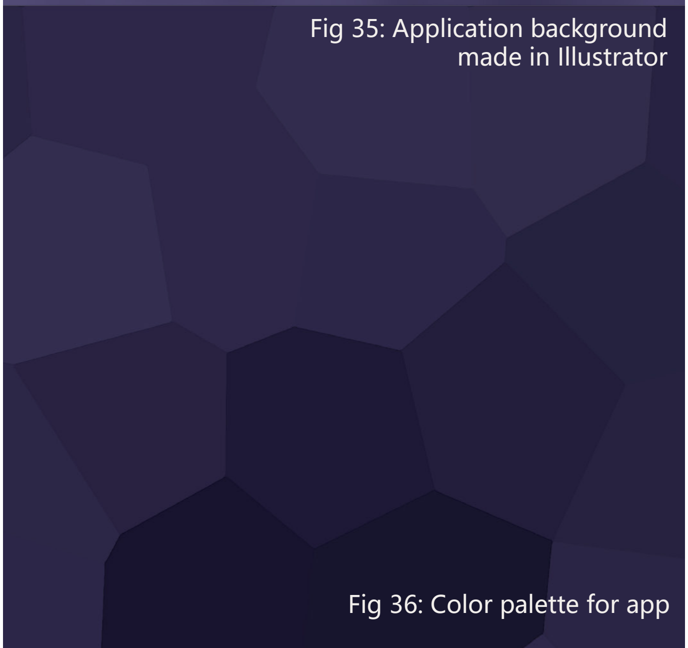


Fig 35: Application background made in Illustrator


Fig 36: Color palette for app

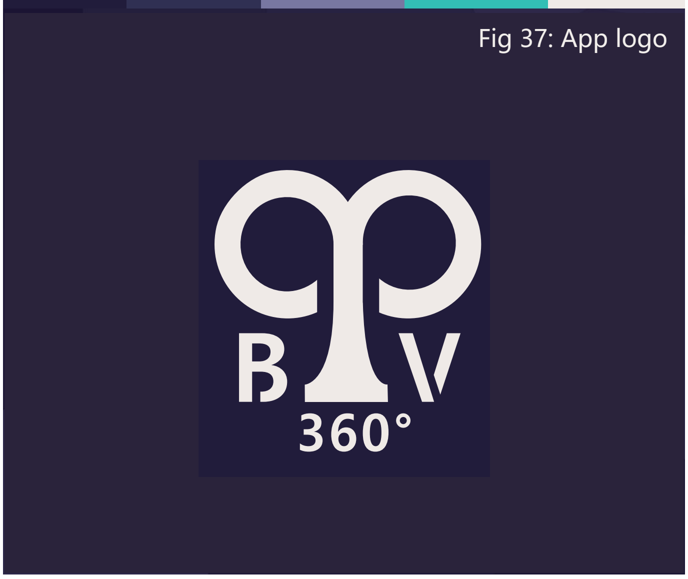
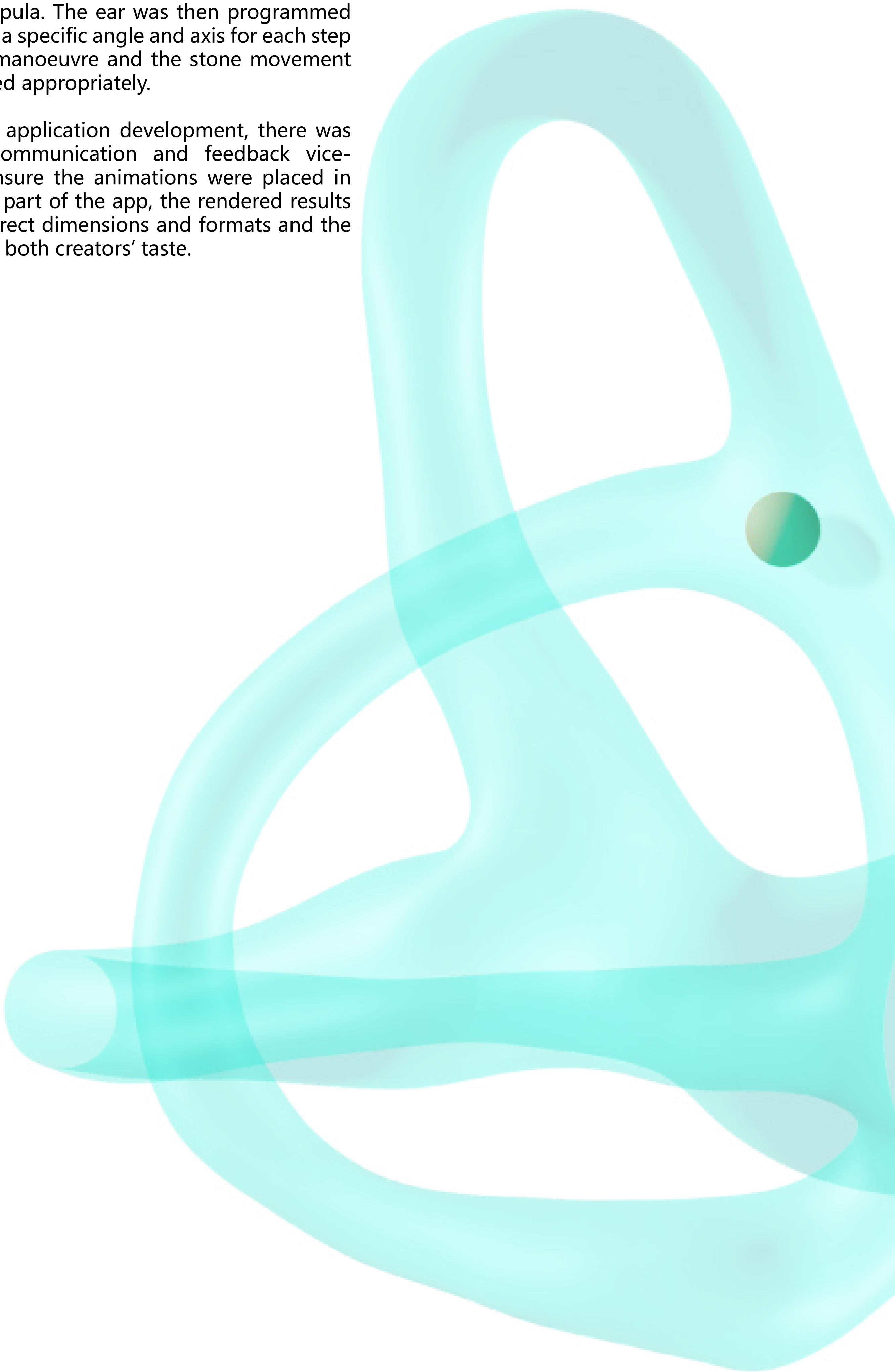
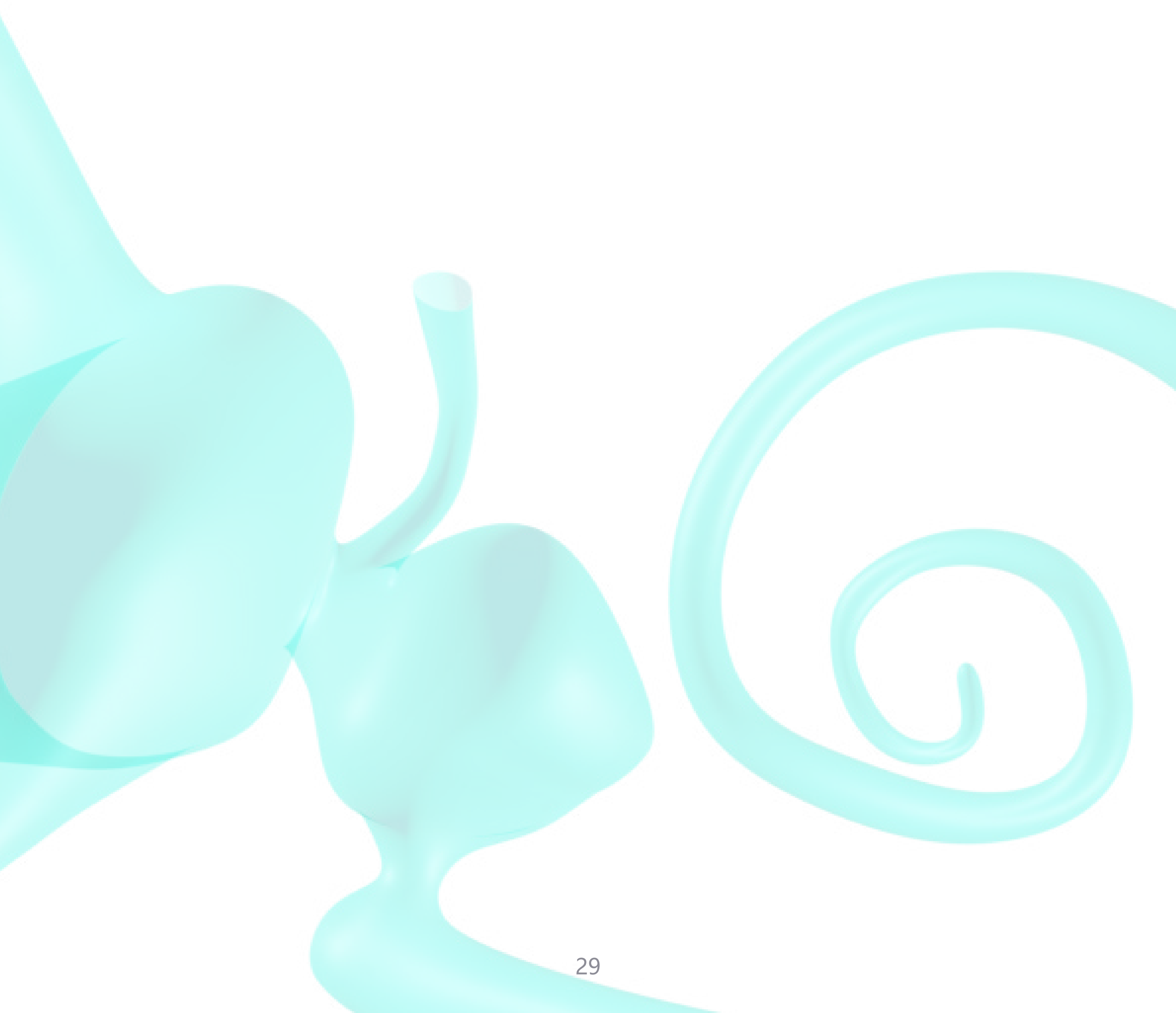


