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Recommended Citation
Valente, Michael; Schuchman, Gerald; Potts, Lisa G.; and Beck, Lucille B., "Performance of dual-microphone in-the-ear hearing aids" (2000). *Publications*. Paper 19.
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J Am Acad Audiol 11: 181–189 (2000)

Performance of Dual-Microphone In-the-Ear Hearing Aids

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Abstract

Fifty subjects with mild to moderate-severe sensorineural hearing loss and prior experience with binaural amplification were evaluated at two sites (25 subjects at each site). Signal-to-noise ratios (SNRs) were measured using the Hearing in Noise Test (HINT) after each subject wore binaural in-the-ear hearing aids programmed for omnidirectional and dual-microphone performance, for 4 weeks. Both microphone conditions were evaluated under "ideal" (signal at 0°; noise at 180°) and "diffuse" (signal at 0°; correlated noise at 45°, 135°, 225°, and 315°) listening conditions. Results revealed statistically significant mean improvements in SNRs between 3.7 and 3.5 dB at Site I and 3.2 and 2.7 dB at Site II for the ideal and diffuse listening conditions, respectively, for the dual-microphones in comparison to the performance provided by the omnidirectional microphone.

Key Words: Diffuse, dual-microphone, HINT thresholds, ideal, omnidirectional, signal-to-noise ratio, super compression with adaptive release time

Abbreviations: DI = directivity index, HINT = Hearing in Noise Test, NAL-R = National Acoustic Laboratory-Revised, REIG = real-ear insertion gain, SAV = select-a-vent, SC+aRT = super compression with adaptive release time

Reduced recognition of speech in noisy backgrounds is a significant problem for listeners with sensorineural hearing loss (Beck, 1991). In the past, hearing aids have done little to resolve the problems for listeners whose primary complaint is having increased difficulty understanding speech in noise (Kochkin, 1996). To address this problem, some behind-the-ear (BTE) hearing aids have been designed with conventional directional microphones (i.e., single microphone with front and rear ports) that allow greater amplification for signals originating from the front of the listener than for sounds originating from directly behind. Several studies have demonstrated the efficacy of conventional directional microphones in improving the recognition of speech in noise (Lentz, 1972; Sung et al, 1975; Madison and Hawkins, 1983; Hawkins and Yacullo, 1984). In these studies, the directional microphone had a cardioid polar pattern (i.e., null at 180°) and, therefore, the advantage of the conventional directional microphone was greatest when the signal was in front and the noise originated from a single source from behind. Several studies have shown that the directional advantage decreases in a reverberant or diffuse noise environment (Studebaker et al, 1980; Madison and Hawkins, 1983; Ricketts and Dhar, 1999).

Valente et al (1995) evaluated the performance of a BTE instrument allowing the user to electronically switch between dual-microphone (i.e., two perfectly matched omnidirectional microphones resulting in a cardioid polar pattern) and omnidirectional microphone performance. The results of this study revealed mean improvements in the signal-to-noise ratio (SNR) of 7.4 to 8.5 dB under *ideal* laboratory conditions where the signal arrived from the front and the noise from directly behind. Agnew and Block (1997) reported a mean improvement

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in the SNR of 7.5 dB under similar experimental conditions using a dual-microphone BTE hearing aid with a cardioid polar pattern. Lurquin and Rafhay (1996) reported a mean improvement in the SNR of 6.6 dB for the same hearing aid used by Valente et al (1995) when using bisyllabic words presented at 0° and cocktail party noise presented at 180°. Gravel et al (1999) reported mean improvements in SNRs of 4.2 to 5.3 dB for young and older children with speech material appropriate for the pediatric population presented at 0° and multitalker babble presented at 180° using the same dual-microphone BTE hearing aid used by Valente et al (1995).

Recently, several researchers have investigated the performance of the same dual-microphone hearing aid used by Valente et al (1995), but with noise presented under *diffuse* listening conditions (i.e., multiple noise sources surrounding the listener). For example, Ricketts and Dhar (1999) reported on SNRs using uncorrelated noise presented at 90°, 135°, 180°, 225°, and 270° azimuth under anechoic and reverberant (0.6 sec) conditions. Under anechoic conditions, the mean improvement in SNR (re: omnidirectional performance) was approximately 7.5 dB, while under the reverberant condition, the improvement in SNR was approximately 6.5 dB. Pumford et al (1999) reported a 5.8-dB improvement in the SNR with the noise presented at 72°, 144°, 216°, and 288° azimuth. Thus, these two studies have reported similar improvements in SNR for the same dual-microphone BTE hearing aid used by Valente et al (1995) even though the noise was presented under reverberant and/or diffuse listening situations.

