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Flow behaviour in normal and Meniere's disease of endolymphatic fluid inside the inner ear

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Abstract. Meniere's disease is a rare disorder that affects the inner ear which might be more severe if not treated. This is due to fluctuating pressure of the fluid in the endolymphatic sac and dysfunction of cochlea which causing the stretching of vestibular membrane. However, the pattern of the flow recirculation in endolymphatic region is still not fully understood. Thus, this study aims to investigate the correlation between the increasing volume of endolymphatic fluid and flow characteristics such as velocity, pressure and wall shear stress. Three dimensional model of simplified endolymphatic region is modeled using computer aided design (CAD) software and simulated using computational fluid dynamic (CFD) software. There are three different models are investigated; normal (N) model, Meniere's disease model with less severity (M1) and Meniere's disease model with high severity (M2). From the observed, the pressure drop between inlet and outlet of inner ear becomes decreases as the outlet pressure along with endolymphatic volume increases. However, constant flow rate imposed at the inlet of endolymphatic showing the lowest velocity. Flow recirculation near to endolymphatic region is occurred as the volume in endolympathic increases. Overall, high velocity is monitored near to cochlear duct, ductus reuniens and endolymphatic duct. Hence, these areas show high distributions of wall shear stress (WSS) that indicating a high probability of endolymphatic wall membrane dilation. Thus, more severe conditions of Meniere's disease, more complex of flow characteristic is occurred. This phenomenon presenting high probability of rupture is predicted at the certain area in the anatomy of vestibular system.

1. Introduction

Meniere's disease is an incurable vestibular disorder in the inner ear characterized by a triad of vertigo, tinnitus or ringing in the ear and sensorineural hearing loss by the Committee of Hearing and Equilibrium of American Academy of Otolaryngology [1]. Meniere's disease usually affects only one ear and attacks of dizziness may come suddenly or after a short period of muffled of hearing or tinnitus.

Meniere's disease is also a form of episodic endolymphatic hydrops that produces recurring set of symptoms as a result of abnormally large amount of a fluid called endolymph collecting in the inner ear. This endolymphatic hydrops is instability of pressure difference between endolymph and perilymph caused by the dysfunction of cochlear [2]. People who effected with the disease have extremely severe dizziness which also known as vertigo lead to loss of their balance and suddenly fall.

The build-up of excess fluid in the vestibular system of the inner ear, called endolymph is also one of the causes for the symptoms of Meniere's disease. As the excess endolymphatic fluid keeps increasing, the volume inside the membranous labyrinth increases. The membranous labyrinth is also called as endolymphatic wall membrane. The membranous labyrinth covers the endolymphatic fluid from the cochlear duct to ductus reuniens, utricle, endolymphatic duct, saccule, ampullae and semicircular canals as seen in figure 1 with black shaded region [3]. A high dilation of the membranous labyrinth is tending to break which allows the mixing of perilymph and endolymph [4]. This mixing is actually one of endolymphatic hydrop factor that cause injury to the hair cells producing characteristic symptoms such as vertigo, tinnitus and hearing loss [5].