Fig 37: App logo

the ampulla were also created, to simulate the invisible cupula. The ear was then programmed to rotate in a specific angle and axis for each step of the CR manoeuvre and the stone movement was adjusted appropriately.

During the application development, there was constant communication and feedback vice-versa to ensure the animations were placed in the correct part of the app, the rendered results were in correct dimensions and formats and the design met both creators’ taste.





Results

The outcome of this project was a smartphone application containing twenty-two 3D animations distributed into four diagnostic tests for BPPV, four canalith repositioning manoeuvres and three levels of vestibular rehabilitation exercises. The application also contains four options for an interactive ear simulation and information related to the creators and the disease. In addition to that, a promotional video was created and reviewed by a health professional and the completed 3D ear model was uploaded on an online 3D model platform.

Application

Firstly, the app was named “BPPV 360°” to highlight its unique 3D inner ear simulation feature for CRM. At the time of writing, the finished app has been submitted to both the Google Play Store and the iOS App Store and is awaiting evaluation for official release. Meanwhile, the unofficial Version 1.5x (beta) can be downloaded from the software developer’s platform via this link: https://ellinikaprogrammata.eu/bppv360.html. The app size is 249MB, and all descriptions and images refer to version 1.58 (beta).

Upon opening the app, the logo appears in full screen and fades into a disclaimer (Fig.38). At the bottom of the screen the option “Continue” leads to the main menu in horizontal rotation of the screen (Fig.39). The main menu includes the logo on the left upper corner, the app version on the right upper corner, an exit button at the bottom and six options in the middle:

1. About BPPV:
2. Diagnostic Tests:
3. Canalith Repositioning Manoeuvres
4. Practise in 3D
5. Vestibular Rehabilitation
6. Application Information

The “About BPPV” section provides written information on the terminology, pathophysiology, epidemiology, risk factors, differential diagnoses, diagnosis, and management of Benign Paroxysmal Positional Vertigo, along with an anatomical picture of the membranous labyrinth (Fig. 40).

Selecting “Diagnostic Tests” or “Canalith Repositioning Maneuvers” triggers an “Attention” note that informs users of the health professional-specific content and reminds them of potential contraindications and adverse effects (Fig.41).

The “Diagnostic Tests” sumenu options between “Dix-Hallpike” and “Supine Roll Test” (Fig.42). Regardless of choice the user is then asked to select the side of the affected ear (Fig.43). Once both selections are made, the user is guided to the animation of the homonymous test broken down into steps. The human model animations are accompanied by nystagmus animations in a smaller frame (Fig.44-45). At the end of the animation, the screen freezes on the last frame, and the user can exit by clicking “Return.”

