Partial Deafness Cochlear Implantation (PDCI) and Electric-Acoustic Stimulation (EAS)

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ABSTRACT *The purposes of this paper are to (1) review briefly the experience to date with combined EAS for patients with some residual, low-frequency hearing; and (2) describe the further results that have been obtained with the combination for patients with higher levels of residual hearing at the low frequencies, termed "PDCI." In broad terms, PDCI and combined EAS have produced large improvements in the speech reception abilities of the treated patients, compared with pre-operative scores or with post-operative scores for electric stimulation only or acoustic stimulation only. The benefits have been especially large for recognition of speech presented in competition with interfering sounds such as speech-spectrum noise. Although PDCI and combined EAS have been established as highly effective procedures, questions remain about optimal combinations of electric and acoustic stimuli; the ideal depth of insertion for the electrode array; whether the ideal depth may vary from patient to patient; and whether the reliability of hearing preservation in an implanted cochlea can be increased beyond the present high levels. The answers to these questions could lead to even-better treatments for persons with little or no hearing at high frequencies and at least some remaining hearing at low frequencies.*

Keywords: electric-acoustic stimulation; cochlear implants; cochlear implantation; partial deafness; partial deafness cochlear implantation; hearing preservation; residual hearing

Introduction

A common pattern of hearing loss is a precipitous decline in the sensitivity to sounds above a certain frequency, typically in the range of 250 to 500 Hz and sometimes extending up to about 1000 Hz. The pattern has been called a "ski slope" or "corner audiogram" loss. The remaining residual hearing at low frequencies is often insufficient for speech understanding in everyday acoustic environments with multiple talkers or other interfering sounds. Persons with ski slope losses have until recently been caught in an unfortunate circumstance of (1) not being able to understand speech even with the use of either properly fitted hearing aids or relatively high levels of residual hearing without hearing aids, and (2) at the same time failing to meet the candidacy criteria for a standard, fully-inserted cochlear implant.

Two remarkably effective treatments have been introduced recently for such persons. The treatments include a deliberately short insertion of a cochlear implant – along with other aspects of the surgery and adjunctive use of certain drugs – to preserve the residual low-frequency hearing in the implanted ear. Once the patient has recovered from the surgery, the basal end of the cochlea is stimulated electrically via the implant, and the apical end is stimulated in the normal way with acoustic stimuli. This approach was first described by Professor von Ilberg and his team in Frankfurt, Germany, and is called combined electric and acoustic stimulation (combined EAS) of the auditory system (von Ilberg et al., 1999). In combined EAS, low-frequency sounds are perceived with the preserved residual hearing, and high-frequency sounds are represented with the cochlear implant.

Partial Deafness Cochlear Implantation (PDCI) is a special case of combined EAS in which the residual hearing at low frequencies is relatively good. PDCI was first described by Professor Skarzynski and his team in Kajetany (near Warsaw), Poland (Skarzynski et al., 2003, 2008).

The purposes of this paper are to present on behalf of the investigator teams the experiences to date with these two treatments.

Combined EAS

One of the earlier studies to evaluate the efficacy of combined EAS was conducted in our laboratories at the Research Triangle Institute (RTI) in North Carolina, USA, in cooperation with three groups in Europe and one other group in the United States (Lawson et al., 2000; Wilson et al., 2002, 2003). The results from these early studies are representative of results from contemporaneous studies and of results from studies conducted since then.

The RTI studies included tests with the first EAS patient in Frankfurt and six additional subjects. Each of the subjects traveled to the RTI Laboratories for her or his participation in the studies. The studies were conducted with the permission and oversight from the RTI Institutional Review Board. Each subject read and signed an informed consent prior to her or his participation. The investigator team included Blake Wilson, Robert Wolford, Dewey Lawson, Reinhold Schatzer, and Stefan Brill from the RTI; Jan Kiefer, Thomas Pfennigdorff, Marcel Pok, Jochen Tillein, and Wolfgang Gstoettner from Frankfurt; Wolf-Dieter Baumgartner from Vienna; Carol Higgins (now Carol Pillsbury) and Harold Pillsbury from Chapel Hill, USA; and Artur Lorens from Warsaw.

