Self-powered Artificial Hair Cell Array Based on Carbon Nanotube

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***Abstract*—We devised a new cochlear implant system to compensate for the shortcomings of the existing cochlear implant. The current device is bulky and requires a large incision when implantation surgery, leading to a potential risk of infection and skin flap. In addition, the existing device must be mounted on the outside of the skin, causing discomfort to the patient. A low hearing resolution compared to the inherent auditory sense is one problem. Our new artificial hair cell array mimics the function and mechanism of natural hair cells by combining a novel energy harvesting technology with a CNT coil and a flexible and biocompatible substrate. An additional battery is not required so that miniaturization can be achieved, resulting in smaller incisions when implantation and higher frequency resolution. We expect to improve the convenience of many people in the future by using this new technology.**

***Index Terms*— Artificial hair cell, biomechanical energy harvesting, carbon nanotubes, cochlear implant, flexible electronics, self-powered sensor**

I. Introduction

The human ear is the most indispensable organ for hearing ability. Cochlear implants (CIs) have contributed substantially to the treatment of hearing loss. CI improves hearing by delivering sound signals captured by an exterior sound processor to the auditory nerve. The electrodes inside the cochlear receive the signal and stimulate the nearby auditory nerve so that CI can compensate for the malfunction of hair cells in the inner ear.

Although there have been significant advances in CI technology for decades, there are still several unresolved issues regarding CI.[1] First, the incision during implant surgery is large because of the size of the receiver under the ear. Also, because some parts of the CI like the sound processor and microphone are equipped on the exterior of the skin, it poses a risk of side effects like infection and discomfort to patients. Especially, infant and child patients feel this exterior device is cumbersome, therefore, this issue should be addressed for ensuring patient comfort and safety.

Recently, energy harvesting technology has arisen due to its ability to convert mechanical energy to useful electrical energy. To overcome the issues of CI, diverse approaches with energy harvesting techniques have been attempted. For example, piezoelectric sensors do not require an external power supply, having the advantage of miniaturization for the implantable devices. H. Lee et al. reported a flexible acoustic nano-sensor made of piezoelectric materials on a flexible substrate.[2] Despite its great sensitivity in the audible frequency range, its relatively bulky size may limit its application.

Here, we introduced an implantable artificial hair cell array that harvests the natural vibration of BM and converts it to electricity for nerve stimulation. Damaged hair cells are replaced by a new type of electrochemically driven energy harvester comprising carbon nanotubes (CNT) developed recently.[3] A coil-shaped CNT yarn can generate electricity when deformed in the perilymph electrolyte without the need for an external power supply. Due to the self-powered, lightweight, small-sized, durable, and biocompatible characteristics of CNT as an energy harvester, CNT has the potential to replace damaged hair cells. Artificial CNT coil hair cells are integrated into the elastomeric PDMS nanomembrane for tight adhesion under BM without any strain. We expect that this novel approach to replacing hair cells will significantly reduce its size and ultimately eliminate the complications regarding CI.

II. Methods

To fabricate a CNT coil that works as a working electrode, a precursor carbon nanotube (CNT) sheet (length: 30 cm, width: 6 cm) was drawn from the multi-walled CNT forest produced by the chemical vapor deposition (CVD) process. Then the CNT sheet was rolled into a hollow cylindrical shape, with its axis matching the direction of length. The cylindrical CNT sheet was suspended vertically to a rotational motor and a load of 107 MPa was applied to the bottom part of the cylinder. A twist was exerted on the CNT cylinder in one regular direction by the rotational motor. After a CNT yarn was twisted ~26 turns/cm, by exerting more twists with a lighter load, this densely twisted CNT yarn transformed into a coiled CNT yarn. After coils were completed along the entire length with the total twist density of 61 turns/cm, a fully coiled CNT yarn was then reversely twisted around 8% of the total twisting density under the same coiling load for higher flexibility and performance. The stretching range and following performance can be adjusted by changing the load and twist density.