The “Canalith Repositioning Maneuvers” submenu offers options between the “Epley Maneuver (Posterior Canal)” and the “Barbecue Roll Maneuver (Horizontal Canal)” (Fig.46). After selecting a maneuver, the user chooses the affected ear side, “Left” or “Right.” The human model animations play in steps at the center of the screen (Fig.47-48). At the end of the animation, the user receives advice on how frequently to perform the maneuver.

During both diagnostic and therapeutic animations, written captions describing the movements appear on the right side of the screen, accompanied by a voiceover.

After each animation step, an option to move to the “Next” step is provided. On the left side of the screen, a “Return” option remains visible to end the animation at any time.

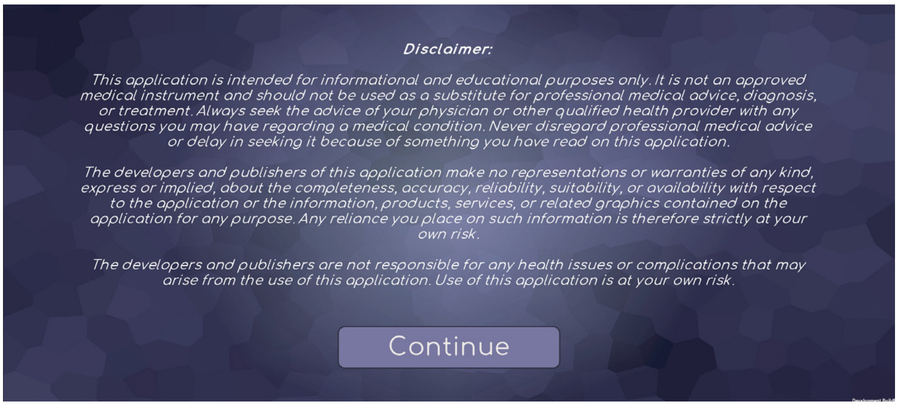


Fig 38: Disclaimer Screen

Fig 39: Main Menu

Fig 40: About BPPV screen

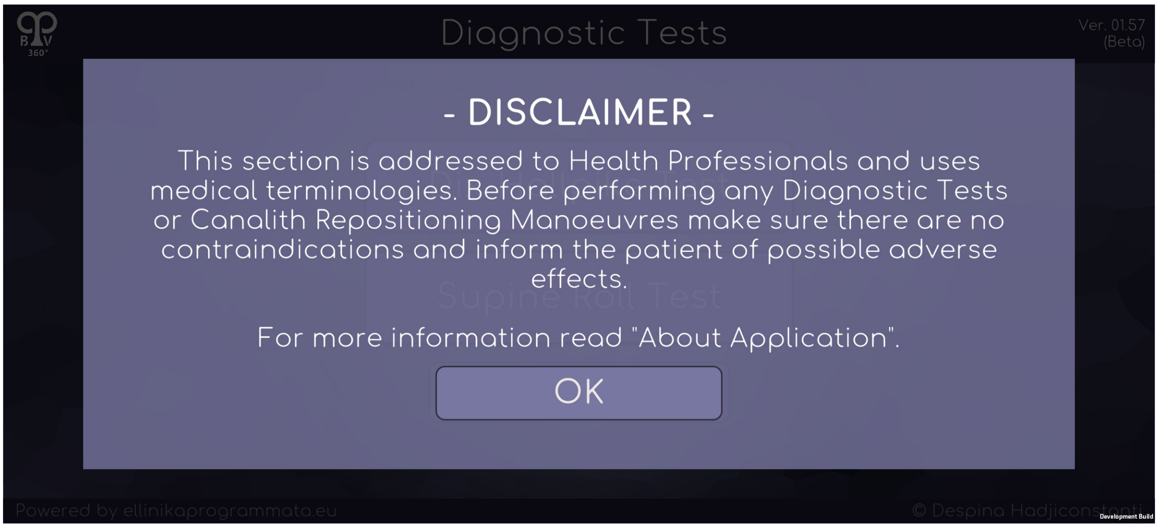


Fig.41: Disclaimer of audience-specific content before entering “Diagnostic Test” and “Canalith Repositioning Manoeuvres” submenus.