Information about the subjects is presented in Table 1 and their post-operative clinical audiograms are presented in Figure 1. Subjects SR3 and ME14 had full insertions on one side of Ineraid and standard MED-EL implants, respectively, and the remaining subjects had insertions on one side to 18 or 20 mm of either the standard MED-EL implant or a compressed array variation of the standard implant, with a closer spacing between adjacent electrode sites. Subjects

SR3 and ME14 had no residual hearing in the same ear as the implant, but had at least some residual hearing contralateral to the implanted side. All of the remaining subjects had at least some preserved residual hearing in the implanted cochlea, and four of those five subjects had residual hearing on the contralateral side as well. Tests with the subjects included identification of consonants in an /a/-consonant-/a/ context presented in quiet and in competition with noise, and recognition of sentences in each subject's native language, at various speech-to-noise (S/N) ratios. Only the most important results from the sentence tests are presented here. Further details about the subjects, tests, and test results are presented in Wilson et al., 2002.

In Figure 1, the closed symbols show audiograms for ears contralateral to a cochlear implant, and the open symbols show audiograms for ears ipsilateral to an implant. The hearing loss at 1 kHz is 70 dB or worse for all audiograms. Hearing thresholds are generally better at progressively lower frequencies for each of the audiograms, but the range of thresholds is wide, from nearly normal thresholds at the audiometric frequencies of 125, 250, and 500 Hz for subject ME23 to substantial losses at those frequencies for subject SR3 (who had residual hearing on the contralateral side only) and subject ME19 on the implanted side.

Results for the recognition of key words in sentences are presented in Figure 2. Scores obtained with electric stimulation only are shown with the black bars; scores for acoustic stimulation only are shown with the dark gray bars; and scores for combined EAS are shown with the light gray bars. The error bars are the standard error of the mean for each of the measures. Each of the panels shows results for one of the subjects across the range of tested S/Ns for that subject's best aided condition. For subjects SR3 and ME14 this included delivery of the acoustic stimulus to the side contralateral to the cochlear implant and the standard full range of frequencies represented by the electrical stimulation with the implant. For the remaining subjects this included delivery of the acoustic stimulus to either the side ipsilateral to the implant only or to both sides. In addition, the range of frequencies represented by the implant varied across the subjects to produce the best results. For some subjects the full range was represented, whereas for others the lower end of the range was moved upwards to correspond with the upper limit of the residual hearing for the subject. For example, if a subject had relatively good thresholds at the audiometric frequencies of 500 Hz and lower, then the frequency range represented with the implant might be altered from 350-7000 Hz to 500-7000 Hz. In general, the effects of such manipulations were small but nonetheless significant in some cases. The acoustic stimuli were generated by first filtering the input signal (speech or speech plus noise) with a 1 kHz low-pass filter and then amplifying the output of the low-pass filter linearly such that the loudness of the acoustic stimuli matched or approximated the loudness of the electric stimuli for a subject. The acoustic stimuli were delivered through circumaural earphones. Results for the optimal conditions for each subject are presented in Figure 2. Results for other conditions and additional S/Ns (including presentation of the sentences in quiet) are presented in Wilson et al., 2002.

The S/Ns included in Figure 2 ranged from presentation of the sentences in quiet to the highly adverse S/N of -5 dB. Results for the S/N of +5 dB are highlighted in the figure because all subjects were tested at this S/N and because +5 dB approximates the S/Ns encountered in many typical acoustic environments such as workplaces or cafeterias.

Scores for combined EAS are significantly higher than the scores for both electric stimulation only or acoustic stimulation only for five of the seven subjects at the S/N of +5 dB. Indeed, the scores for combined EAS are greater than the sum of the scores for electric stimulation only and acoustic stimulation only for three of the subjects (ME14, ME6, and

ME23). Findings like these have been called “synergistic effects” of combined EAS (e.g., Gstoettner et al., 2004).

In some cases, a benefit of combined EAS is obtained even when the score for electric stimulation only or for acoustic stimulation is zero or close to zero. Such instances are seen for subject ME14 at the S/N of +5 dB; subject ME6 also at +5 dB; subject SR3 at +5 dB; ME20 at -5 dB; and ME23 at 0 dB.

