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# Design of Implantable Microphone for Artificial Middle Ear System

Min-Kyu Kim[1], Hyung-Gyu Lim[2], Young-Ho Yoon[2], Jyung-Hyun Lee[2], Il-Yong Park[3],
Byung-Seop Song[4], Myoung-Nam Kim[1], Jin-Ho Cho[1,3]

[1]Dept. of Biological & Medical Engineering, School of Medicine, Kyungpook National University
[2]School of Electrical Engineering & Computer Science, Kyungpook National University
[3]Advanced Research Center for Recovery of Human Sensibility, Kyungpook National University
[4]Department of Rehabilitation Engineering, Daegu University

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**Abstract:** An implantable microphone that can be utilized as part of a totally implantable hearing aid is designed and implemented. The proposed microphone is implanted in the center of the pinna, and designed to ensure the speech frequency range and the appropriate sensitivity. The characteristics of the proposed microphone are evaluated using a finite element analysis (FEA). The microphone is composed of a small electric condenser microphone, titanium case 6.2 ㎜ in diameter and 3 ㎜ high, and 10 ㎛ SUS316L vibrating membrane in contact with hypodermic tissue to maintain the sensitivity of the microphone. The microphone components are all made of biocompatible materials, then the assembled microphone is hermetically sealed using a polymer and ceramic. Experiments with the fabricated microphone confirm an operational bandwidth of up to 5 ㎑ without any decline of sensitivity in 6 ㎜ of hypodermic tissue.

**Key words:** Microphone, Totally implantable middle ear, Sensitivity

## INTRODUCTION

Although many different hearing aids have been produced on a commercial scale and effectively used to solve a variety of hearing difficulties, performance problems and structural limitations are still encountered by people with a severe hearing loss or sensorineural hearing loss. One solution has been the development of an implantable middle ear for people with a moderate or severe hearing loss [1-2].

Most existing implantable hearing aids are only partially implanted and consist of an internal and external device [3-4], however, new advances in rechargeable batteries, minimized wireless control units, and signal processing chips has resulted in the recent development of totally implantable hearing aids [5-7]. The essential parts of a totally implantable hearing aid are an implantable microphone, minimized signal processor, wireless charger, and miniature actuator that transmits the sound signal to the inner ear.

When designing an implantable microphone, the key considerations are the sensitivity, dynamic range, biocompatibility with the human body, and design suitability for surgical implant. As such, various implantable microphones have already been proposed, including one for the IMPLEX AG hearing technology developed in Germany, where the microphone is piezoelectric in type and designed to be located in the skin of the ear canal in front of the eardrum [8]. Yet, in this case, the surgical operation is very difficult and acoustic feedback can occur due to vibration of the eardrum as a result of the transducer attached to the middle ear. A piezoelectric type microphone was also designed for the Envoy system by St. Croix Medical in America, however, feedback is also a problem in a high gain state [9]. One idea for avoiding feedback is to use a liquid pouch located in the hypodermis of the temporal bone to receive a sound signal, then deliver the signal to the middle ear by a thin tube, yet there has been no report on its realization [10]. Meanwhile, another research team at Ehime University in Japan have produced remarkable results with a microphone 8 ㎜ in diameter and 6 ㎜ high that can be implanted in the hypodermis [11], however, this microphone is slightly too large for an ear implant and located in the skin near the eardrum. As such, when the microphone is implanted in the hypodermic tissue, this requires

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**Corresponding Author:** Jin-Ho Cho
101 Dong-In 2-Ga, Chung-gu, Daegu 700-422, KOREA
Tel. 053-427-5538 Fax. 053-427-5539
H P. 011-811-5538 E-mail. jhcho@ee.knu.ac.kr

cutting into the temporal bone quite deeply to hide the projected part of the microphone. Plus, when the microphone is implanted in the bone beneath the skin, this also leaves the potential of acoustic feedback due to vibration through the bone.

Accordingly, this paper presents a miniaturized microphone that can be effectively utilized with a totally implantable hearing aid. The proposed microphone is implanted at the center of the pinna in the skin and designed to ensure the necessary dynamic range and the appropriate sensitivity. The biocompatibility with the human body is also considered to protect the safety of the user. The characteristics of the designed microphone are estimated using a FEA, based on a theoretical formula for an acoustic analysis. After fabricating the designed microphone, several experiments are carried out to verify its performance.