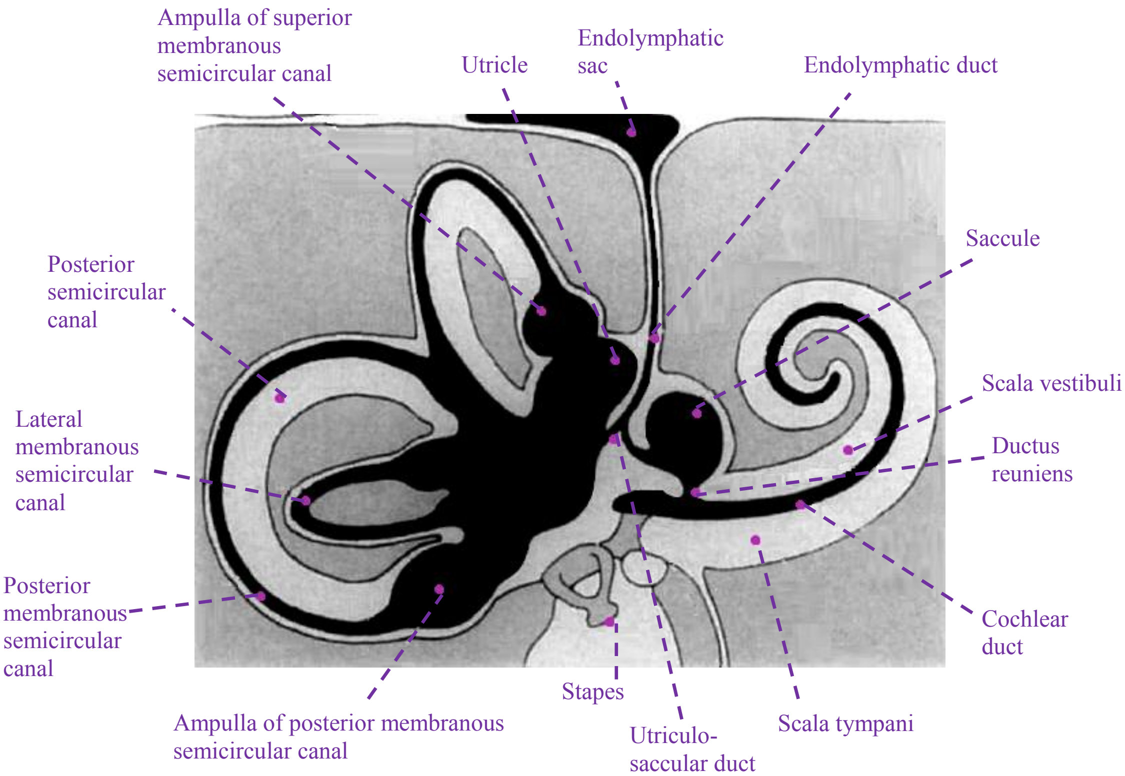

Figure 1. Schematic drawing of inner ear which endolymphatic fluid is black region, temporal bone is grey region and perilymph is white region [3].

Furthermore, the dilation of the endolymphatic wall membrane could be detected through the method of computational fluid dynamic (CFD) which is numerical analysis on flow characteristics. The main parameter of flow characteristic to determine critical area of high dilation probability is wall shear stress which is due to high velocity of the viscous endolymphatic fluid flow [6, 7]. The most commonly used commercial CFD software nowadays is ANSYS (Canonsburg, PA, USA) that can predict the flow characteristics of fluid flow. In 2012, Boselli et al did a study on vestibular system focussing on utricle and ampulla in determining the area with high probability of dilation. From the study, the geometrical model ellipticity of the cross-section plays a fundamental role in the shear stress distribution [8].

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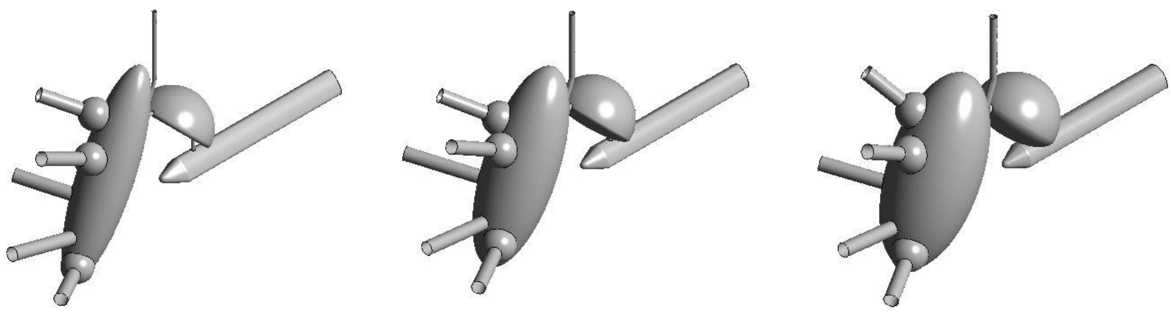
The existence of the CFD analysis could facilitate the medical practitioner in order to detect the critical area for treatment. Currently, the Meniere's disease still don't have a cure but there are some recommendation for the treatments that given by the doctor. This recommendation only helps the patient to control the disease. Doctor always prefers medication to control the disease because this way can relieve dizziness and shorten the attack. There is other treatment such as salt restriction and diuretics, cognitive therapy, injections, alternative medicine and most use is surgery. The surgery extremely effective and control vertigo in about 95% of operated patients. There is two way of surgery exist that is through ear canal and one more is through the mastoid bone behind the ear. The operation through the mastoid will removes dysfunctional balance organ and allows the tiny nerves from the balance organ been cut.

From scientist's research, an estimation ratio of six from ten people get better by their own and also control their vertigo with drug, diet and devices, and only some people get relief with Meniere's disease only by going surgery. Many researches are developing an ear device and studying about the relationship between endolymph volume and inner ear function in process of reduce or eliminate dizziness. Thus, the present study is established to investigate the correlation between the increasing volume of endolymphatic fluid and flow characteristics such as velocity, pressure and wall shear stress inside the three dimensional inner ear simplified model by using numerical analysis of CFD.