Currently, in-the-ear (ITE) hearing aids account for over 80 percent of the hearing aids sold in the United States (Kirkwood, 1997). This has motivated manufacturers to design and develop a dual-microphone ITE hearing aid in the hope that its performance will equal or exceed the performance of a dual-microphone BTE hearing aid. A recent report by Wolf (1999) indicated that the directivity index (DI), a measure of directional performance, was superior for a dual-microphone ITE hearing aid in comparison to a dual-microphone BTE hearing aid. The inference is that users can expect greater improvement in SNR with a dual-microphone ITE hearing aid than can be achieved with a dual-microphone BTE hearing aid. Similar findings were reported by Roberts and Schulein (1997).

Recently, Phonak, Inc. introduced a dual-microphone ITE hearing aid (Micro-Zoom). This is a programmable multiple-memory hearing aid allowing the user to electronically switch between omnidirectional and dual-microphone performance by pressing a button on a remote control or a switch on the faceplate of the hearing aid. Through the accompanying software (PFG-6), the overall, low-frequency, mid-frequency, and high-frequency gain as well as overall output can be programmed into one or more of the three memories. In addition, different methods of signal processing can be programmed into the hearing aids. For example, one method is linear amplification with a high compression threshold and super compression (10:1 compression ratio) with adaptive release time (SC+aRT).

The primary objectives of the study were to determine if

1. significant differences were present in SNR when the dual-microphones were active in comparison to when the omnidirectional microphone was active,
2. significant differences were present in SNR when the listening situation was ideal or diffuse, and
3. significant differences were present in SNR between Site I and Site II.

METHOD

Subjects

Twenty-five adults with mild to moderate-severe sensorineural hearing loss and experience using binaural amplification were included as participants at each of two sites. Site I was Washington University School of Medicine in St. Louis, Missouri, and Site II was the Veterans Administration Medical Center in Washington, DC. At Site I there were 13 males and 12 females with a mean age of 69.5 years and a range from 35 to 83 years. At Site II there were 24 males and 1 female with a mean age of 69.7 years and a range from 55 to 85 years.

Air- and bone–conduction pure-tone thresholds (ANSI, 1989) were measured at 250 to 8000 Hz in the conventional manner (ASHA, 1978), and the results indicated the presence of sensorineural hearing loss. Figure 1 reports the mean air-conduction thresholds at Site I (upper panel) and Site II (lower panel). In addition, immittance audiometry indicated normal middle-ear function.

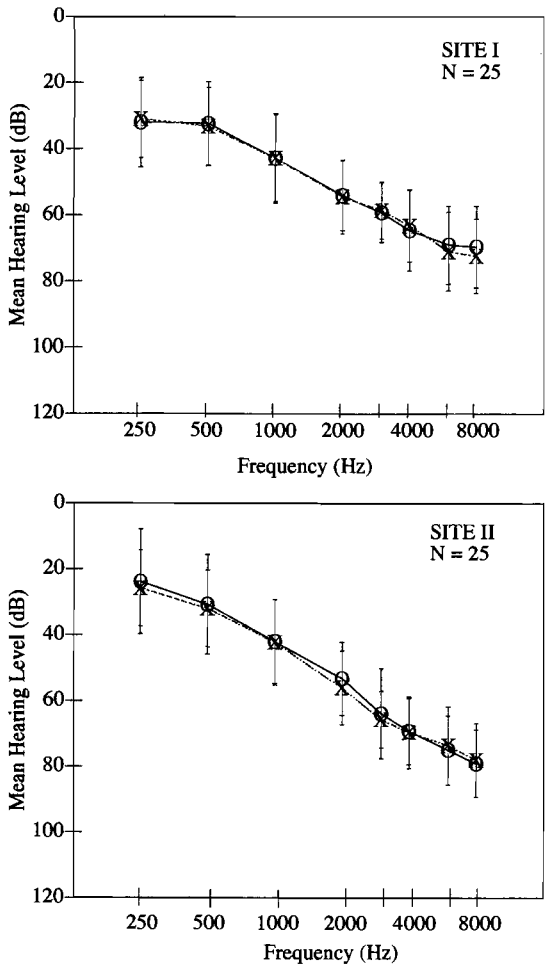

Figure 1 Mean air-conduction thresholds (dB HL) for the 25 subjects each at Site I (upper panel) and Site II (lower panel). Also included is ± 1 standard deviation.

