Computational fluid dynamics simulation of pressure and velocity distribution inside Meniere's diseased vestibular system

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Abstract. Meniere's disease or known as endolymphatic hydrops is an incurable vestibular disorder of the inner ear. This is due to the excessive fluid build-up in the endolymphatic sac which causing the vestibular endolymphatic membrane to start stretching. Although this mechanism has been widely accepted as the likely mechanism of Meniere's syndrome, the reason for its occurrence remains unclear. Thus, the aims of this study to investigate the critical parameters of fluid flow in membranous labyrinth that is influencing instability of vestibular system. In addition, to visualise the flow behaviour between a normal membranous labyrinth and dilated membranous labyrinth in Meniere's disease in predicting instability of vestibular system. Three dimensional geometry of endolymphatic sac is obtained from Magnetic Resonance Images (MRI) and reconstructed using commercial software. As basis of comparison the two different model of endolymphatic sac is considered in this study which are normal membranous labyrinth for model I and dilated membranous labyrinth for model II. Computational fluid dynamics (CFD) method is used to analyse the behaviour of pressure and velocity flow in the endolymphatic sac. The comparison was made in terms of pressure distribution and velocity profile. The results show that the pressure for dilated membranous labyrinth is greater than normal membranous labyrinth. Due to abnormally pressure in the vestibular system, it leads to the increasing value of the velocity at dilated membranous labyrinth while at the normal membranous labyrinth the velocity values decreasing. As a conclusion by changing the parameters which is pressure and velocity can significantly affect to the instability of vestibular system for Meniere's disease.

1. Introduction

Prosper Meniere first described the symptom complex known as Meniere's disease in 1861. In 1938, Hallpike and Caims first proposed an underlying mechanism of periodic endolymph fluid accumulation or known as endolymphatic hydrops as a cause of the hearing loss and vertigo in the disorder. Although this mechanism has been widely accepted as the likely mechanism of Meniere's syndrome, the reason for its occurrence remains unclear [1].

Meniere's disease or endolymphatic hydrops is a disorder of the inner ear that causes severe dizziness or known as vertigo, ringing in the ears or tinnitus, hearing loss, and a feeling of fullness or congestion in the ear. Meniere's disease usually affects only one ear. Attacks of dizziness may come on suddenly or after a short period of tinnitus or muffled hearing. Based on Sajjadi & Paparella (2008), some people will have single attacks of dizziness separated by long periods of time while others may experience many attacks closer together over a number of days. Some people with Meniere's disease have vertigo. so extreme that they lose their balance and fall. These episodes are called "drop attacks" [2].

There are four symptoms that causes by elevated pressure in the endolymph which are (a) fluctuating sensorineural hearing loss, (b) occasional episodic vertigo, (c) tinnitus, and (d) aural fullness. Meniere's disease is alternatively called as endolymphatic hydrops due to the swelling seen in histologic sections of the endolymphatic space [3].

Meniere's disease is a common inner ear disease characterized by vertigo, hearing loss, and tinnitus. According to Yokota et al (2015), 80-90% of cases with Meniere's disease can be controlled by medication and/or modification of their life style. However, 10-40% of cases unilateral Meniere's disease gradually becomes bilateral year by year. Bilateral disease is associated with the development of profound bilateral sensor neural hearing loss, resulting in mental illness more often than unilateral one. Bilaterally and mental disorder are the main causes to make treatments for Meniere's disease much more difficult. For this reasons, Meniere's disease was designated as a specific disease by Japan's Ministry of Health, Labour, and Welfare in 1957 [4].

1.1. Membranous labyrinth

Like most of the hollow organs, the membranous labyrinth is lined with epithelium which is a sheet of specialized cells that covers internal and external body surfaces. It is filled with a fluid called endolymph, which has a markedly different ionic content from perilymph. As shown in the figure 1, the endolymph and perilymph are not mix because the membranous labyrinth is a closed system.

