Wearable Technology (2022) Volume 3 Issue 2, *pp. 91–98*.
doi: 10.54517/wt.v3i2.2139

Asia Pacific Academy of Science Pte. Ltd.

ORIGINAL RESEARCH ARTICLE

Finite element simulation of ciliary structure optimization of complete implant cochlear sensor

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ABSTRACT

At present, the cochlear implant needs microphone and special circuit to realize the function of frequency sorting, which makes the volume and power consumption of the device large. MEMS technology can be used to miniaturize the device. In bionics, the ciliated cells of the human ear are like the lateral line ciliated cells of fish, and the hearing system of mammals has rich characteristics. These key features include frequency sorting, nonlinear amplification of low-level stimuli, and compression, which allow mammalian ears to sense at larger sound pressure levels. On this basis, according to the specific structure of fish lateral line ciliated cells and human ear lateral line ciliated cells, two simulation models were designed. Through comparative analysis, further to explore the effect of ciliary structure of sensor performance, found that the elliptic cylinder cilia cylindrical structure contrast cilia structure on the modal frequency distribution is uniform gradient, difference obvious advantage, this makes a single sensor measurement of multi-channel signal may be, can reduce the cochlear cilia sensor cell array to cover the amount of bandwidth measurement.

Keywords: cochlear implant sensor; MEMS; vibration sensor; finite element simulation; resonant frequency

1. Introduction

According to the Global Hearing Implant Market Outlook Report in 2020, the hearing implant market in 2020 will reach RMB 2.9 billion, and cochlear implants are expected to account for the largest share. As early as 2015, the domestic market size of cochlear implants has reached RMB 1.259 billion. Before 2012 alone, about 324,000 people in the world had cochlear implants, making cochlear implants the most widely implanted nerve repair equipment.

Damage to cochlear outer hair cells caused by aging, disease and environmental conditions usually leads to neural hearing loss, which makes it necessary to develop better hearing prostheses. The prosthesis converts the sound induced vibration into electrical signals by imitating the human ear ciliary cells, and simulates the nonlinear behavior of the human ear ciliary cells[1]. Dhanasingh et al. have proved that the most important factor[2] in designing the electrode array is to provide a non-invasive insertion solution, because trauma will cause a variety of side effects and complications. Chole found that in order

ARTICLE INFO
Received: July 13, 2022 | Accepted: August 29, 2022 | Available online: September 15, 2022

CITATION
Zhu X, Wang R, Zhang G, et al. Finite element simulation of ciliary structure optimization of complete implant cochlear sensor. Wearable Technology 2022; 3(2): 91–98.

to provide high-definition electrical stimulation to neurons that could not be excited by acoustic stimulation, a balance must be achieved between the number of stimulation channels and the minimum cross channel interaction. Flexible electrode[3] can reduce the trauma caused by electrode implantation. Park S reported an implantable MEMS microphone device based on polyvinylidene fluoride material, and the effect is good[4]. Inaoka reported a MEMS sound pressure transducer made of silicon frame polyvinylidene fluoride material, and carried out experiments in guinea pig cochlea[5]. However, there are few MEMS sensors applied to the artificial cochlear system in China, which is different from the relatively mature artificial lateral line system at home and abroad. The artificial cochlear system is required to achieve a better frequency sorting ability to support the interaction of complex and diverse information scenarios between people and between people and the environment. Therefore, the human ear cilia cells have evolved more specifically in this function than the lateral line organs of fish. Because the manufacturing process of the artificial lateral line system has been relatively mature, and the development of the MEMS fully implanted cochlear cilia sensor is still in the initial stage. On the basis of the artificial lateral line system, the improvement of the microstructure and enhancement of the functional specificity of the artificial cochlear cilia cells is one of the current research programs of the artificial cochlear cilia sensor. This requires the observation of the differences between fish lateral cilia and human ear cilia, and the correspondence between the structural differences and the functional strength.

