PVDF Piezoelectric Nanofibers As Hair Cell Substitutes: A Feasibility Study

C. R. Pérez[1], J. J. Santiago-Avilés[2]

[1]Department of Materials Science and Engineering, University of Pennsylvania, Philadelphia, PA, USA
[2]Department of Electrical and Systems Engineering, University of Pennsylvania, Philadelphia, PA, USA

Abstract

Sensorineural hearing loss is the most common sensory deficit in the world, and within this category damage or loss of the primary sensory cells of the inner ear, known as hair cells is the most common cause [1]. Partial hearing loss is addressed by the use of hearing aids, electronic devices that greatly amplify sound directly into the user's ear, but for more severe cases cochlear implants are needed (Figure 1). The cochlea is the spiral-shaped cavity of the inner ear, and its auditory portion. Within the cochlea, the Organ of Corti functions as the sensory organ of hearing, and is located on the basiliar membrane, responding to mechanical vibrations from the outside world (Figure 2). A complete picture of the transduction process remains debated, but the motion of stereocilia, hair like structures projecting from the hair cells ultimately converts vibration to a potential difference via opening and closing ion channels between regions of different concentration. These potentials then travel along the auditory nerve to the brainstem where they are processed.
Polyvinylidene fluoride (PVDF) is a bio-compatible thermoplastic fluoropolymer, which can be synthesized into self-poled piezoelectric nanofibers [3]. These fibers can be fabricated to have dimensions matching those of stereocilia, and have the potential to, working as their functional equivalent, treat hearing loss. The non-chirurgical delivery of nanoparticles into the inner ear has already been demonstrated [4], so the question becomes one of system design: would nanofiber-based artificial hair cells provide similar Voltage-Current response to vibration as healthy structures?
In this work we make use of COMSOL Multiphysics® software to estimate the performance of piezoelectric nanofibers in cylindrical cantilever configuration as functional hair cell substitutes. Eigenfrequency is first used to determine optimal dimensions fiber (length and diameter) for 200-2500 Hz, the range of the auditory spectrum most important to the perception of speech (Figure 3). Then, Frequency Domain simulations are performed to obtain transconductance vs. frequency characteristics for the fibers under both of the proposed cochlear mechanics models (Figure 4). Our findings indicate that while reaching comparable potentials (<200 mV) will not be an issue, gathering large enough currents (~1 nA) will require a large number of fibers per hair cell equivalent, and there needs to be contact rectification. The use of COMSOL informs ongoing experimental work in fiber synthesis and delivery.

Reference

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Figures used in the abstract

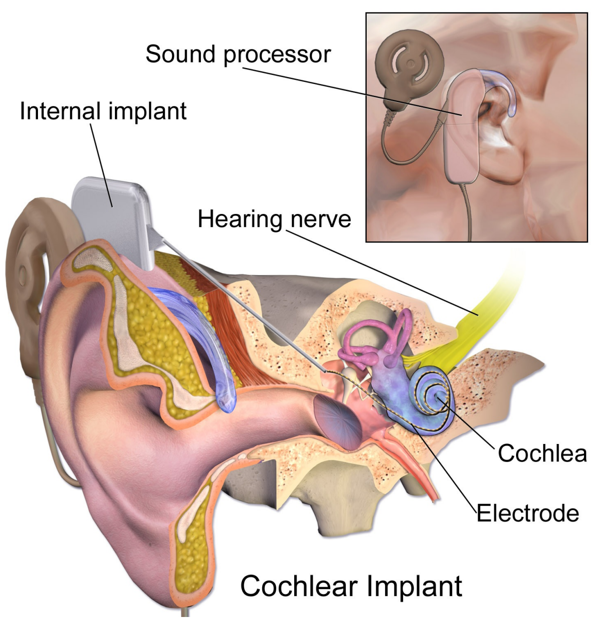

Figure 1: Illustration of the ear with a cochlear implant. Inset shows external components (microphone and sound processor) of the implant. From Ref. 5.