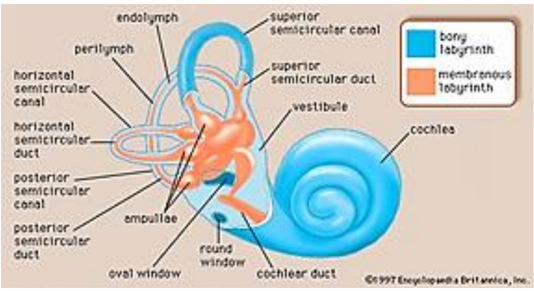

Figure 1: The labyrinths in the inner ear [5]

The two membranous sacs of the vestibule, utricle and saccule, are known as the otolith organs. Each sac has on its inner surface a single patch of sensory cells called a macula, which is about 2 millimetres (0.08 inch) in diameter and which monitors the position of the head relative to the vertical. In the utricle the macula projects from the anterior wall of that tubular sac and lies primarily in the horizontal plane.

In the saccule the macula is in the vertical plane and directly overlies the bone of the inner wall of the vestibule. In shape it is elongated and resembles the letter J. Each macula consists of neuroepithelium, a layer that is made up of supporting cells and sensory cells, as well as a basement membrane, nerve fibres and nerve endings, and underlying connective tissue. The sensory cells are called hair cells because of the hairlike cilia-stiff, nonmotilestereocilia and flexible, motile kinociliathat project from their apical ends. The nerve fibres are from the superior, or vestibular, division of the vestibulocochlear nerve [6].

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2. Methodology

2.1. Computational fluid dynamics

Computational Fluid Dynamics (CFD) is based on the solution of the fundamental conservation laws of mass, momentum and energy in a set of partial differential equations (PDEs). The set of PDEs, coupled to initial and boundary conditions, is solved by numerical methods and discretization techniques of the domain such as the finite volume method and finite different equation method [7]. The governingequation for the endolymph flow is theNavier-Stokes equations. As shown below, equation 1 represented for momentum equation while equation 2 is continuity equation for incompressible.

$$-\nabla \mathrm{p(x)} + \mu\nabla^2 u(x) = f(x,t) \quad (1)$$

$$\nabla \cdot u(x) = 0 \quad (2)$$

With no slip boundary conditions at the wall; t is the time, $x = (x_1,x_2,x_3)$ are the coordinates, and pand $u = (u_1,u_2,u_3)$ are the pressure and the velocity of the fluid, respectively.

2.2. Geometry of the inner ear

A magnetic resonance imaging (MRI) scan is an imaging test that uses powerful magnets and radio waves to create pictures of the body. This study used MRI of human inner ear where is the image is importedfrom commercial software so called 3D Slicer software (http://www.slicer.org) [8].

The 3D Slicer software shows in three different planes where it mimicsthe real model. To get the image of human inner ear this study use crop volume properties from the software and crop from the MRI scan of human head. To generate the model it follows the selected region and the model is generated by the software. The 3D modeling was used in this study as geometry as shown in the figure 2.

Figure 2: Geometry of the inner ear

2.3. Modelling and meshing

The modeling of magnetic resonance image (MRI) is reconstructed using commercial software. The modelingis converted to .iges format to make it compatible to the ANSYS software (Canonsburg, PA, USA) which is used for the simulation. This software manages to analyse multiple, automated parametric.

The mesh of model is started by setup the size. The more advance size function is set on the proximity and curvature while the reference canter is set as fine. To get more accurate resultanalysis, the total of node is determined and the model is meshed smoothly. Two main commandswhich are patch conforming method and inflationare finalizedto make the model meshed completely and suitable for the analysis. The process of meshing is very important stage where the total value of node, element, and the shape of each element connected can give different result. From the shape element it also shows the pattern flow in the model. The mesh operation are performed with the all the data requirement such as the spacing for each element and the surface at wall. Figure3 show the final meshing of the model geometry.

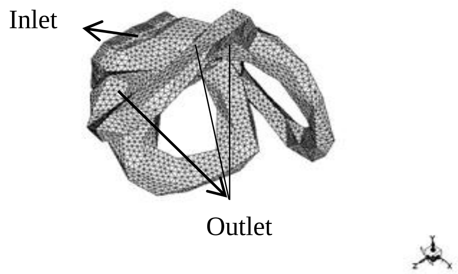

Figure 3: The meshing of the inner ear

2.4. Boundary condition setup
Before running the solver, all boundaries must be initialized and specialized by specified parameters as illustrated in Table 1. Four different pressure were imposed in this study are 200 Pa, 313.6Pa, 400 Pa and 500Pa. Normal pressure of 313.6 Pa was simulated as a basis of comparison. All of the pressure values are absolute pressure.