2. Working principle of piezoelectric cochlear ciliary receptor

2.1. Biomimetic mechanism

Listening is an important ability for many creatures to interact with the natural environment. Through the recognition of sound frequency, the entire auditory system can recognize the characteristics of sound frequency to respond to the environment. Human ear cilia cells can transform the sound attribute of frequency into electrical signals that can be recognized by auditory neurons to achieve the frequency sorting function of the human ear. Each ciliated cell has its own characteristics, either long or short. The differential gradient distribution of these ciliated cells can fully cover the entire range of auditory frequencies of the human ear. With the increase of age, human ear cilia cells begin to age and apoptosis, which leads to different distribution of hearing in people of different ages. The most obvious is that the sensitivity of the elderly to low-frequency sounds is reduced. According to medical literature[6], this is related to the death of cilia cells with high aspect ratio. However, by referring to the relevant literature of the artificial lateral line system[7], it can be found that the greater the ratio of cilia depth to width, the lower the first-order resonance frequency of the sensor. This explains the reason why the apoptosis of cells with high aspect ratio reduces the low frequency sensitivity of human ear hearing. In order to further explore the similarities and differences between fish lateral cilia cells and human ear cilia cells, the structural differences between the two cells were observed from the perspective of bionics. The ciliated cells of human ear are shown in **Figure 1**. Human ear cilia cells are located in the lymph of the cochlea, and the energy transmission of sound in the lymph will trigger the electrical feedback of cilia cells. Through observation, it can be found that the human ear ciliated cells cluster together to form a flattened, three-dimensional structure similar to an oval column, while the ciliated structure of the lateral line organs of fish[9] is shown in **Figure 2**. The cilia of this structure are long, similar to the cylindrical structure. At present, many hydrophone cilia use this structure[8], and have achieved good results. By observing the difference between the two kinds of ciliated cells, this paper designs two kinds of three-dimensional cilia with elliptical and cylindrical structures for simulation and comparison, and reveals the influence of the structural difference of cilia in the two different systems through the simulation results.

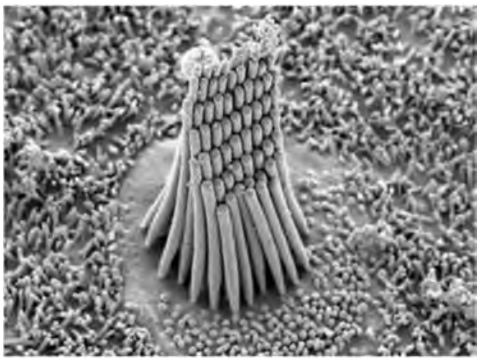

Figure 1. Human ear ciliated cells.

Figure 2. Lateral ciliated cells of fish.

2.2. PVDF piezoelectric film effect

Piezoelectric effect principle: When some dielectrics are deformed under the action of external forces in a certain direction, polarization will occur inside them, and positive and negative charges will appear simultaneously on its two opposite surfaces. When the external force is removed, it will return to the uncharged state, which is called positive piezoelectric phenomenon. When the direction of the force is changed, the polarity of the charge is also changed; On the contrary, when an electric field is applied to the polarization direction of the dielectric, the dielectric will also deform. After the electric field is removed, the deformation of the dielectric will disappear. This phenomenon is called the inverse piezoelectric effect[10].

The signal translation ability of cell structure means that external physical signals are transmitted to synapses through neurotransmitters to generate electrical signals, and then the generated electrical signals are transmitted to higher level processing centers to complete the translation. The sensor can imitate and reproduce a series of processes of signal translation through the piezoelectric unit. When the pressure acts on the piezoelectric material to generate charge movement, the collection of charges makes the electric potential change slightly. Through the charge amplification circuit, the signal generated by the piezoelectric film structure equivalent to the capacitance in the circuit is amplified to obtain a suitable value, which is transmitted to the center used to identify and process the signal.

Piezoelectric polymer polyvinylidene fluoride material is used as the sensing unit because polyvinylidene fluoride itself is a flexible material, which can generate less stress on blood vessels and also increase the service life of the equipment. Secondly, it has strong toughness and corrosion resistance, has bandwidth frequency sensitivity covering the range of human voice perception, and polyvinylidene fluoride is easy to process into various shapes and sizes. In the cochlea, it can be made into a variety of specific shapes to adapt to cochlear differences, which can better solve the problem of cochlear equipment fit due to the difference of people's age and individual cochlear characteristics, and reduce the risk of inflammation caused by rigid materials rubbing the inner epidermis of the cochlea during movement. Polyvinylidene fluoride (PVDF) has been used in a variety of devices, such as cardiopulmonary monitors, energy collection devices, tactile devices, and acoustic sensors. After conducting biological experiments in the cochlea of guinea pigs, polyvinylidene fluoride (PVDF) has been used to make artificial cochlear ciliated cells. These mouse experiments can further support the feasibility of applying such materials to the artificial cochlea. On this basis, different ciliated structures of the device are simulated through finite element simulation to obtain a more perfect ciliated structure model.