Hearing Aid Experience

At Site I, the subjects' mean years of hearing aid experience was 9.1 years with a mean of 4.1 years of experience with their current aids. Eleven subjects wore single-memory, single-channel hearing aids with linear signal processing, while 14 subjects wore multimemory and/or multichannel hearing aids with nonlinear signal processing. Six subjects wore ITE hearing aids, 10 subjects wore in-the-canal (ITC) hearing aids, and 9 subjects wore completely in-the-canal (CIC) hearing aids.

At Site II, the mean years of hearing aid experience was 14.1 years with a mean of 3.0 years of experience with their current aids. Twenty-three subjects wore single-memory, single-channel hearing aids with linear signal processing, while 2 subjects wore multimemory, multichannel hearing aids with nonlinear signal processing. Twenty-one subjects wore ITE hearing aids, 2 subjects wore ITC hearing aids, and 2 subjects wore CIC hearing aids.

Experimental Hearing Aids

After completing the audiometric evaluation, impressions were made of each ear using silicone material to order full-shell, ITE hearing aids. While the impression material was hardening, a flat-edged card was inserted into the impression material marking the required horizontal position for alignment of the dual-microphones. When the hearing aids arrived they were placed in the ear canal and the investigators observed the alignment of the dual-microphones. Hearing aids were returned for remake if, in the opinion of the investigators, the dual-microphones were not aligned horizontally. Mueller and Wesselkamp (1999) reported that a deviation of 10° relative to perfect horizontal alignment did not significantly affect the directivity index (DI), an electroacoustic measure that is used to predict microphone performance in a diffuse listening environment. The higher the DI, the better the predicted performance in diffuse listening environments. When the microphone alignment was off by greater than 10°, the DI decreased by 0.5 dB. Theoretically, this would result in poorer performance in a diffuse listening situation when compared to perfect alignment (± 10°).

Figure 2 reports the free-field polar pattern at 500, 1000, 2000, and 4000 Hz for the experimental hearing aid. It can be seen that this hearing aid, unlike the cardioid polar pattern present in the BTE version of the same hearing aid, provides a hypercardioid polar pattern where nulls are present at approximately 120° and 210°. Figure 3 reports the free-field DI for the experimental hearing aid. As can be seen in Figure 3, the DI is between 4 and 5 dB at 500 to 5000 Hz with a small decrease at around 1800 Hz.

Each hearing aid was ordered with a volume control and the investigator programmed the hearing aids so that only omnidirectional or dual-microphone performance was available at any one time (i.e., the subject could not switch between omnidirectional and dual-microphone performance). Typically, this hearing aid is delivered with the dispenser being able to program up to three memories and the user can switch between omnidirectional and dual-microphone

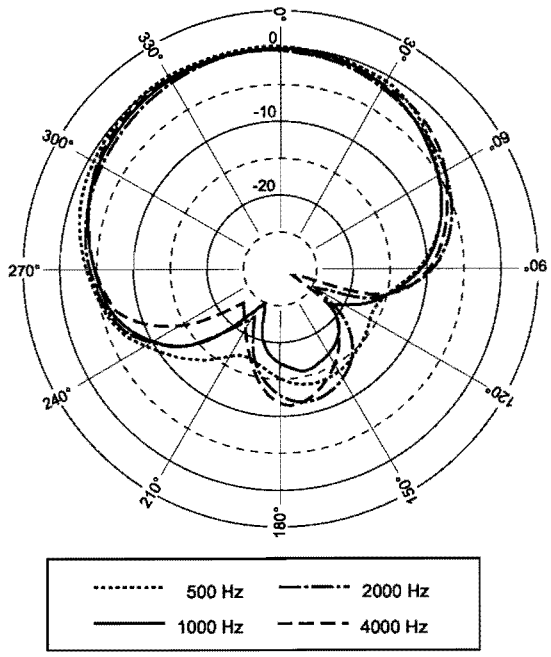

Figure 2 Free-field polar pattern for the hearing aid used in the present study.

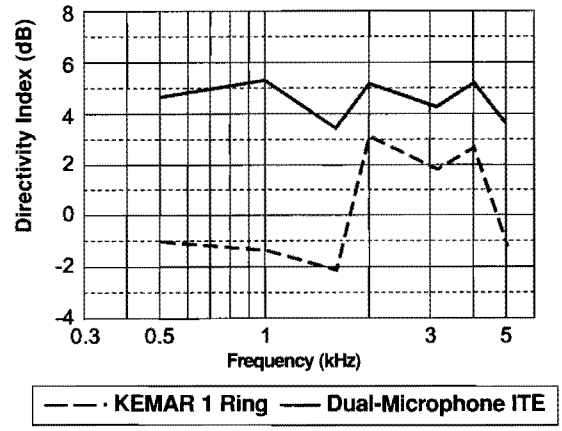

Figure 3 Free-field DI for the hearing aid used in the present study.

performance by pressing a button on a remote control or by the dispenser programming the telephone switch to provide dual-microphone performance.

