Brief Communication

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Pitch estimation of a deeply inserted cochlear implant electrode

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Key Words

Pitch estimation curves
Place–pitch
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Abstract

In this short communication, we evaluate the place–pitch relation of a newly designed, deeply inserted, cochlear implant electrode. The insertion depths ranged from 471° to 662°. Pitch perception was measured in eight subjects with monopolar stimulation on each electrode contact at intensities of 50% and 80% of the dynamic range. We observed a monotonic reduction of pitch estimate with insertion depth. For about half of the subjects, a flattening of the pitch estimate at the basal end of the electrode was seen, while for the other half, pitch continued to decrease monotonically up to the most apical part of the array. We conclude that deeper insertion could increase pitch range for at least some cochlear implant recipients, and could hence potentially increase group performance.

Cochlear implants provide auditory sensation to people with severe-to-profound sensorineural hearing loss by electrically stimulating intra-cochlear neurones through surgically inserted electrodes in the scala tympani. The subjectively estimated pitch of electrical stimulation decreases monotonically with insertion depth, as demonstrated, for example, by Cohen et al (1996) for subjects with insertion depths under 540°. This decrease of pitch with insertion depth of the electrode is due to the tonotopic organization of the cochlear nerve, and is similar to the place–pitch principle in normal hearing. It is well known from the literature that the spiral ganglion does not extend all the way to the apex of the cochlea, but rather that the apical organ of Corti is innervated from more basally positioned cell bodies (Spoendlin & Schrott, 1988; Ariyasu et al, 1989). It was suggested that, because of the lack of spiral ganglion cells in the apical part of the cochlea, there would be no regular decrease of pitch percept after about 540° (1.5 turns), but to date there is no scientific evidence to either support or falsify this assumption. In this paper, we examine the pitch perception with a newly designed cochlear implant electrode, called the TRACE electrode. This electrode has an optimized mechanical structure, which makes deep insertions (beyond 540°) in the cochlea possible. The details of the electrode are given elsewhere (Deman et al, 2003). Briefly, the electrode received internal mechanical fortification comprising a rib of stiffer silicone that was added in a specific pattern. Insertion force measurements were performed on an acrylic transparent model of the scala tympani to determine the most optimal mechanical stiffness for optimal non-traumatic deep insertion. As it is believed that the insertion depth of cochlear implant electrodes influences the subject's performance (Blamey et al, 1992; Dorman et al, 1997; Hodges et al, 1999; Hamzavi et al, 2003), further examination of deeply inserted cochlear implant electrodes is necessary.

Materials and methods

Study group

Eight adult subjects were implanted by the same surgeon after approval by the Ethical Committee of the St Augustinus Hospital in Wilrijk. In this communication, the subjects are labelled S1–S8.

Implant/electrode

The TRACE electrode, which has 31 contacts directed to the habenula perforata (Figure 1a), was connected to a Nucleus CI24R stimulator, allowing 21 of the 31 contacts to be connected to the current source (Figure 1b). Healon (Pharmacia Corporation, Peapack, NJ, USA) was used as a lubricant for all insertions. The electrodes were implanted with insertion angles from 471° to 662° (Table 1). Measurements were performed 6 months post-implantation.

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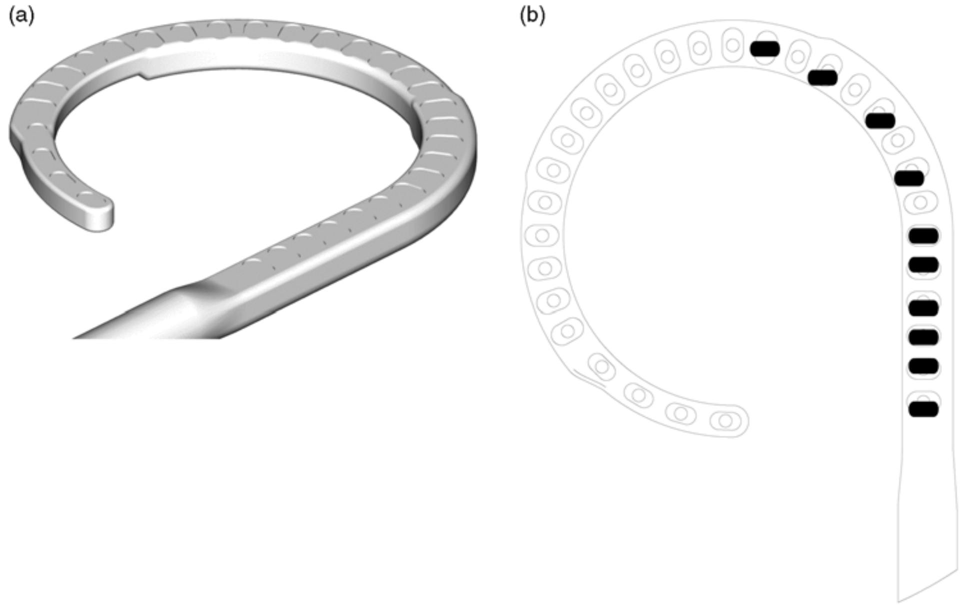

