COMPARISON OF HALF-BAND AND FULL-BAND ELECTRODES FOR INTRACOCCHLEAR ELECTRICAL STIMULATION

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It was hypothesized that intracochlear stimulating electrodes oriented toward the modiolus would require a lower stimulus current to elicit a threshold neural response than longitudinal band electrodes. Electrically evoked auditory brain stem responses (EABRs) and electrode impedances were recorded with full-band and oriented half-band scala tympani electrodes in anesthetized, deafened cats. To elicit a threshold EABR, the stimulus current required for stimulation through half-band electrodes oriented toward the modiolus was not significantly different from the current required for stimulation through full-band electrodes. The impedances of full-band electrodes were significantly lower than those of half-band electrodes. Considering the significantly higher impedance and current density of half-band electrodes in comparison to full-band electrodes, as well as the critical orientation of half-band electrodes during implantation, we believe that full-band electrodes have advantages over half-band electrodes for scala tympani implantation.

KEY WORDS — cochlear implant, electrically evoked auditory brain stem response, half-band electrode.

INTRODUCTION

For the improvement of cochlear prostheses, it is desirable to stimulate discrete groups of auditory nerve fibers with the minimum current. A model of electrical stimulation of the cochlea¹ has predicted the stimulus current required to elicit a threshold neural response to be lower for stimulation through a longitudinal pair of electrodes close to and oriented toward the modiolus than for stimulation through the banded electrode array used by the University of Melbourne/Cochlear² device. There are two possible reasons for this to be so. First, the banded array was modeled to lie further from the modiolus, and the distance between the electrode and the modiolus has been shown to be important in determining stimulus current at threshold.³ Second, the banded array was nondirectional, whereas the longitudinal pair was oriented toward the modiolus. If the electrodes are oriented toward the modiolus, it is possible that the current spread will be directed toward the modiolus, thereby reducing the stimulus current required to evoke a threshold neural response. It was hypothesized that the stimulus current required to evoke a threshold neural response for stimulation through half-band electrodes oriented toward the modiolus would be lower than that for stimulation through full-band electrodes. We tested this hypothesis in the anesthetized, deafened cat by comparing electrically evoked auditory brain stem responses (EABRs) elic-

ited by stimulation through full-band and half-band scala tympani electrodes.

MATERIALS AND METHODS

Electrode Array. The electrode array consisted of three pairs of accurately aligned half-band platinum electrodes on a Silastic MDX-4-4210 carrier (Fig 1). The radius of each electrode was 0.25 mm and the width was 0.3 mm. Each half-band electrode was connected to a platinum-iridium wire. The gap between each pair of half-band electrodes was 0.1 mm, edge to edge, and the distance between the adjacent pairs of electrodes, center to center, was 0.75 mm. The three pairs of half-band electrodes occupied the first 2.2 mm for the tip. At 6 mm from the tip, there was a banded dummy electrode used as a guide to insertion depth during the operation. Between 7 and 9 mm from the tip, a longitudinal Silastic mark was made to assist in the orientation of the electrodes.

Animals. Two adult cats were used in this study. They had otoscopically normal tympanic membranes and normal hearing thresholds (<37dB peak equivalent sound pressure level re 20 μ N/mm²) as measured by click-evoked auditory brain stem responses (ABRs). Under anesthesia of Saffan (Alphaxalone, 9 mg/kg, intravenously), the animals were profoundly deafened by the coadministration of kanamycin sulfate (300 mg/kg, intramuscularly) and ethacrynic

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Fig 1. Electrode array consisting of three pairs of half-band electrodes, dummy electrode, and orientation mark on Silastic carrier. T — tip electrodes, M — middle electrodes, B — basal electrodes, D — dummy electrode.

acid (Merck Sharp & Dohme, ethacrynate sodium, 15 to 25 mg/kg, intravenously).⁴ Two and a half years later, acute electrical stimulation was conducted on the two cats under general anesthesia (ketamine, 18 mg/kg, intramuscularly, and xylazine, 38 mg/kg, intramuscularly). Anesthesia was maintained by supplemental doses of ketamine (10 mg, intravenously) and xylazine (2 mg, intravenously) as required. Click-evoked ABR thresholds were confirmed to be above 97 dB peak equivalent sound pressure level, the maximum output of the speaker. A postauricular incision was made and the bulla and the round window were exposed. The inferior-posterior edge of the round window niche was trimmed so that after the round window was opened, the modiolus, osseous spiral lamina, and basilar membrane could be clearly brought into view. The electrode array was inserted 6 mm into the scala tympani with three half-band electrodes oriented toward the modiolus and their counterparts oriented toward the outer wall of the scala tympani (Fig 2). After the lead wire was fixed at the bulla wall, the orientation of the electrode array was checked and a small piece of muscle was packed at the round window. Both cochleas in each cat were stimulated, but the results from the right cochlea in one cat were discarded because the stimulus current

polarity was not controlled in this cochlea.

Impedance Measurement In Vitro and In Vivo.