2. Methodology

2.1. The simplified model of vestibular system

Figure 2 shows the simplified model of vestibular system for all three cases which are normal (N), meniere's disease 1(M1) and meniere's disease 2 (M2). The models are drawn by using computer aided design software which is SOLIDWORKS (Dassault Systèmes Solidworks Corporation, Waltham, MA). M2 model is representing more severe disease than the M1 model. For each of the inner ear model, only seven components are focused in the endolymphatic region of the vestibular systems as shown in figure 3 and table 1. The dimensions of the model are based on the previous research that has been done by Buckingham et al in 2001 and Krombach et al in 2005 [3, 9]. However, a specific model on arrangement of the vestibular anatomy has not been studied anywhere. Thus, the arrangement of the vestibular anatomy for this study is only an approximation based on literature study to facilitate the parametric study [10, 11].



(a) (b) (c)

Figure 2. The different model of simplified vestibular system, (a) normal (N), (b) Meniere's disease (M1) and (c) Meniere's disease (M2).

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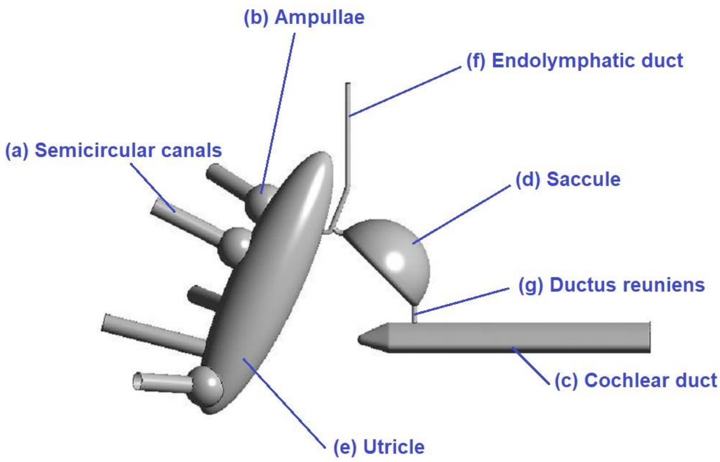
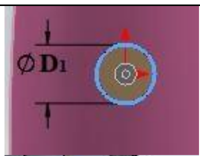
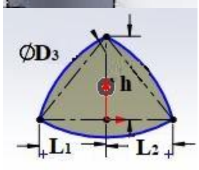
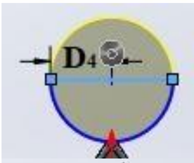
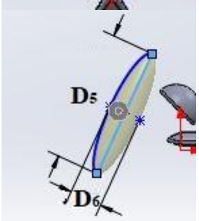
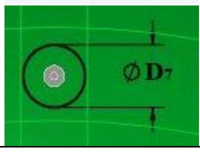


Figure 3. The simplified of vestibular system components.

Table 1. Dimension of the simplified computational model [3, 9].

Anatomy	**Shape**	**Model drawing**	**Dimensions (mm)** Model N	Model M1	Model M2
(a)	cylinder		D=0.34	D=0.37	D=0.40
(b)	sphere		D_2=0.80	D_2=0.90	D_2=1.00
(c)	cylindrical triangle		D_3=1.60 h=0.50 L_1=0.40 L_2=0.40	D_3=1.20 h=0.50 L_1=0.40 L_2=0.40	D_3=0.90 h=0.50 L_1=0.40 L_2=0.40
(d)	hemisphere		D_4=1.00	D_4=1.10	D_4=1.20
(e)	oval		D_5=5.50 D_6=1.35	D_5=5.50 D_6=1.93	D_5=5.50 D_6=2.50
(f)(g)	cylinder		D_7=0.10	D_7=0.15	D_7=0.20

2.2. Meshing of vestibular model

The geometry is meshed up to sufficient number of nodes make sure it can be run in the ANSYS solver which called as ANSYS FLUENT 16.1. Usually, the different numbers of node in the meshed up model affects the result computed by the ANSYS solver. Thus, a Grid Independent Test (GIT) as shown in figure 4 is done to get accurate result without consuming much time by the ANSYS solver. A normalized error is analyzed from the error of current mesh by referencing to the previous mesh. The GIT setting that has 842672 nodes is chosen for the lowest average normalized error of 0.311 percent compared to other settings that have 0.314 percent by the 483961 nodes and 0.529 percent by the 1294742 nodes. The chosen GIT setting of the generated mesh can be seen in Figure 5.