Figure 1. (a) Three-dimensional view of the TRACE cochlear implant electrode. (b) Schematic top view of the TRACE cochlear implant electrode. Black dotted contacts are not connected to the receiver–stimulator.

Insertion depth
A radiograph was taken for each subject, using the modified Stenvers view, as described by Marsh et al (1993) and Xu et al (2000). We used the computerized method of Cohen et al (1996) to determine the position of the electrode contacts in terms of angle within the cochleovestibular framework. The position is defined in terms of the angle and is expressed as radial degrees. A full-turn insertion thus means 360°. This facilitates comparison of data from electrode arrays that follow different intracochlear trajectories: one array might follow the outer wall of the scala tympani, whereas another might follow the inner wall. Furthermore, cochleas differ in diameter, and from a physiological point of view, defining the insertion depth as number of turns (degrees) seems more appropriate than defining it as absolute distance (mm) from a fixed reference such as the cochleostomy.

The methodology of the computer analysis has been described in detail previously (Cohen et al, 1996). In short, the radiographs are digitized and the position of the apex of the semicircular canal and the midpoint of the vestibule is specified. A template is fitted to the partially visible outer wall of the otic capsule, using also the positions of the superior semicircular canal and the vestibule. This process places the individual electrode contacts within a cochleovestibular framework and gives an estimate of the size and central axis of the cochlea. This method provided estimates of electrode insertion angle and round-window position that were resistant to the effects of rotation of the cochlea relative to the X-ray beam and to interobserver variations.

Threshold and loudest acceptable presentation levels
Stimuli of 500 ms, consisting of biphasic electrical pulses (100 μs per phase, inter-phase gap (IPG) 25 μs, 500 pulses/s), were given on each electrode at different levels to determine the threshold (T-level) and the loudest acceptable presentation level (LAP level). All stimuli were monopolar: the stimulation occurred between an intra-cochlear active electrode and an extra-cochlear reference electrode.

Table 1.

Subject	*Gender*	*Age at implant (years)*	*Aetiology*	*Duration of deafness*	*Insertion depth*
1	M	60	Meningitis	>30	548°
2	F	64	Progressive unknown	10	471°
3	F	39	Progressive unknown	18	642°
4	F	42	Unknown sudden onset	12	653°
5	F	72	Genetic	14	662°
6	M	48	Acoustic trauma progressive	6	643°
7	F	45	Genetic	4	578°
8	F	70	Otosclerosis progressive	6	598°

Pitch estimation curves

All pitch estimation experiments were performed using loudness-balanced stimuli at approximately 50% and 80% of the dynamic range (dB re 1 μA). Pitch measurements were performed using a numerical estimation procedure, similar to those used by Shannon (1983), Dorman et al (1990), Busby et al (1994) and Cohen et al (1996). After a test run, in which all stimuli were presented, the actual test was started. During the test, the stimuli were given in random order to the different electrodes. The subject was instructed to report the pitch of each stimulus by means of a visual analog scale ranging from 1 to 100, representing the lowest and the highest pitch level respectively. During the experiment, eight stimuli were presented on each individual electrode contact. The 50% and 80% pitch estimation curves were not measured in the same session, due to time constraints.

Results

Threshold and loudest acceptable presentation levels

The median, minimum and maximum values of the T-levels and LAP levels on all electrodes for all eight subjects are shown in Figure 2.

Individual pitch estimation curves

In Figure 3, the individual pitch estimates for the 50% stimuli are shown versus the percentage of length along the organ of Corti (Cohen et al, 1996). Each individual data point is an average of eight measurements, and 95% confidence intervals are included. For S2, S3, S4 and S6, we see a clear flattening effect at the apical side of the electrode. For S2, there are no data on the most basal contact, due to uncomfortable sound sensations.