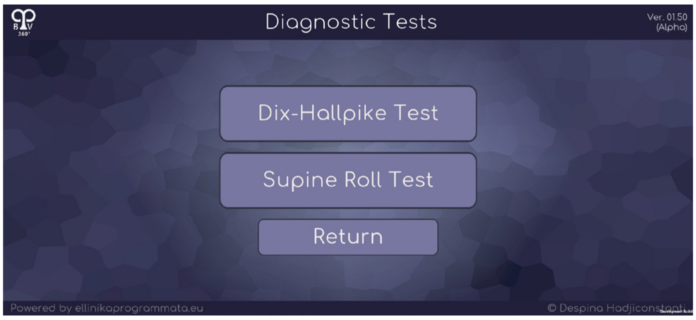


Fig.42: Diagnostic Test submenu

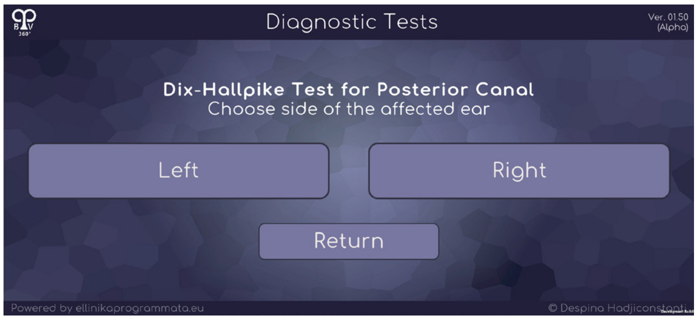


Fig.43: Choosing Side for Dix-Hallpike Test

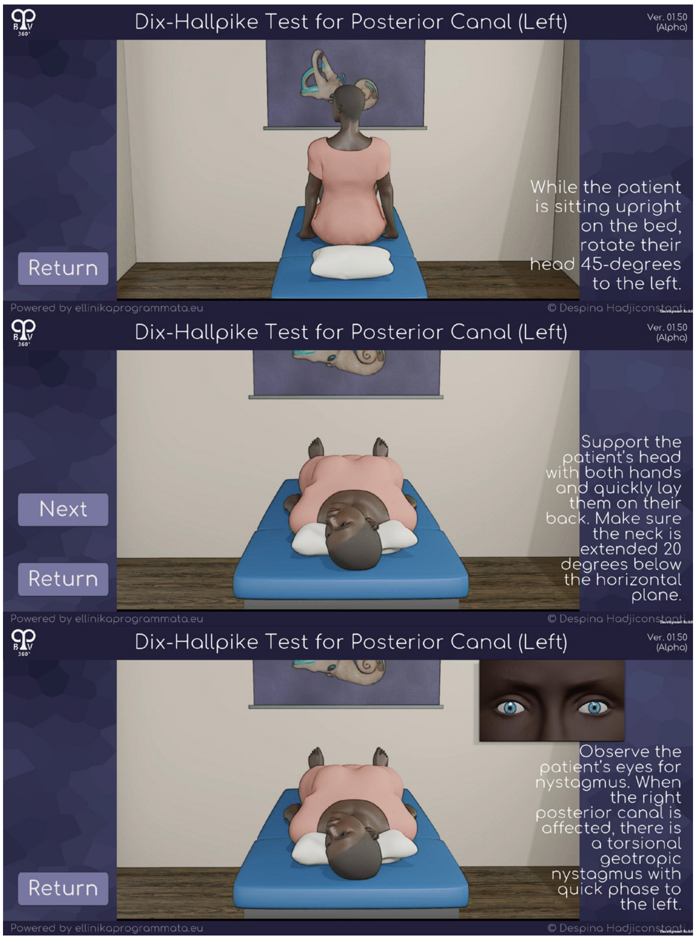


Fig.44: Steps of Left Dix-Hallpike Test animation

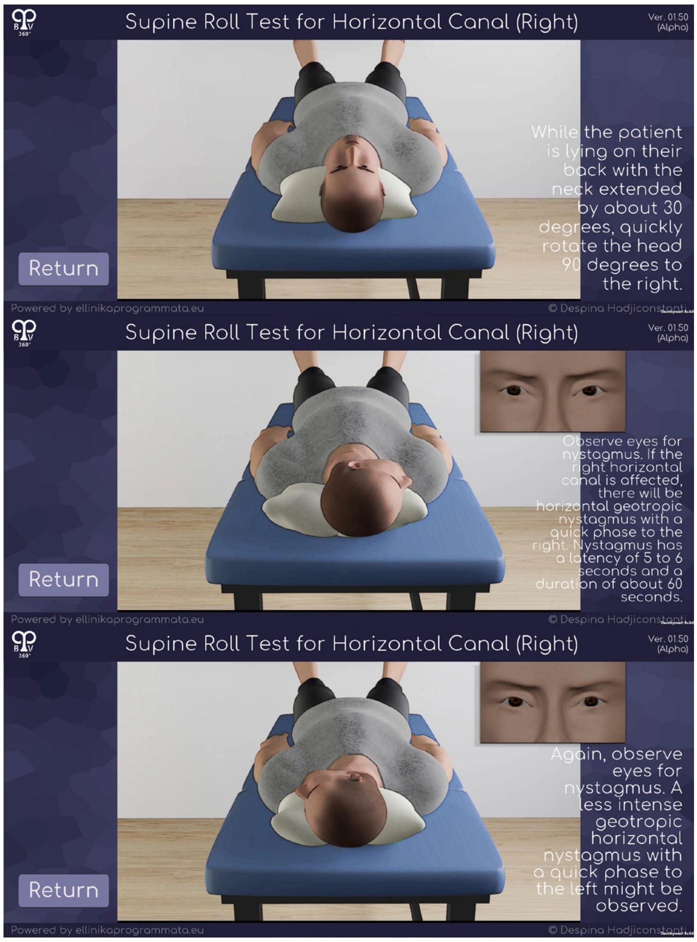


Fig.45: Steps of Right Supine Roll Test animation

Fig.46: Canalith Repositioning Manoeuvres Submenu

Fig.47: Steps of Right Epley Manoeuvre animation

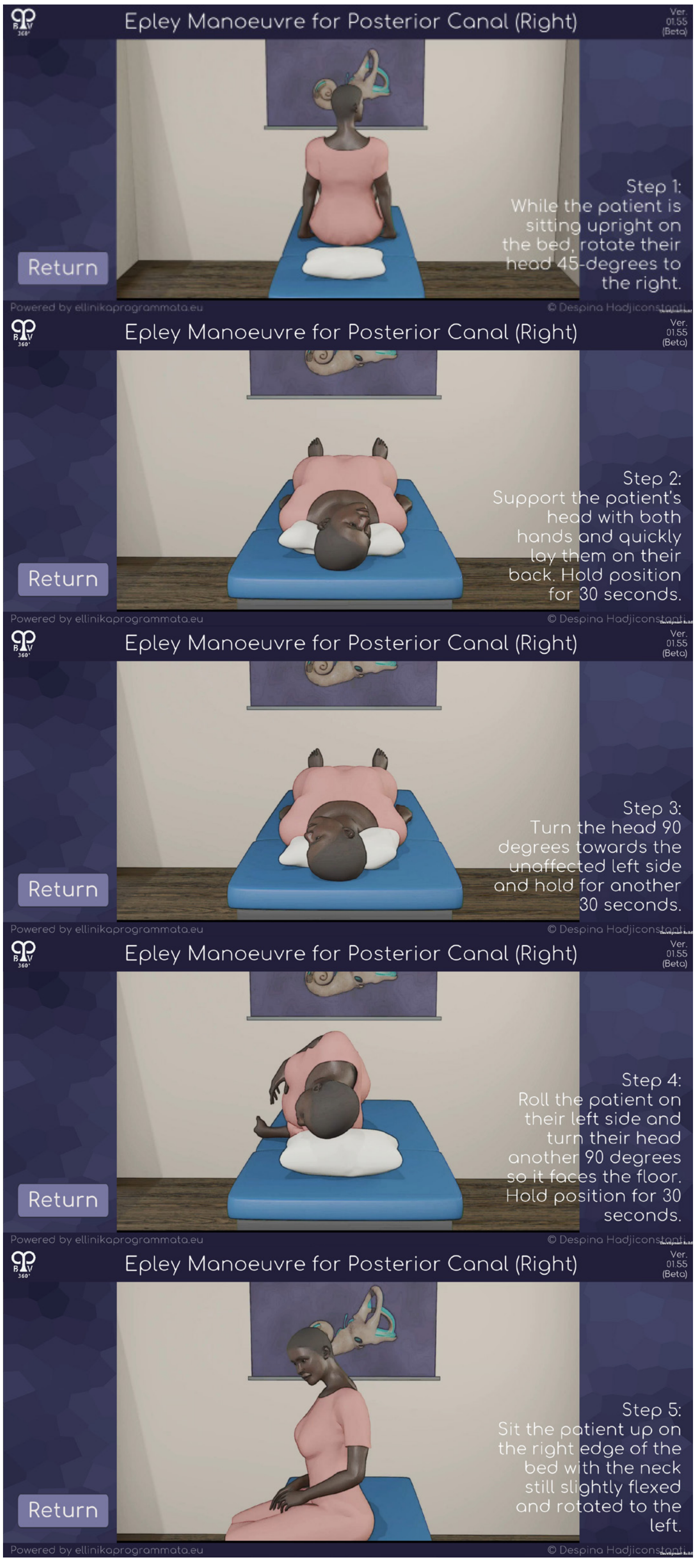
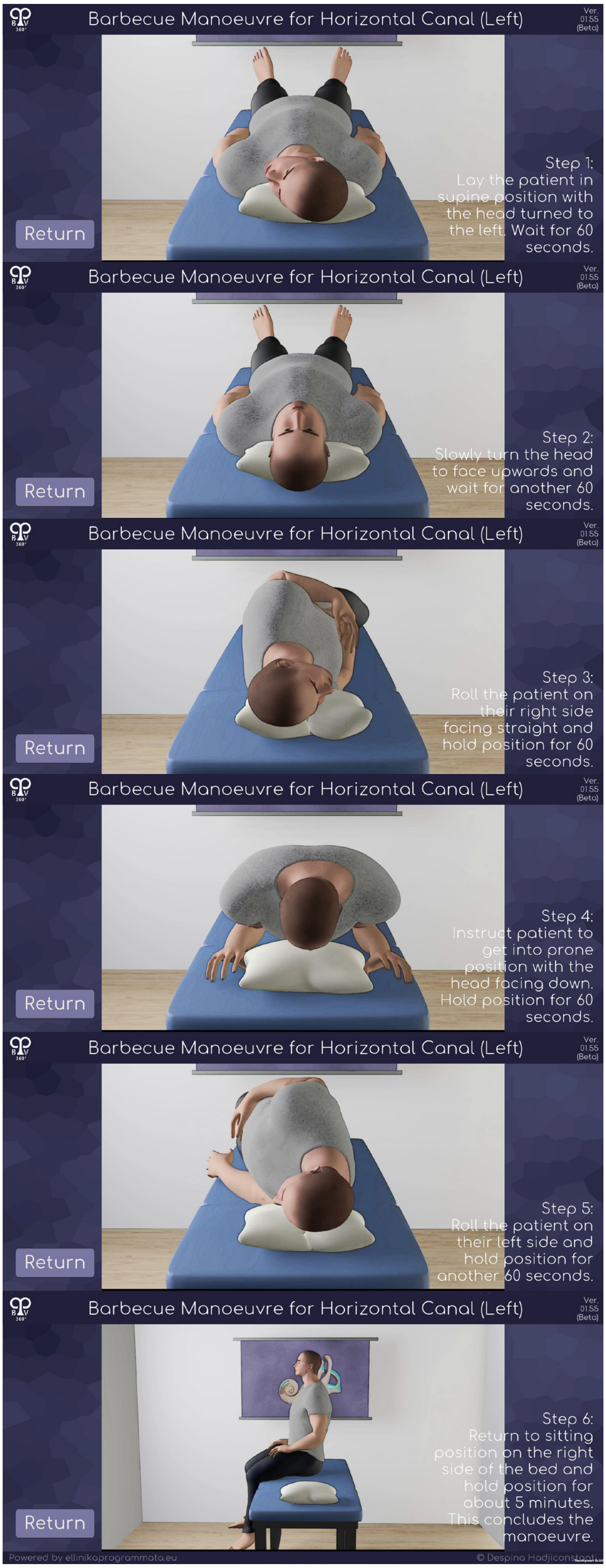


Fig.48: Steps of Left Barbecue Roll Manoeuvre animation



"Practise in 3D" is an interactive section designed to assess the user's recollection of CRP. Users start by selecting one of four options: Epley or Barbecue maneuvers for the left or right ear. A 3D inner ear simulation accompanied by a 3D head then appears on the screen. Users are prompted to choose from three options to determine how the head moves in each step of the maneuver. When the