Speech Intelligibility in Noise With a Pinna Effect Imitating Cochlear Implant Processor

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Objective: To evaluate the speech intelligibility in noise with a new cochlear implant (CI) processor that uses a pinna effect imitating directional microphone system.

Study Design: Prospective experimental study.

Setting: Tertiary referral center.

Patients: Ten experienced, unilateral CI recipients with bilateral severe-to-profound hearing loss.

Intervention: All participants performed speech in noise tests with the Opus 2 processor (omnidirectional microphone mode only) and the newer Sonnet processor (omnidirectional and directional microphone mode).

Main Outcome Measure: The speech reception threshold (SRT) in noise was measured in four spatial settings. The test sentences were always presented from the front. The noise was arriving either from the front (SN0), the ipsilateral side of the CI (SN1), the contralateral side of the CI (SN2), or the back (SN3).

Results: The directional mode improved the SRTs by 3.6 dB (p < 0.01), 2.2 dB (p < 0.01), and 1.3 dB (p < 0.05) in the SN0, SN1, and SN2 situations, when compared with the Sonnet in the omnidirectional mode. There was no statistically significant difference in the SN3 situation. No differences between the Opus 2 and the Sonnet in the omnidirectional mode were observed.

Conclusion: Speech intelligibility with the Sonnet system was statistically different to speech recognition with the Opus 2 system suggesting that CI users might profit from the pinna effect imitating directionality mode in noisy environments. Key Words: Directional microphone systems—Oldenburg sentence test—Sonnet—Speech reception threshold—Two-microphone noise reduction.


Cochlear implants (CIs) are a well-established and effective treatment for severe-to-profound sensorineural hearing loss. Although CI recipients are able to achieve high speech recognition scores in quiet surroundings, their performance in background noise is often impaired (1–4). The limited speech understanding in noise results from many factors such as the loss of fine spectral and temporal information and the narrow dynamic range available for electrical stimulation (5,6).

To improve the speech in noise performance of CI users, several noise reduction strategies using single or multiple microphones have been implemented and evaluated in the past. Particularly directional microphones have consistently shown to ease the speech understanding in noisy environments. In commercial CI audio processors fixed and adaptive directional microphone systems can be differentiated. Fixed polar pattern systems provide benefits through spatial filtering of sound input from defined directions (5). Previous studies have reported on speech reception threshold (SRT) improvements of CI users around 3–7 dB, depending on the experimental conditions (5–12). Even further improvements of the SRT can be achieved with adaptive systems that are capable of steering the zero-direction toward the noise source (13). The speech in noise performance of CI recipients using adaptive systems was tested in several studies and showed SRT improvements between approximately 5 and 15 dB (8–11,14–17).

Recently, a new behind-the-ear processor with a dual microphone noise reduction system (Sonnet, Med-El Corporation, Innsbruck, Austria) was introduced. The CI audio processor comprises optional microphone directionality settings. The “natural” directionality mode combines a fixed directional pattern with a filter-implemented imitation of the natural pinna directivity. The primary aim of this study is to assess the benefit on speech intelligibility in noise with the Sonnet and the...
“natural” directionality mode in different spatial hearing situations. An evaluation of the efficacy of the directional microphone system is of clinical relevance and may provide an idea of the expected benefit for CI users. Furthermore, the results are compared with the measurements with the older CI audio processor (Opus 2, Med-El Corporation).

MATERIALS AND METHODS

Participants

Ten unilateral CI recipients with binaural severe-to-profound sensorineural hearing loss were included in the study. All the participants were native German speakers and experienced CI users. The details of the study participants are summarized in Table 1. The subjects were Opus 2 audio processor users and had never tried the Sonnet audio processor before this study.

Study Protocol

The study protocol was approved by the local Ethical Committee and was conducted according to the Declaration of Helsinki. The study was initiated, planned, and conducted at our institution and was not supported by any industrial partners. Three aided conditions were compared: the Opus 2 audio processor in the omnidirectional microphone mode (AP1), the Sonnet audio processor in the omnidirectional microphone mode (AP2-OMNI), and the Sonnet processor in the “natural” microphone mode (AP2-DIR). The “natural” mode introduces a fixed microphone directionality to imitate the natural pinna amplification of high frequencies arriving from the listener’s front (18–20). This setting was preferred over the optional, and potentially more effective, adaptive directional mode to exclude the influence of time-dependent filter coefficient readjustments and to avoid a situation-specific directionality. Before testing, the subjects indicated their most favored current program and to avoid a situation-specific directionality. Before testing, the subjects were instructed to keep their head in a straight position. No hearing aids or earplugs were used in the contralateral ear. To minimize training and fatigue effects, the order of the tested directionality modes, spatial situations, and test lists were varied systematically.