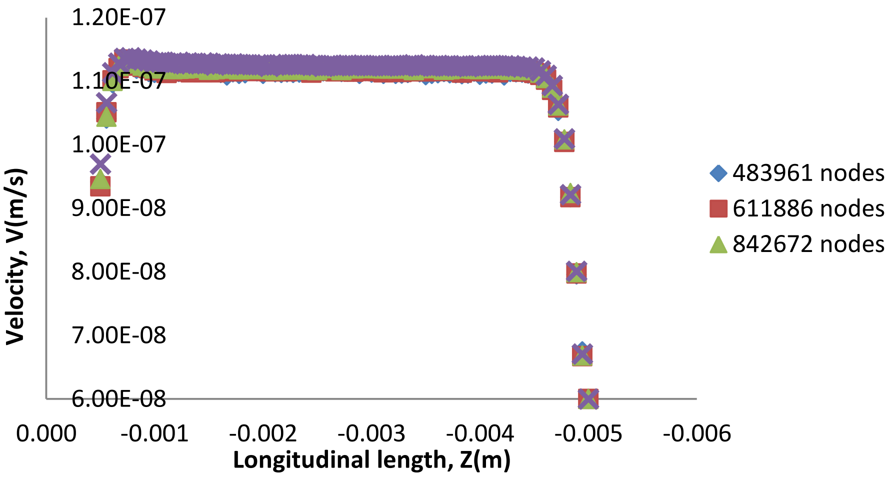


Figure 4. GIT of meshed up model.

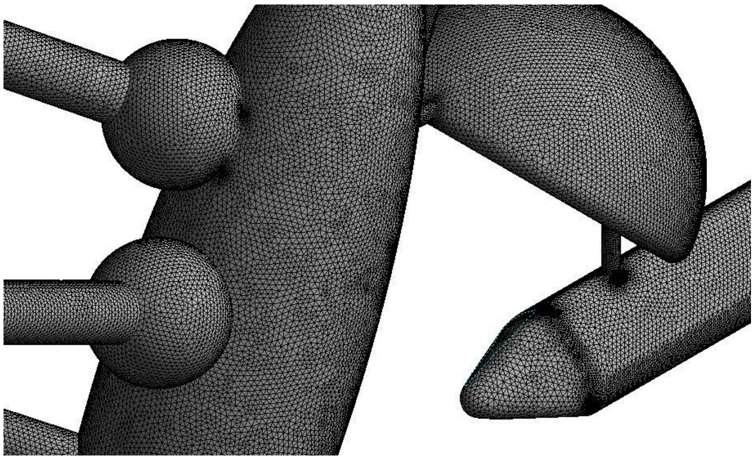


Figure 5. Generated mesh of the geometry.

2.3. Parameter assumptions and boundary conditions

Endolymphatic fluid is assumed as incompressible and Newtonian fluid which mimicking the mechanical properties of water that has an average density of approximately 1000 kg/m^3 and kinematic viscosity of 10^{-6} m^2/s [12, 13]. The endolymphatic membrane wall is assumed to be rigid and no slip condition. The given inflow from the cochlear duct is 0.00112 mm^3/min [14]. The mean outlet pressure of N model condition is 2.8 cm H_2O while the Meniere's disease condition of M1 model is 3.2 cm H_2O and M2 model is 3.6 cm H_2O [15]. Steady flow is considered into the analysis of endolymphatic effect on different volume of endolymphatic region. Figure 6 shows the stated boundary conditions of the computational model. The viscous model used is Shear Stress Transport (SST) in order to capture the visualization of flow recirculation.

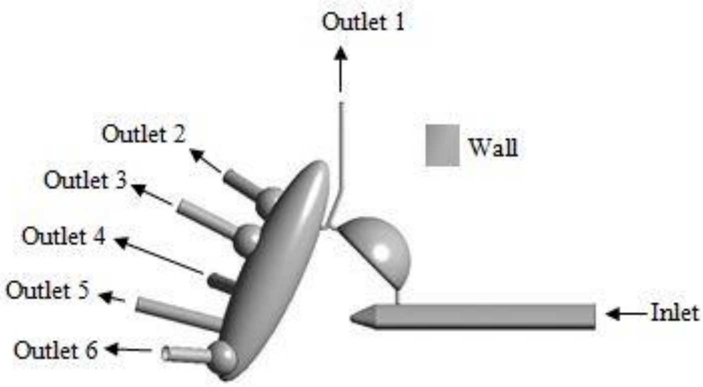


Figure 6. Boundary condition of simplified model.