PVDF, a flexible film material, has low cost and high durability[11]. It has flexible characteristics different from traditional piezoelectric materials. It is also used as the carrier of cilia. Its flexible characteristics make it easier to produce local pressure concentration effect at the cilia substrate. Compared with piezoelectric ceramics, PVDF has more than 20 times the piezoelectric performance of piezoelectric ceramics, and has advantages such as wide frequency response and low acoustic impedance[12].

3. Mathematical model

The spring bond damping model is equivalent to the structure designed in this paper. The motion equation of this type of model is:

$$m\frac{\mathrm{d}^2 z(t)}{\mathrm{d}t^2}+c\frac{\mathrm{d}z(t)}{\mathrm{d}t}+kz(t)=-m\frac{\mathrm{d}^2 x(t)}{\mathrm{d}t^2} \tag{1}$$

Where, k is the elastic coefficient of the spring; m is the mass of the adhesive; c is the damping coefficient of the damper. The energy transmitted by sound acts on the cilia of the sensor, making the vibration sensor vibrate under force, which is a stable periodic motion with constant vibration coefficient and constant vibration period. This also makes it possible to apply the special solution in the equation to the displacement between the adhesive body and the mechanical shell which vibrates relative to it under the stable periodic motion. The equation is:

$$z(t)=Z\sin(\omega t-\phi) \tag{2}$$

Where, Z is the maximum amplitude of the relative displacement $z(t)$ between the adhesive and the vibrating shell; ϕ is the phase difference between the displacement $x(t)$ of the external vibration and the relative displacement $z(t)$ of the viscous body and the vibrating shell. Under the uncertain periodic vibration, the force equation of the viscous body is:

$$F=m\frac{\mathrm{d}^2 z(t)}{\mathrm{d}t^2}=mZw^2\sin(\omega t-\phi) \tag{3}$$

In this paper, PVDF piezoelectric film material with type piezoelectric working mode d_{31} is used. When the applied force is F, the charge generated on the beam is:

$$Q=d_{31}F \tag{4}$$

The equivalent capacitance of piezoelectric film is[13]:

$$C=\frac{\varepsilon_{31}\pi r^2}{h} \tag{5}$$

Where, h is the thickness of the piezoelectric film, r is the radius of the piezoelectric film, and ε_{31} is the dielectric constant, then the output voltage is:

$$U=\frac{Q}{C}=d_{31}\frac{mZh\omega^2\sin(\omega t-\phi)}{\varepsilon_{31}\pi r^2} \tag{6}$$

4. Simulation analysis of bionic structure

Through investigation on various piezoelectric sensor structures, it can be found that there are many kinds of beam structures, including cross beam, straight beam, special-shaped beam and other structures, as well as a whole piezoelectric film as the sensor sensing unit. The thickness of 28 μm. The area is 800 μm × 800 μm. The whole piezoelectric film of m is used as the processing substrate of the sensing unit, and its upper and lower surfaces are covered with 5 μm metal layer, this piezoelectric film is widely used in the market and easy to purchase. With the piezoelectric module in structural mechanics in COMSOL 5.5, the parameterized modal difference analysis and the difference comparison of potential output were carried out for the models shown in **Figure 3** and **Figure 4**.

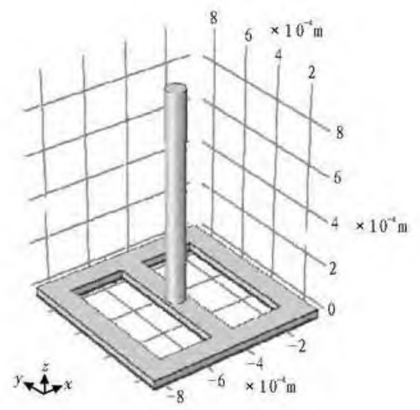

Figure 3. Cylindrical ciliated structure sensor.

