Published in final edited form as:

Otol Neurotol. 2014 January ; 35(1): e45–e49. doi:10.1097/MAO.0000000000000186.

Silicone-Coated Thin Film Array Cochlear Implantation in a Feline Model

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Abstract

Objectives—Some limitations of cochlear implants can be attributed to a restricted spectral representation of sound provided by contemporary electrode arrays. Microfabricated high-density thin film array (TFA) technology enables a greater density of stimulating sites and, thus, a more complete spectral representation. Previous pilot cadaveric studies have documented insertion characteristics, although not electrical characteristics.

Study Design—Electrode evoked auditory brainstem response (ABR) testing in a feline model.

Methods—Six healthy, normal hearing cats were unilaterally deafened and implanted with a silicone coated TFA, measuring $27.8 \times 0.4 \times 80$ mm (L $\times$ W $\times$ H). Monopolar stimulation of single electrodes was used to evoke a triple peaked ABR. Thresholds to evoke a minimal ABR were determined.

Results—All 6 cats underwent successful full insertion and activation. Thresholds to evoke minimal ABR's varied among implants ranging from 75 to 450 μ A. Over the basal portion of the array, thresholds were either larger or unable to evoke an ABR.

Conclusion—Two-thirds of the implants showed ABR's along the entire array, whereas the others evoked ABR's at the apical end and less robustly more basally. This may reflect increased distance of the electrodes from the modiolus, as the basal half of the array is narrower relative to the width of the scala. A tapered design to ensure array distance to modiolus is minimized may enable the basal half of the arrays to stimulate more consistently.

Keywords

Cochlear implant; Thin film array; microfabricated array

Cochlear implants (CI) are well established in the treatment of severe-to-profound hearing loss. Current US criteria for implantation include prelingual children 12 months or older with bilateral profound sensorineural hearing loss and postlingual adults with bilateral severe-to-profound sensorineural hearing loss with minimal speech perception using best aided conditions (1). Over the past several decades, subject performance postimplant has steadily increased (2). Current implants, however, are still limited in their functional ability to provide a high resolution of pitches (3). Therefore, subjects are unable to fully appreciate music or to understand speech in crowded environments (3).

At the current time, 3 manufacturer's cochlear implant devices are available in the United States (3). These implants have electrodes that are 10 to 31 mm in length and use up to 22 intracochlear electrode contacts to deliver impulses tonotopically to the cochlear nerve (2,3). It has been proposed that increasing the number of electrode stimulating sites will improve music appreciation and speech recognition in crowded situations (3). Current electrode designs prevent increasing electrode density because of the small size of the human cochlea scala tympani (3). Expanding the number of electrodes would increase the overall diameter of current implants and subsequently inhibit successful, atraumatic insertion. Thin film arrays (TFAs) were proposed to overcome this problem. Early TFA electrode designs, although efficacious with respect to activating auditory nerve fibers, were unable to be advanced past the basal turn of the cochlea, limiting the portion of the cochlea available for stimulation (3). This limitation was thought to be due to the thin-film silicone substrate lacking the mechanical flexibility (4). To overcome this design constraint, researchers at the School of Electrical and Computer Engineering, Georgia Institute of Technology, in collaboration with Georgia Regents University created a prototype polymeric TFA coupled with an insertion test device in hopes of gaining successful insertion (3).

This study is a continuation of a previous implantation trial of TFAs into cadaveric human temporal bones using an insertion test device (ITD) backed TFA electrode. The ITD was similar in size to a cochlear implant electrode but lacked the current conducting component. It had a maximal insertion length of 17 mm to a T-stopper, and the array did not extend beyond its length. Results showed successful insertion of the TFA past the basal turn of the cochlea with a mean insertion depth of 17 mm. The authors concluded that their TFA electrode could be successfully and reliably inserted into human cochlea with minimal trauma when using the insertion test device (3).

The end goal for the TFA electrode is to create an improved implant for use in humans. Before implantable devices can be used as human prostheses, however, function, efficacy, and safety must be documented in an animal model. Several previous studies have noted successful cochlear implantation in cats, with reliably observed responses to sound and the ability to elicit evoked auditory brainstem responses (2,5,6).

The aim of this study was to implant a modified silicone coated TFA electrode cochlear implant in live cats to test the in vivo characteristics.

MATERIALS AND METHODS

This study was a prospective cochlear implant insertion analysis using electrically evoked auditory brainstem response testing in a feline model. Previously published feline implantation techniques were used (2,6,7). Approval was obtained from both the Georgia Regents University, and the Georgia Institute of Technology Institutional Animal Care and Use Committees.

The commercially fabricated polymeric TFAs were engineered at the BioSystems Interface Laboratory in the School of Electrical and Computer Engineering. Each array measured $27.8 \times 0.4 \times 80 \mu\text{m}$ ($L \times W \times H$). This was coated with MED-2000 Silicone RTV Adhesive (NuSil Silicone Technology LLC, Carpinteria, CA, USA) to improve structural integrity. The adhesive was applied to the back surfaces of each array at a thickness of approximately 1 mm as well as to the array tip to minimize potential insertion trauma. This rendered the most apical site of each array nonfunctional. In all, there were 20 active platinum sites spaced at $250 \mu\text{m}$ in pitch and $180 \mu\text{m}$ in diameter spanning the array. Site impedances were measured to test integrity of the device.