2.4. *Velocity profile validation*

Present study is validated through the endolymphatic velocity profile inside semicircular canal of previous research by Boselli et al and Grieser et al in 2012 as shown in figure 7 [8, 16]. From figure 7, the error differences are taken at L_0 equals to 0.125, 0.375, 0.625 and 0.875. Thus, the mean percentage error of present study as compared to the previous study by Boselli et al is 8.12 percent while Grieser et al is 8.36 percent.

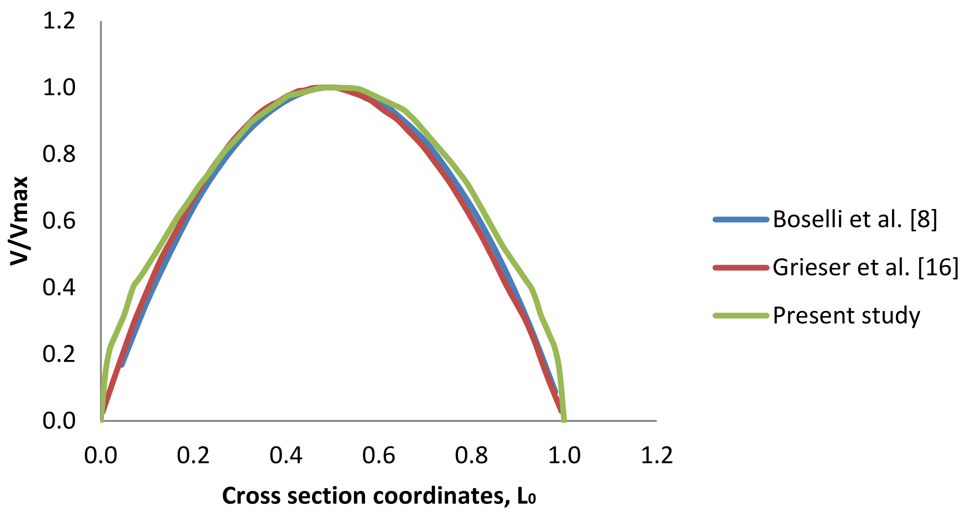


Figure 7. Validation of velocity profile in semicircular canal for both numerical and experimental study.

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3. Result and Discussion

3.1. Pressure drop in vestibular models

M1 model is designed to be 75% larger than N model, while M2 model is 169% larger than N model. The designed model is set along with outlet pressure according to the disease severity and the result at the endolymphatic wall membrane could be seen in figure 8. Although the pressure looks qualitatively constant, the increased volume of endolymphatic fluid gives low pressure drop. If the pressure drop reaching zero as shown in figure 9, the high pressure from inlet will remains constant till reaching the outlets. Thus, the wall membrane becomes easier to be dilated causing more severe Meniere’s disease.