Before the operation, the electrode array was immersed in normal saline. Biphasic pulses of constant current (1.0 mA, 100 microseconds per phase) were delivered to each pair of electrodes, and the electrode voltage and current were shown on an oscilloscope. The voltage across the electrodes is proportional to their impedance. These measurements were repeated after the electrode array was inserted into the scala tympani. Differences in resistance and impedance between half-band and full-band electrodes were tested for statistical significance with a paired comparison *t* test.

EABRs. Electrical stimuli were biphasic, charge-balanced current pulses (200 microseconds per phase, 30 pulses per second). Bipolar stimulation was delivered between two longitudinally placed electrodes (tip-middle, middle-basal, or tip-basal). These electrodes were either half-band or full-band electrodes (Fig 3). The inner half-band electrodes were oriented toward the modiolus, and the outer half-band electrodes were oriented toward the outer wall of the scala. Stimulation through a full-band electrode was achieved by the parallel connection of both inner and outer half-band electrodes.

Fig 2. Inner half-band electrodes (arrowhead) oriented toward modiolus and outer half-band electrodes (arrow) oriented toward outer wall of scala tympani. T — tip electrodes, M — middle electrodes, B — basal electrodes.

The EABRs were recorded with subcutaneous needle electrodes (positive at the vertex; negative at the nucha; ground at the abdomen). The gain of the differential preamplifier (WPI, DAM-5A) was 60 dB, and the signals were further amplified by 40 dB. The electrical artifact was suppressed by a sample and hold circuit that released following the electrical stimulus. The signals were filtered by a 50-Hz rejection filter and a band pass filter (Krohn-Hite 3750, high pass 150 Hz, 24 dB per octave; low pass 3 kHz, 6 dB per octave). The EABRs were sampled by an analog to digital converter and averaged over 500 trials. For each current level, two sets of averaged

Fig 3. Summary of electrical stimulation paradigms used. Filled electrodes indicate those activated during various modes of electrical stimulation. For electrical stimulation using full-band electrodes, inner and outer half-band electrodes of each pair are connected, having same electrical potential, and current is only between electrodes placed longitudinally.

responses were stored in an IBM-compatible personal computer. The amplitude of the response was measured as the amplitude of the wave P3-N4 (latency between 2.5 and 3.5 milliseconds). The current level at which the EABR amplitude was $0.5 \mu\text{V}$ was estimated by linear interpolation and arbitrarily defined as threshold. Differences in stimulus current required to evoke a threshold EABR between stimulation through half-band and full-band electrodes were tested for statistical significance with a paired comparison *t* test.

RESULTS

Impedance. On the injection of current through electrodes placed in electrolyte, the voltage across the electrodes increases rapidly to a level proportional to the access resistance of the electrodes (Fig 4). There is also a voltage increase with a longer time constant. The maximum voltage across the electrodes is proportional to the peak impedance of the

Fig 4. Voltage across electrodes immersed in electrolyte (upper trace) on injection of constant current (*I*; lower trace) increases rapidly to level (*V_r*) that is proportional to access resistance of electrodes. Voltage across electrodes increases further to level (*V_z*) that is proportional to peak impedance of electrodes for pulse duration used.

electrodes, which includes resistive and reactive components. Full-band electrodes had significantly lower access resistances and peak impedances than either of the component half-band electrodes *in vivo* (see Table) and *in vitro* ($p < .05$). There were no significant differences ($p > .05$) between the *in vivo* and *in vitro* measurements of the access resistance or peak impedance.

EABR Amplitude. The amplitude of the EABR increased with increasing current (Fig 5). The P3-N4 wave (wave IV) could be reliably measured over a wide range of currents without interference from electrical stimulation artifact. The amplitude of wave IV of the EABR was measured for different electrode configurations for currents up to 1 mA peak. When data from all electrodes, cochleas, and currents were pooled, the EABR amplitude elicited by stimulation through full-band electrodes was slightly but significantly less than that elicited by stimulation through the inner half-band electrodes ($p < .01$, paired *t* test). However, this difference was not as large as that between the amplitudes of the EABRs elicited by full-band and outer half-band stimulation (Fig 6). These differences in EABR amplitude were larger for stimulation between longitudinally adjacent elec-

ACCESS RESISTANCE AND PEAK IMPEDANCE OF ELECTRODES *IN VIVO*

Electrodes	Tip-Middle	Middle-Basal	Tip-Basal
Inner half-band	(1.6) 4.0	(1.6) 3.8	(1.6) 4.0
Outer half-band	(2.0) 4.6	(1.6) 4.2	(1.8) 4.4
Full-band	(1.0) 3.2	(1.0) 3.1	(1.1) 3.3

Data are in kilo-ohms. Access resistances (in parentheses) and peak impedances of electrodes in left cochlea of cat 513 were significantly lower for full-band electrodes than for either of half-band electrodes ($p < .05$). Activated electrodes are indicated in Fig 3.

Fig 5. Two averages of electrically evoked auditory brain stem response (EABR) to electrical stimulation were recorded for each current level. Responses illustrated are to stimulation through full-band tip-basal electrodes in right cochlea of cat 513. Amplitude of EABR was obtained by measuring P3-N4 wave (latency of 2.5 to 3.5 milliseconds).

trodes than for stimulation between the tip and basal electrodes.