The prototype TFA was sized for a shallow insertion into the first turn of the scala tympani. When compared with conventional arrays the TFAs differ in 2 aspects. First, the TFAs are much thinner. The TFA thickness is $20 \mu\text{m}$ ($80 \mu\text{m}$ when coated) and maintains a width of $400 \mu\text{m}$; conventional arrays have an $800\text{-}\mu\text{m}$ basal diameter. Thus, the coated TFA has an aspect ratio of 1:5 rather than 1:1 when compared with conventional arrays. Second, with respect to electrode site spacing, the $250 \mu\text{m}$ spacing of the TFA sites is at least 3 times less than that of conventional array sites, which are 750 to $1,000 \mu\text{m}$ apart.

Three male and 3 female, healthy, wild-type adult cats were obtained for implantation. All proper quarantine protocols were strictly adhered to. Subjects were randomly assigned to undergo implantation of the right or left ear with the aforementioned TFA device. Each cat acted as its own control using the contralateral unimplanted ear.

Anesthesia

This study used an anesthesia technique similar to that described by Rajguru et al. (2) in their study of CI in cats. Induction was acquired with an intramuscular injection of ketamine (3 mg/kg) and medetomidine. Intravenous access was obtained in a vein from the front leg. The animals were then intubated to assure adequate ventilation. Anesthesia was maintained with isoflurane titrated as necessary using an anesthesia workstation. Later experiments used an acepromazine/ butorphanol induction followed by propofol. The cat was then intubated and anesthesia maintained with isoflurane. This latter anesthetic technique proved to be much more stable. Heart rate, respiratory rate, body temperature, oxygen saturation, and end tidal CO_2 were continuously monitored. Body temperature was maintained at 38°C using a controlled heating pad. Subjects receive continuous infusion of Ringer's lactate solution with 2.5% dextrose at a rate of 10 ml/kg per hour (2).

Baseline Auditory Brain Response

After induction of general anesthesia but before any surgical intervention, preoperative ABRs were obtained to ensure normal bilateral hearing. ABRs were provoked by using a loudspeaker in a free sound field. After initial ABR testing, a foam earplug was placed in the nonoperated ear to avoid ambient noise stimulating the control ear.

Surgical Approach

Surgical approach was modeled after previously published feline studies by Rajguru et al., (2) Kretzmer et al., (6) and Kirby and Middlebrooks (7). One of 2 surgeons performed each insertion. After palpating surgical landmarks including the temporal line and the posterior aspect of the external auditory canal, a C-shaped incision was made with a 15-blade scalpel behind the randomly chosen surgical ear. Dissection was carried through the soft tissue until the bony cranium and bullae were identified. A self-retaining retractor was placed to aid with exposure. Next, an approximately 5 × 5-mm bullotomy was drilled, under magnification, to gain access to the round window of the cochlea. Adequate hemostasis was achieved with bipolar cautery. Fascia covering the round window was incised with a sharp Rosen pick. Perilymph was removed via wicking through the cochleostomy and replaced with 10% neomycin sulfate solution to induce acute hearing loss. After 2 minutes, fluid was once again wicked from the basal turn of the cochlea and replaced with 10% neomycin. ABR was obtained to ensure no response from the surgical ear. If a response was still elicited, application of 10% neomycin was repeated until the ear was deafened. ABR was tested with increased stimulus to evoke a response from the unimplanted ear. At this point, the silicone adhesive backed TFA electrode was manually inserted into the round window under microscopy. The TFA was secured in place with a hemostat to avoid movement during electrical testing.

Processor Activation

The implants were stimulated using a PlexStim™ 2.0 (Plexon Inc., Dallas, TX, USA) 16-channel stimulator. Each stimulus was a biphasic, monopolar, negative-first, current pulse with 100 microseconds per phase. The lowest current in μA able to reliably yield a response was recorded as the ABR threshold. Typically, the ABR Wave IV, at 4 milliseconds, was the wave reliably detected at threshold. In each array, the most apical site was Site 2. The most basal site was 21. In all insertions, the most apical, basal and several intermediate sites were stimulated. Noise artifacts were rejected by averaging phase inverted stimulation with negative-first stimulation.