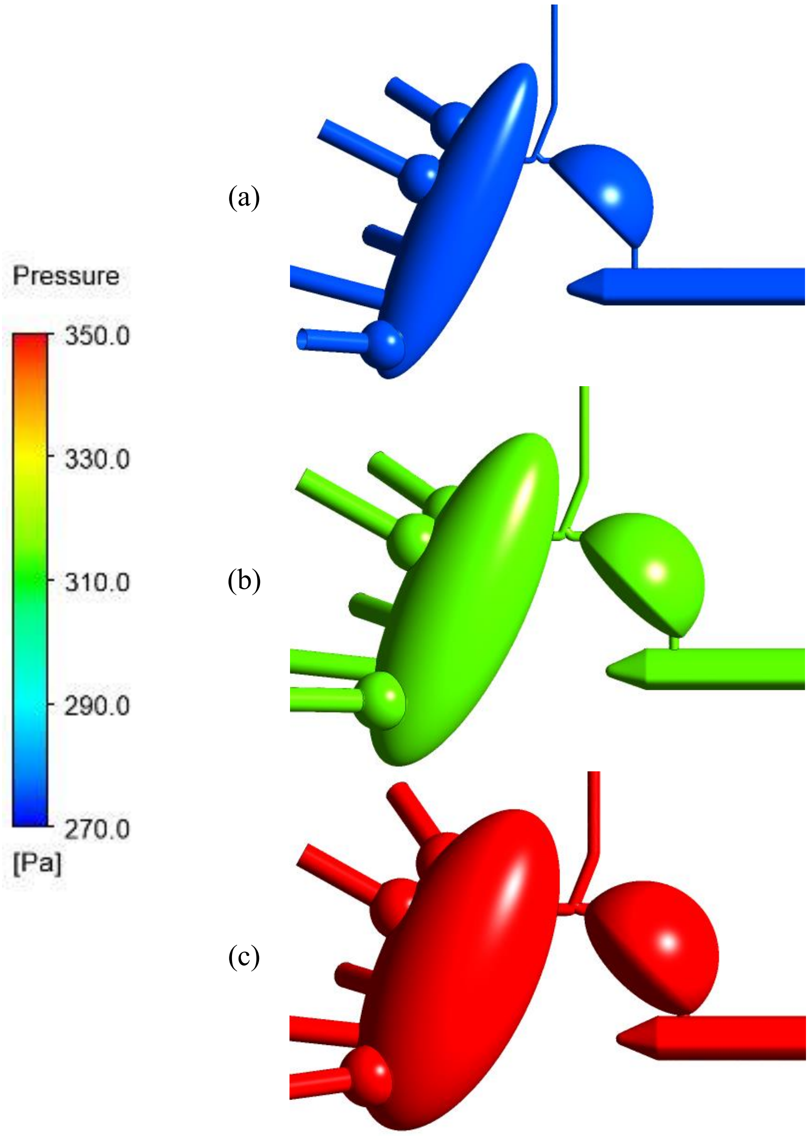

Figure 8. Pressure of endolymphatic wall membrane of (a) N model, (b) M1 model and (c) M2 model.

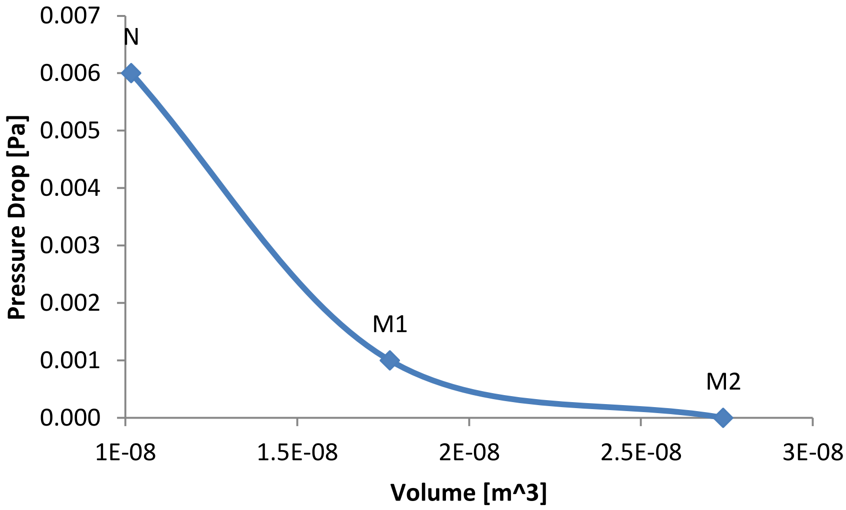

Figure 9. Pressure drop against volume of vestibular systems of N model, M1 model and M2 model.

3.2. Velocity of endolymphatic fluid

Velocity from the inlet is affected by the cochlear duct sectional area and the constant endolymphatic flow rate. If the area of the sectional inlet increases, the velocity of endolymphatic fluid decreases. Figure 10 shows the velocity contour has the lowest velocity in cochlear duct compared to M1 and N model. However, the highest velocity distributions for all models are seen in cochlear duct, ductus reuniens and endolymphatic duct compared to other inner ear anatomies. As the velocity distribution in certain part increases, the wall shear stress (WSS) parameter also will be affected and goes higher too.

The range of detected velocity for N model is from 4.91845e-12 m/s to 4.5651e-6 m/s. The velocity range for M1 model is from 7.09624e-12 m/s to 2.0342e-6 m/s, while M2 model is from 3.3349e-13 m/s to 1.1231e-6 m/s. Thus, the mean velocity for N model is 4.3570e-8 m/s, M1 model is 1.9692e-8 m/s and M2 model is 1.4167e-8 m/s, meaning M2 model have the lowest mean velocity. This is due to many flow recirculation that occurred in the increased endolymphatic volume as shown in figure 10 that give very low velocity distribution. The flow recirculation occurred is one of the highest probabilities to the sudden attack of vertigo in the inner ear.