Another aspect of the results presented in Figure 2 is the demonstration of a remarkable immunity to noise interference that is conferred with combined EAS. For example, the results for subject ME20 show a sharp decrement in scores for the electric stimulation only conditions, across the S/Ns ranging from +5 dB to -5 dB. In contrast, scores for combined EAS remain high for this subject across the same range of S/Ns. Indeed, the score at -5 dB is well above 60 percent correct, which is consistent with good communication even at this highly adverse S/N and which approaches the performance at this S/N of subjects with normal hearing.

The sharp decrement in scores across S/Ns seen for ME20 and other subjects (ME14, ME19, ME23, and ME26) for electric stimulation only is typical of the broader experience with cochlear implants. In particular, the speech reception performance of implant patients is highly sensitive to noise interference and indeed implant patients are not usually tested at S/Ns more adverse than +10 dB because performance at worse S/Ns is often very poor or zero. The addition of the acoustic stimulus provides a major advantage.

Conclusions from the RTI studies are that (1) the results show a highly beneficial effect of combinations of electrically plus acoustically elicited hearing for most tested subjects; (2) the measured immunity to noise interference is remarkable for some subjects with the combinations; (3) benefits are present even for subjects with low levels of residual hearing; (4) benefits are present for some subjects even when the score for electric stimulation only or acoustic stimulation only is zero or close to it; and (5) an increase in the lower limit of the range of frequencies represented by the implant can be helpful for some subjects. These conclusions also are consistent with the findings from many other studies of combined EAS with depths of electrode insertion approximating 20 mm or angles of electrode insertion approximating 360 degrees. Significant benefits of combined EAS have been observed as well for shallower depths or smaller angles, e.g., insertion depths of 10 mm (Gantz and Turner, 2003; Gantz et al., 2009), 16 mm (Lenarz et al., 2009), or 17-19 mm (James et al., 2005). No data are available at present comparing in the same studies and with the same measures the relative efficacies of the different depths, either for speech reception or for preservation of hearing in the implanted cochlea.

PDCI

As mentioned previously, PDCI is a special case of combined EAS in which the level of residual hearing is relatively good. An example of PDCI-level hearing can be seen in the audiograms for subject ME23 in Figure 1. Her hearing level (HL) in either ear is 20 dB or better at the audiometric frequencies of 125, 250, and 500 Hz.

Although such hearing is good at the low frequencies, it is insufficient for adequate communication in everyday acoustic environments. Thus, Professor Skarzynski and his team have extended the concept of combined EAS to include these patients.

The experience with PDCI to date is summarized in a recent report by the Warsaw team (Skarzynski et al., 2008). The described studies included 28 subjects, 18 adults and 10 children, who were diagnosed with partial deafness and received a partial insertion of the standard MED-EL array (n = 15), a full insertion of the MED-EL “M” (or “Medium”) array (n = 10), or a partial insertion of the MED-EL "Flex" (or "Flex^{SOFT}") array (n = 3), all to approximately 20 mm from the round window membrane.

A special surgical approach was used for these implant operations, that included insertion of the electrode array through the round window as opposed to making a cochleostomy and inserting the array through that fenestration. Five additional steps in the approach were all aimed at preservation of residual hearing in the implanted ear.

Hearing preservation results for the three different types of electrode arrays and for all 28 subjects are presented in Figure 3. At least some hearing was preserved and found to be stable over 1-4 years post implant for 84 percent of the subjects. Hearing within 10 dB of the pre-operative thresholds was maintained in 13 of the subjects. No significant differences in preservation were found among partial insertion of the standard array (top panel in Figure 3), full insertion of the "M" array (middle panel), or partial insertion of the Flex array (bottom panel), all to 20 mm. The reductions in hearing sensitivity following the operation were small for many of the subjects and the remaining hearing for the great majority of the subjects was useful, as demonstrated in tests of speech reception using combined EAS.