Test Room and Test Equipment

The speech in noise experiments was performed in an acoustic chamber (6.0 × 4.1 × 2.2 m³) with a broadband reverberation time of 170 ms. The measurements were controlled using an in-house developed software. The speech and noise signals were amplified with an audio amplifier (Audiobox, Merz Medizintechnik, Reutlingen, Germany) and presented through Control 1 pro (JBL Professional, Northridge, California, USA) loudspeakers positioned at a distance of 1.0 m from the listener.

Statistical Analysis

The experimental results were analyzed with a nonparametric repeated measures ANOVA (Friedman test, level of significance = 0.05). The two-tailed Wilcoxon signed rank test with Bonferroni correction was applied for paired posttests whenever a statistically significant effect was identified. The statistical analysis was performed using the Instat 3.10 software (GraphPad, Inc., La Jolla, California, USA).

RESULTS

Influence of the Pinna on Speech Intelligibility in Noise

At the time of the study it was not possible to record the microphone output signals of the new audio processor for an objective comparison between the microphone directional patterns (AP2-OMNI, AP2-DIR). Therefore, two datasets (one from published data and one from our measurements) were used to compare the influence of the pinna directivity in the tested speech in noise situations: the speech signal was always presented from the front, whereas the noise was presented from the front (S₀N₀), from the side ipsilateral to the CI (S₀N₀L), from the side contralateral to the CI (S₀N₀R), or from the back (S₀N₁₈₀).

At the beginning of the experiments, each subject went through two training lists, the results of which were not used for analysis. All the measurements were performed for the AP1, the AP2-OMNI, and the AP2-DIR mode. During the tests, the participants were instructed to keep their head in a straight position. No hearing aids or earplugs were used in the contralateral ear. To minimize training and fatigue effects, the order of the tested directionality modes, spatial situations, and test lists were varied systematically.

Table 1. Synopsis of the study participants

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Age, yr</th>
<th>Experience CI, yr</th>
<th>Implant Model</th>
<th>CI Side</th>
<th>Active Electrodes</th>
<th>Monosyllables at 60 dB, %</th>
<th>Pure Tone Average at 0.5/1/2/3 kHz, dB HL</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>F</td>
<td>74</td>
<td>11</td>
<td>Combi40+</td>
<td>L</td>
<td>11</td>
<td>90</td>
<td>120</td>
</tr>
<tr>
<td>02</td>
<td>M</td>
<td>54</td>
<td>6</td>
<td>Pulsar</td>
<td>L</td>
<td>11</td>
<td>90</td>
<td>96</td>
</tr>
<tr>
<td>03</td>
<td>F</td>
<td>61</td>
<td>9</td>
<td>Pulsar</td>
<td>L</td>
<td>12</td>
<td>90</td>
<td>119</td>
</tr>
<tr>
<td>04</td>
<td>F</td>
<td>59</td>
<td>11</td>
<td>Combi40+</td>
<td>L</td>
<td>8</td>
<td>75</td>
<td>120</td>
</tr>
<tr>
<td>05</td>
<td>M</td>
<td>63</td>
<td>13</td>
<td>Combi40+</td>
<td>L</td>
<td>10</td>
<td>90</td>
<td>68</td>
</tr>
<tr>
<td>06</td>
<td>M</td>
<td>58</td>
<td>2</td>
<td>Concerto</td>
<td>L</td>
<td>12</td>
<td>80</td>
<td>103</td>
</tr>
<tr>
<td>07</td>
<td>F</td>
<td>27</td>
<td>6</td>
<td>Sonata</td>
<td>R</td>
<td>10</td>
<td>70</td>
<td>120</td>
</tr>
<tr>
<td>08</td>
<td>F</td>
<td>55</td>
<td>7</td>
<td>Sonata</td>
<td>L</td>
<td>12</td>
<td>70</td>
<td>106</td>
</tr>
<tr>
<td>09</td>
<td>M</td>
<td>69</td>
<td>18</td>
<td>Combi40</td>
<td>R</td>
<td>8</td>
<td>80</td>
<td>120</td>
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<tr>
<td>10</td>
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<td>63</td>
<td>5</td>
<td>Sonata</td>
<td>R</td>
<td>8</td>
<td>75</td>
<td>113</td>
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</table>
situations. The first dataset consisted of measurements performed in the above-mentioned test setup. A head and torso simulator (Brüel & Kjær, Type 4128, Naerum, Denmark) with built-in ear and pinna simulators (Brüel & Kjær, Type 4158/4159) was placed in the center of the loudspeaker array. The transfer functions of the ear simulators (case including pinna effects) and the microphone of an AP1 attached behind the ears (omnidirectional case) were measured from the directions according to the speech in noise tests. An audio analyzer (R&S UPV, Rohde & Schwarz, Germany) was used to generate sine sweep excitation signals and to record the microphone outputs. The second dataset was obtained from the head-related impulse response database provided by Kayser et al. (22). The transfer functions were computed from the measurements of the “in-ear” and the “front” (omnidirectional, behind-the-ear microphone) situations (anechoic room, loudspeaker distance of 0.8 m). In both datasets the transfer functions were averaged over the left and the right side. For each test situation the signal-to-noise ratio was calculated over 21 critical bands and weighted according to their contribution to speech intelligibility (23). The expected differences in SRT between the in-ear and behind-the-ear patients are shown in Table 2.

