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Abstract

The total and partial loss of hearing is a widespread disability that affects approximately 20% of the adult population. At the age of 65, hearing loss is even more prevalent. After this age, approximately one in every three people report some level of hearing loss.[1] For this reason, the market size for addressing hearing loss is immense, with an estimated growth prediction at 3.2% annually.[2] The two primary treatments for hearing loss, hearing aids and cochlear implants, have their limitations and disadvantages. One major problem facing current devices is the fact that they are extremely expensive, averaging at $3000 dollars per hearing aid. Another major drawback with both technologies is that they are located in a hostile part of the body. Nanocoating a hearing device with a hydrophobic layer could assist the device in rejecting foreign debris, liquids etc. Also, current technology can be large and uncomfortable, require a lot of power, and can have low speech recognition due to the small amount of electrodes. For this reason, we propose using nanotechnology and nanomaterials to decrease the cost of hearing aids and cochlear implants and to allow for improvement in areas such as repelling water and oils in the devices.[3] Finally, current technologies face a major drawback: an anatomical gap between the electrode array and the auditory nerves. We propose adding fibers of carbon nanotubes to replace damaged inner ear hairs and to bypass this gap. Finally, we suggest using nanoparticles for continuous drug delivery and gene therapy to assist in auditory nerve repair and cell repair, which will in turn improve a person’s ability to hear.

Introduction

Anatomy

The ear consists of three main components: the outer ear, middle ear, and inner ear. Sound first reaches the outer ear, which has multiple functions. Firstly, it acts as a funnel to collect sound waves. Secondly, its eardrums vibrate at a rate according to the vibrations of the sound wave. Next, the vibrations reach the middle ear. Here, the vibrations are amplified using the ossicle bones. Finally, the vibrations reach the inner ear. The inner ear consists of the cochlea, which is a snail shaped figure filled with fluid and tiny hairs. Depending on the amplitude and frequency of the sound wave, different electrical signals are sent to the brain to be interpreted via the inner hairs. The movement of the hairs, which are caused by the oscillatory movement of the basilar membrane, is what generates electricity, opening up ion channels and sending auditory nerve signals to the brain.
Pathology

Hearing loss can be divided into three categories: conductive, sensorineural, and central diseases. Conductive diseases refer to damages in the middle ear, sensorineural diseases are associated with the inner ear, and central diseases stem from problems with the brain stem. Sensorineural diseases are the most common form of hearing loss and the type we will be focusing on for our project. Common causes for sensorineural hearing loss include age, Meneier’s disease, noise exposure, immune disorders, ototoxic medications, infections, head trauma, and rarely tumors.

Treatment

The two most common treatments for sensorineural hearing loss are cochlear implants and hearing aids. Cochlear implants is a surgically implanted device that bypasses the damaged cochlea, sending electrical signals to the auditory nerve. The cochlear implant consists of a receiver/stimulator, which controls the incoming sound, and a sound and speech processor, which processes the sound and converts it to digital signals (in a manner similar to a hearing aid). The digital signals are then sent to the implant and converted to an electrical signal. The electrical signal is then sent through a wire containing electrodes into the cochlea. These electrodes replace the inner ears and send sound information to the brain.

The other most common form of treatment for hearing loss is hearing aid devices. Hearing aids, unlike the cochlear implant, simply amplify the sound, but rely on the fact that the cochlea still works to some degree. A hearing aid consists of a silicon chip that processes incoming sounds, interpreting and amplifying the desired sound waves and decreasing the
design and application. It has five key components: A microphone, microchip, amplifier, battery, and receiver.

For our project, we present a nano-device that can be implanted into the cochlea. It will include an amplifier, receiver, and electrode array, similar to those in current hearing aids and cochlear implants. We propose inserting a fiber with carbon nanotubes which could be inserted into the cochlea and would connect the auditory nerves with the electrode array.

There are many “add-ons” necessary for implementation. For example, magnetic nanosensors can be used to detect the use of a phone or other electronic device in order to signify the need for switching signal processing modes. This way, when a person is using a cell phone, the mode could switch automatically, in order to analyze the incoming acoustic waves appropriately.