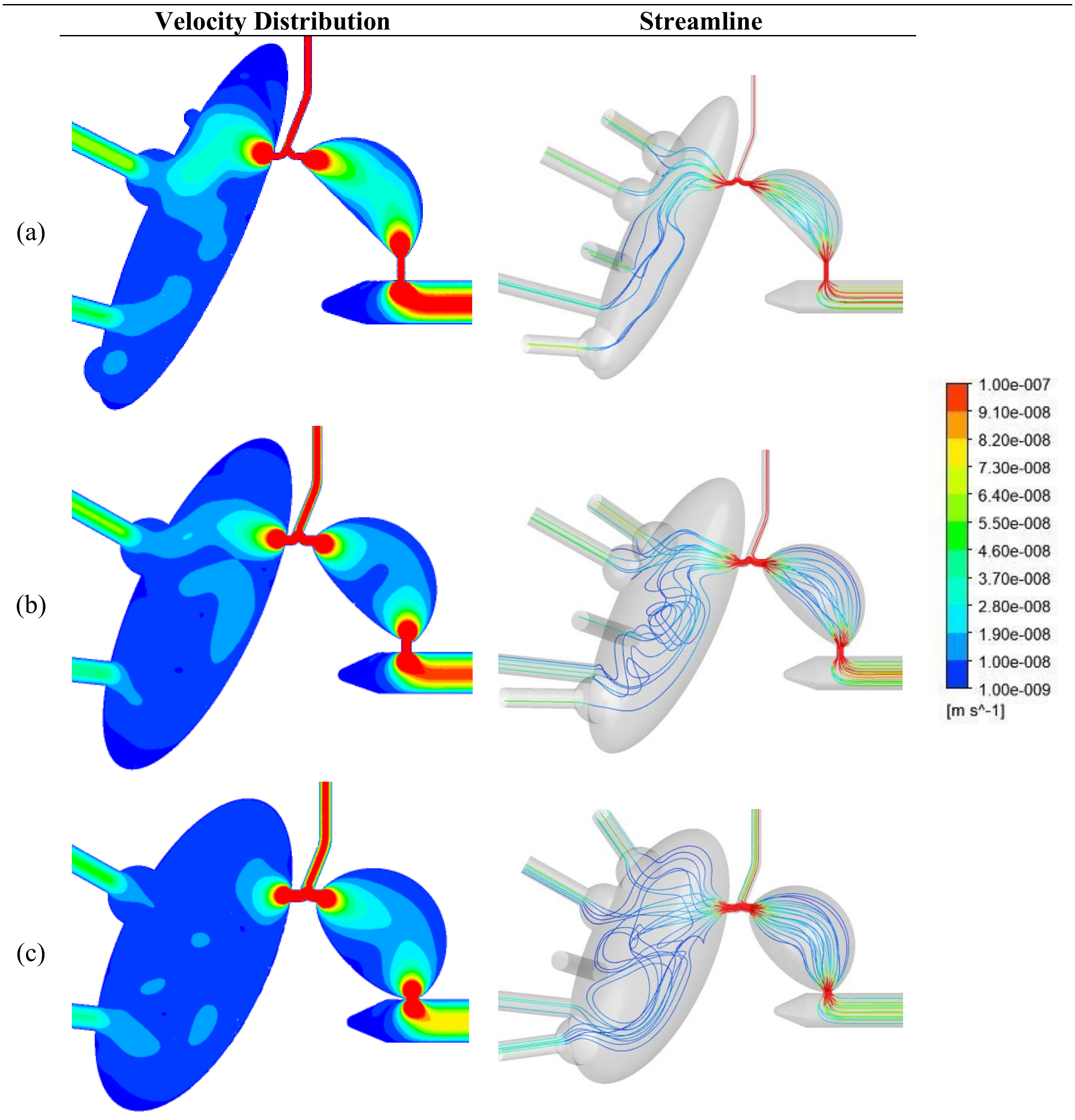

Figure 10. Velocity distributions and streamline of vestibular systems for (a) N model, (b) M1 model and (c) M2 model.

3.3. Wall shear stress (WSS) at endolymphatic wall membrane

WSS is affected by the velocity of the viscous endolymphatic fluid at the wall membrane. High WSS value on soft tissue including the endolymphatic wall membrane tends to rupture. Therefore, endolymph fluid is mixed with perilymph fluid leading to an abnormal increase of fluid within the endolymphatic chamber. This abnormality of the Meniere's disease can be occurred such as vertigo, tinnitus and hearing loss.

In Figure 11, cochlear duct, ductus reuniens, endolymphatic duct and semicircular canals probably tend to rupture due to high WSS distributions. WSS distributions of model N at utricle and saccule is higher compared to M1 and M2 model. N model has mean WSS value of 5.0427e-6 Pa, while M1 model has mean WSS value of 9.8473e-7 Pa and M2 model has mean WSS value of 5.4604e-7 Pa.