Finally, all hearing aids were ordered with a select-a-vent (SAV). At the time of the fitting, venting was used that was appropriate for the magnitude of hearing loss between 250 and 500 Hz as well as to address issues relative to the occlusion effect and feedback. Mueller and Wesselkamp (1999) reported that venting can significantly reduce the DI for frequencies below 1000 Hz and, to a lesser extent, at 1000 to 2000 Hz. Mueller and Wesselkamp (1999) reported an average DI (averaged at 500, 1000, 2000, and 4000 Hz) of 4.2 dB for a closed mold. The DI decreased to 2.9 dB for a 1-mm vent, 1.9 dB for a 2-mm vent, and 1.6 dB for a 3-mm vent. Virtually all hearing aids fitted in this study included some degree of venting.

Hearing Aid Fitting

Each subject was tested under two hearing aid conditions. For one condition, the hearing aids were programmed with the omnidirectional microphone active and the frequency-gain response of the hearing aids programmed using the "Fine-Tuning" menu of the software (PFG-6) so that the measured real-ear insertion gain (REIG) matched the National Acoustic Laboratory-Revised (NAL-R) prescriptive target (Byrne and Dillon, 1986). For the second condition, the settings were the same as condition 1, but with the dual-microphones activated. Activation of the dual-microphones reduces the low-frequency response. No measures of the magnitude of the low-frequency response or efforts to equalize the two responses were made. Finally, the two microphone conditions were counter-balanced to minimize order effects.

For each subject, real-ear measurements were made using either a Frye 6500 (Site I) or Virtual 340 (Site II) to verify that the measured REIG matched the NAL-R prescribed gain with the omnidirectional microphone. With the probe and reference microphones located in the standard positions, and the loudspeaker placed at 0° azimuth, the hearing aids were programmed so the measured REIG matched the prescribed NAL-R target using a speech-weighted composite noise presented at 65 dB SPL. In all 100 ears, the measured REIG came within 5 dB of the prescribed REIG from 500 to 2000 Hz and within 10 dB from 2000 to 4000 Hz. For both sites, linear amplification with SC+aRT was programmed into the hearing aids along with the output value selected by the software.

Hearing in Noise Test Threshold

Subjects wore their hearing aids (half were omnidirectional fittings, half were dual-microphone fittings) for 4 weeks prior to objective measures to accommodate possible acclimatization effects (Turner et al, 1996). To measure the benefit obtained from the experimental conditions, the Hearing in Noise Test (HINT)

(Soli and Nilsson, 1994) was selected for this study. The HINT consists of 250 sentences (25 lists of 10 sentences per list) read by a male speaker. The sentences are of approximately equal length (six to eight syllables) and difficulty (first-grade reading level). The HINT estimates the SNR at which the sentences, embedded in noise, can be repeated correctly 50 percent of the time.

In this study, SNR was measured under two conditions. First, the sentences were presented at 0° azimuth, and the noise, which is temporally and spectrally matched to the sentences, was presented at 180°. This will be referred to as the *ideal* listening condition. Second, the sentences were presented at 0° azimuth and correlated noise was presented via loudspeakers at 45°, 135°, 225°, and 315°. This will be referred to as the *diffuse* listening condition. The two conditions were counter-balanced to minimize order effects.

The subject was seated 1.0 m (Site I) and 1.5 m (Site II) equidistant from two loudspeakers (0° and 180°) with the center of the diaphragm 100 cm above the floor for the ideal condition. For the diffuse condition, the subject was seated 1.0 m (Site I) and 1.5 m (Site II) from the front loudspeaker and equidistant from the surrounding loudspeakers. Site 1 used a single-walled sound-suite with internal dimensions of 198 cm by 198 cm. Site II used a double-walled sound-suite with internal dimensions of 305 cm by 284 cm. At Site I, the sentences and competing noise were presented through an Amplaid AA30 clinical audiometer via a Sony compact disc (CD) player. At Site II, the sentences and competing noise were presented through a Virtual 322 clinical audiometer via a Sony CD player. The output was forwarded to six Crown D-150A amplifiers to independently adjust the output for each loudspeaker. The calibration of the loudspeakers was monitored daily using the calibration noise signal from the HINT CD (track 30) to ensure that the level of the noise was 65 dBA.