In addition, we would like to implement different nanomaterials that can reject unwanted water and foreign material into the hearing aid. To do this, we would apply a nanocoating polymer layer to the hearing aid as a gas, which would allow it to penetrate the outer layer and repel liquids. Finally, piezoelectric materials could be used to replace a damaged basilar membrane if necessary.

Literature Review

Different research is continuously being published in the field of nanotechnology for the hearing sense. In the paper, “Flexible Inorganic Piezoelectric Acoustic Nanosensors for Biomimetic Artificial Hair Cells”, by Hyun Soo Lee, et.al., Lee and his team propose using piezoelectric acoustic nanosensors (iPANS) for artificial inner hairs to replace damaged hairs. In addition, they propose using a trapezoidal silicone-based membrane (SM) as a
replacement for the basilar membrane in frequency detection. The SM was proved to successfully differentiate different incoming frequencies and succeeded in converting a vibration displacement of 15nm to an electrical output of 55microvolts.

In this paper, there is a discussion regarding the use of inorganic piezoelectric materials. These are useful materials for cochlear replacement due to their high charge constant. The drawback is that they are inflexible and have brittle properties. To overcome the inflexibility, this group demonstrated that they could increase flexibility of these materials by crystallizing lead zirconate titrate onto a flexible plastic substrate, otherwise known as lead magnesium niobate-lead titanate solid solution (PMN-PT). In many instances, the basilar membrane is still intact, and it is only necessary to replace the damaged hairs which cause dysfunction.

For fabrication, Lee et al. used a thick PZT film attached to a PET substrate using adhesive UV light. Interdigitated electrodes were placed on the PZT film using Au deposition by radio frequency sputtering. Lastly, iPANS were attached to the SM with double sided adhesive tape.[6]

Research has also been published regarding the replacement of damaged basilar membrane. In the paper, “Characterization and Modeling of an Acoustic Sensor Using AIN Thin-Film for Frequency Selectivity” by Sangwon Kim et al.[7], researchers used beams of different lengths for acoustic frequency selectivity. They used a 1-D piezoelectric thin film and added Aluminum Nitride as an active layer for frequency selectivity. This technology uses the beams as band pass filters which correspond to different resonance frequencies.

Other ideas for cochlear replacements have been discussed. White and Grosh et al. built a cochlear model with a membrane made up of isotropic silicon nitride.[8] Wittbrodt et al. fabricated an artificial basiliar membrane using a polyimide plate with discrete aluminum ribs.[9] Overall, research has gone into using pizioelectric materials for many different components of artificial nanosensors including microspeakers, transducers, and microvalves. Research has been studied regarding optimizing the pizioelectric material, which has been proven to be the most effective material for cochlear replacements. These variations include changing the temperature of the pizioelectric material as well as adding different amounts of Ag2O in the material.[10]

In addition, papers have focused on the subject of gene and drug delivery nanoparticles that can be inserted after a cochlear implant for improved results. Ya Zhang et al. in their paper “Inner ear biocompatibility of lipid nanocapsules after round window membrane application” successfully delivered polyethyleneimine into the inner ear which led to gene expression. However, polyethyleneimine proved to be toxic to cells. They also used lipid
nanocapsules (LNCs) for drug delivery. LNCs have the advantage of being biodegradable when below 100nm.[11] Inner ear drug delivery is relevant for hearing diseases such as Meniere’s disease, tinnitus, and NF2. Nanoparticles with gene delivery are used to assist in gene expression of nerve growth factors in the inner ear such as TrkB, C-ret, and others that play a crucial role in the survival of neurons sent from the inner ear.[12] One method of nanoparticles used for drug delivery was polycaprolactone-polyethylene oxide micelles which contain the fluorescent probe dil.[13] Another method for nanoparticle drug delivery used was black copolymers which is a form of nanocontainer which releases the target molecules in a periodical, controlled manner.[14]

**Project description**

**Characterization**

The main features of our design will allow the patient to hear most of the frequencies in the normal hearing range (20-20,000 Hz). Most of the population suffers from hearing loss of the higher frequencies. The problem today is the bottleneck for optimal stimulation. It is caused by the anatomical gap between the electrode array and the auditory neurons in the inner ear. As a consequence, current devices are limited through low frequency resolution, leading to poor sound quality and strong signal amplification.