Speech in Noise Performance

Figure 1 shows the individual SRTs for the tested spatial situations and audio processors. A summary of the observed SRT improvements is listed in Table 3. The largest SRT difference between the AP2-OMNI and AP2-DIR modes was measured in the in the S$_{N180}$ situation, showing an average improvement of 3.6 dB ($p < 0.01$). In the S$_{N11}$ and S$_{N1CL}$ situations, smaller but statistically significant SRT improvements were observed (2.2 dB, $p < 0.01$ and 1.3 dB, $p < 0.05$). As expected, the participants had comparable SRTs with the AP2-OMNI and AP2-DIR modes in the S$_{N0}$ situation. There is no advantage of directional processing, because the signal and noise sources are not spatially separated. No statistically significant differences were measured between the two conditions with omnidirectional microphone modes (API and AP2-OMNI). This shows that the participants had a similar speech in noise performance with both tested CI audio processors.

<table>
<thead>
<tr>
<th>Table 2. Estimated SRT improvements caused by the directivity of the pinna simulator</th>
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</thead>
<tbody>
<tr>
<td><strong>Expected SRT Improvement, dB</strong></td>
</tr>
<tr>
<td>Test</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>S$_{N0}$</td>
</tr>
<tr>
<td>S$_{N11}$</td>
</tr>
<tr>
<td>S$_{N1CL}$</td>
</tr>
<tr>
<td>S$_{N180}$</td>
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</tbody>
</table>

D indicates distance to the loudspeakers; RT$_{60}$, reverberation time.

DISCUSSION

This study assessed the influence of a pinna directivity imitating directional microphone mode on speech intelligibility in noise. The directional mode yielded equal or better SRTs when compared with the omnidirectional mode and caused no negative effects on the speech intelligibility in the tested situations. Therefore, patients using the new CI audio processor can be expected to benefit from the “natural” directional microphone setting in noisy environments.

Better SRTs were observed in all situations with spatially separated speech and noise signals using the “natural” directionality mode. An immediate improvement in SRT was found for all participants, regardless of the implant type and number of active stimulation channels. The largest SRT improvements were observed in the S$_{N180}$ patient, indicating that the masking noise from behind is effectively attenuated by the directional microphone system. The comparison of the SRTs between the S$_{N11}$ and the S$_{N1CL}$ patients shows an average head shadow effect in the range of 4–5 dB.

In the S$_{N0}$ situation, the participants performed well and achieved SRTs ranging from −2.4 to 2.6 dB. Comparable SRTs were measured with the AP1, AP2-OMNI, and AP2-DIR modes. As expected, no benefits for the speech reception are introduced by the directional microphone system, because both the test sentences and the noise were presented from the same speaker. In addition, the similar SRTs indicate that no disadvantageous effects on the speech intelligibility were introduced by the directional filtering algorithm.

There are several factors limiting a comparison of our results to the findings of previous studies, specifically the differences in the tested microphone directionality strategies, additionally applied noise suppression algorithms, differences in the test conditions (single noise versus multinoise), the measurement set-up (i.e., the distance, position, and directionality of the loudspeakers), and the room characteristics (reverberation time). The SRT improvements found in this study lie within the range of previously reported findings using fixed directionality microphone systems (5–12).