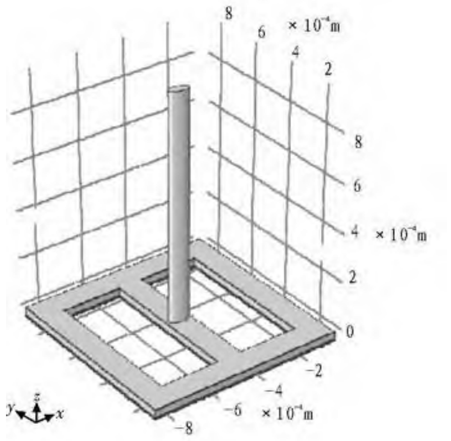

Figure 4. Sensor with elliptical cylindrical ciliary structure.

First, establish the model diagram through SOLIDWORKS, and then import COMSOL software. In the import column, set the absolute import tolerance value to 10^{-6}, select the physical field control grid, select the mesh division refinement, and set the boundary conditions including solid mechanics and static electricity. The boundary conditions of solid mechanics include fixed constraints and boundary loads, and the electrostatic boundary conditions are set as grounding[14]. The cilia of the sensor are made of polypropylene material with the same good safety, which has a sandwich structure of copper, PVDF and nickel[15]. The middle layer is a piezoelectric layer, and the upper and lower layers are electrode layers. The corresponding properties of the material are shown in **Table 1**. After grid division, apply a load of 1 Pa to simulate the external physical signal as the excitation signal of cilia perception. The structural parameters of cilia and sensitive units are shown in **Table 2**.

Table 1. Material properties of sensors

Attribute material	Polypropylene	Polyvinylidene fluoride
Density	0.91 g/cm^3	1,780 kg/m^3
Young's modulus	2.2 GPa	8.3 GPa
Poisson's ration	Zero point three nine four	Zero point one eight

Table 2. Structural parameters of two types of cilia and sensitive units

Structure name	Data/μm
Length of cantilever beam	Six hundred
Width of cantilever beam	One hundred
Thickness of cantilever beam	Thirty-eight
Height of polypropylene cilia	Nine hundred and fifty
Radius of polypropylene cilia	forty

As shown in **Figure 5**, by observing the results of the maximum stress simulation analysis of the sensitive unit of the device, it can be found that the maximum stress on the sensitive unit beam of the cylindrical sensor is 105, which is significantly lower than the 107 level of the elliptical column cilia shown in **Figure 6**. This shows that this type of cilia has obvious advantages under the stress pair ratio, and the difference in magnitude may be caused by the lever principle in mechanics. Because fulcrum of the force on cilia of the elliptical column is closer to center of the gravity of the cilia, stress should be more easily concentrated at fulcrum. According to the piezoelectric principle, the greater the stress under the same conditions, the stronger the charge movement, and the greater the potential generated. In order to enhance the preciseness of the experiment, we further explored whether the potential generated in the sensitive unit domain can match the stress results. In this project, the sensor with cylindrical ciliary structure as its structural feature, under a specific simulation environment, has its sensing unit voltage output cloud diagram and the frequency voltage output curve at the ciliary base, as shown in **Figure 7** and **Figure 8**, respectively. Under the same simulation environment, the voltage output nephogram of the sensing unit and the frequency voltage output curve of the sensor with the elliptical ciliary structure as the structural feature are shown in **Figure 9** and **Figure 10**, respectively. According to the maximum electric potential energy level in the figure, it can be found that the voltage value result of the simulated piezoelectric nephogram is proportional to the stress value result of the stress nephogram. On this basis, the one-dimensional line graph simulation results of the circumference and ellipse circumference of the cilia base position in contact with the sensitive structure are extracted, and the output curve is obtained. After fitting, it can be found that the potential output at the characteristic frequency is far greater than the potential output points at other frequency positions, and the potential output on the elliptical column cilia sensor is still greater than the cylindrical cilia structure. In order to further explore whether the characteristic frequencies of the cilia structure itself at the characteristic frequency interfere with each other and evaluate the ability of sensor frequency sorting, the fourth order frequencies of the two structures are solved through the characteristic frequency simulation, and the results are shown in **Figure 11**. The comparison results show that the frequency difference between the corresponding characteristic frequencies of the elliptical column ciliated sensor is large and uniform, while the frequency difference of the cylindrical ciliated sensor is between the first and second order frequencies, and the difference between the third and fourth order frequencies is very small, which will lead to its own frequency interference. The large and uniform frequency difference can support the elliptical column cilia sensor to achieve multi-channel function, which will minimize the need for more artificial cilia cells to cover the target bandwidth in the form of array in the limited space of the cochlea.