correct choice is made, the ear and head model rotate accordingly, and the ear stone moves inside the canal. The test is split into equal parts as the CRM animations. Once all correct choices are made, the otolith is repositioned back into the utricle, concluding the simulation.

Fig 49. Screenshots of the "Practise in 3D".

From top to bottom:
- Attention Screen before choosing type of CRM with information about the simulation.
- First Step of Right Epley Manoeuvre. The user is asked to pick the correct anser from the list on the left.
- Correct choice selected. Green check mark shows next to it and simulation begins.
- Wrong choices selected. Red X marks appear next to them and no movement of the model is observed.
- Completion of Left Epley Manoeuvre.

Fig.50: Screenshot of “Vestibular Rehabilitation” submenu

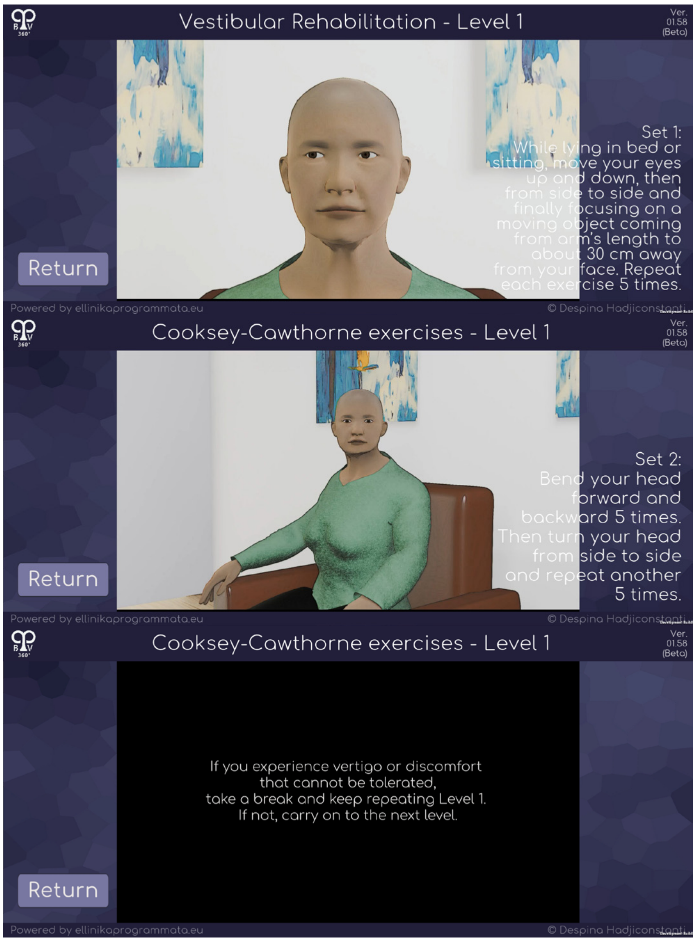


Fig.51: Screenshots of the Cooksey-Cawthorne animations.
Left column: Level 1 exercises
Right column: Level 2 exercises