The administration of the HINT requires two lists to be presented (20 sentences) for each experimental condition. The first sentence was presented at 10 dB below the attenuator setting necessary for the noise to be presented at 65 dBA from either the back loudspeaker for the ideal condition or the four loudspeakers for the diffuse condition. The first sentence was presented repeatedly, increasing the level of the presentation by 4 dB, until repeated correctly by the subject. Subsequently, the presentation level was decreased by 4 dB and the second sentence presented. Stimulus level was raised (incorrect response) or lowered (correct response) by 4 dB after the subject's responses to the second, third, and fourth sentences. The step size was reduced to 2 dB after the fourth sentence, and a simple up-down stepping rule was continued for the remaining 16 sentences. The calculation of the SNR necessary for 50 percent sentence recognition was based on averaging the presentation levels of sentences 5 through 20, plus the intensity of a 21st presentation.

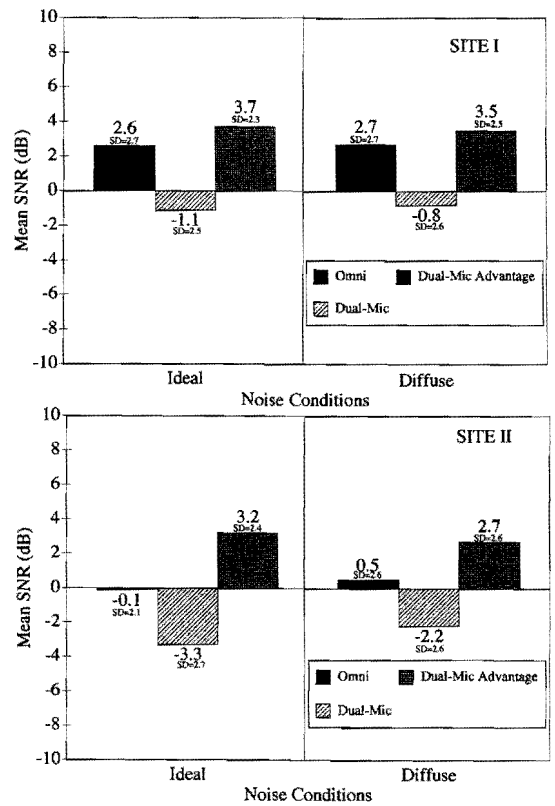

Figure 4 Mean SNR (dB) for the omnidirectional and dual-microphone conditions for the ideal (left panel) and diffuse (right panel) for SC+aRT signal processing. Upper panel: Site I; lower panel: Site II. Also included is ± 1 standard deviation.

RESULTS

Figure 4 reports the mean SNR (dB) for the two microphone (omnidirectional and dual-microphone) and noise (ideal and diffuse) conditions. The upper panel in Figure 4 reports the SNR for Site I; the lower panel reports the SNR for Site II. Also reported is the mean advantage provided by the dual-microphone (i.e., dual-mic advantage).

A three-way split-plot analysis of variance (ANOVA) was performed on the SNR (Kirk, 1982) for the two treatment levels for each of the within-subject independent variables of microphone and noise condition and the between-subject independent variable of site. Results revealed that significant differences in SNR were present for each of the main effects of the three independent variables. Significant differences, however, in SNR were not found for any of the interactions.

Microphone Condition

The overall mean SNR for the omnidirectional microphone condition averaged across listening conditions and sites was 1.4 dB, while the overall mean SNR for the dual-microphone condition averaged across listening condition and sites was –1.9 dB. This resulted in a mean dual-microphone advantage of 3.3 dB. The results of the ANOVA ($F = 307.37$; $df = 1/24$; $p < .0001$) revealed that this difference was significant and that the mean SNR observed for the dual-microphone condition was significantly better than the mean SNR observed for the omnidirectional condition.

Listening Condition

The overall mean SNR for ideal listening averaged across microphone conditions and sites was –0.5 dB, while the overall mean SNR for diffuse listening averaged across microphone conditions and sites was 0 dB. This resulted in a mean advantage of 0.5 dB for ideal listening. The results from the ANOVA ($F = 6.73$; $df = 1/24$; $p < .02$) revealed that this difference, although not clinically important, was statistically significant. This indicated that the mean SNR observed for ideal listening was statistically better than the mean SNR observed for diffuse listening.

Site Condition

The overall mean SNR for Site I averaged across microphone and listening conditions was 0.9 dB, while the overall mean SNR for site II averaged across microphone and listening conditions was –1.3 dB. The results from the ANOVA ($F = 15.26$; $df = 1/24$; $p < .001$) revealed that the 2.2 dB difference was significant and that the mean SNR at Site II was significantly better than the mean SNR at Site I.