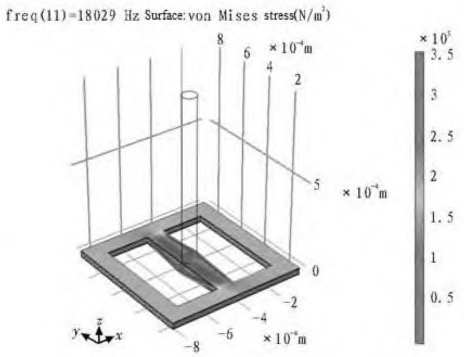

Figure 5. Stress nephogram of sensing unit of cylindrical sensor.

A good sensor requires that its measuring range is not easy to be saturated upward and has a lower detection threshold downward. To achieve this, the structure needs to be optimized in the simulation process to make the sensitive unit move in the sensitive direction. By observing the stress nephogram, it can be found that the cilia displacement direction of the cylindrical ciliated sensor is perpendicular to the direction of the beam, and the sensitive element in this direction is easy to reach the saturation point due to the lack of more support. By changing the structure of the elliptical cylinder sensor, the direction of the cilia movement of the sensor is adjusted to the direction of the beam, which greatly improves the upper limit of the sensor range. Considering the complex underwater flow, when facing the transverse flow perpendicular to the beam, its anti-lateral disturbance ability is also due to the anisotropy of its force bearing surface is stronger than that of the isotropic cylindrical ciliated sensor.

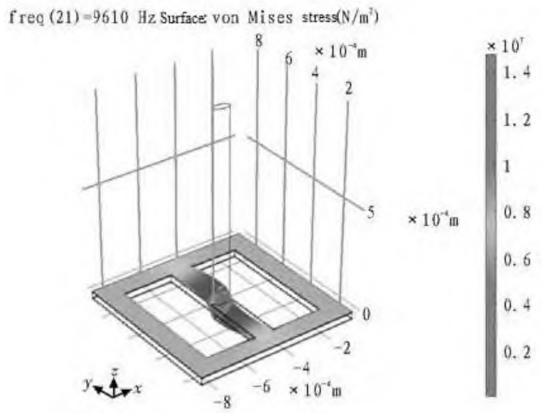

Figure 6. Stress nephogram of sensing unit of elliptical cylinder sensor.

Figure 7. Cloud chart of voltage output of cylinder sensor sensing unit.

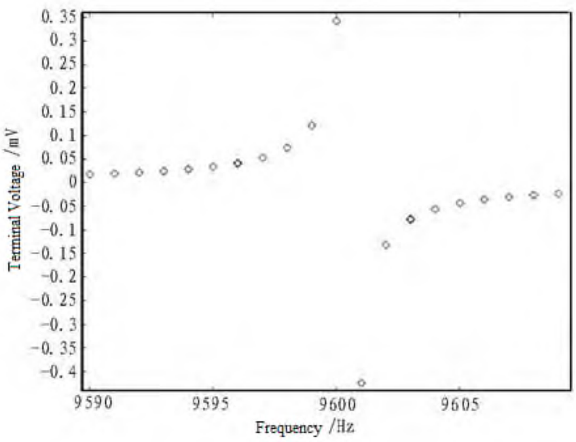

Figure 8. Frequency voltage output curve at ciliary base of cylindrical sensor.

Figure 9. Cloud chart of the voltage output of the sensing unit of the elliptic column sensor.

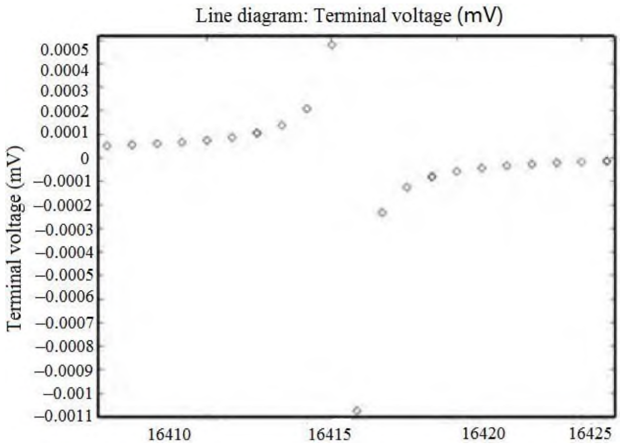

Figure 10. Frequency voltage output curve at ciliary base of elliptical column sensor.