The estimation model shows no SRT differences in the S$_{N0}$ situation, because the speech and noise originate from the same source (Table 2). In the S$_{N180}$ and S$_{N11}$ situations, the SRT improvements as estimated from the datasets were smaller than observed with the tested CI users. A more comparable estimation was found in the S$_{N1CL}$ situation. The validity of the estimation model is obviously limited; nevertheless, it indicates that SRT improvements because of the pinna effect can be expected in the experimental setup. The differences between the estimated and measured SRT values suggest that the AP2-DIR mode provides a stronger directionality toward the front than a natural pinna. A hypercardiod polar pattern for frequencies above 2 kHz was reported to be sufficient for a compensation of the pinna effect in behind-the-ear hearing aids (20). Currently there is,
however, no data available for an objective evaluation of the directionality pattern provided by the AP2-DIR setting. The speech in noise tests was performed with a single-noise source. Considering a multinoise scenario, the mean expected signal-to-noise ratio benefit could be estimated by a superposition of the tested situations because of the linearity of the microphone inputs in the fixed directionality mode. It is expected that a bigger benefit for speech intelligibility in noise can be achieved with the adaptive directionality mode of the CI processor. The evaluation of the adaptive directionality mode, however, lies beyond the scope of the presented work.

The identical test setup was used in a previous study investigating the speech in noise performance with a single-unit CI audio processor of the same manufacturer (24). The study showed that an omnidirectional microphone placed further behind the ear leads to worse SRTs in the S0N0 situation. A directional microphone system, such as the one investigated in this study, may compensate for the disadvantage caused by the shift of the microphone position. The participants had similar SRTs in all tested situations with the AP1 and the AP2-OMNI conditions. This indicates that the interchange of the CI audio processors and the conversion/transfer of the fittings between the processors had no negative effects on the speech intelligibility.

**FIG. 1.** The individual speech reception thresholds (SRTs) for the tested spatial situations and audio processors. Lower values denote better speech intelligibility in noise. The lines show the mean SRT and the standard deviation. The brackets show the level of statistical significance (n.s., no statistical significance, *p < 0.05, **p < 0.01). The position of the tested CI audio processor (implanted side) is indicated by a gray cross. AP1 indicates audio processor 1; AP2-DIR, audio processor 2 (fixed directional mode); AP2-OMNI, audio processor 2 (omnidirectional mode); CL, contralateral; IL, ipsilateral; N, noise (gray speaker); S, signal (white speaker).

**TABLE 3.** Speech reception threshold (SRT) differences listed as the mean value, the standard deviation, and the corresponding Bonferroni-corrected probability

<table>
<thead>
<tr>
<th>Test Situation</th>
<th>AP1 vs. AP2-OMNI</th>
<th>AP1 vs. AP2-DIR</th>
<th>AP2-OMNI vs. AP2-DIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0N0</td>
<td>0.6 (±1.2), p = 0.39</td>
<td>0.6 (±1.4), p = 0.72</td>
<td>0.0 (±0.5), p = 1</td>
</tr>
<tr>
<td>S0NIL</td>
<td>0.1 (±1.1), p = 1</td>
<td>2.3 (±1.3), p = 0.006</td>
<td>2.2 (±0.8), p = 0.006</td>
</tr>
<tr>
<td>S0NCL</td>
<td>0.6 (±1.4), p = 0.70</td>
<td>1.9 (±1.6), p = 0.006</td>
<td>1.3 (±0.9), p = 0.012</td>
</tr>
<tr>
<td>S0N180</td>
<td>0.0 (±1.3), p = 1</td>
<td>3.7 (±1.8), p = 0.006</td>
<td>3.6 (±1.4), p = 0.006</td>
</tr>
</tbody>
</table>

AP1 indicates audio processor 1; AP2-DIR, audio processor 2 (fixed directional mode); AP2-OMNI, audio processor 2 (omnidirectional mode).
reception of the participants. The subjects tested in this study represent a cohort in which bilateral implantation should be preferred (25). It is assumed that the pinna effect imitating directional microphone may provide benefits for patients with bilateral CI. In the same way, the influence of the directional microphone system on sound localization may be interesting. This was not evaluated in the presented work and is subject to ongoing studies.

REFERENCES