Because it is known that the results of pitch-ranking experiments can differ when different loudness levels are used, we also measured the curves at 80% of the dynamic range (Figure 4). The results of the 80% stimuli are, in general, very similar to the 50% data. Although the 80% data show more scattering in S3 and S8, they still give the same trend. The only remarkable difference is that, in the 50% curves, some recipients show a flattening at the basal end of the curve that is not present in their respective 80% curve. This can probably be explained by the fact that the very soft high-pitched sounds are difficult to rank in pitch. S1 is the only subject where a flattening at the apical side is present in the 80% data but is not seen in the 50% data.

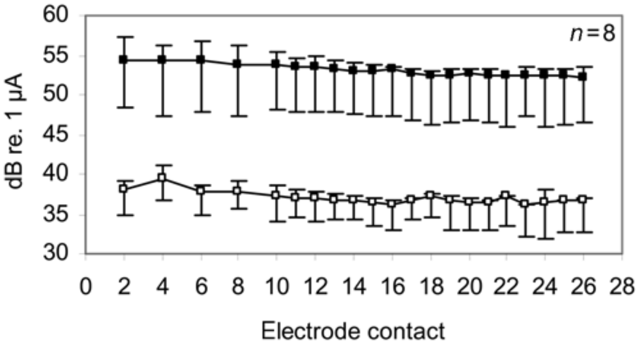

Figure 2. Median, maximum and minimum levels of the T-levels and LAP levels in monopolar stimulation mode across the eight subjects in this study. T-levels and LAP- levels were obtained using a standard clinical methods. The stimuli were 500-ms trains of biphasic pulses (100 μs per phase, IPG 25 μs, 500 pulses/s).

Discussion

It is well known that the perceived pitch of electrical stimulation in the cochlea decreases with increasing insertion depth, similar to the normal-hearing place–pitch relation. However, the insertion depth of cochlear implant electrodes has been under discussion, mainly because the spiral ganglion only reaches 1.5 turns into the cochlea (Spoendlin & Schrott, 1988; Ariyasu et al, 1989), while the organ of Corti extends to about 2.5 turns. Also, there is evidence that the probability of cochlear damage increases with insertion depth (Kennedy, 1987). When electrode insertion is stopped at the first point of resistance, however, deep electrode insertions are possible without increased trauma, as shown in temporal bone experiments (Gstoettner et al, 1997).

To answer the question of how deep an electrode should be inserted, it is important to collect psychophysical data on deeper electrode insertions. The data reported so far in the literature were obtained using electrodes with insertion depths ranging from less than 1 turn up to 1.5 turns maximum (Busby et al, 1994; Cohen et al, 1996). In our patient group, we have estimated insertion depths between 471° and 662° (Table 1).

Figure 2 shows that the threshold and comfort level profiles did not show a difference in the excitability of neural populations towards the most apical end of the array. Because of the changes in scale geometry, it is difficult to draw conclusions from this observation, but it does indicate that apical electrodes (1.5–2.5 turns) can still effectively stimulate neural elements in the cochlea.

In Figures 3 and 4, the pitch-ranking data for the 50% and 80% stimuli are displayed. Our data confirm the conclusion of Cohen et al (1996) and Busby et al (1994) that there is a monotonic decrease in pitch estimation with insertion depth in monopolar stimulation mode. Furthermore, we conclude that deeply inserted electrodes up to 662° can effectively stimulate neural elements along the whole array, and that, at least for some subjects, this leads to an extended pitch range. We see that even with insertions above 540°, there can be a smoothly decreasing pitch estimate as a function of depth of stimulation. In half of our subjects, we did observe a flattening trend at the basal end of the pitch estimate curves. This flattening could be due to the absence of spiral ganglion cells and low survival of peripheral dendritic cells deeper than 1.5 turns into the cochlea.

Subject 2, however, who had the shallowest insertion in our study group, also showed a clear flattening of pitch percept already beyond 50% of the length of the organ of Corti, which could indicate that for this subject the above argument is not valid.

The fact that we did observe a regular pitch decrease up to very deep insertion lengths for half of the subjects could indicate that, for those subjects, stimulation in the apical part of the cochlea does not occur at the spiral ganglion, but takes place at the peripheral process. This suggestion is further supported by the notion that the TRACE electrode contacts are in very close contact with the basilar membrane, rather than with the modiolus. If this is true, then the flattening of the pitch percept for some of the recipients is probably correlated with the absence of dendritic structures peripheral to the spiral ganglion. This