Evaluation of the PDCI treatment included recognition by the subjects of Polish monosyllabic words (from the Pruszewicz Monosyllabic Word Test) presented either in quiet or in competition with speech-spectrum noise at the S/N of +10 dB. Recordings of the words or the words plus noise were presented via a loudspeaker at 60 dB SPL in an acoustically isolated and sound treated room. The subject for each test was located in the room in front of the loudspeaker. The Pruszewicz Test corpus includes 20 lists of 20 words each. Three lists were used for each S/N condition (quiet and +10 dB) for each subject and at each measurement interval to reduce the variance that otherwise would occur with administration of a single list only. Scores for each test session were calculated as the means of the scores from the three lists. The lists were randomized among S/N conditions, subjects, and intervals. The intervals included a pre-operative session and sessions at 1, 3, 6, and 12 months post implant.

Results from the tests are presented in Figure 4. The scores from 25 of the 28 subjects are included in the figure, as the tests were too difficult to complete for three among the ten children.

No statistically significant difference was found between the results for the seven tested children and the 18 adults, so the data for the two groups were pooled for the final analyses. Figure 4 presents the pooled results. Means and standard deviations are shown. Pair-wise comparisons with the Tukey test following a significant Repeated Measures ANOVA indicate that: (1) for quiet, the differences in the means between the pre-operative and 1-month intervals, the 1- and 3-month intervals, the 1- and 6-month intervals, and the 3- and 12-month intervals are all significant; and (2) for speech presented in competition with noise, the same pattern of significant differences is found. Significant increases in the mean scores are observed out to the maximum tested interval of 12 months post implant.

Eight of the subjects had accrued 48 months of experience at the time of the publication by Skarzynski et al. (2008) and were tested at additional intervals. Their mean scores for recognition of the words presented in quiet increased from 29.4 percent correct before the operation to 83.1 percent correct 6 months after the operation. Performance increased more gradually after that, with mean scores of 84.8, 85.9, 87.5, and 90.0 percent correct at 12 months and at the additional tested intervals of 24, 36, and 48 months, respectively. The difference in the mean scores between the 6- and 48-month intervals is not significant. Thus, rapid (and highly significant) increases in the mean scores are found up to 6 months following the operation, and the scores plateau after that.

The mean scores for recognition of the words in noise by these same eight subjects increased out to 24 months post implant, i.e., the differences in the means between the pre-operative and 3-month intervals, the 1- and 3-month intervals, the 1- and 6-month intervals, and the 3- and 24-month intervals are all significant. The mean scores at and beyond the 24-month interval are nearly identical and not significantly different from one another (the percent correct scores at the 24-, 36-, and 48-month intervals are 64.3, 62.8, and 64.5, respectively) . Thus, performance increases monotonically up to 6 months for recognition of the words in quiet, and up to 24 months for recognition of the words in noise. Performance remains unchanged out to the maximum tested interval of 48 months following these initial increases.

Conclusions from the Warsaw studies are that (1) the results show a highly beneficial effect of combinations of electrically plus acoustically elicited hearing for subjects with relatively high levels of residual hearing; (2) children can benefit from PDCI as much as adults; (3) residual hearing can be preserved in an implanted cochlea for the great majority of patients, using a six-step procedure that includes careful insertion of the electrode array through the (incised) round window membrane and a depth of insertion from the membrane that approximates 20 mm; and (4) results for the first eight subjects in the series (who had accrued considerable experience with PDCI) demonstrate highly stable performance out to the tested limit of four years.

Summary and closing remarks

Combined EAS and PDCI have been established as effective treatments for persons with little or no hearing at high frequencies and at least some remaining hearing at low frequencies. Highly significant benefits have been demonstrated across a wide range of residual hearing, from only a modest amount of residual hearing to high levels of residual hearing. In addition, the results to date have shown that hearing can be preserved – to a large extent and for most patients – in an operated cochlea into which an electrode array has been inserted.

Although these two treatments have been remarkably effective, questions remain about optimal combinations of electric and acoustic stimuli; the ideal depth or angle of insertion for the electrode array; whether the ideal depth may vary from patient to patient; and whether the reliability of hearing preservation in an implanted cochlea can be increased beyond the present high levels. Work is in progress to address each of these questions, and the answers may well lead to further improvements in speech reception performance and hearing preservation.

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Table 1: Information about the subjects in the Research Triangle Institute (RTI) studies. Entries in the Hearing column indicate the presence of residual hearing ipsilateral or contralateral to the cochlear implant.