III. Results and Discussion

We devised an implantable artificial hair cell array that can replace damaged hair cells (**Figure 1A**). To make CNT coil

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electrodes oscillate according to the vibration of the BM, a super thin flexible PDMS film is used as the substrate of the CNT hair cell array. The nanomembrane integrated with CNT coil hair cells can adhere tightly under the BM inside the scala tympani and it does not cause any mechanical constraint for the BM to vibrate due to the super thin characteristic of PDMS nanomembrane. Additionally, since PDMS is known as a flexible material with great biocompatibility, it is suitable material for implantable devices inside the biological environment. A ~3 cm length trapezoidal-shaped PDMS membrane is used considering the unique structure of BM and the length of the scala tympani.[4] Sets of working and counter electrodes are arranged along the length of the PDMS membrane, each in charge of sensing discrete frequency (**Figure 1B**). A platinum wire is used as the counter electrode, and by making platinum wire have a serpentine structure, the flexibility of the entire hair cell array can be successfully maintained despite containing metal on the flexible substrate.

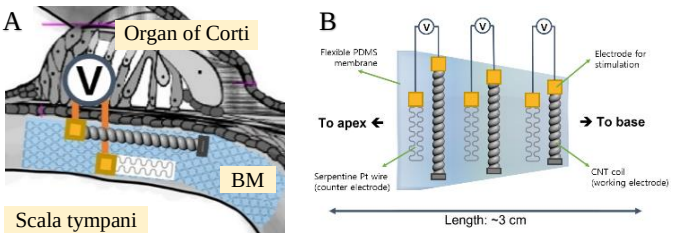


Figure 1 Structure of CNT coil artificial hair cell array.

When a specific part of the BM vibrates in response to the sound of a certain frequency, the CNT hair cell array under that area of the BM vibrates together. Then, the coil length is fluctuated, resulting that the proximity between CNT bundles changing and ions inside the perilymph migrating from and to the CNT coil. This constantly changes its capacitance, and the amount of charge (Q) is determined as the product of capacitance (C) and voltage (V) (Q = CV), voltage increases as capacitance decreases. Therefore, the constant fluctuation of capacitance by deformation eventually leads to the potential difference between the working and counter electrode. The generated electricity from a certain area under the BM is delivered to the nearby auditory nerve through tissues, provoking the action potential. This implies that this CNT hair cell array can generate electricity for nerve stimulation from the natural movement of BM without any external power source, resulting in a great decrease in device size and further, smaller incision when implantation.

Roughly, a typical CNT coil having a yarn diameter of ~30 μm and a coil diameter of ~45 μm can produce 0.1 V of peak-to-peak open circuit voltage and 80 μA of peak current when stretched to its maximum strain sinusoidally. In this case, however, CNT coils oscillate according to the BM's vibration, therefore lower electricity generation is expected than when the coil is stretched sinusoidally. Assuming that the CNT coil vibrates and considering the typical auditory nerve stimulation threshold for the CI (Cochlear™ Nucleus® Profile™ Plus), which is 74 μA of the current pulse, a parallel connection of multiple electrode sets can produce enough current to stimulate the nearby auditory nerve.

By electricity and the working mechanism is purely natural, such as utilizing the mechanical movement BM and natural migration of ions contained in perilymph, a crosstalk between the electrodes which is the current obstacle of CI electrodes can be prevented. Therefore, more electrodes can be placed along the BM so that more diverse frequency channels can be implemented. Considering the structure of the cochlear which has a narrower end towards the apex and the magnitude of the electrode set, 50 electrode sets can be contained in the hair cell array, and this number is 2.27 times larger than that of conventional CI electrodes, resulting in higher frequency resolution.

IV. Conclusion

We fabricated a CNT coil artificial hair cell array that converts the vibration of the BM to enough current to stimulate the auditory nerve. Its significant flexibility and biocompatibility were also assessed. Furthermore, we confirmed the possibility of higher frequency resolution by preventing crosstalk between electrodes and placing more electrodes than conventional ones. This new attempt can change the whole CI system with the new approach using and mimicking the natural mechanism inside of the cochlear.

Despite our research, there are still some problems to be addressed left. Firstly, how to insert this thin film inside the cochlear should be figured out. We will devise a method for safe insertion using bioresorbable materials or a guiding apparatus. And since it has not been applied to actual patients, additional signal processing may be required. If extra signal processing is required through clinical trials, circuits for signal processing or amplifier can be added while maintaining the flexibility of the device by using serpentine structures. Finally, the adaptation to cochlear growth is worth considering given the increasing rate of child patients. In the future, we expect to introduce a new creative CI system and help people in need through the technology we developed.

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