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Cochlear Implant Microphone Location Affects Speech Recognition in Diffuse Noise

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Abstract

Background—Despite improvements in cochlear implants (CIs), CI recipients continue to experience significant communicative difficulty in background noise. Many potential solutions have been proposed to help increase signal-to-noise ratio in noisy environments, including signal processing and external accessories. To date, however, the effect of microphone location on speech recognition in noise has focused primarily on hearing aid users.

Purpose—The purpose of this study was to (1) measure physical output for the T-Mic as compared with the integrated behind-the-ear(BTE) processor mic for various source azimuths, and (2) to investigate the effect of CI processor mic location for speech recognition in semi-diffuse noise with speech originating from various source azimuths as encountered in everyday communicative environments.

Research Design—A repeated-measures, within-participant design was used to compare performance across listening conditions.

Study Sample—A total of 11 adults with Advanced Bionics CIs were recruited for this study.

Data Collection and Analysis—Physical acoustic output was measured on a Knowles Experimental Mannequin for Acoustic Research (KEMAR) for the T-Mic and BTE mic, with broadband noise presented at 0 and 90° (directed toward the implant processor). In addition to physical acoustic measurements, we also assessed recognition of sentences constructed by researchers at Texas Instruments, the Massachusetts Institute of Technology, and the Stanford Research Institute (TIMIT sentences) at 60 dBA for speech source azimuths of 0, 90, and 270°. Sentences were presented in a semi-diffuse restaurant noise originating from the R-SPACE 8-loudspeaker array. Signal-to-noise ratio was determined individually to achieve approximately 50% correct in the unilateral implanted listening condition with speech at 0°. Performance was compared across the T-Mic, 50/50, and the integrated BTE processor mic.

Results—The integrated BTE mic provided approximately 5 dB attenuation from 1500–4500 Hz for signals presented at 0° as compared with 90° (directed toward the processor). The T-Mic output was essentially equivalent for sources originating from 0 and 90°. Mic location also

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significantly affected sentence recognition as a function of source azimuth, with the T-Mic yielding the highest performance for speech originating from 0°.

Conclusions—These results have clinical implications for (1) future implant processor design with respect to mic location, (2) mic settings for implant recipients, and (3) execution of advanced speech testing in the clinic.

Keywords

Cochlear implants; microphone location; R-SPACE; restaurant noise; T-Mic; SNR; speech recognition

Introduction

Modern adult cochlear implant (CI) recipients are achieving increasingly higher levels of speech understanding with mean monosyllabic word recognition in the range of 60–70% correct for implanted ears (e.g., Gifford et al, 2014; Holden et al, 2013). Despite increasing levels of performance, implant patients continue to struggle with speech understanding—particularly in everyday listening environments including diffuse noise and/or reverberation. Indeed, one of the most common complaints expressed by implant recipients is the difficulty understanding speech in the presence of background noise.

Poor speech recognition performance in background noise for adult CI recipients has even been documented when tested at what would be considered an optimal signal-to-noise ratio (SNR) in regard to realistic listening environments. Research has shown speech recognition performance ranging from 43–70% for AzBio sentences (Spahr et al, 2012) at +10 dB SNR for implanted ears alone and 66–80% for bimodal and bilateral hearing configurations (e.g., Dorman et al, 2008; Neuman and Svirsky, 2013). For a large sample of adult CI recipients ($n = 81$), Gifford et al (2014) reported mean scores for AzBio sentence recognition at +5 dB SNR of 55% and 63% for single implant and best aided conditions, respectively. Although these levels are much higher than reported in the past, by comparison, adults with normal hearing would expect-edly reach ceiling-level performance at +5 dB SNR (e.g., Summers et al, 2013; Wilson and Dorman, 2008). This clearly illustrates that implant users continue to face considerable communicative deficits in noise.

Various solutions have been proposed to help improve the SNR for CI users. Solutions include signal processing techniques for noisy environments, as well as the use of wireless accessories such as an FM system and induction loop technology. Another potential solution to increase the SNR is to vary the device's microphone location.

With respect to microphone location for hearing aids, Festen and Plomp (1986) measured speech reception thresholds (SRTs) for noise sources at 0 and 90° azimuth. They found a smaller difference for SRTs across the two noise sources for hearing aids with a microphone placed at the entrance of the ear canal as compared with the typical behind-the-ear (BTE) hearing aid microphone. Specifically, the microphone located at the entrance of the ear canal provided a 2 dB advantage versus that of the BTE microphone for signals originating at 0° azimuth.