Subject	**Center**	**Electrode Array**	**Hearing**	**Language**
ME6	Frankfurt	MED-EL, 20 mm	Ipsilateral (tested), contralateral	German, English
SR3	Long-standing RTI subject	Ineraid, full	Contralateral	English
ME14	Chapel Hill	MED-EL, full	Contralateral	English
ME19	Vienna	MED-EL, 20 mm (compressed array)	Ipsilateral, contralateral	German
ME20	Frankfurt	MED-EL, 20 mm	Ipsilateral, contralateral	German
ME23	Warsaw	MED-EL, 20 mm (from the round window membrane)	Ipsilateral, contralateral	Polish
ME26	Frankfurt	MED-EL, 18 mm (compressed array)	Ipsilateral	German

Figure captions

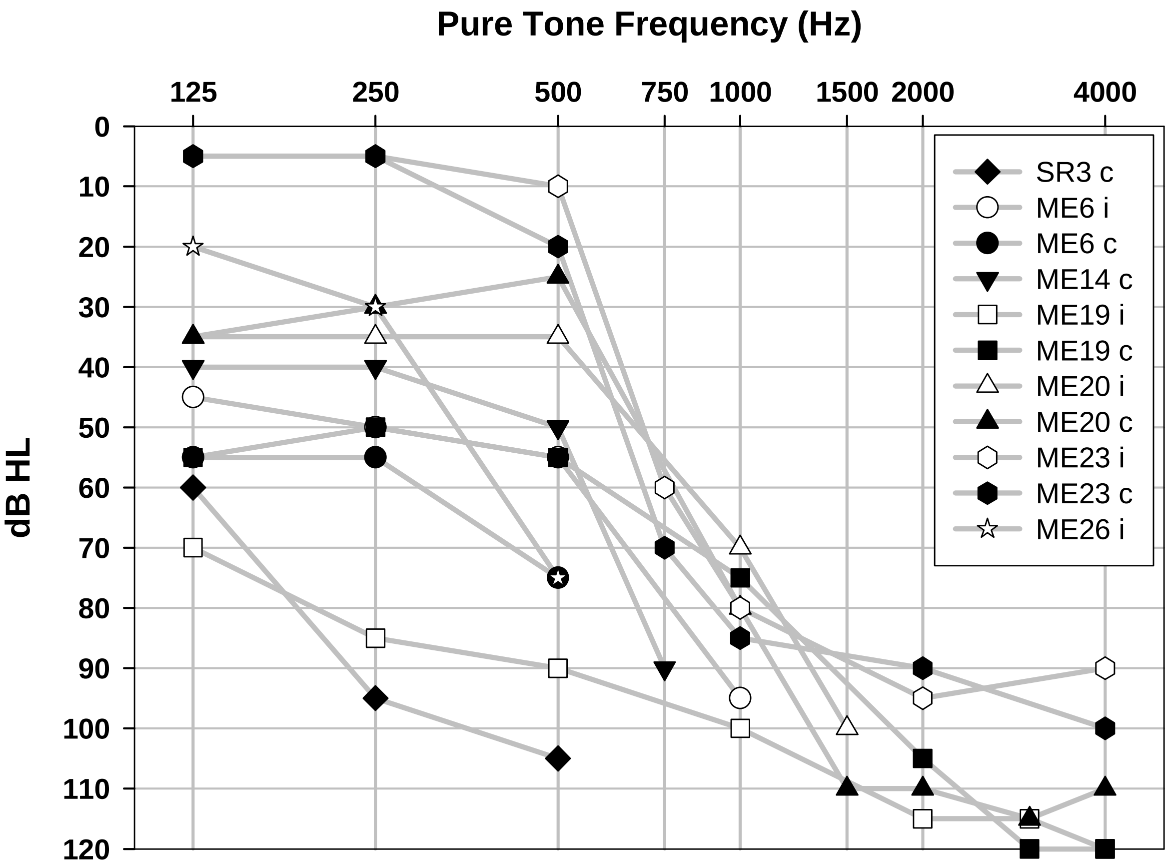
Figure 1: Clinical audiograms for the subjects participating in the Research Triangle Institute (RTI) studies. Open symbols show audiograms for ears ipsilateral to a cochlear implant, and the closed symbols show audiograms for ears contralateral to the implant. The y axis is the Hearing Level (HL) in decibels (dB). The audiograms are the most recent ones measured for each subject prior to her or his participation in the studies and well after her or his implant operation (at least three months after the operation and usually much longer than that).

