ABSTRACT

The concept of virtual channels has been in the scientific community for many years and has been implemented with varying levels of success. While individual electrodes typically have different place pitches, it has been discovered that intermediate pitches between those of individual electrodes could be perceived by stimulating two adjacent electrodes, either simultaneously or sequentially. However, it was unclear how much those intermediate pitches—already available through speech coding strategies—could be discriminated by individual recipients and processed for speech recognition and music appreciation.

In an experiment with twelve adult ears—all with Nucleus® cochlear implants (CI)—the average aggregate number of discriminable pitches across the entire array was 161, which is substantially higher than the number previously reported in competitive data. When intensity was roved to eliminate loudness cues, that number moved to 127 discriminable pitches across the entire array.

This article will review and discuss the Nucleus® data demonstrating that virtual channels can be elicited with non-simultaneous stimuli and without the need for multiple current sources.

INTRODUCTION

Monopolar stimulation through a single cochlear implant electrode produces a tonotopically organized place pitch sensation. In general, perceived pitch becomes progressively lower as the place of stimulation is shifted in the basalo- apical direction. Many Nucleus® cochlear implant users can distinguish 22 distinct pitches associated with the 22 intracoachlear (i.e. physical) electrodes. However, the number of distinct pitches that can be perceived by a CI user is not necessarily limited to the number of physical electrodes. It has been known since the mid 1980s that concurrent stimulation of two electrodes can produce a pitch percept that is intermediate between those elicited by the individual physical electrodes. Townshend et al. (1987) demonstrated that “It is possible to produce intermediate pitches by stimulating more than one electrode at a time.” The pitch produced by their so called “dual electrode stimuli” varied continuously with the ratio of the currents applied to the two physical electrodes.

Wilson et al. (1993) first coined the term “virtual channel” to describe using such dual electrode stimuli as a means of increasing the effective number of
stimulation sites beyond the number of physical electrodes. McDermott and McKay (1994) subsequently demonstrated that two electrodes need not be stimulated simultaneously to produce an intermediate pitch. Their results showed that intermediate pitches could also be produced using sequential stimulation of two electrodes. The implication of their finding is that sequential pulsatile strategies such as SPEAK, ACE™, and CIS have always implicitly capitalized on this phenomenon due to the slopes of the overlapping “skirts” of channel bandpass filters. As an input audio frequency component shifts from one channel band into the next, the corresponding pulses automatically weaken on one channel and strengthen on the adjacent channel, producing a continuous shift in the ratio of intensities and corresponding place pitch percept.

More recently, the pitch steering phenomenon has been revisited by Donaldson et al. (2005), and in a white paper published by Advanced Bionics, Inc. (2005). In the latter, just-noticeable-differences (JNDs) in pitch discrimination were measured as a function of current ratio using simultaneous dual-electrode stimuli. The total number of discriminable pitches extrapolated across the entire electrode array varied substantially among individuals, averaging 93 pitches among 49 subjects.

The study reported here was undertaken to measure the number of intermediate pitch percepts between adjacent electrodes that are discriminable by Nucleus® cochlear implant recipients using pitch steering with sequential pulse pairs.

**METHODS**

**Subjects**

Intermediate pitch discrimination was measured in 12 adult ears implanted with Nucleus® 24 Straight, Contour™ and Contour Advance™ and Freedom™ (with Contour Advance™) cochlear implants. A total of 11 subjects (one with bilateral implants) with at least six months of CI listening experience participated in the study.

<table>
<thead>
<tr>
<th>Subject ID</th>
<th>Device</th>
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<tr>
<td>S1</td>
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<td>S2</td>
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<td>S5</td>
<td>Contour</td>
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<td>S6L</td>
<td>Freedom with Contour Advance</td>
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<td>S6R</td>
<td>Straight (CI24RST)</td>
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<td>S7</td>
<td>Straight (CI24M)</td>
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<td>S8</td>
<td>Freedom with Contour Advance</td>
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<td>S9</td>
<td>Contour Advance</td>
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<td>S10</td>
<td>Contour Advance</td>
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<tr>
<td>S11</td>
<td>Contour</td>
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**Stimuli**

Each stimulus comprised a 500 μs burst of interleaved biphasic monopolar pulses (25 μs/phase and an inter-phase gap of 8 μs) on two adjacent electrodes (Figure 1). The two interleaved pulses on each electrode were separated by a 19 μs gap, and pulse pairs were repeated at the channel stimulation rate of the subject’s clinical MAP. In the figure, electrode 19 and 18 are shown to demonstrate the adjacent pair, respectively. The figure specifies the continuum of intermediate pitches between apical and basal pitches. The
intermediate pitch relies on the relative current intensity between the two electrodes; if the current on electrode 19 is higher than that on electrode 18, the pitch is steered lower, and vice versa. The steering factor, $\beta$, is defined here as the difference in logarithmic units of Current Level (CL) between the electrodes: $\beta = CL_{18} - CL_{19}$. This is the logarithmic equivalent of $\alpha$ used in the studies with 90K/CII recipients. A negative $\beta$ indicates that the current from the apical electrode is greater than that from the basal electrode, and vice versa. The apical or basal single electrode stimulus corresponds to $-\infty$, or $+\infty$, respectively. The figure illustrates intermediate values of $\beta$.

**Pitch Discrimination**

The goal of the study was to quantify the number of JNDs between two adjacent electrodes. To accomplish this, a series of two-interval forced-choice tasks are used to quantify the JNDs between two adjacent electrodes. (The end-to-end total was extrapolated by multiplying the mean number of JND by 21). If the subject demonstrated a non-perfect score in a pitch-ranking test (e.g., the subject showed correct pitch judgment in only 90% of presentation trials), the score could be converted to a discrimination index, or $d'$, and this could indicate the number of JND (discriminable) steps based on a set criterion.