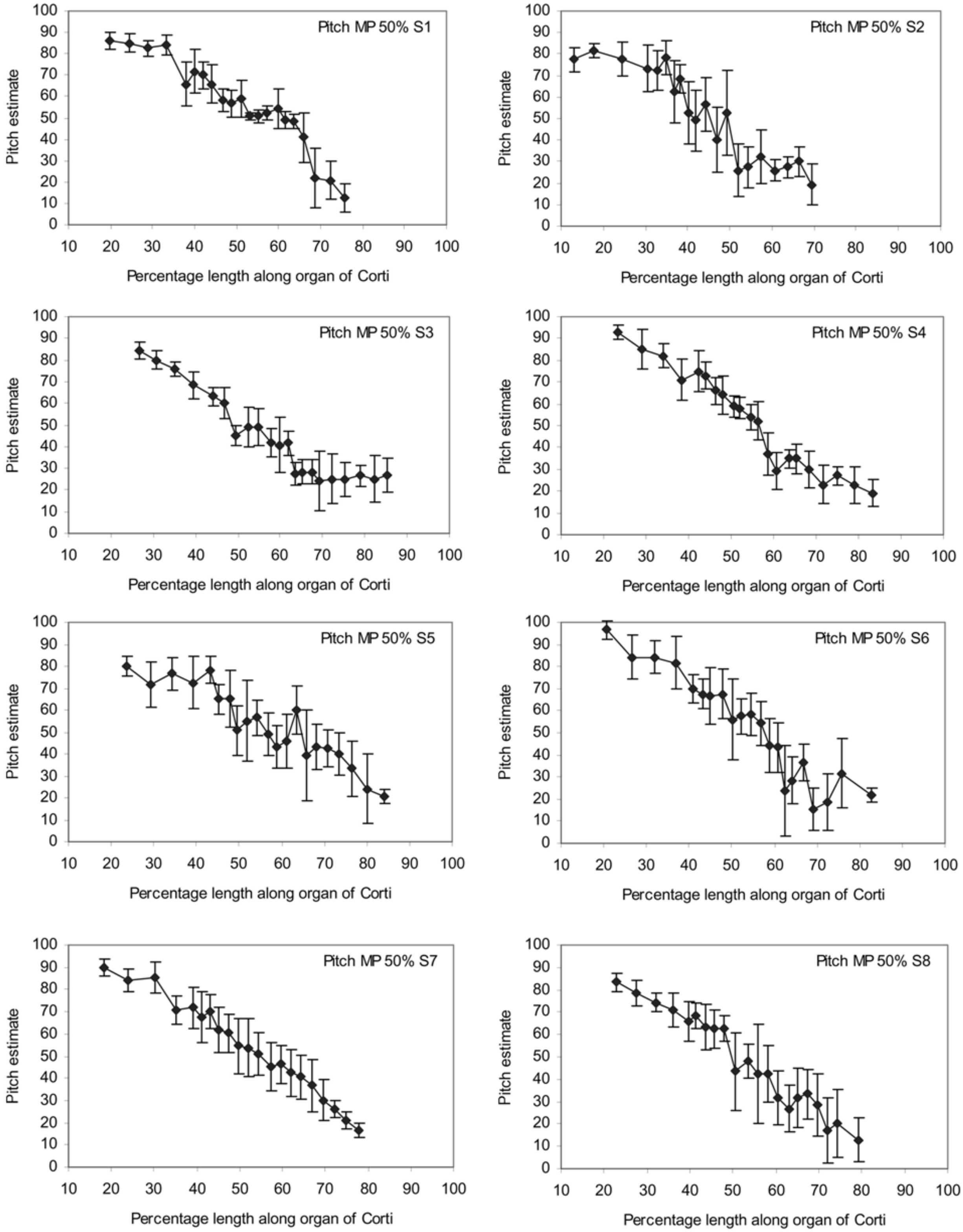

Figure 3. Individual pitch-ranking results for the eight subjects: pitch estimation versus depth of stimulating electrode for monopolar (MP) stimulation mode. Each data point represents a mean value of eight presentations, and 95% confidence intervals are included. The stimuli were 500-ms trains of biphasic pulses on 50% of the dynamic range (100 μs per phase, IPG 25 μs, 500 pulses/s), loudness balanced across the array.