In a similar study, Pumford et al (2000) demonstrated a 2.4 dB improvement in the SNR for an in-the-ear (ITE) omnidirectional mic as compared with a BTE omnidirectional mic for signals originating at 0° azimuth. In fact, they showed that the mic location of an ITE hearing aid provided equivalent improvement in the SNR to a directional dual microphone configuration in a BTE hearing aid.

In the CI literature, Mantokoudis et al (2011) measured spatial discrimination via minimal audible angle and speech recognition performance for adult implant recipients using head-related transfer functions (HRTFs) for both an in-the-canal (ITC) and a BTE microphone. They found that significantly better spatial discrimination was noted for the ITC HRTF as compared with the BTE HRTF for spatial discrimination. They also found a 3 dB reduction in the SNR required for threshold with the ITC HRTF, indicative of better performance. The differences in speech recognition across the mics, however, did not reach statistical significance.

Aronoff et al (2011) obtained SRTs for normal-hearing listeners using the HRTFs obtained for various CI microphones. Of primary interest here was the difference between SRTs obtained for the Advanced Bionics (AB) T-Mic—which is located at the opening to the ear canal—as compared with the standard BTE mic location. Specifically, they found that the T-Mic yielded significantly better SRT as compared with the BTE mic, with the difference being approximately 2 dB. They further reported that the SRT obtained with the T-Mic HRTF was not significantly different from that obtained with the standard Knowles Experimental Mannequin for Acoustic Research (KEMAR) HRTF representing unaided acoustic hearing including pinna effects.

Gifford and Revit (2010) investigated the effect of mic location for speech recognition in noise for 14 adult AB CI recipients. They obtained SRTs in semi-diffuse noise using the R-SPACE 8-loudspeaker array. They found significantly lower (i.e., better) SRTs with the T-Mic as compared with the BTE mic, with a mean difference of 4.2 dB between mic locations.

AB is currently the only CI manufacturer offering the use of a microphone that can be positioned at the opening of the ear canal. This is surprising given the known effects of BTE microphone placement dating back to the 1980s. In fact, the very first US Food and Drug Administration-approved CI system—the House 3M single channel device—placed the microphone at the level of the ear canal, as it was fastened to the exterior of an acrylic earmold. Similarly, the T-Mic was originally designed for ease of use with the telephone, allowing for natural receiver placement over the ear. It has been hypothesized that the T-Mic may allow the user to take advantage of pinna cues, thereby offering natural directivity (e.g., Gifford and Revit, 2010; Aronoff et al, 2011).

All published studies described here have investigated the effect of mic location for speech originating at 0° azimuth with noise at either 0, ± 90 , or in a 0–360° configuration. To date, no study has specifically investigated the effect of CI mic location for speech originating from various source azimuths, as is typically encountered in real-world listening environments such as in a small-group gathering or dinner party. Thus, it is unclear whether

the T-Mic would offer a similar advantage to that observed with ITE mics as compared with BTE mic configurations. The primary aims of this study were (1) to determine whether physical level differences exist for the T-Mic as compared with the integrated processor microphone for various source azimuths and (2) to determine the effect of CI processor mic location on speech recognition in semi-diffuse noise with speech originating from various source azimuths as typically encountered in everyday communicative environments. On the basis of previous literature examining the effect of mic location for hearing aids and CIs, the study hypotheses were (1) the use of the T-Mic will result in significantly higher levels of speech recognition than the integrated processor BTE microphone, (2) the greatest difference in speech recognition will be noted between T-Mic and BTE mic for speech originating from $\pm 90^\circ$, and (3) speech recognition for stimuli at 0° will be highest for the T-Mic condition.

Method

Participants

A total of 11 adult CI recipients of AB devices participated in the study in accordance with Vanderbilt University Institutional Review Board (IRB) approval. Participants' ages ranged from 19–67 yr with a mean age of 42.5 yr. All participants were required to have at least 6 mo experience with the CI(s) to meet inclusion criteria. The 11 participants had 7.8–174.7 mo (mean = 96.8 mo) of CI listening experience. Seven of the eleven participants were bilateral CI recipients. Of the four unilateral recipients, only two used amplification in the nonimplanted ear for a bimodal hearing configuration; the other two recipients did not have usable hearing in the nonimplanted ear and had not yet elected to pursue a second CI. All participants were wearing Harmony sound processors. Demographic information for all participants is shown in Table 1.