This is due to the decreasing of velocity and volume is increase at endolymphatic as the WSS distributions are observed from N to M2 model.

WSS Distribution

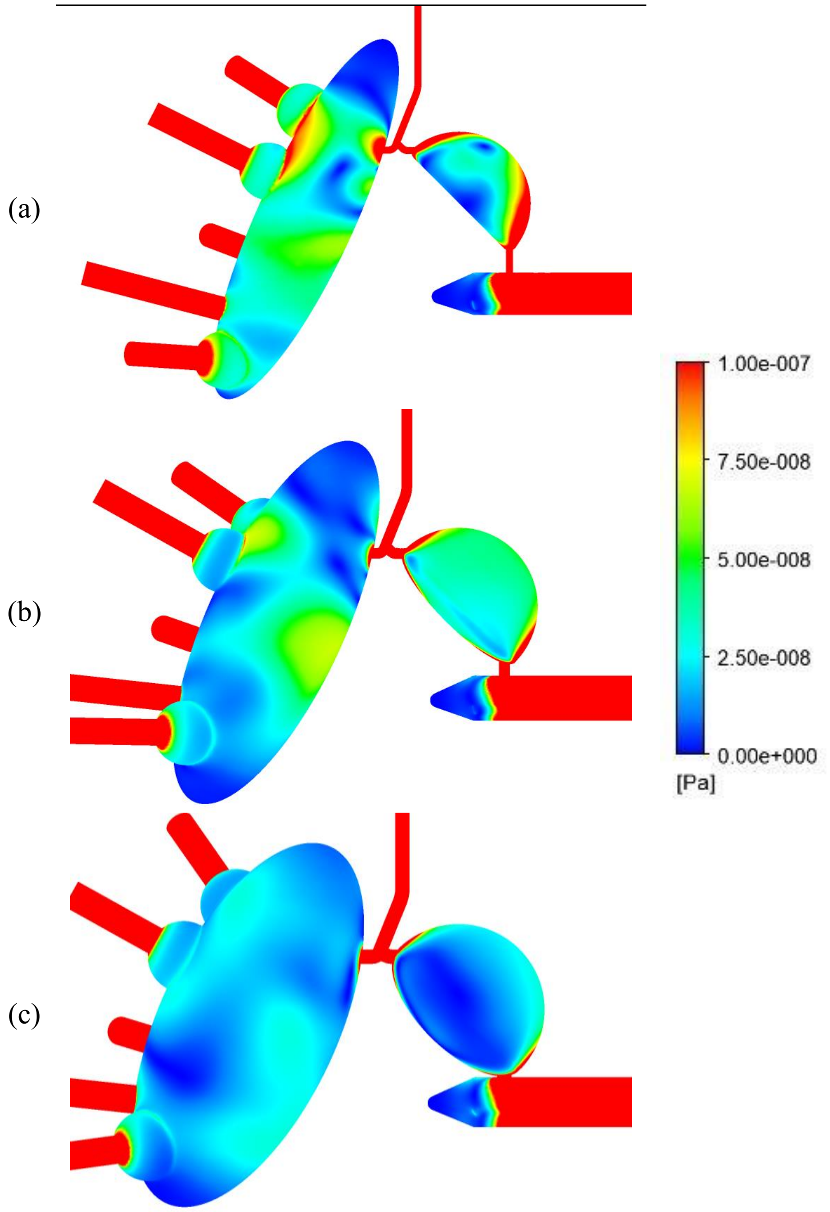

Figure 11. WSS distributions on endolymphatic wall membrane for (a) N model, (b) M1 model and (c) M2 model.

4. Conclusion

From this study, pressure of the outlet is affected by the volume of the endolymphatic fluid. The pressure drop between inlet and outlet of normal condition is high compared to the severe Meniere's disease condition. Since severe Meniere's disease condition has very small negligible pressure drop, the endolymphatic fluid volume fail to control the outlet pressure.

Besides that, the components of vestibular models where the highest velocity distributions occur, is in the cochlear duct, ductus reuniens, endolymphatic duct and semicircular canals. Thus, these components clearly have high WSS distributions compared to other components which also having high probability of wall membrane dilation and rupture. However, if the WSS distributions observed closely from N model to M2 model at the wall membrane of saccule, utricle and ampullae, the distributions become lower due to flow recirculation. The endolymphatic fluid flow recirculation actually is an instable flow because of the increasing volume of the fluid. Based on the analysis that has been made, these could lead to the high probability of vertigo unpredictable attack, tinnitus and hearing loss.

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