DISCUSSION

Comparison to Previous Studies

Few studies are available concerning the performance of dual-microphone ITE hearing aids. However, the results of the present study are remarkably close to the results recently reported by Pumford et al (2000) for the same hearing aid used in this study for diffuse listening using correlated noise. Pumford et al (2000) reported a mean SNR of 2.7 dB for the omnidirectional condition and –0.6 dB for the dual-microphone condition. This resulted in a mean dual-microphone advantage of 3.3 dB. At Site I for the same microphone and listening conditions (i.e., diffuse), the mean SNR for the omnidirectional, dual-microphone, and the resulting dual-microphone advantage was 2.7, –0.8, and 3.5 dB respectively. At Site II, the mean HINT thresholds for the same microphone and listening conditions were 0.5, –2.2, and 2.7 dB respectively. That is, the mean performance reported at Site II revealed better performance for both the omnidirectional and dual-microphone conditions than was reported at Site I or by Pumford et al (2000). It is difficult to determine why these findings occurred.

Preves et al (1999) reported on the results of a study of dual-microphone, ITE hearing aids in which *uncorrelated* HINT noise was presented at 115° and 245° and the frequency response for the dual-microphone was both unequalized and equalized to the frequency response for the omnidirectional microphone. For the unequalized condition, they reported a mean SNR of –1.2 dB for the omnidirectional condition and –4.0 dB for the dual-microphone condition. For the equalized condition, they reported a mean SNR of –1.9 dB for the omnidirectional condition and –4.3 dB for the dual-microphone condition. This resulted in a mean dual-microphone advantage of 2.8 and 2.4 dB for the unequalized and equalized conditions, respectively. As will be discussed in the next section, the reason for the apparent poor advantage provided by the dual-microphone ITE hearing aid was the relatively good performance of the omnidirectional microphone.

Most published research on the advantage provided by dual-microphones was accomplished without the investigators equalizing the frequency response to match the frequency response of the omnidirectional condition (Valente et al, 1995; Agnew and Block, 1997; Gravel et al, 1999; Pumford et al, 2000; Ricketts and Dhar, 1999).

The results from the Preves et al (1999) study suggest that little difference in performance occurs if the investigators equalize the frequency response for the dual-microphone condition. This finding has some clinical relevance because hearing aids with dual-microphones are available (e.g., D-Mic™) that provide the clinician with the option of ordering the hearing aids with unequalized and/or equalized frequency responses. It would appear from the results of the Preves et al (1999) study, that little change in the recognition of speech in noise will occur if one or the other frequency response is ordered.

Dual-Microphone Performance of ITE and BTE Hearing Aids

As mentioned in the introduction, two studies (Wolf, 1999; Roberts and Schulein, 1997) reported that the DI was higher for a dual-microphone ITE hearing aid than for a dual-microphone BTE hearing aid. The inference is that clinicians should expect greater improvement in SNRs in diffuse listening situations with a dual-microphone ITE hearing aid than should be expected with a dual-microphone BTE hearing aid.

Pumford et al (2000) compared the performance between dual-microphone ITE hearing aids and BTE hearing aids on the *same subjects*. They reported that the dual-microphone advantage for the ITE hearing aids (re: omnidirectional performance) was on average 2.5 dB *poorer* than the advantage provided by the dual-microphone BTE hearing aids. The Pumford et al (2000) study is the only study, to the authors' knowledge, that directly compared the performance of dual-microphone ITE and BTE hearing aids on the same subjects. There are, however, several studies reporting the benefit provided by *either* dual-microphone ITE or BTE hearing aids. Two studies (the present study and Preves et al, 1999) have reported on dual-microphone ITE hearing aid performance. The results from these two studies, when compared to the studies reporting the mean performance of dual-microphone BTE hearing aids, indicate that the performance provided by a dual-microphone ITE hearing aid is typically *poorer* than that provided by a dual-microphone BTE hearing aid under either ideal (Valente et al, 1995; Lurquin and Rafhay, 1996; Agnew and Block, 1997; Gravel et al, 1999) or diffuse (Pumford et al, 2000; Ricketts and Dhar, 1999) listening conditions. That is, the studies on dual-microphone ITE hearing aids report advantages of 2.4 to 4.5 dB (re: omnidirectional performance), depending on experimental conditions. In comparison, the studies on dual-microphone BTE hearing aids report advantages of 4.2 to 8.5 dB, depending on experimental conditions (Valente et al, 1995; Lurquin and Rafhay, 1996; Agnew and Block, 1997; Gravel et al, 1999; Ricketts and Dhar, 1999). Thus, it would appear that clinicians should expect dual-microphone BTE hearing aids to provide almost double the improvement in SNRs that corresponding dual-microphone ITE hearing aids do.