Stimuli

Testing was performed in a single-walled sound booth using the Revitronix R-SPACE sound simulation system. The R-SPACE system consists of an 8-loudspeaker array with the speakers arranged at 45° intervals in a circle surrounding the listener. Each speaker is placed at a distance of 24 inches from the participant's head, in order to simulate a realistic restaurant setting such as those described in detail in previous studies (e.g., Revit et al, 2007; Compton-Conley et al, 2004).

TIMIT sentences were constructed by researchers at Texas Instruments (TI), the Massachusetts Institute of Technology (MIT), and the Stanford Research Institute, for experimental use with automatic speech recognition systems. TIMIT sentence materials (e.g., Lamel et al, 1986; Loizou et al, 2000; Dorman et al, 2003, 2005; King et al, 2012) were presented at 60 dBA from a single speaker. The TIMIT sentences are spoken by both male and female speakers representing eight different American English dialects. The TIMIT corpus as used in the current study represents a subset of the original 6300 sentences that were assembled into 34 lists of equal intelligibility as described by Dorman et al (2003, 2005) and Loizou et al (2000).

The R-SPACE proprietary restaurant noise was presented from all of the speakers, with the exception of the speaker who was presenting the speech signal. The restaurant noise presentation level used was individually determined to yield approximately 50% correct (± 12 percentage points) when listening with the better-implanted ear only and the speech presented at 0° azimuth. The method of SNR determination was first approximated based on pilot data collected in the laboratory. These pilot data were based upon the decrease in performance observed for speech-in-noise testing as compared with the quiet condition. As compared with sentence recognition in quiet, we have observed that testing at +15 dB yields a performance decrement of approximately 10 percentage points, +10 dB yields a performance decrement of approximately 20–25 percentage points, and +5 dB yields a performance decrement of approximately 40 percentage points. Using this approximation, if the initial SNR chosen did not yield performance of approximately 50% correct, we manually adjusted the SNR in 2 dB steps and completed testing with a single TIMIT list. The final SNR used ranged from +2 to +23 dB with a mean of +8.0 dB (see Table 1).

Procedure

Two 20-sentence lists of TIMIT sentences were presented in the R-SPACE restaurant noise for each of the following conditions:

- Randomly from 0, 90, or 270° (for a total of 120 sentences) in a unilateral CI condition which was the CI for the unilateral participants and the better CI ear for the bilateral participants.
- Randomly from 0, 90, or 270° (for a total of 120 sentences) with the bilateral, best-aided condition (bilateral CI or bimodal).

For the two unilateral CI recipients not making use of contralateral acoustic amplification, only the single CI condition was run. The order of listening conditions was randomly selected by the test administrators before experimentation. Testing in each of the conditions, as noted above, was completed with T-Mic only, the BTE mic, and in the 50/50 T-Mic/BTE mixing condition. The reason for testing the 50/50 mixing condition was that at the time of experimentation, the 50/50 condition was the default microphone setting for the AB clinical programming software (SoundWave 2.0). Consequently, 50/50 audio mixing was a common everyday use setting for many AB implant recipients. If the participant had bilateral implants, the mic settings were the same for both ears.

In addition to speech recognition testing, physical sound level measurements were also collected. An AB shell processor was placed on a KEMAR and used to perform physical level measurements with both the T-Mic and BTE mic for a broadband, speech-shaped, steady-state noise originating from both 0 and 90° azimuth. The reasoning for completing these measures was that although the HRTFs for the T-Mic and a BTE mic have been published (Aronoff et al, 2011), no published data have detailed the output response characteristics associated with each microphone location for a speech-like stimulus.