EABR Threshold. An EABR wave IV amplitude of 0.5 μV was arbitrarily defined as a threshold response. The stimulus current required to elicit a threshold response was estimated by linear interpolation of the EABR input-output functions. It was generally found that stimulation through full-band electrodes required a slightly higher current to evoke a threshold EABR than did stimulation through the inner half-band electrodes, but required much less than did stimulation through the outer half-band electrodes (Fig 7). The current required for a threshold EABR was less for widely spaced electrodes (tip-basal) than for longitudinally adjacent electrodes (tip-middle or middle-basal). Higher stimulus currents were required to elicit a threshold EABR for cochlea 513L than for the other two cochleas. This may have resulted from a difference in the survival of auditory nerve fibers, or a slight difference in the radial position of the electrode within the scala. There was no significant difference ($p > .05$) in the current required to elicit a threshold EABR between stimulation through the inner half-band and full-band elec-

Fig 6. Amplitude of EABR as function of stimulus current for middle and basal electrodes in cochlea 522L. Stimulation was delivered through inner half-band, outer half-band, and full-band electrodes. Stimulation through inner half-band electrodes generally evoked similar or slightly larger EABR amplitude than did stimulation through full-band electrodes, and much larger amplitude than did stimulation through outer half-band electrodes.

trodes. The stimulus current required to evoke a threshold EABR was significantly higher ($p < .01$) for stimulation through the outer half-band than through either the inner half-band electrodes or the full-band electrodes.

DISCUSSION

This study investigated differences in EABR amplitude, stimulus current at EABR threshold, and electrode impedance between stimulation through half-band and full-band scala tympani electrodes. Stimulation through full-band electrodes evoked a threshold EABR at current levels not significantly different from those evoked by stimulation through half-band electrodes oriented toward the modiolus. The access resistance and peak impedance of full-band electrodes were significantly lower than those

Fig 7. Stimulus current required to elicit threshold EABR for stimulation through full-band, inner half-band, and outer half-band electrodes. Activated electrodes are indicated in Fig 3. T/M — tip-middle electrodes; M/B — middle-basal electrodes; T/B — tip-basal electrodes; L — left ear; R — right ear; 513, 522 — cat numbers.

of half-band electrodes.

A previous study of half-band electrodes was conducted,⁵ but the EABR was contaminated by electrophonic components.⁶ In order to study direct electrical stimulation of the auditory nerve without contamination of the EABR by electrophonic responses, we deafened the cats with kanamycin and ethacrynic acid.⁴ This technique results in a loss of spontaneous and acoustically evoked activity in auditory nerve fibers (R. K. Shepherd and E. Javel, unpublished observations, 1987), as well as a complete bilateral loss of hair cells and a moderate to severe loss of spiral ganglion cells.⁷ These animals should therefore be good models of profoundly deaf patients.

The EABR had a slightly larger amplitude and a threshold response was elicited by slightly lower stimulus currents when stimulation was delivered through the inner half-band electrodes, rather than through the full-band electrodes. However, the difference in stimulus current required to evoke a threshold response was not statistically significant. The EABR had a significantly lower amplitude and a significantly higher current was required to elicit a threshold response when stimulation was delivered through the outer half-band electrodes than when it was delivered through either the inner half-band or full-band electrodes. The clinical implication of these results is that patients may not gain significant im-

provement by using inner half-band electrodes instead of the full-band electrodes. Furthermore, a large fenestration at the cochlea is needed for accurate orientation of the half-band electrode, and if the electrode array is rotated during or after insertion, the current required to evoke a threshold neural response may be significantly higher than for the full-band electrode.

The access resistances and peak impedances of full-band electrodes were significantly lower than those of half-band electrodes. This would result in a greater range of currents being available to the full-band electrodes without exceeding the maximum voltage output of the stimulator. The lower impedance of the full-band electrodes indicates the passage of electrical current through the whole surface of the full-band electrodes, resulting in a lower charge density than that for the half-band electrode. For the full-band electrode, stimulation at 1 mA for 100 microseconds per phase results in a charge density of 21.2 microcoulombs per square centimeter per phase. Stimulation through the half-band electrodes would result in a charge density of 42.4 microcoulombs per square centimeter per phase, which is close to the levels that cause cochlear damage.⁸ From considerations of surgical implantation, impedance, and charge density, we conclude the full-band electrodes to be more suitable for cochlear implantation than half-band electrodes.

ACKNOWLEDGMENT — The authors thank Dr Robert Shepherd for comments on the manuscript.

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Title:

Comparison of half-band and full-band electrodes for intracochlear electrical stimulation

Date:

1993

Citation:

Xu, S., McAnally, K. I., Xu, J., & Clark, G. M. (1993). Comparison of half-band and full-band electrodes for intracochlear electrical stimulation. *Annals of Otology, Rhinology and Laryngology*, May, 102(5), 363-367.

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