“Vestibular Rehabilitation” includes animations of three levels of the Cooksey-Cawthorne exercises. Level 1 shows two animations of eye exercises. At the end of the video the user is advised to proceed to the next level only if it is tolerable. Level 2 contains instructions to perform Level 1 exercises in sitting position and two new set of torso exercises. Level 3 contains instructions for the previous levels to be repeated in standing position and four new exercises. When level 3 is completed, the user gets a congratulatory message. Like in the previous animations, the instructions are given in writing and through audio.

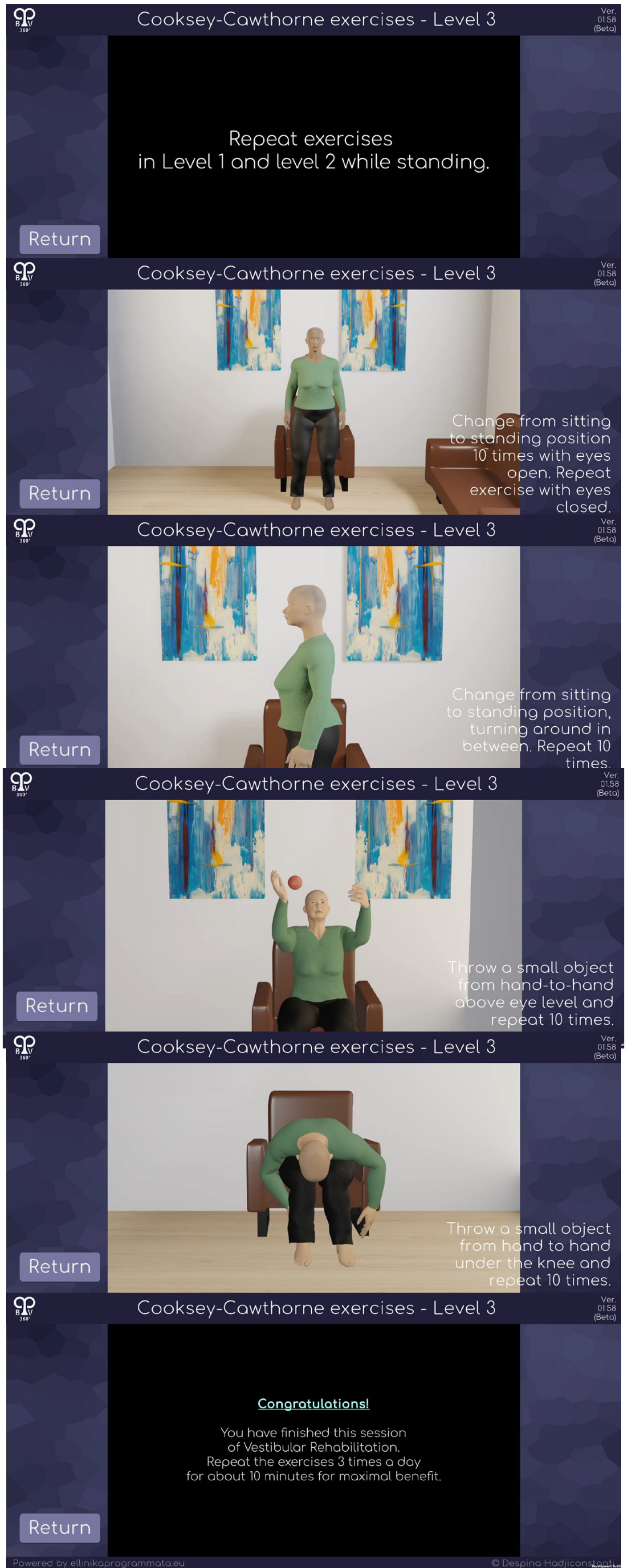


Fig.52: Screenshots of the Cooksey-Cawthorne animations Level 3 exercises

"Application Information" includes details about the version of the app, the purpose of its creation, its goals, precautions of use, adverse effects of the manoeuvres and finally it names the author as a producer and developer, and Ellinikaprogrammata.eu as the software developer.

Fig.53: Combined screenshots of the "Application Information" section (disclaimer on the bottom not in view)

Promotional Video and Feedback

While the application's development was in progress, a promotional video was created by the software developer. This video was sent to the ENT fellow who had been giving feedback during the 3D modelling. He praised the product, stating "The images and animations are great!". He also mentioned that the ENT Department would be interested in using them in their GP referral guide. A modified version of the video will also be projected during the Masters Exhibition .

Finally, the 3D model of the inner ear was uploaded on Sketchfab where it was annotated, emphasizing on the membranous labyrinth and a visible otolith inside the posterior cupula. It can be viewed on this link: https://skfb.ly/oZAMQ.