## DESIGN AND IMPLEMENTATION

### Design of Microphone

The proposed microphone consists of a small electret condenser microphone (ECM), a titanium case, and a vibrating membrane made of very thin stainless steel. Figure 1 shows the microphone structure and implant location in the ear.

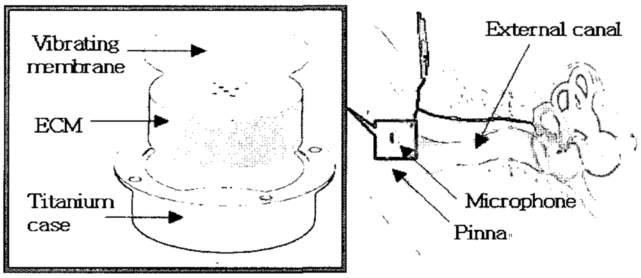


**Fig. 1.** Microphone structure.

A high sensitivity is the most important factor for an implantable microphone, while reliability is essential for a steady long-term operation *in vivo*. Therefore, a 10 μm-thick flexible vibrating membrane with a wider area than the ECM was used to collect more sound energy and increase the sensitivity of the microphone.

Sound vibrations are applied to the vibrating membrane of the microphone through the skin, then transferred to the vibrating membrane of the ECM. Figure 2 shows a cross-section of the microphone and indicates the path of the sound vibrations.

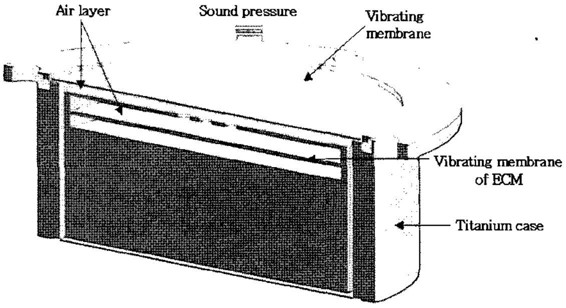


**Fig. 2.** Cross-sectional diagram of microphone.

The sensitivity of the proposed microphone can be theoretically understood based on the following progression. As shown in figure 2, the sound vibrations from outside are transmitted to the vibrating membrane of the microphone, where they change the fluid pressure of the air layer, then the changed air pressure is transmitted to the vibrating membrane of the ECM. The original sensitivity of the ECM was 46 dB V/Pa, which was then used to calculate the sensitivity of the proposed microphone.

### Theoretical Analysis of Microphone

In acoustical fluid-structure interaction problems, the structural dynamics equation needs to be considered along with the Navier-Stokes equations of fluid momentum and the flow continuity equation [12]. The structural dynamics equation can be formulated using the structural elements, as shown in equation (1).

$$M\frac{\partial^2 x}{\partial T^2} + D\frac{\partial x}{\partial T} + Kx = F(t)\cos\omega t \tag{1}$$

where, $M$ : mass of microphone vibrating membrane

$D$ : damping factor

$K$ : stiffness of microphone vibrating membrane

$F(t)\cos\omega t$ : input source function

$x$ : displacement of microphone vibrating membrane

The fluid momentum and flow continuity equations are simplified to obtain the acoustic wave equation using the following assumptions: the fluid is compressible and inviscid, there is no mean flow of the fluid, and the mean density and pressure are uniform throughout the fluid.

The acoustic wave equation is given by:

$$\frac{1}{c^2}\frac{\partial^2 P}{\delta t^2} - \nabla^2 P = 0 \qquad (2)$$

where, $c$ : speed of sound $(\sqrt{k/\rho_0})$ in fluid medium

$\rho_0$ : mean fluid density

$k$ : bulk modulus of fluid

$P$ : acoustic pressure

$t$ : time

Since viscous dissipation is neglected, equation (2) is referred to as a lossless wave equation for sound propagation in fluids. The fluid pressure acting on the structure at the fluid-structure interface is considered in the final subsection to form the coupling stiffness matrix. Multiplying equation (3) reveals the virtual change in pressure and integrating over the volume of the microphone.