Results

Mic Output

Physical measurements taken on a KEMAR are displayed in Figures 1A-C. Figures 1A-B display the physical output level in dB, for a broadband noise presented at 0° (dashed line) and 90° (solid line). Figure 1C displays the difference in the mic response (in dB) between 0° and 90° as a function of frequency for the T-Mic (solid line) and BTE mic (gray line). This difference score is expressed as the mic output level at 90° subtracted from 0°. Therefore, a negative value indicates that the mic output was higher for signals originating from 90° as compared with 0°. As shown in Figure 1A-C, for the 600–4000 Hz range, the BTE mic provides approximately 5 dB attenuation for signals originating from 0° as compared with 90°. For the T-Mic, however, little to no differences in signal amplitude were noted between 0 and 90° for the frequency range of approximately 1900–4000 Hz. The mean difference between the T-Mic and BTE mic, averaged across frequency, was 2.6 dB. Statistical analysis was completed comparing the difference in the physical output for the two mics at 0 and 90° as a 2151-point vector encompassing the spectral range from 150–6600 Hz (3 Hz steps). A *t*-test revealed a significant difference in source azimuth effects on mic output ($t = 35.93$, $p < 0.0001$).

Speech Recognition

Figure 2 displays mean TIMIT sentence recognition scores for the stimuli originating at 0 and 90° in all three microphone conditions: T-Mic (black circles), BTE mic (white circles), and 50/50 (gray circles). Panels A and B of Figure 2 display unilateral ($n = 11$) and bilateral or best-aided ($n = 9$) listening conditions, respectively.

Unilateral, Best CI Performance

Focusing first on Figure 2A for unilateral CI conditions, performance is plotted against source azimuth referencing the non-CI ear, front (0°), and the CI ear. Performance was lowest for all mic configurations when speech was directed toward the non-CI ear. This is an effect of head shadow as the head poses a physical barrier attenuating the signal. Mean performance for speech directed toward the non-CI was 23.9% for the BTE mic, 26.1% for the T-Mic, and 23.4% for 50/50. In the unilateral CI condition (Fig. 2A), performance was generally highest (i.e., best) when speech was directed toward the CI ear. Mean performance for speech directed toward the CI ear was 45.8% for the BTE mic, 50.2% for the T-Mic, and 36.4% for 50/50. Performance was most variable across mic configurations for signals originating from the front (0°) in the unilateral CI condition (Fig. 2A). Mean unilateral performance for 0° was 29.0% for the BTE mic, 44.4% for the T-Mic, and 38.7% for 50/50.

A two-way repeated-measures analysis of variance was completed using source azimuth and mic configuration as the independent variables and speech recognition performance as the dependent variable. Statistical analysis revealed a significant effect of source azimuth [$F_{(2,10)} = 15.6$, $p < 0.001$], mic configuration [$F_{(2,10)} = 14.4$, $p < 0.001$], and a significant interaction [$F_{(2,2)} = 5.1$, $p = 0.002$]. Collapsed across source azimuth, post hoc analyses using all pairwise multiple comparisons with the Holm-Sidak statistic revealed that the T-Mic yielded significantly higher scores than both the BTE mic ($t = 4.6$, $p < 0.001$) and 50/50

($t = 4.7, p < 0.001$). There was no difference, however, between scores obtained with the BTE mic and 50/50 ($t = 0.07, p = 0.950$).

Further understanding of the interaction term can be gleaned from post hoc analyses within speech source azimuth. For speech originating from 0° , the T-Mic yielded significantly higher scores than the BTE mic ($t = 4.8, p < 0.001$) but not different from 50/50 ($t = 1.7, p = 0.09$). The BTE mic and 50/50 were also significantly different at 0° ($t = 3.06, p = 0.007$). For speech directed toward the CI ear, the T-Mic yielded significantly higher scores than 50/50 ($t = 4.4, p < 0.001$) but not different from the BTE mic ($t = 1.4, p = 0.17$). The BTE mic and 50/50 were also significantly different for speech directed toward the CI ear ($t = 3.0, p = 0.008$). Finally, for speech directed toward the non-CI ear, no significant difference between scores was obtained with any of the three mic configurations.

Bilateral CI

For the bilateral CI condition, outcomes were similar to those obtained with the unilateral/best CI (Fig. 2B). Focusing on Figure 2B for bilateral CI, performance was lowest (i.e., worst) for all mic configurations when speech was directed toward the poorer CI ear. Mean performance for speech directed toward the poorer CI ear was 37.4% for the BTE mic, 39.8% for the T-mic, and 30.6% for 50/50. Similar to that observed in the unilateral CI condition, performance in the bilateral CI condition (Fig. 2B) was generally highest (i.e., best) when speech was directed toward the better CI ear. Mean performance for speech directed toward the better CI ear was 51.2% for the BTE mic, 54.5% for the T-Mic, and 35.6% for 50/50. For signals originating from 0° in the bilateral CI condition (Fig. 2B), performance was best with the T-Mic. Mean bilateral performance for 0° was 39.3% for the BTE mic, 54.4% for the T-Mic, and 41.3% for 50/50.