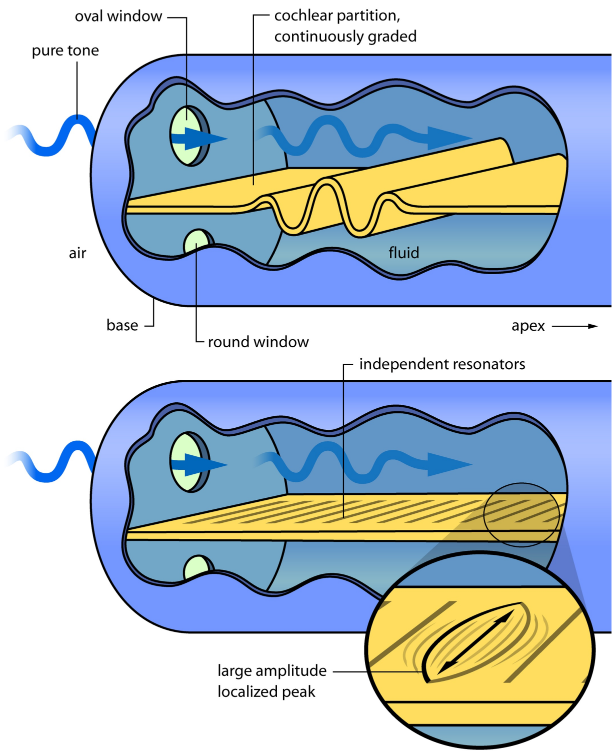

Figure 2: Two Views of Cochlear Mechanics. The cochlea, shown uncoiled, is filled with liquid. In the accepted travelling wave picture (top), the partition vibrates up and down like a flicked rope, and a wave of displacement sweeps from base (high frequencies) to apex (low frequencies). Where the wave broadly peaks depends on frequency. An alternative resonance view (bottom) is that independent elements on the partition can vibrate side to side in sympathy with incoming sound. It remains open whether the resonant elements are set off by a travelling wave (giving a hybrid picture) or directly by sound pressure in the liquid (resonance alone). From Ref. 2.

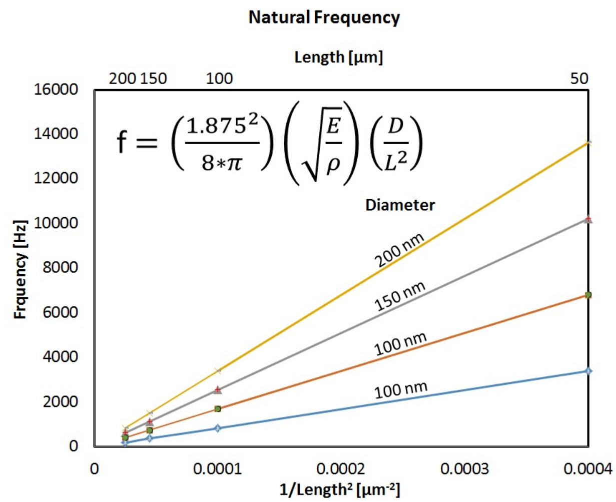

Figure 3: Natural frequency of oscillation of cylindrical cantilevers as a function of size. Values closely follow analytic formula.

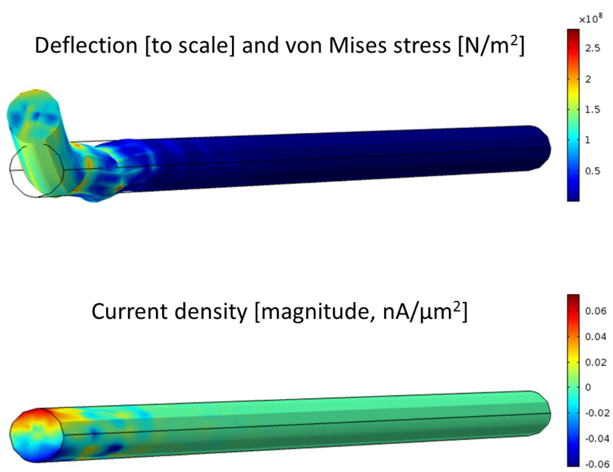

Figure 4: COMSOL Frequency Domain simulation of base-displaced cylindrical cantilever showing deflection and stress (top) and induced current (bottom) for a L = 10 µm, D = 100 nm fiber at 1 KHz.