$$\int_{vol} \frac{1}{c^2}\delta P \frac{\partial^2 P}{\partial t^2} d(vol) + \int_{vol} \delta P \nabla^2 P d(vol) = \int_S \{n\}^T \delta P \nabla P d(S) \qquad (3)$$

where, $vol$ : volume of domain

$\delta P$ : a virtual change in pressure

$S$ : surface where derivative of pressure normal to surface is applied

$\{n\}$ : unit normal to interface S

In the fluid-structure interaction problem, surface S is treated as the interface. To simplifying the assumptions made, the fluid momentum equations yield the following relationships between the normal pressure gradient of the fluid and the normal acceleration of the structure at the fluid-structure interface S. In matrix notation, equation (4) is given by:

$$\{n\}^T(\nabla P) = -\rho_0\{n\}^T\left(\frac{\partial^2}{\partial t^2}\{u\}\right) \qquad (4)$$

where, $\{u\}$ : displacement vector of structure at interface

Practically, the acoustic wave characteristic of the microphone can be presented by equation (5). After substituting equation (4) into equation (3), the integral is given by:

$$\int_{vol} \frac{1}{c^2}\delta P \frac{\partial^2 P}{\partial t^2} d(vol) + \int_{vol} \delta P \nabla^2 P d(vol) = -\int_S \rho_0\{n\}^T \delta P\left(\frac{\partial^2}{\partial t^2}\{u\}\right) d(S) \qquad (5)$$

The acoustic characteristic of the microphone was simulated based on the theoretical concept of equation (5) using an FEA. The sensitivity of the microphone was then calculated by an algebraic formula using the sound pressure from the simulated results.

## FEA Simulation of Microphone

Figure 3 shows the modeled result of the FEA simulation and sound pressure of the vibrating membrane of the ECM at 9 ㎑.

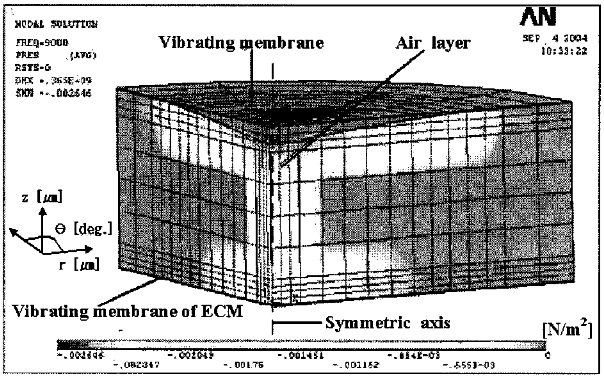


Fig. 3. FEA model for simulation of designed microphone and the simulated result of acoustic analysis at 9 ㎑.

When 70 dB sound pressure was transmitted to the vibrating membrane of microphone, a loading pressure ranging from 0.1 ㎑ to 9 ㎑ was simulated on the electric microphone membrane. The sensitivity of the microphone was calculated by an algebraic formula using the simulated sound pressure, and figure 4 shows the calculated results.