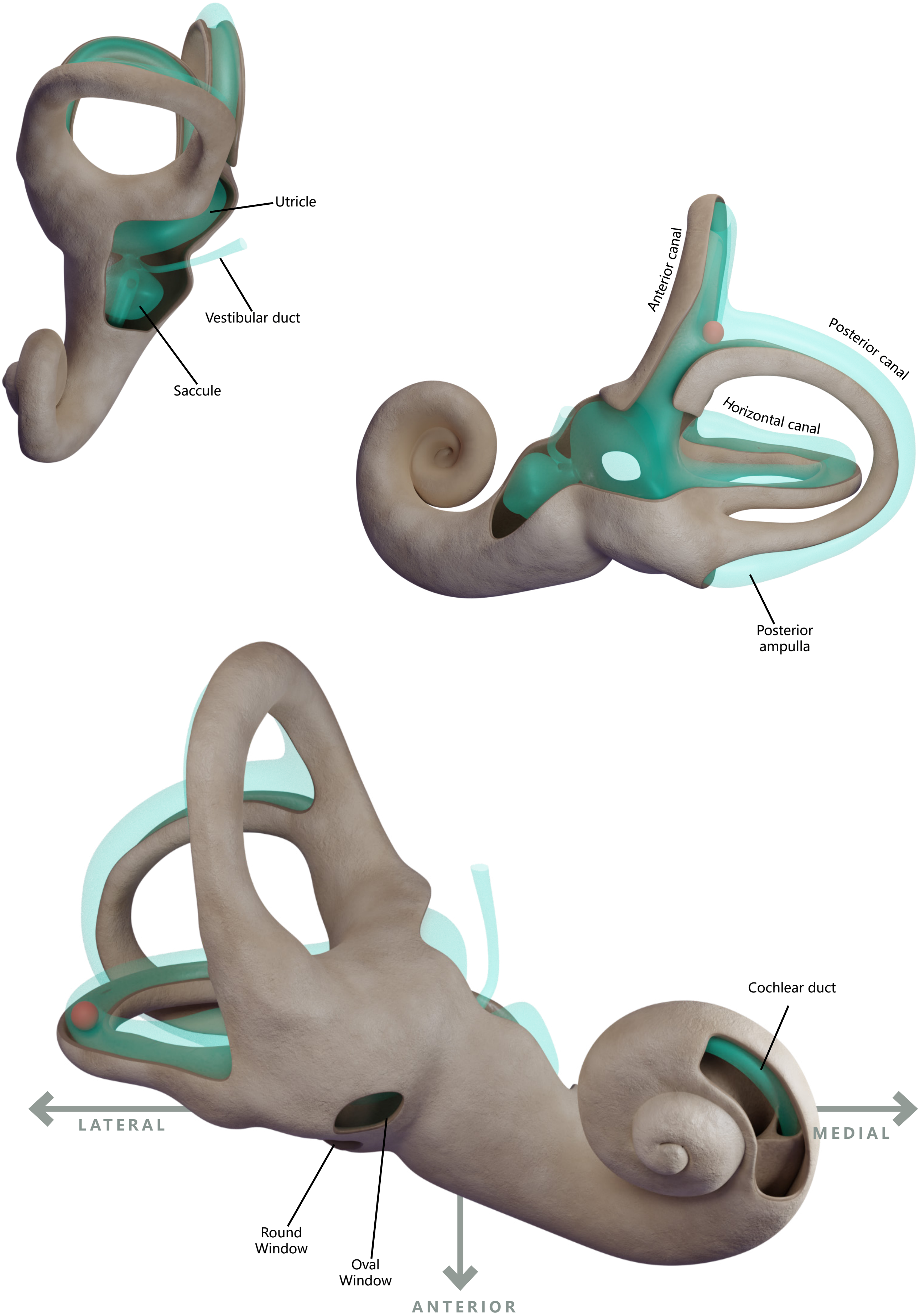


Fig.54: Rendered images of the 3D right inner ear model with anatomical annotations.
Left top image: Superior view
Right top image: Medial-posterior view
Bottom image: Anterior view

Discussion

This application aimed in serving as an educative tool for diagnosis of BPPV and comprehension of canalith repositioning manoeuvres based on the anatomical position of the inner ear. At the same time, it aimed in offering practice opportunities for health professionals to test their skills. Moreover, it aimed in being an affordable and accessible option for patients to perform vestibular rehabilitation by providing engaging step-by-step 3D animations. The final goal was to instruct patients how to perform CRP on their own and reaffirm their technique, by designing a 360-degree simulation of the otoliths moving in the inner ear. Overall, the final product has successfully fulfilled most of the set goals, leaving some room for improvement.

Although the current version of the application has only one user interface addressing both audiences, the sections remain clear to whom they are intended for. This was achieved by providing written warnings before the beginning of each animation and by the tone of language used. Thus, diagnostic and therapeutic techniques are addressed to health professionals whilst all the other sections are addressed to both audiences. This distinction was made even for the CRM animations, which may be performed by patients. The reason for that, was the choice for language consistency in the diagnostic process of BPPV, which brings therapeutic manoeuvres after the diagnostic tests. Therefore, the instructions for both cases are addressing health professionals in the setting of an office by saying for example "Instruct the patient to..." or "Turn the patient's head to the...". The use of medical terms, such as "flexed neck", also made the section less fitting for the public. Patient users are still free to view the CRM animations, but the warning signs are there to clarify that "This section is addressed to Health Professionals..." . The animations about Vestibular Rehabilitation, on the other hand, are clear, don't use difficult medical language and address the patient directly, for example "Turn your head..." or "pick up objects from the floor". This adaptation in language for each animation serves in distinguishing between the audience-specific sections in the app.

The creation of 3D patient animations effectively facilitated the understanding of diagnostic tests and therapeutic maneuvers for BPPV. For starters, the back view of the patient during the manoeuvres closely resembles an actual office setting, making the animations relatable to health professionals. For the general public using the CRM animations for home treatment, this back view corresponds to the side of the user's body, ensuring that the movements align with the written instructions. This design choice aims to minimize confusion regarding the direction of movement for each technique. Moreover, both the diagnostic tests and the CRM animations are broken down into clear, manageable steps, further enhancing user comprehension and application.

At the same time, the application provides an accessible and user-friendly guide for Vestibular Rehabilitation at home. The home scene, featuring an elderly woman performing VR exercises, was designed to replicate a comfortable home environment, distinguishing it from the more clinical aspects of the app. Furthermore, the Cooksey-Cawthorne exercises were split into three levels and additionally into multiple steps for each level, allowing users to follow along based on their tolerance.

This project has also successfully introduced diversity into the models used for each animation. The three models aspired to be different from each other as well as diverse from the commonly used Caucasian male. The modeling incorporated a range of skin colors, ethnic backgrounds, and age-related features. The practical need for light eye colours which do not match most people with black or Asian heritage, also helped represent a minority of the human population which is often not included in common medical artwork. This approach not only enhanced the inclusivity of the app but also promoted broader representation in medical artwork.

In addition, the application tried to address users with accessibility needs. To do so, instructions for the step-by-step animations were given in three forms: visual, written, and audio. While the 3D animations took up the majority of the screen, the movement was also explained with captions on the side. A large font was used for the captions to enhance readability. Simultaneously, the captions were read aloud by a voiceover, catering to users who prefer audio over written information. These adjustments aimed to ensure that the app could be easily used by a diverse range of users, including those with visual or reading impairments.