For example, if the score is 90%, $d'$ is 1.81 in this task. If the criterion stipulates that a score of 71% (corresponding to 0.78 of $d'$) would be considered as “discriminable,” then it could be concluded that there are 2.3 JNDs (1.81/0.78) between the stimuli in this example.
In reality, many Nucleus® 24 or Freedom® recipients are capable of ranking pitches perfectly from adjacent electrodes; a perfect pitch-ranking score (100%) corresponds to $d'$ of infinity and the assessment of JNDs becomes impractical. Thus, it was necessary to add intermediate dual-electrode stimuli, presumably with shorter perceptual distance for the new pair, to make the task more difficult. If the score from each of these sub-pairs was not perfect, then $d'$s from each pair could be added together, and this summation, cumulative $d'$, could be used to estimate the total number of JNDs between the two single-electrode stimuli. The subjects were initially given the $\beta$ pair of $\{-\infty, +\infty\}$ (single-electrode comparison) and if the score was perfect, which was the case for the most subjects, the interval was subdivided (for example, $\{-\infty, 0\}$ and $\{0, +\infty\}$) and scores for the subintervals were measured. Successive subdivision continued until a non-perfect score was obtained (see Figure 2 for illustration). If the score was at or near chance (≤ 55%), indicating that the task became too difficult, then the interval was re-adjusted.

The method of constant stimuli was used to measure discrimination. A block of twenty 2-interval forced-choice trials was conducted for a given stimulus pair specified by two fixed values of $\beta$. All stimulus pairs were loudness balanced against one another, and the presentation order was randomized. In each trial the subject was asked to identify the interval higher in pitch. If the subject chose the interval with higher $\beta$, it was counted as “correct.”
Once all the pairs were tested, the cumulative $d'$ (i.e., sum of $d'$ values for the subintervals) was converted to an equivalent number of JNDs. One JND was defined as a $d'$ of 0.78, corresponding to the 71% correct level that would be determined by a 2-down/1-up adaptive paradigm. During pilot experiments, the number of JNDs derived by this method was compared with explicit measures of individual JNDs using a series of adaptive procedures with 2 subjects and a close agreement was observed between the two methods.

Pitch percepts could be easily confused with the loudness sensation, i.e., implant recipients often associate a stimulus with higher intensity with a sound of higher pitch. Therefore, in addition to the careful loudness balancing for each pair tested, it is important to rove the intensity levels to reduce any confounding effects from potential loudness cues. Thus, the entire experiment was repeated using random roving of stimulus levels (2 CL) to reduce the effects of residual loudness cues on the measured discrimination. In order to measure the sensitivity in fine pitch change at different cochlear locations, the following three electrode pairs were chosen for testing: E19/18, E11/10 and E4/3.

RESULTS

In Figures 3 and 4, the estimated number of discriminable pitches is denoted on the left vertical axis. The estimated number of discriminable pitches is denoted on the left vertical axis. Corresponding cumulative $d'$ values are indicated on the right vertical axis. Pitch comparisons were made with loudness-balanced pairs without intensity roving. Figures 3 and 4 display the results of pitch discrimination for adjacent electrodes in terms of the estimated number of discriminable pitches and cumulative $d'$. The overall average number of discriminable pitches is 7.67 without intensity roving, and 6.06 with intensity roving. By extrapolating across the 21 pairs of the electrode array, these correspond to totals of 161 and 127 discriminable pitches, respectively.
DISCUSSION

These data demonstrate that the intermediate place-pitch percepts upon which “virtual channels” are predicated can be elicited with non-simultaneous stimulation through Nucleus® cochlear implants. Multiple current sources are not required to exploit this phenomenon.

These results are similar to those reported for 90K/CII recipients in two ways:

1. First, performance widely varies across individual subjects.

2. Second, there is a tendency toward somewhat better pitch resolution between the apical electrode pairs when compared to basal pairs.

The average number of JNDs between adjacent electrodes was similar with the two devices (7.7 in this study vs. 6.2 among 90K/CII recipients, both without intensity roving). However, due to the greater number of electrodes in the Nucleus implant, the average aggregate number of discriminable pitches across the entire array was substantially higher among Nucleus recipients (161) than reported for 90K/CII recipients (93). When intensity roving was introduced to minimize residual loudness cues, that number dropped to 127 discriminable pitches in these Nucleus data. A similar drop would have been expected in the HiRes 90K/CII data had loudness roving been implemented within that experiment.
SUMMARY

In the Nucleus® system, it is possible to elicit intermediate pitches using non-simultaneous stimuli and without multiple current sources. As noted earlier, in an experiment with twelve adult ears with Nucleus cochlear implants the average aggregate of discriminable pitches was 161 without intensity roving, and 127 with intensity roving. Performance on these tasks varies by individual and, as with other reported data, there is a tendency toward better pitch resolution in the apical versus the basal end of the electrode array.

It is possible that some patients may benefit from virtual channels, while others may benefit from more traditional sound-processing paradigms. Further research is needed to elucidate objective performance data using virtual channels and the potential clinical implications. Cochlear has consistently engineered Nucleus cochlear implants to provide highly reliable and flexible solutions so that each user has access to a broad range of customized programming options.

REFERENCES:

8. Increasing spectral channels through current steering in HiResolution Bionic Ear® users (2005), Advanced Bionics Corp., Valencia, CA.

*Not yet available for clinical use.