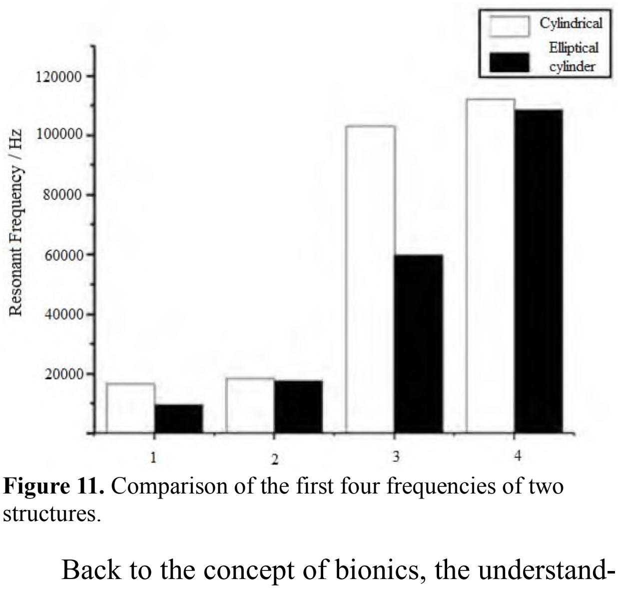

Figure 11. Comparison of the first four frequencies of two structures.

Back to the concept of bionics, the understanding of language and the recognition of timbre are higher requirements, and the human ear requires higher voice recognition. The morphology of the cilia under the electron microscope is similar to that of an elliptical column. In the simulation results, it shows a greater modal difference, which makes its anti-interference ability and frequency sorting ability strengthened. The static cilia, which are distributed step by step at the bottom of the fish cilia, can provide the fish with the ability to filter the turbulence[16], so that the moving cilia can capture the current flow rate information that is more important to the whole fish. The ciliated cells of fish need to be able to sense the frequency information of plankton swinging tail under water, and thus achieve the ability to locate and track prey, during which the fish can follow the current and swim with the fish flock in the current of different velocities.

The ability range of the whole lateral line system of fish is widely distributed. In terms of the coordination of various abilities, the ciliated cells of fish have been naturally selected, leaving ciliary structures more similar to columns, which indicates that the cilia of this structure must be more adaptable to the underwater environment. This isotropic stress surface structure can achieve balance in the realization of multiple functions, and it pursues the average value of the entire functional system. Hearing is the primary function of the human ear. The liquid environment in the cochlea is stable enough, and the external environment of the ciliated cells in the organ is not easy to change. These characteristics support the naturally selected cochlear ciliated cells to stay in the elliptical column like shape, because this ciliated shape can better realize the frequency sorting function, and enhance the language communication and information recognition between people. The ability of these ciliated cells focuses on the simulation results of ciliated structures.

4. Conclusions

As for the comparison of fish lateral line organs and human ears, human ears pay more attention to the accuracy of hearing recognition, which corresponds to a stronger frequency sorting ability. In order to explore the influence of cilia morphology on their functions, the cilia structure observed under the electron microscope was modeled in a pseudo way.

The piezoelectric coupling simulation was carried out through the linkage of Comsol solid mechanics and electrostatics modules. The elliptical column and cylindrical cilia models were introduced to verify the rationality of the application of elliptical column cilia structure in the field of cochlear implants. It is found that the elliptical columnar cilia are superior to the cylindrical cilia in frequency sorting ability and anti-interference ability. This discovery enables the preparation of the cochlear cilia sensor to be completed on the basis of a specific piezoelectric artificial lateral line system, which is compatible with the process technology of the MEMS artificial lateral line system, and will greatly accelerate the development process of the MEMS artificial cochlear sensor. At the same time, the advantages of no external power supply, miniaturization, low price, etc. will completely change the current situation of the expensive and inconvenient wearing of the artificial cochlea. The wide and uniform frequency difference can support the elliptical column ciliated sensor to achieve multi-channel frequency sorting function, which will minimize the number of artificial ciliated cell sensors covering the target bandwidth in the form of array. Compared with the traditional microphone + hardware circuit artificial cochlear architecture, it can effectively enhance the space utilization in the cochlea.

Conflict of interest

The authors declare no conflict of interest.

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