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Simulation of Endolymph Flow Dynamics in the Human Semicircular Canals based on Magnetic Resonance Images using the Moving Particle Semi-implicit Method

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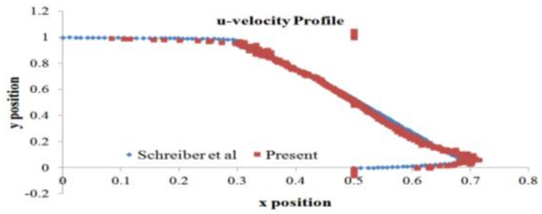
With the recent advances in medical devices, authors would like to revisit the endolymph fluid dynamics of the semicircular canals within the exact structure of the in-vivo human semicircular canals. This study is especially focus on understanding the mechanism that lead to the disease called Benign Paroxysmal Positional Vertigo, which is the most common vestibular disease nowadays [1].

The Moving particle semi-implicit method is chosen for its ease of shape construction as well as its potential of incorporating new features in the future [2]. The code is verified with a lid-driven cavity flow over a range of Reynolds number (Re=400, 1000, 4000, and 10000) in order to gain confidence on the implementation of the full Newmann boundary problem of pressure Poisson equation. The diameter of the particles is set to be 0.01m and 100×100 fluid particles are used in a 2D cavity. The horizontal and vertical velocities along the vertical and horizontal line through geometric center of the driven cavity for Re = 10000 are shown in Figure 1.



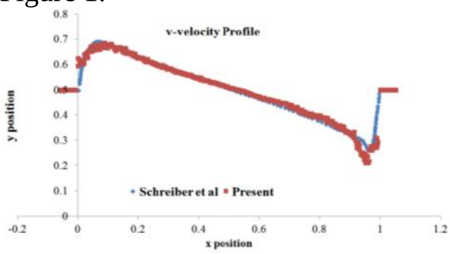


Fig 1. The velocity profile with Reynolds number 10000.

The red plots are generated by taking all the v-velocity of the particles lie within the range of y=0.5±0.02, while the blue plots are benchmark solution in [3]. Overall, the velocity profiles at Re = 1000 and 10000 compares well with the numerical results in [3].

After verifying the code, the authors were able to reconstruct the three-dimensional structure of the endolymph fluid with particles from the magnetic resonance images of one volunteering subject. Additionally, the particles surrounding the fluid particles are added to represent the bony labyrinth and the flow dynamic of the endolymph fluid is simulated. The parameters for simulation are summarized in the following Table 1.

Density (kg/m^3)	1000	Effective Radius (Ratio)	3.1
Kinematic Viscosity (m^2/s)	0.000001	Number of Particles	14,000~15,000

Table 1. Parameters for Simulation

Simulation on both the translational and rotational motions have been calculated. For the setting of the translational motion utilizes a sinusoidal motion in the x-direction at frequency 1000 Hz is given. The time interval is 0.000001 second and the amplitude of displacement is 1mm and is achieved at time 0.00025 seconds.

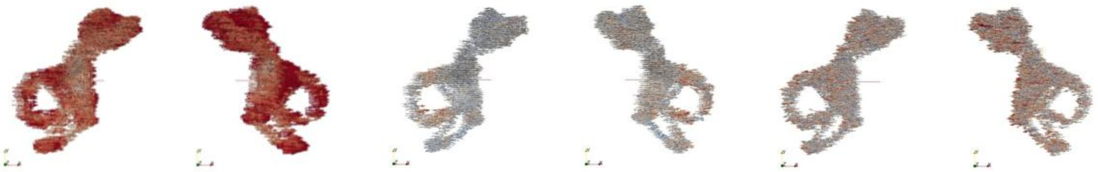


Fig 2. The vibration of the semicircular canals in x-direction.

The simulation result of the vibration of the semicircular canals is shown in Figure 2. The first figure shows the velocity distribution of the semicircular canals at 0.00001 second with 0.063mm displacement. The second figure was at 0.00004 second with 0.249mm displacement. We see that the velocity magnitude was largely reduced. Moreover, the third figure shows the velocity distribution at 0.0025 second, where the semicircular canals return to its original position where maximum velocity occurs during a sinusoidal motion. The simulation result is as expected to be similar to the velocity of the pendulum problem and no velocity is observed when maximum displacement occurs.

In addition to the translational motion, the rotational motion was also simulated to cover the motion of the head. The rotation frequency of this simulation is set to 1000°/s. The direction of motion is counterclockwise along the y-axis.

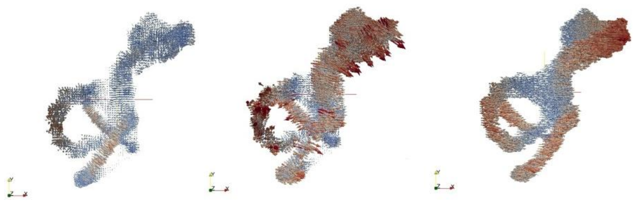


Fig 3. The rotational motion of the semicircular canals.

The simulation result of the rotational motion of the semicircular canals is shown in Figure 3. The first figure is the image at 0.00001 second with relatively small rotation of 0.05°. At the beginning of the rotation, the velocities of the particles are largely influenced by the shape of the semicircular canals and were mostly arranged perpendicular to the surface of the wall. The second figure shows the simulation result at time 0.00004 second and the rotation angle is 0.20°. At this point, we see large velocity vectors at the lateral semicircular canals. The third figure shows the simulation result at time 0.0035 second. The rotation angle at this point reaches 17.21 degree and the velocity of the particles begins to agree with the direction of rotational motion.

Overall, this paper shows reasonable result for the simulation of endolymph fluid inside the semicircular canals in both translational and rotational motion and provides a promising method for future study on the endolymph fluid.

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