The only aspect of the application which did not meet the expectations was the idea of the 3D ear simulation due to time limitations. However, even if the plan for manual rotation of the ear model could not be accomplished, the alternative function of utilizing multiple choice to simulate the Epley and Barbecue manoeuvre still managed to fulfil an unset goal. It has given a practical opportunity for users to test how well they remember each step of the manoeuvres. At this moment, this function cannot serve as a practice tool for clinical skills. Nor can it be used for patients while lying in bed performing the manoeuvres to reassure them of their technique. Nevertheless, as long as the users know which direction the otolith is supposed to follow within the canal, they can make their choices not just by memory but based on logic. Consequently, this section can be used by users looking to test their recollection of the steps of CRMs, but also by those who wish to gain a deeper understanding of the anatomical reason behind their sequence.

Conducting a survey during the masters show from the public was a personal goal that could not be accomplished. Due to the animation process taking longer than anticipated, and the resulting changes to the app, it was no longer feasible to ask the public for formal comments. However, users who download the app from Play Store or App Store will be able to give a star rated review and comments on the platforms if they choose to. Therefore, eventually some feedback from the public might be expected.

Nonetheless, feedback from health professionals has been received and seems extremely positive. Based on the comments, it is believed that BPPV 360° will be a practical and useful application for the patients suffering from BPPV.

The objectives of offering a tool to reassure patients about their CPR technique and to help health professionals practice their clinical skills are still pending. That is why, plans for future updates have already been made to enhance the application's effectiveness and user experience. Eventually, the current application will become focused on the health professional community and a new patient-specific version of the app will be released. These updates will include advanced simulation features for professionals and tailored guidance for patients. Ultimately, the app will continue to evolve, shaped by the valuable feedback from both health professionals and patients.

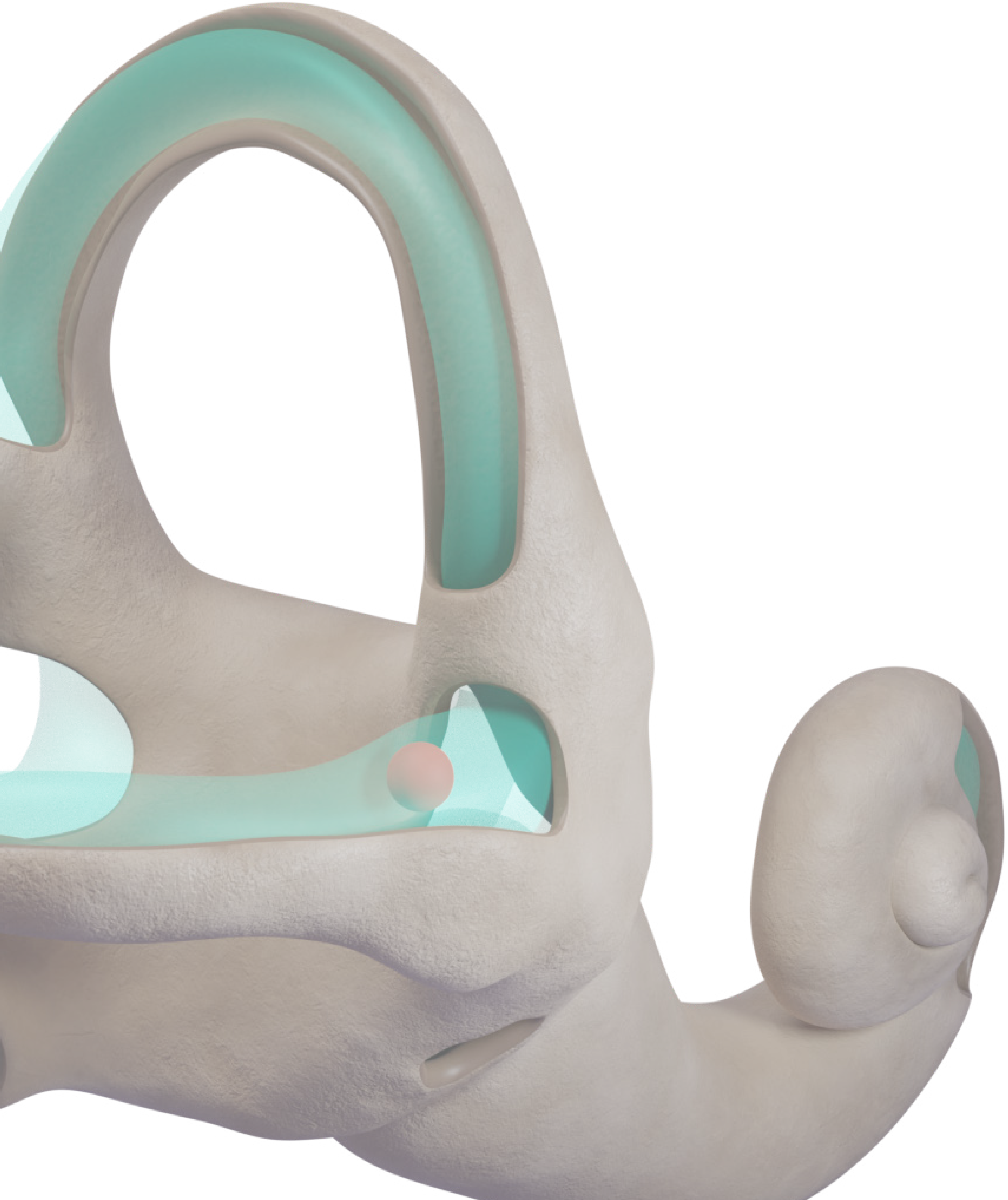
Conclusion

Benign Paroxysmal Positional Vertigo, although manageable, remains challenging for health professionals to treat by remembering canalith repositioning manoeuvres effectively. At the same time, patients struggle with recurrent attacks, financial burden and lower quality of life. Home treatment is a good solution with effective visual materials after official diagnosis has been made. Health professionals' issues and patient's needs led to the creation of an accessible educative tool for diagnosis and management of BPPV by utilizing the anatomy of the inner ear. For the purpose of this project, 3D modelling, and animation were chosen to make an interactive, visually appealing and user-friendly smartphone application.

Many of the goals of this project have been met and plans for updates have already been set. The feedback received from ENT specialists is enthusiastic and reassuring of the app's use and promotion once it has officially been released. So, it can be concluded that this application will serve as a valuable guide and practise tool for health professionals who are looking to improve their skills in diagnosing and managing BPPV. Finally, it is going to act as an encouraging and appealing vestibular exercise coach for the home treatment of vertigo.

"[...] the animations look great! We would love to use them in our GP (General Practitioner) *referral guide".*

~NHS Ear Nose and Throat Specialist



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