When viewing the results from the Pumford et al (2000) study, however, several observations become clear. First, the mean SNR for the ITE omnidirectional hearing aid was 2.7 dB, while the mean SNR for the BTE omnidirectional hearing aid was 5.1 dB. That is, the pinna effect (microphone of the ITE hearing aid in the concha region of the outer ear) provided a 2.4-dB advantage in ITE hearing aid performance relative to that of the BTE hearing aid. Second, the mean SNR for the dual-microphone ITE hearing aid was –0.6 dB, while the mean SNR for the dual-microphone BTE hearing aid was –0.7 dB (virtually identical). When the mean dual-microphone performance was subtracted from the mean omnidirectional performance for each hearing design, it appears as if the dual-microphone BTE hearing aid performed better (5.8 dB) than the dual-microphone ITE hearing aid (3.3 dB). Performance in the dual-microphone condition, however, was nearly identical for the two hearing aid designs. That is, the advantage provided by the dual-microphone ITE hearing aid is *penalized* for providing better performance in the omnidirectional position.

This situation presents a dilemma for audiologists. What should they anticipate and counsel their patients who switch between the omnidirectional and dual-microphone positions? The effect is sometimes referred to by clinicians as the "wow" effect or "dramatic" reduction in the loudness of the noise presented from behind as they switch from omnidirectional to dual-microphone positions. Clinically, it is possible, for the reasons described above, that patients will not report as dramatic a reduction in the loudness of the noise presented from behind when switching between the two microphone positions for a dual-microphone ITE hearing aid as they might report for a dual-microphone BTE hearing aid. That is, typically, the difference in performance between the omnidirectional and directional positions in an ITE fitting will be less dramatic because of the improved

performance of the omnidirectional microphone in an ITE hearing aid, relative to the poorer performance of the omnidirectional microphone on the BTE hearing aid. This occurs in spite of the fact that performance in the dual-microphone position can be virtually identical between the two hearing aid designs. In the opinion of the authors, the importance of reporting the performance of the different microphone positions is often overlooked. Often, results are only reported as dual-microphone advantage (Valente et al, 1995; Lurquin and Rafhay, 1996; Agnew and Block, 1997). For the reasons cited above, the authors believe that future studies should report the *absolute* results for the omnidirectional and directional conditions *and* the *relative* result for the directional advantage (i.e., directional-omnidirectional).

Why is the performance reported for dual-microphone ITE hearing aids less than or equal to the performance reported for dual-microphone BTE hearing aids although the DI would predict better performance for the ITE hearing aid? Pumford et al (2000) cited Agnew (1996), who reported that the effectiveness of directional microphones in an ITE fitting is highly dependent on the depth of the shell in the pinna. For directional microphones to function appropriately and provide maximum attenuation, signals from the back need to enter both microphone ports with specific amplitude and time differences. The deeper the faceplate is in the concha, the greater the natural shielding effects of the pinna, and ultimately the less effective the directional advantage. As stated by Agnew, "to consistently produce the same directional effects as a BTE instrument, an ITE [instrument] would have to be built so it extends far enough out of the concha to be flush with the pinna." In fact, having a shell protruding outside the concha is contradictory to why subjects desire the ITE hearing aid instead of the BTE hearing aid (i.e., cosmetics).

Ideal versus Diffuse Listening

One criticism of previous studies (Valente et al, 1995; Lurquin and Rafhay, 1996; Agnew and Block, 1997; Gravel et al, 1999) that reported on the mean benefit provided by dual-microphone technology was that the experimental conditions unnecessarily favored the microphone design incorporated in the hearing aid. That is, the noise was presented at 180°, and this mode of presentation favored the cardioid microphone design used in these hearing aids. The implication is that the results might have been different if a more realistic mode of presentation (i.e., diffuse listening conditions) was used.

In the present study, average performance for the diffuse condition was poorer than the ideal condition, but these differences were barely significant. Intuitively, it would be reasonable to think performance would be poorer when noise is arriving from four sound sources than when the noise arrives from a single sound source at 180° azimuth. However, it is important to remember that, in the present study, the overall noise level (65 dBA) was the same for the ideal and the diffuse listening conditions. More importantly, the noise source in the present study was correlated (i.e., the same noise source was presented at 45°, 135°, 225°, and 315° azimuth). Because correlated noise was used, the predicted differences in interaural time, intensity, and/or phase one would expect due to the presentation of the noise by spatially separated loudspeakers were absent. If uncorrelated noise (i.e., different noise sources presented at 45°, 135°, 225°, and 315° azimuth) was used, differences in performance between the ideal and diffuse listening conditions might have been present because of the presence of these interaural differences. Possible differences in performance between correlated and uncorrelated noise is under investigation by the first author and will be reported at a later time.