Figure 2: Sentence recognition with electric stimulation only (black bars, Elec only), acoustic stimulation only (dark gray bars, Acoust only), and combined electric plus acoustic stimulation (light gray bars, EAS) for the subjects participating in the Research Triangle Institute (RTI) studies. The error bars show standard errors of the means.

Figure 3: Hearing preservation for three types of electrode arrays, all inserted through an incision in the round window membrane and to a depth of approximately 20 mm from the membrane. The averages of the audiograms for all subjects implanted with each type of electrode array are shown. Pre-operative Hearing Levels (HLs) in decibels (dB) are shown with the closed symbols and the post-operative HLs are shown with the open symbols. The error bars show standard deviations. (Data from Skarzynski et al., 2008)

Figure 4: Recognition of the Pruszewicz monosyllabic words by 25 subjects in the study of Skarzynski et al., 2008. The top panel shows the mean scores for the words presented in quiet,

and the bottom panel shows the scores for the words presented in competition with speech-spectrum noise at the speech-to-noise ratio of +10 dB. The times given for the measurement intervals are referenced to the time of the implant operation. The error bars show standard deviations. (Data from Skarzynski et al., 2008)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110
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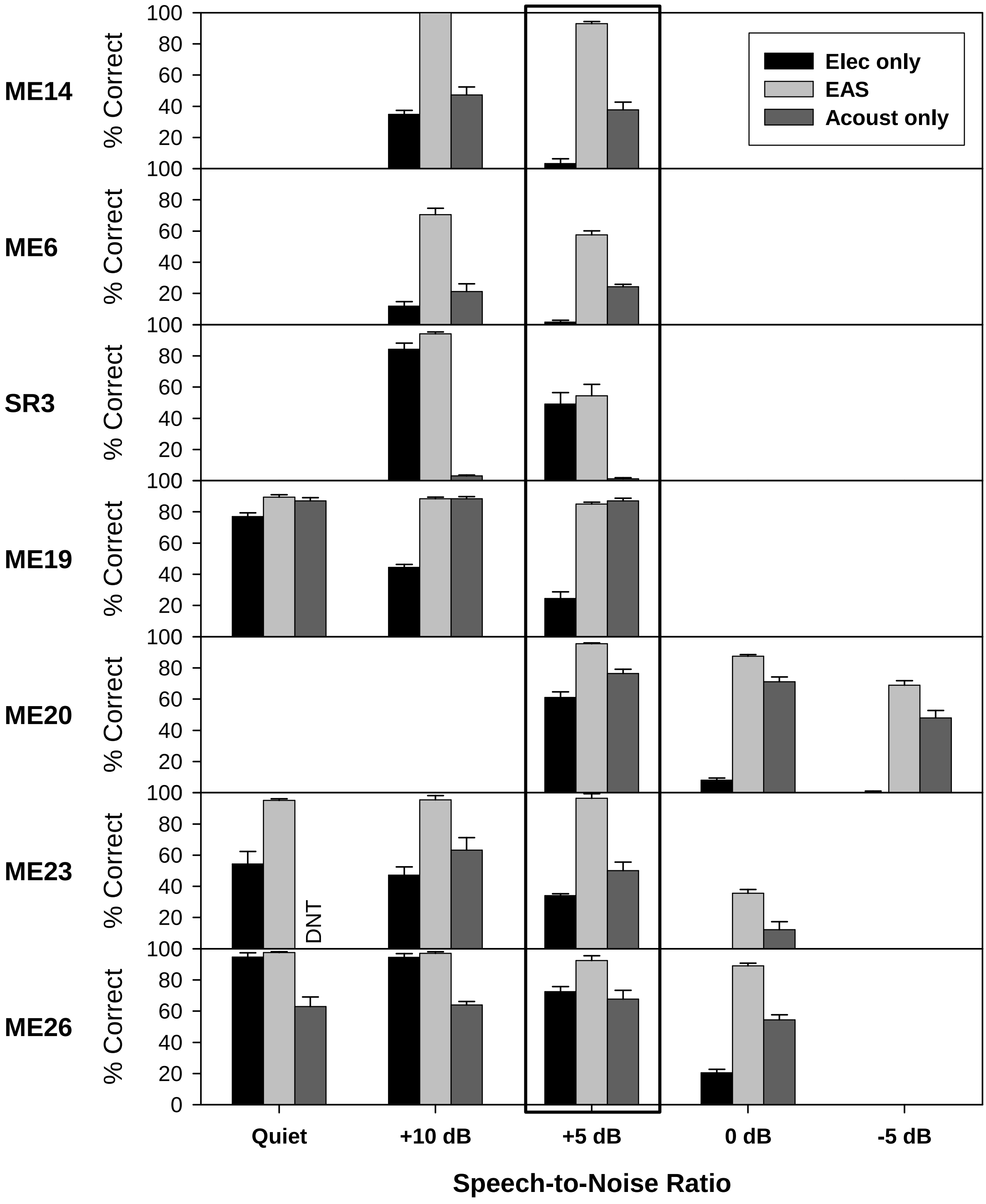
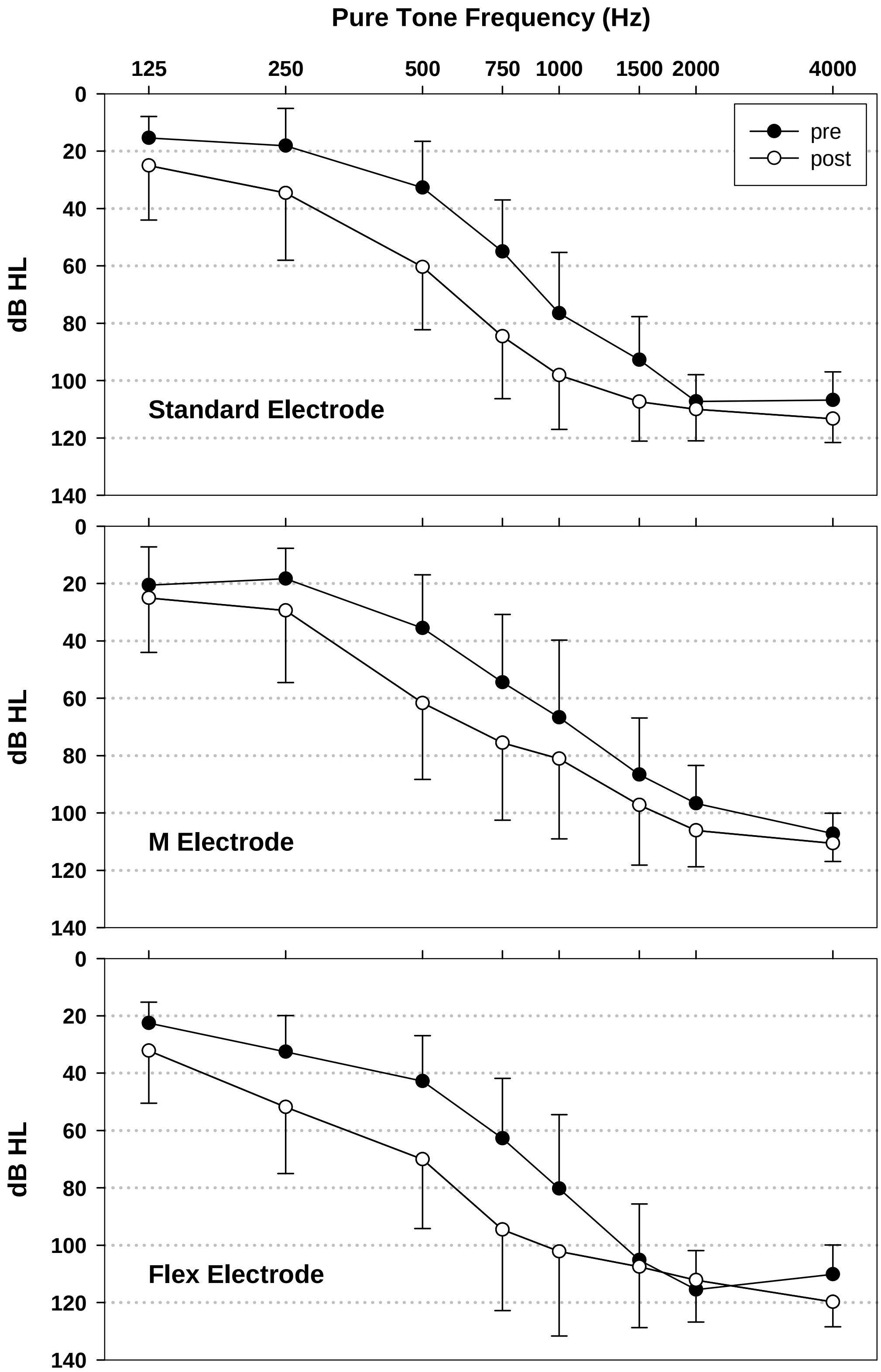
ME23 c
ME26 i