Table 1: Physical and geometrical parameters [9, 10]

Fluid Properties	Boundary Condition Value
Rate Production (Flow Rate), Q	0.36 l/min
Density, ρ	998 kg/m^3
Viscosity, μ	0.001003 kg/ms^2
Hydrostatic pressure for healthy inner ear, p	205.8 Pa
Hydrostatic pressure for Meniere's Disease, p	200 Pa 313.6 Pa (Reference Value) 400 Pa 500 Pa

3. Result and discussion

3.1. Flow characteristics
The analysis was divided into two models which is model I for normal membranous labyrinth in Meniere's disease while model II represent dilated membranous labyrinth in Meniere's disease ear. The models are classified as a closed system. Flow characteristics are done to investigate the critical parameters of fluid flow which is the pressure distribution and velocity profile in membranous labyrinth that is influencing instability of vestibular system. The visualization flow is shown by the contour results images from the post-processing.

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3.1.1 Normal membranous labyrinth. In normal condition the endolymphatic hydrostatic pressure at the inlet is 205.8Pa. Figure 4illustrates the pressure contour obtained for model I. As shown in figure 4, the pressure distribution of the inner ear is constant shown by green colour contour which the value obtained is 4.508x10^{-15}Pa. The changing of colour pressure occurred mostly in the outlet part.

Figure 5 shows the velocity contour results for model I. The endolymph enters through the inlet and exit to three outlets. From the figure, it shows that high velocity occurs at one of the outlet which the value obtained is 5.266 m/s. At the other parts the endolymphs flow with very low velocity movement.

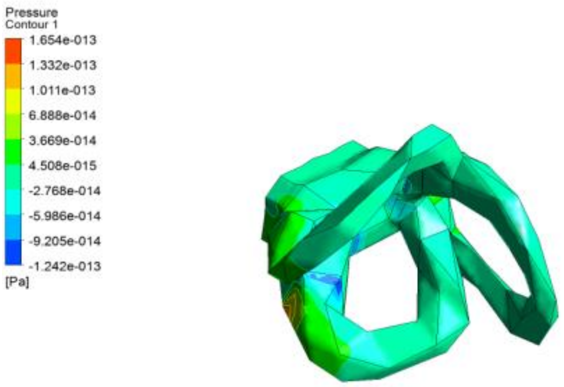


Figure 4: Pressure distribution of endolymph flow in model I

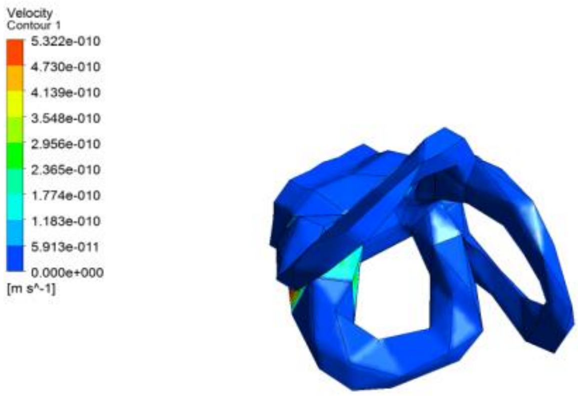
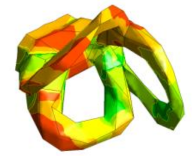
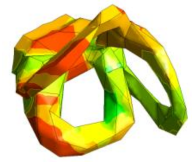
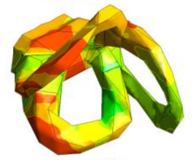
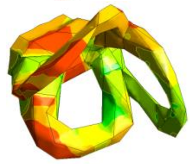


Figure 5: Velocity profile of endolymph flow in model I

3.1.2 Dilated Membranous Labyrinth. Next, comparison between pressure distribution and velocity profile in dilated membranous labyrinth are shown below.For dilated membranous labyrinth in Meniere's disease condition the endolymphatic hydrostatic pressure at the inlet is 313.6Pa.

Figure6 shows the pressure distributions in the inner ear with different pressure value. From the observed, the pressure distribution of inner ear is not much different for each pressure value. The differentpressure values are expected to influence the pressure distribution in the inner ear. However, the higher pressure is expected to increase the possibility of abnormality in the inner ear which leads to dulled hearing. When look at the graph contour at the outlet area, it can see that at the pressure of 200 Pa it shows redder contour then the other pressure does. In addition, the colour contour are changing vary with the distance due the movement of the endolymph in the inner ear.