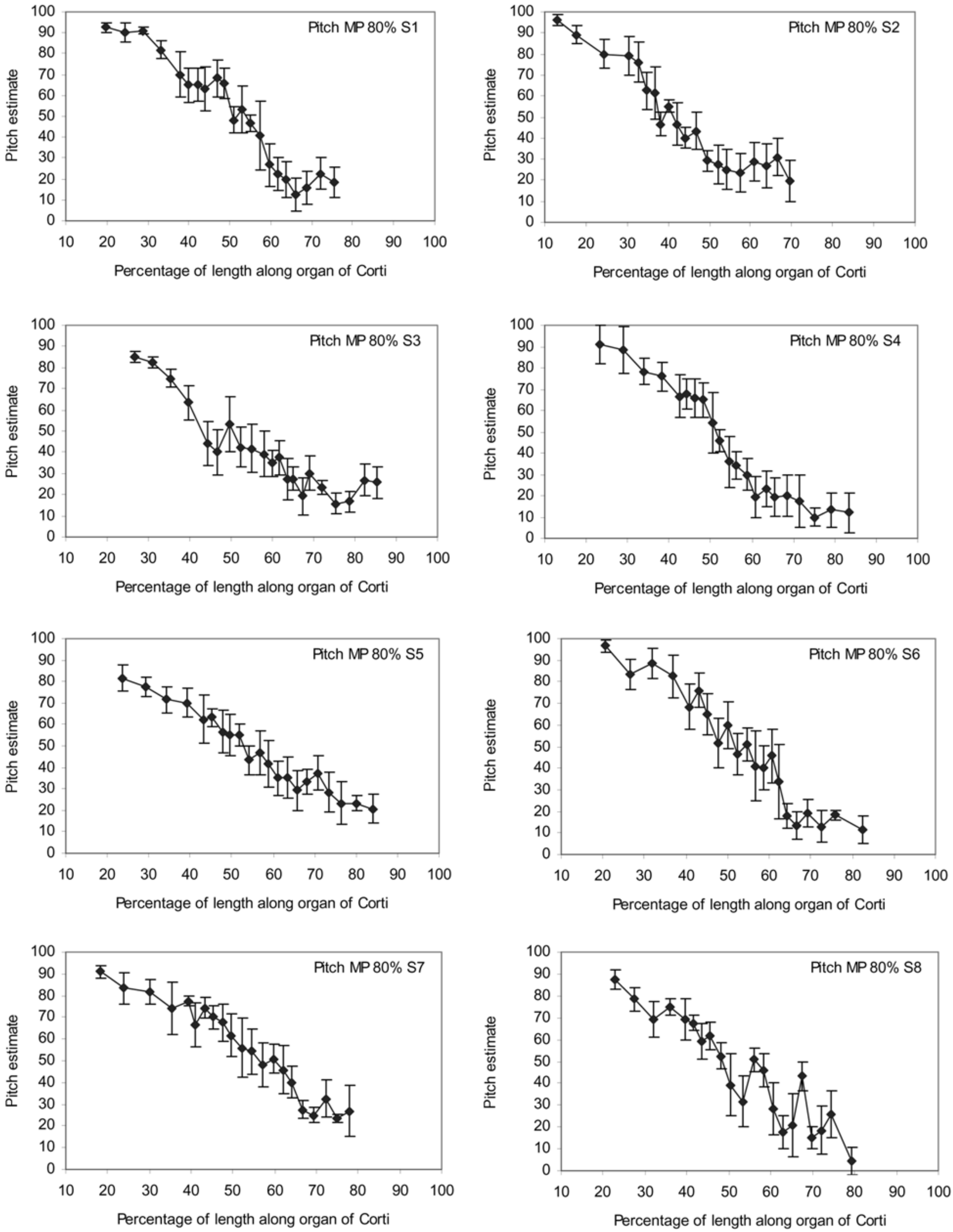

Figure 4. Individual pitch-ranking results for the eight subjects: pitch estimation versus depth of stimulating electrode for monopolar (MP) stimulation mode. Each data point represents a mean value of eight presentations, and 95% confidence intervals are included. The stimuli were 500-ms trains of biphasic pulses on 80% of the dynamic range (100 μs per phase, IPG 25 μs, 500 pulses/s), loudness balanced across the array.

would also indicate that, to obtain the full benefit of the extended pitch range of deeply inserted electrodes, care must be taken that new electrode designs are optimized for stimulation of apical peripheral processes. Alternatively, another reason for the flattening of pitch could be cochlear damage at the apical end of the electrode for some of the recipients. From this data set, we cannot rule out or confirm any of these suggestions, or a combination of both.

Conclusions

With deeply inserted cochlear implant electrodes, a monotonic decrease of pitch estimate versus depth of the stimulating electrode was observed in four of the eight subjects in this study, effectively increasing the range of perceived pitch. Increasing insertion depths may be beneficial to (at least some of the) cochlear implant users. When designing deep cochlear implant electrodes, care must be taken that the electrode placement allows for stimulation at the dendrite level, and that insertion trauma is minimal. With these factors taken into account, the future design of deeper electrodes with dense patterns of electrode contacts may increase cochlear implant group performance.

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