Statistical analysis was completed for the bilateral CI conditions as well. A two-way repeated-measures analysis of variance was completed using source azimuth and mic configuration as the independent variables and speech recognition performance as the dependent variable. Statistical analysis revealed a significant effect of source azimuth [$F_{(2,8)} = 28.9, p < 0.001$], mic configuration [$F_{(2,8)} = 13.0, p = 0.002$], but no interaction [$F_{(2,2)} = 2.1, p = 0.115$]. Collapsed across source azimuth, post hoc analyses using all pairwise multiple comparisons with the Holm-Sidak statistic revealed that the T-Mic yielded significantly higher scores than the BTE Mic ($t = 3.9, p = 0.007$) and 50/50 ($t = 7.6, p < 0.001$). Unlike the unilateral CI condition, however, there was a significant difference between scores obtained with the BTE mic and 50/50 ($t = 3.8, p = 0.004$).

Discussion

The current study highlights significant differences between the BTE mic and T-Mic, both for physical acoustic measurements and speech recognition outcomes. The standard BTE mic provides approximately 5 dB attenuation for the 1500–4500 Hz range for signals presented at 0° as compared with $\pm 90^\circ$ (directed toward the processor, see Figure 1). This is a known effect of mic location (Festen and Plomp, 1986) for ports opening to the side of the head, as in standard BTE mic configurations. In fact, when considering the output differences for 0 and $\pm 90^\circ$ for the spectrum transmitted by CIs (150 through ~ 7000 Hz), we

found a mean 2.6 dB difference between the BTE mic and T-Mic. This result is in agreement with that of previous reports favoring a side source azimuth for BTE mics in hearing aids (e.g., Festen and Plomp, 1986; Pumford et al, 2000) and in HRTF studies with CI processors (e.g., Mantokoudis et al, 2011; Aronoff et al, 2011).

The results of the sentence recognition tests indicate that the T-mic yielded significantly higher speech understanding in diffuse noise than the BTE mic for speech originating at 0° azimuth. For the unilateral condition, the 50/50 configuration afforded significantly poorer speech understanding than both T-Mic and BTE mic for signals originating from both 0 and 90°. For bilateral implant recipients, there was no difference between performance obtained with the BTE mic and 50/50, although both were significantly poorer than the T-Mic for signals at 0°.

The results of this study pose significant implications for the future design of CI processors. Although most current CI processors utilize an integrated BTE mic, this microphone location may not yield the best performance in noise. This is particularly true for group listening environments, in which the target source will vary. This highlights the benefits afforded by the AB T-Mic as compared with the standard BTE mic placement. It is important to note here that AB is the only implant system currently offering a microphone option at the level of the ear canal.

It is important to recognize the limitations of the current study. The current study examined the use of an omnidirectional mic in different locations. The newest CI processors—including the AB Naida CI Q70 as well as the Nucleus Freedom, N5, and N6 processors—have multiple microphones designed to offer directional configurations to improve speech recognition in noise. Such programs, however, are not recommended for full-time use given the audibility loss for signals not originating from 0°. This is particularly true for pediatric implant recipients. Thus, a follow-up study is warranted to investigate the effectiveness of the T-Mic system, which offers natural directivity via pinna effects, as it is compared with the directivity offered by multiple microphone directional processing.

A second limitation involves the investigation of 50/50 audio mixing, which evenly delivers the incoming signal to both the T-Mic and BTE mic. For the newest AB sound processor (Naida CI Q70), the T-Mic option continues to be available in two configurations: (1) T-Mic only (formerly AUX only), and (2) Processor mic plus T-Mic (formerly 50/50). The default configuration when choosing T-Mic continues to be Processor mic plus T-Mic (i.e., 50/50). The difference associated with the newest processor is that T-Mic is no longer treated as an auxiliary or AUX input, but rather one of the primary mic sources. The 50/50 (or Processor mic plus T-Mic) option is a popular choice for clinicians because it serves as a proverbial “safety net,” as it continues to offer sound in cases of T-Mic malfunction. These data suggest, however, that the 50/50 setting is less effective for speech understanding in noise as compared with 100% T-Mic input. Thus, it is recommended that clinicians consider offering T-Mic only in programs for everyday listening and a secondary program for Processor mic (or BTE mic) to be used in cases of concern. Of course, this will require frequent and effective counseling for our patients and their families on the use of these multiple programs and for troubleshooting when concerns arise.