This, in turn, leads to high energy consumption which is responsible for significant battery costs and for impeding the development of fully implantable systems.[15] We suggest to create a CNT based fiber for implantation inside the cochlea. The fiber will be thin enough to prevent destruction of the residual hearing left in the patient physiological system. Our device will allow the fiber to insert CNT spines into the cochlea to bypass the anatomical gap between the electrode array and the auditory nerves. This action will allow the fiber a close relation to the auditory neurons. The risk of injury is minor because of the small diameter of the nanowires. Recent findings indicate that auditory nerve fibers can grow under...
neurotrophin stimulation towards the electrodes, which opens the door to address the problem of the anatomical gap in a more efficient way. [15] This property would allow us to coat the nanofibers with neurotrophin and make the auditory nerve fibers grow on the CNT.

**Fabrication**

For synthesis, we suggest using a bottom up fabrication approach with long CNTs on the surface of the fiber. The fiber will be coated in neurotrophin before insertion to the patent cochlea. The current that will go through the fiber will fix the CNTs on the surface of the fiber to the surrounding tissue and the auditory nerves.

For improving the electrochemical characteristics of the microelectrodes we employ a reversible charge injection process either via a double layer capacitive mechanism or via a reversible Faradaic mechanism. Neural electrodes, normally in electrode arrays, are the key elements in long-term implantable neural prostheses, because it determines the interaction with target neurons, thus affecting the safety and the efficacy of the neural prostheses. Neural stimulating electrodes are not only required to possess a high maximum safe charge injection (Qinj) limit, but also should be highly stable (both mechanically and electrochemically) and friendly in a living body for a long period of time. The combination of CNTs and conducting polymers (CPs) demonstrated significant advantages, such as low electrode impedance, high capacitance and fast charge transfer rate as well as good mechanical stability.[16]

The main feature of this fiber are the long CNTs on its surface, we will need to use an electron laser beam technique or another technique to open CNT chains so we could get a spiky structure which will allow the CNTs to attach to the surrounding of the tissue inside the cochlea.

**Applications**

There are a number of different applications for our design of a nanosensor for hearing. The primary application for the hearing nanosensor would be for implementation into the human ear area to replace a damaged cochlea. It can be inserted into patients with damaged hair cells with complete or partial hearing loss. There are other possibilities for application worth discussing.

An additional application would be to insert the nanosensor into healthy patients to increase their hearing capabilities. This could be performed by adding CNTs in addition to the properly functioning human ear hairs, which would have the ability to respond to frequency
below or above the frequencies of the human ear. Another possibility would be to insert the nanosensor into devices—and to use algorithms to teach those devices how to hear.

Conclusions and recommendations

In this paper, we suggested a unique approach for improving cochlear implants using nanotechnology. The main problem facing current cochlear implants are the low quality sound of the devices. We suggest a technique that would improve the fiber inserted into the cochlea. This fiber will have CNTs on its surface that could stimulate the auditory nerves. Our solution addresses a major challenge in current technologies: the auditory gap between the auditory nerves and the fiber. In addition, coating the CNTs with neurotrophin would allow for stimulation of the fiber. Using these techniques would eliminate the gap and increase conductivity and thus create a better hearing experience.

Future research and experiments

The ideal solution for patients suffering from hearing loss is to return the functionality of already present hair cells by attaching CNTs to the damaged hairs. The application of this solution could be implemented by creating CNT with affinity to inner hair cells. The CNTs would attach to the broken hairs and reconstruct them. In order to implement this idea, there are many obstacles to solve, including the method of attachment of CNTs to the hair cells and how to limit the amounts of CNT that would attach to the hair cells.

References

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**figure 1:**
http://www.ssc.education.ed.ac.uk/courses/deaf/aud2ad.html

**figure 2:**
http://kidshealth.org/PageManager.jsp?dn=familydoctor&article_set=34740&lic=44&cat_id=192#

**figure 3:**
Licklider, 1951

**figure 4:**
http://biotechview.blogspot.co.il/2010_03_01_archive.html