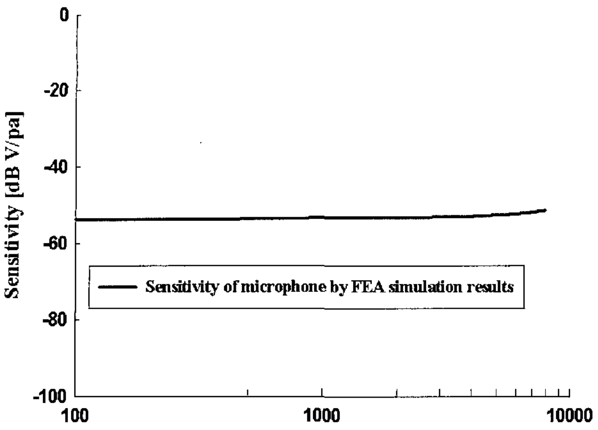


**Fig. 4.** Simulation results for unit sensitivity.

## Implementation of Microphone

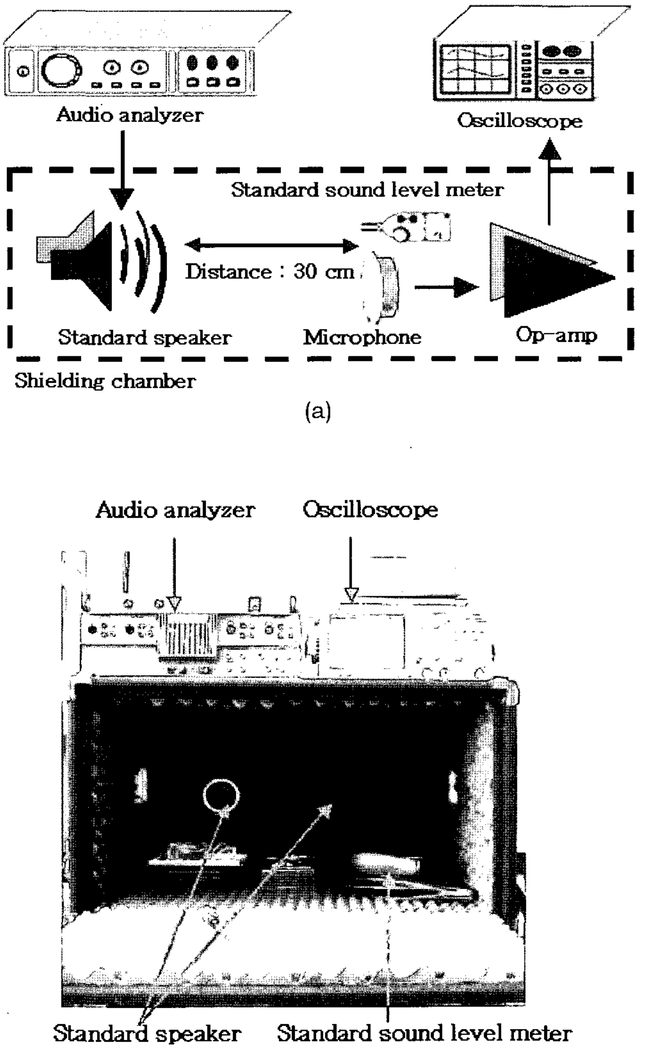
The microphone case was made of biocompatible titanium with a polymer coating and a hermetic sealing processing for safety purposes, and the vibrating membrane was fabricated using 10 ㎛ SUS316L stainless steel. After assembling the fabricated components and the miniaturized ECM, the resulting microphone was 6.2 ㎜ in diameter and 3 ㎜ high, as shown in figure 5.

(a) (b)

**Fig. 5.** Picture of fabricated microphone: (a) top view, (b) bottom view.

## EXPERIMENT AND RESULTS

In this study, the frequency characteristics of the fabricated microphone were measured using an experimental method that excluded any effects due to environmental noise, the characteristics of the speaker, and the shielding chamber. Figure 6 shows the measurement system used to determine the microphone characteristics. In the shielding chamber, the microphone and a standard sound level meter (Brüel & Kjær, Hand-held Analyzer Type 2250) were placed opposite the standard speaker (Brüel & Kjær, Omnisource 4295) at a distance of 30 ㎝. Despite the nonuniform speaker characteristics, a uniform 70 dB sound pressure level (SPL) was applied to the surface of the microphone by carefully controlling the output signal level of the audio analyzer (Audio precision, System Ⅱ 2222). The output signal from the microphone was amplified with a 20 dB voltage gain and delivered to a digital oscilloscope (Tektronix, TDS 380).



(a)

(b)

**Fig. 6.** Measurement system used to test fabricated microphone:(a) block diagram of experimental method, (b) picture of experimental equipment.

