A Benchtop Fluid Dynamic Model of the Inner Ear

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Abstract

Mathematical models of fluid dynamics have been useful in understanding the inner ear and a bench-top model has received little attention. Perilymph and endolymph are two parallel fluid systems that must be in hydrodynamic equilibrium. Changes in head position will result in a change in relative hydrostatic pressure. New equilibrium must be achieved quickly. Time to reach equilibrium may explain the temporary distortion of the membranous labyrinth and increases the time to reach hydrodynamic equilibrium with a change in position.

Methods and Materials

A fluid-filled bench-top model consisting of compliant membranes was constructed to represent a semicircular canal as shown in Figure 1. Fiberglass and plexiglass formed a water-tight rigid box to represent a bony semicircular canal. Polyvinyl chloride pipes and rigid connectors formed the endolymphatic canal and the cochlear aqueduct. Balloons represented the compliant portions of the endolymphatic and perilymphatic compartment. The former include the membranous labyrinth and the endolymphatic sac. The latter includes structures such as the oval and round windows. A valve, when turned, increased the resistance in the pipe representing the endolymphatic canal.

The model was fit onto a platform attached to a wheel with a radius of 0.125 m. A string attached the wheel to a Newport High-Performance M-ILS250PP linear stage (Irvine, CA), driven by a Newport ESP300 Motion Controller (Irvine, CA), rotating the model from horizontal to vertical at 4 degrees per second. Five trials were performed under the four conditions via the software Scion Image (Scion Corporation, Frederick, Maryland), the area of the balloon representing the membranous semicircular canal was measured for each picture. Deformation of the membrane was recorded every second. Absolute deformation was converted to percentage deformation from mean starting membrane size. The mean area under each curve and the single factor ANOVA for the area under the curve was calculated.

Results

With the valve in the open position, the membranous portion of the model demonstrated no deformation, indicating immediate hydrostatic equilibrium across the compliant membrane. With the valve in the closed position, the membranous portion of the model demonstrated the maximum deformation of 10% to 15% by seven seconds, significantly lower than the open trials (p = 8.9 x 10^-5). This deformation did not change during the observation period. Figure 2 compares the size of the original balloon to that of the deformed balloon caused rotating the model. With the valve in the almost closed and almost open positions, the model responded with initial deformation then slowly reached equilibrium by returning to original size, a size more similar to that of the "open" condition than that of the "closed" condition.

The time constant is proportional to the product of resistance and compliance. The results suggest that as resistance increased, the time constant also increased. Thus, the "open" condition quickly reached equilibrium, the intermediate conditions slowly reached equilibrium, and the "closed" condition hypothetically never reached equilibrium. This is demonstrated in Figure 1, the error bars representing the standard error. The curves were significantly different when the mean area under each curve was analyzed by single factor ANOVA (p = 1.35 x 10^-10).

Conclusions

The bench-top fluid dynamic model of the inner ear is a novel perspective of inner ear disease that may complement current theories such as those of cupulolithiasis and canalithiasis. There is evidence both to support and refute both theories of benign positional vertigo. Other inner ear diseases have been noted to have variations in membrane compliance and resistance to fluid flow. For example, the large endolymphatic duct in enlarged vestibular aqueduct syndrome has been associated with hearing loss and vestibular symptoms.

Time to equilibrium has been shown to be proportional to the resistance-compliance product of a system. The bench-top fluid dynamics model demonstrates how increasing resistance in the endolymphatic system causes temporary distortion of the membranous labyrinth and increases the time to reach equilibrium. The fluid dynamics of the inner ear may explain the etiology of many inner ear diseases, including benign positional vertigo. Better understanding may lead to a better understanding of disease, improve therapy, and provide a model with which to study other diseases potentially related to the fluid mechanics of the inner ear.

Bibliography