RESULTS

All 6 cats had normal baseline hearing documented by ABR. The first 3 cats implanted were females and underwent left-sided insertion. The last 3 cats were males and underwent right-sided insertion. Unilateral deafening was achieved after 4 to 8 applications of 10% neomycin. After this, normal hearing was documented in unimplanted ears. All cats had subjectively easy, full insertion of the silicone-coated TFA. In 2 subjects, 2 arrays were inserted secondary to inability to activate the first array. After successful activation, data were recorded for the second array. In each array, that responses could be recorded,

monopolar stimulation was able to evoke a triple peaked auditory brainstem response partially ($n = 2$) or fully ($n = 4$) along the array (Fig. 1). In 1 case, the facial nerve was stimulated at the basal half of the array. ABR thresholds were recorded for all sites within each cat (Fig. 2). These ranged from 93.8 to 272.5 μA (SD, 17.3–133.3). ABR thresholds at each site across all cats are shown in Figure 3 and ranged from 120 to 280 μA (SD, 0–147.3). ABR thresholds at the apical half of the arrays were 136.3 μA (SD, 39.2) versus 201.3 μA (SD, 53.2) at the basal half. The most basal site yielded no or inappropriate stimulation in 2 subjects. The ABR thresholds along the entire array for female subjects/left-sided insertions were 196.7 μA versus 122.5 μA for male subjects/right-sided. Mean threshold across the entire array in the first 2 cats versus the last 4 cats was 227.5 to 125.6 μA . Cat 1 had very high ABR thresholds at Sites 10 and 12 and no activation basally. Cat 3 showed activation of the facial nerve along the basal half of the array. Of the 4 cats that showed stimulation along the entire array, ABR thresholds were lower for the apical 10 electrodes versus the basal 10 electrodes. Current necessary to stimulate the electrode correlated inversely to order of the cats being implanted (-0.8), suggesting this was related to surgeon experience.

DISCUSSION

All cats had subjectively easy insertion of the silicone-coated array. Four of the implants (60%) yielded ABR's along the entire array, whereas the others elicited ABRs at the apical end and tapered off more basally. These findings may reflect increased distance of the electrodes from the modiolus, as the basal half of the array is narrower relative to the width of the scala. A tapered design to ensure array distance to modiolus is minimized may enable the basal half of the arrays to stimulate more consistently.

There was a trend in ABR thresholds across the entire array from the first 2 cats to the last 4 cats, improving from 227.5 to 125.6 μA . This trend likely represents the learning curve of the surgeon, suggesting with increased experience, there was decreased insertion trauma to the array and/or cochlea.

There did appear to be a difference between the female/ left-sided insertions and the male/ right-sided insertions. As the first 3 cats were the female/left-sided insertions, this, again, may be due to the learning curve of the surgeon and not necessarily reflect sex or side.

One of the limitations of this study can be attributed to using monopolar versus bipolar stimulation. Monopolar electric stimulation affects an area but not a point. Because of this and the narrow distance between the stimulating channels on the electrode, multiple areas may be superposed. Although this manuscript does not present bipolar stimulation or current steering strategies, other work suggests that focused electrical stimulation, which recruits multiple electrodes, can activate restricted populations of neurons (8). This may be particularly important in the basal turn of the cochlea, the site of densest tonotopic mapping. This theory cannot be tested with current designs because increasing the bulk of the array limits our ability to truly visualize the impact of increasing numbers of electrodes. Furthermore, alternate methods for fabricating electrode arrays may be essential to reduce insertion trauma and allow for preservation of residual hearing (9). Producing an electrode

that is less expensive to manufacture will increase access to this technology and foster additional testing. The hope would be that further testing may be able to adequately address the question of whether increasing electrode density can improve musical appreciation and speech recognition in crowded situations.

A second limitation of this study is that of possible acoustic crosstalk via osseous transmission. In our study, we placed a foam earplug in the contralateral ear and used low decibel clicks. The triple peaked response disappeared after deafening and reappeared after CI insertion, and the acoustic level remained the same throughout all stages of testing. However, despite these precautions, the possibility of acoustic crosstalk cannot be discounted completely.

CONCLUSION

This project is of great interest as TFA technology may have the potential to improve speech recognition in crowded situations and music appreciation and could be significantly less expensive to manufacture than current electrode designs. Two-thirds of the implants elicited ABRs along the entire array, whereas the others evoked ABRs at the apical end and less robustly more basally. This may reflect increased distance of the arrays from the modiolus, as the basal half of the array is narrower relative to the width of the scala. A tapered design to ensure array distance to modiolus is minimized may enable the basal half of the arrays to stimulate more consistently. Further studies with design modification and using bipolar stimulation, as well as chronic studies to test the integrity and viability of the implant, are still needed.

Acknowledgments

Conflicts of Interest and Source of Funding: This research was funded in part by an unrestricted educational grant from Med-El and by Georgia Regents University Intramural Grants Program Pilot Study Research Program PSRP00060.

Dr. McKinnon has received research funding and travel support from Med-El.

Dr. Bhatti was supported in part by the PHS grant (UL1 RR025008 and KL2 RR025009) from the Clinical and Translational Science Award program, National Institutes of Health, National Center for Research Resources and by the National Science Foundation Award (1133625).

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FIG. 1. Example electrode evoked ABR demonstrating monopolar stimulation eliciting a triple peaked response.

FIG. 2. The decrease in mean current of activation potentials in μA along the entire array with the order of cats implanted (-0.8), suggesting the change likely reflected increasing surgeon experience.

FIG. 3.

Bars indicate standard deviation. The mean threshold of activation potentials did not correlate with electrode site (0.4).