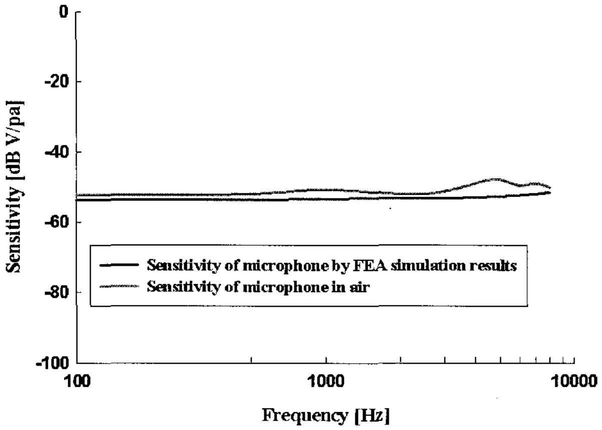


**Fig. 7.** Experimented results with fabricated microphone.

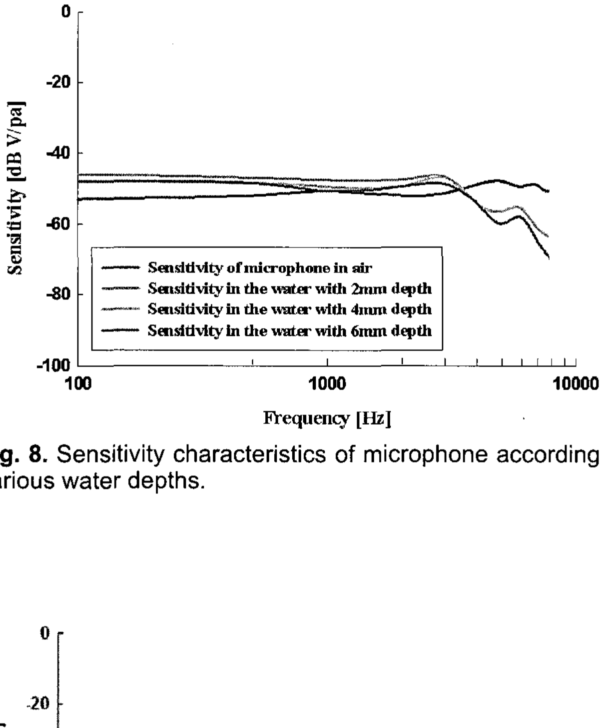


**Fig. 8.** Sensitivity characteristics of microphone according to various water depths.

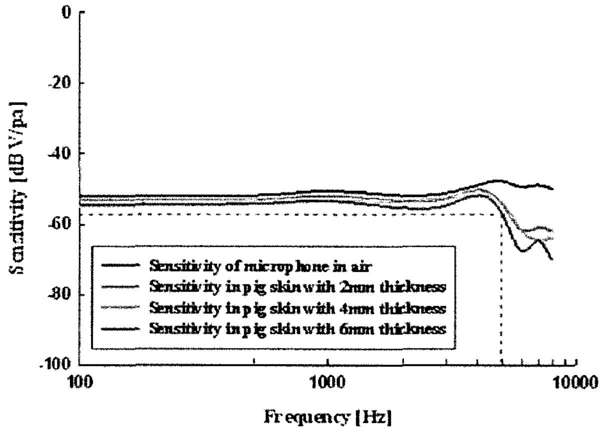


**Fig. 9.** Sensitivity characteristics of microphone according to various thicknesses of a pig skin.

Figure 7 shows the experiment results of the fabricated microphone, which were close to the simulated result.

To investigate the usefulness of the fabricated microphone, an *in vitro* experiment was carried out using water, which is similar to the human body, and pig skin. When the microphone was submerged to a selected depth in a pail filled with water, the microphone exhibited a good sensitivity within a range of 100 ㎐ to 3.5 ㎑, as shown in figure 8. Other tests were also conducted using pig skin. As shown in figure 9, a uniform characteristic was maintained without any sudden decrease within a range of 100 ㎐ to 5 ㎑. Therefore, if the microphone were to be used as a microphone in an implantable hearing aid system, the transmission bandwidth adequately covers the speech frequency range for a verbal conversation.

## CONCLUSION

This paper presented and implemented a miniaturized implantable microphone that can be utilized with totally implantable hearing aids. The proposed microphone can be implanted in the center of the pinna, and has been designed to ensure a proper dynamic range and obtain a sensitivity of over -50 dB SPL. The characteristics of the microphone were evaluated using an FEA. The proposed microphone is composed of a minimized ECM, titanium case 6.2 ㎜ in diameter and 3 ㎜ high, and 10 ㎛ SUS316L vibrating membrane in contact with hypodermic tissue to maintain the sensitivity of the microphone. In addition, since the microphone is implanted under the skin, it has a polymer coating and hermetic sealing for biocompatibility. The fabricated microphone was tested using water, which is similar to the human body, and pig skin. As a result, it was verified that the implemented microphone can operate with a bandwidth of up to 5 ㎑ without any decline of sensitivity in 6 ㎜ of hypodermic tissue, confirming that the proposed microphone can be effective for a T-IME and cochlear implant.

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