Figure 7 shows the velocity profile in the inner ear based on different pressure value. Similar to pressure distributions, the velocity profile of the inner ear shows similardistributions for each pressure value. The distribution of the inner ear is observed to be dominated near the outlet part as illustrated in figure 7. The velocity profile at the wall is mostly constant shown by the blue contour and the higher velocity obtained at the outlet.

Pressure (Pascal)	Pressure Distribution
200	
313.6	
400	
500	

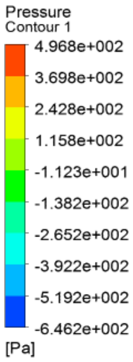
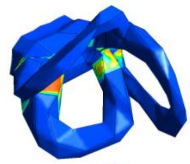
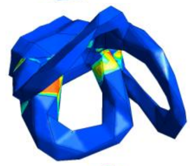
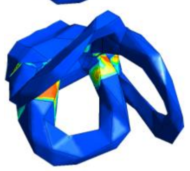
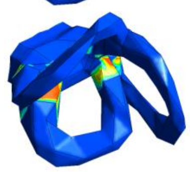


Figure 6: Pressure distributions of inner ear as illustrate 200 Pascal, 313.6 Pascal, 400 Pascal and 500 Pascal.

Pressure (Pascal)	Velocity Profile
200	
313.6	
400	
500	

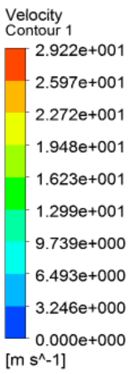


Figure 7: Velocity profile of inner ear as illustrate 200 Pascal, 313.6 Pascal, 400 Pascal and 500 Pascal.

3.2. Pressure distribution

Pressure comparison is done to compare the flow behaviour between a normal membranous labyrinth and dilated membranous labyrinth in Meniere's disease in predicting instability of vestibular system. Based on the figure 8, it shows the pressure comparison between normal membranous labyrinth and dilated membranous labyrinth against distance from inlet to outlet part. The figure shows a pressure fluctuation pattern for both models. For the dilated membranous labyrinth graph, it shows when the distance is increased, the pressure values is increase then decrease and vice versa. The pressure values are not the same at all points in the inner ear. Considering Pascal's Law, a change in pressure at any point in an enclosed fluid at rest is transmitted undiminished to all points in the fluid but it holds for static fluids essentially.

Clearly illustrated in the figure, for a normal membranous labyrinth, the pressure values obtained do not have so much difference between each other's. In normal membranous labyrinth, there is no endolymph build-up in the labyrinth that interferes with normal balance and hearing signals which results to a constant pressure. Based on the figure, the pressure for dilated membranous labyrinth is greater than normal membranous labyrinth. The highest pressure value achieved for both model is at distance 0.109 meter where the pressure value for model one is 0.568 Pascal and the value for model two is 5.036 Pascal. Meanwhile, the lowest pressure obtained for model one is 0.107 Pascal at distance 0.136 meter and for model two the lowest pressure is 1.091 Pascal at distance 0.096 meter.

Therefore, we can say that for a person having a Meniere's disease there will be increasing pressure inside the inner ear compared to normal person. The increasing pressure inside the inner ear is a reason why the vestibular endolymphatic membrane to start stretching and causes swelling of the labyrinth. This abnormality is the factors that lead to instability of vestibular system.