In the short term, the results of this study hold direct clinical applicability. The results of this study, along with others (e.g., Festen and Plomp, 1986; Pumford et al, 2000; Gifford and Revit, 2010; Aronoff et al, 2011; Mantokoudis et al, 2011), suggest that for AB implant recipients, clinicians should consider exclusive use of the T-mic (or T-Comm with Neptune processors) for everyday listening environments, as speech recognition will be less affected by the signal source azimuth. These data also carry clinical implications for clinical speech testing when using multiple speakers, for which the noise may be directed toward the implanted ear. The physical SNR will be lower in this condition—by 2 to 3 dB—than in the standard condition with speech and noise both at 0° (S_0N_0), given that the physical level of the noise directed toward the processor will be higher than the nominal SPL by 2–3 dB. Although the comparison of S_0N_0 and S_0N_{90} and/or S_0N_{270} is included in classic experimental paradigms for assessing spatial release from masking, head shadow, and squelch, these comparisons actually underestimate spatial release from masking and squelch if adjustments for the physical SNR differences related to mic location are not made (also see Gifford et al, 2014).

The hypotheses associated with this study were (1) the use of the T-Mic will result in significantly higher levels of speech recognition than the integrated processor BTE microphone, (2) the greatest difference in speech recognition will be noted between T-Mic and BTE mic for speech originating from $\pm 90^\circ$, and (3) speech recognition for stimuli at 0° will be highest for the T-Mic condition. Given the results of the current study, we were able to reject the null hypotheses on all accounts, as these data suggest that the T-Mic offered the greatest signal availability regardless of source azimuth.

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Abbreviations

AB	Advanced Bionics
BTE	behind-the-ear
CI	cochlear implant
ITE	in-the-ear
HRTFs	head-related transfer functions
ITC	in-the-canal
KEMAR	Knowles Experimental Mannequin for Acoustic Research
SNR	signal-to-noise ratio
SRTs	speech reception thresholds

TIMIT

sentence corpus constructed by researchers at Texas Instruments, the Massachusetts Institute of Technology, and the Stanford Research Institute

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Figure 1.

Physical output of the BTE mic (A) and T-Mic (B) are shown as a function of frequency for the 0 (dashed line) and 90° (solid line) source azimuth. (C) displays the mic response difference, in dB, between the 0 and 90° as a function of frequency for the T-Mic (solid line) and BTE mic (gray line). In (C), a negative value indicates that the mic output was greater for sources originating from 90° as opposed to 0°.

Figure 2. Mean TIMIT sentence recognition (in percent correct) for source azimuths of 0 and $\pm 90^\circ$ in all three microphone conditions: T-Mic (filled circles), BTE mic (unfilled circles), and 50/50 (shaded circles). Panels A and B of Figure 2 display unilateral (n = 11) and bilateral, best-aided (n = 9) listening conditions, respectively.

Table 1

Demographic Information for the 11 Participants

Participant	Age (yr)	Gender	Recipient Type	SNR Used for Testing	Years of CI Experience		Device	
					First CI	Second CI	First CI	Second CI
1	67	Male	Bimodal	2	5.4	–	HR90K	–
2	31	Male	Bilateral	3	9.4	9.3	HR90K	HR90K
3	28	Female	Bilateral	15	7.8	2.5	HR90K	HR90K
4	19	Female	Bilateral	12	10.7	3.4	CII	HR90K
5	22	Female	Unilateral	20	14.6	–	C1.2	–
6	41	Female	Bilateral	13	6.4	2.0	HR90K	HR90K
7	49	Female	Bilateral	11	13.7	5.3	C1.2	HR90K
8	44	Female	Bilateral	15	5.7	5.7	HR90K	HR90K
9	60	Female	Bilateral	23	10.1	3.4	CII	HR90K
10	48	Male	Unilateral	20	0.7	–	HR90K	–
11	58	Female	Bimodal	8	4.4	–	HR90K	–
MEAN	42.5	N/A	N/A	8.0	8.1	4.5	N/A	N/A

Note: Horizontal dashed lines indicate no existing value with respect to the second CI for unilateral CI recipients.