Figure 1



Elec only
EAS
Acoust only
ME14
ME6
SR3
ME19
ME20
ME23
ME26
% Correct
100
80
60
40
20
0
DNT
Quiet
+10 dB
+5 dB
0 dB
-5 dB
Speech-to-Noise Ratio

Figure 2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2000
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pre
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Standard Electrode
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Flex Electrode

Figure 3

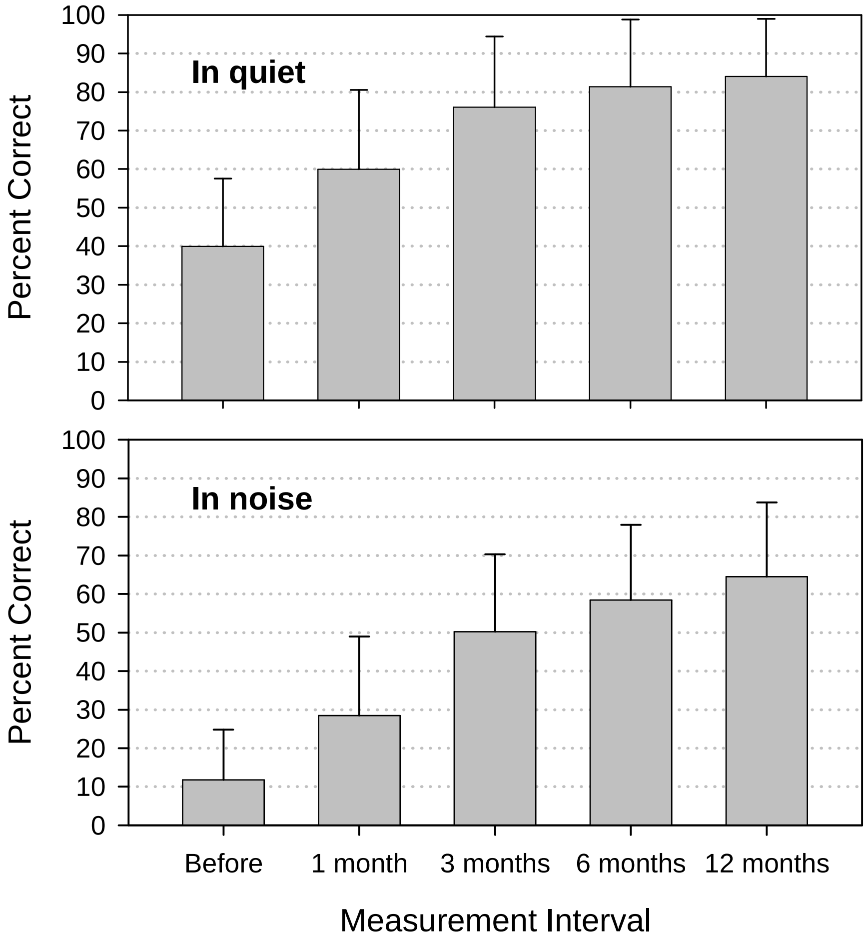
In quiet
In noise
Percent Correct
Percent Correct
0
10
20
30
40
50
60
70
80
90
100
Before
1 month
3 months
6 months
12 months
Measurement Interval

Figure 4