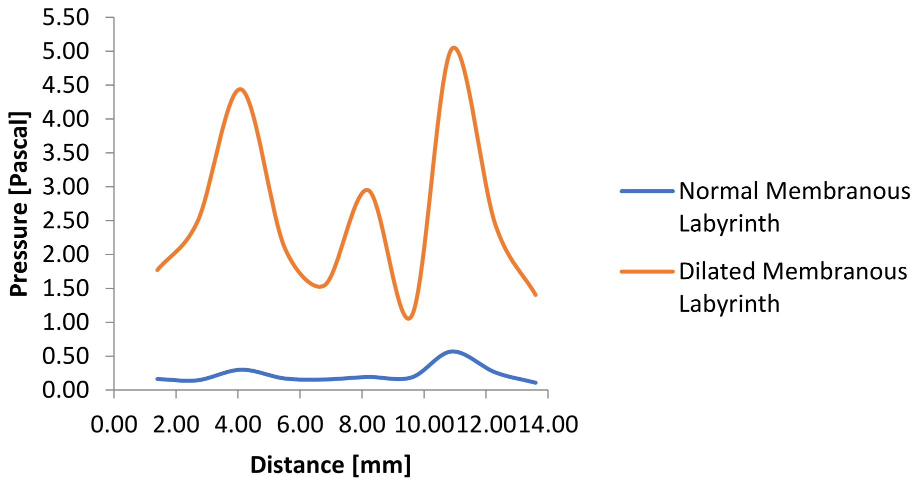


Figure 8: Pressure distribution between model I and model II

3.3. Velocity Profile

Velocity comparison is done to compare the velocity flow between a normal membranous labyrinth and dilated membranous labyrinth in Meniere's disease in predicting instability of vestibular system.

Figure 9 show the velocity comparison between model I and model II. The pattern of graph between dilated membranous labyrinth and normal membranous labyrinth is likely similar at distance between 0 to 0.08 meter which is the value is decreasing. However, at distance 0.082 meter the normal membranous labyrinth continued to decrease while for dilated membranous labyrinth the value increase rapidly and it decrease back at distance 0.136 meter. Due to abnormally increased pressure in the vestibular system it leads to the increasing value of the velocity at dilated membranous labyrinth.

The lowest velocity value for normal membranous labyrinth is 0.004 m/s while for dilated membranous labyrinth the value is 0.012 m/s.

From the figure 9 it shows that the velocity for dilated membranous labyrinth is lower than normal membranous labyrinth. Moreover from the pressure comparison as discussed earlier the dilated membranous labyrinth having higher pressure compare to normal membranous labyrinth. We can conclude that, the results obtained are valid as it applied the concept of Bernoulli's Principle. The higher the pressure of the fluid the lower the velocity it exerts. Fluid pressure is caused by the random motion of the fluid molecules. When the fluid speeds up, some of the energy from that random motion is used to move faster in the fluid's direction of motion. This results in a lower pressure.

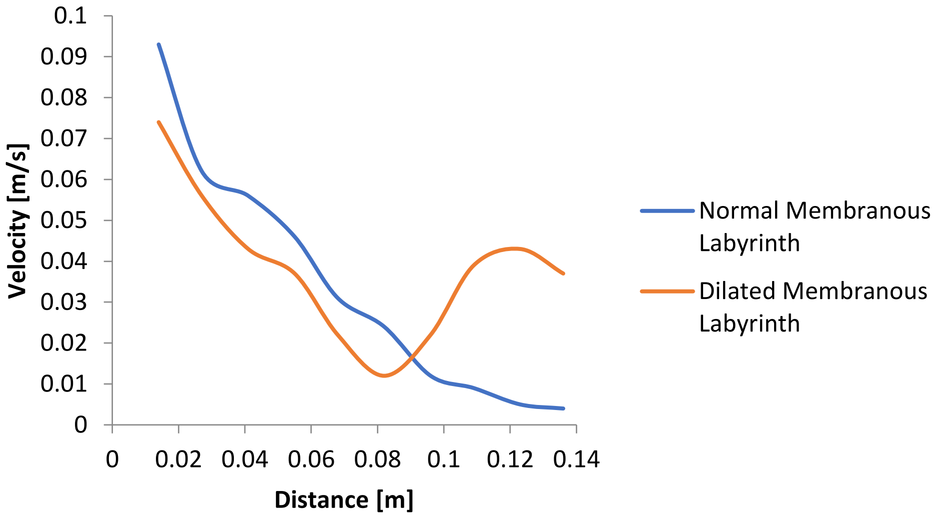


Figure 9: Velocity profile between model I and model II

4. Conclusion

The pressure and velocity of fluid flow can significantly affect to the instability of vestibular system for Meniere's disease. Since there is limited previous study about pressure and velocity parameters, this study refers based on the concept of Bernoulli's principle and Pascal's Law. Based on the results obtained, it shows that by changing the parameters can affect the fluid flow inside the vestibular system. The surface and space of vestibular labyrinth is also a factor that can affect the endolymph flow. For dilated membranous labyrinth it has abnormal increasing pressure compare to normal membranous labyrinth. As the pressure in the inner ear increase the velocity of the fluid flow is decrease.

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