Finally, Soli and Nilsson (1994) reported that an improvement by 1 dB could lead to an improvement in speech recognition scores of 8.5 percent on the HINT. Although it is tempting to speculate that the observed SNR improvement could lead to a 23- to 38-percent improvement in sentence intelligibility, it needs to be pointed out that the normative conditions used in the Soli and Nilsson (1994) study are different from those in the present study. Soli and Nilsson presented noise at 45° and 315°, while, in the present study, noise was presented either from 180° or 45°, 135°, 225°, and 315°. Thus, the slope of the performance-intensity function is probably steeper for the single-noise source and shallower for the multiple-noise sources used in this study. In addition, it must be pointed out that hearing-impaired listeners may show less change in sentence intelligibility than would normal-hearing listeners.

CONCLUSION

Fifty subjects were evaluated with a dual-microphone ITE hearing aid under

three experimental conditions at two sites. The major findings showed the following:

1. On average, dual-microphones improved SNRs by 3.7 and 3.5 dB at Site I and 3.2 to 2.7 dB at Site II under ideal and diffuse listening situations (re: omnidirectional performance), respectively, using SC+aRT signal processing
2. On average, performance under ideal conditions was better than the performance under diffuse listening conditions; however, this mean difference (0.5 dB), although statistically significant, would appear to be of little clinical importance

Acknowledgment. The authors would like to thank Laura Voll and Michael Jones of Phonak, Inc. for providing a grant to offset the direct costs involved in completing this study and for allowing the subjects to purchase the hearing aids at a significantly reduced cost at the conclusion of the study. The authors would also like to thank Stephen Mandel, Senior Statistical Data Analyst in the Department of Biostatistics at Washington University School of Medicine, for his assistance in completing the statistical analysis and interpretation reported in this paper.

The views expressed here are those of the authors and do not reflect official policy of the Department of Veterans Affairs.

REFERENCES

Agnew J. (1996). Directionality in hearing. . .revisited. *Hear Rev* 3(8):20, 22, 24–25.

Agnew J, Block M. (1997). HINT thresholds for a dual-microphone BTE. *Hear Rev* 4(9):26, 29–30.

American National Standards Institute. (1989). *American National Standard for Specification of Audiometers.* (ANSI S3.6-1989). New York: ANSI.

American Speech-Language-Hearing Association. (1978). Manual pure-tone threshold audiometry. *ASHA* 4:297–301.

Beck LB. (1991). Where do we go from here? In: Studebaker GA, Bess FH, Beck LB, eds. *The Vanderbilt Hearing Aid Report II.* Parkton, MD: York Press, 1–12.

Byrne D, Dillon H. (1986). The National Acoustic Laboratories (NAL) new procedure for selecting gain and frequency response of a hearing aid. *Ear Hear* 7:257–265.

Gravel JS, Fausel N, Liskow C, Chobot J. (1999). Children's speech recognition in noise using omnidirectional and dual-microphone hearing aid technology. *Ear Hear* 20:1–11.

Hawkins DB, Yacullo WS. (1984). Signal-to-noise advantage of binaural hearing aids and directional microphones under different levels of reverberation. *J Speech Hear Disord* 49:278–286.

Kirk RE. (1982). *Experimental Design.* 2nd Ed. Pacific Grove, CA: Brooks/Cole Publishing Co.

Kirkwood D. (1997). After record 1996 sales, industry leaders see more growth ahead. *Hear J* 50(1):21–30.

Kochkin S. (1996). Customer satisfaction and subjective benefit with high performance hearing aids. *Hear Rev* 3(12):16–26.

Lentz WE. (1972). Speech discrimination in the presence of background noise using a hearing aid with a directionally sensitive microphone. *Maico Audiol Lib Series* 10(9).

Lurquin P, Rafhay S. (1996). Intelligibility of noise using multi-microphone hearing aids. *Acta Otorhinolaryngol Belg* 50:103–109.

Madison TK, Hawkins DB. (1983). The signal-to-noise ratio advantage of directional microphones. *Hear Instrum* 34(2):18,49.

Mueller G, Wesselkamp M. (1999). Ten commonly asked questions about directional microphone fittings. *Hear Rev* 3(1):26–30.

Preves DA, Sammeth SA, Wynne MK. (1999). Field trial evaluations of a switched directional/omnidirectional in-the-ear hearing instrument. *J Am Acad Audiol* 10:273–284.

Pumford JM, Seewald RC, Scollie S, Jenstad LM. (2000). Speech recognition in diffuse noise using in-the-ear and behind-the-ear dual-microphone hearing instruments. *J Am Acad Audiol* 11:23–35.

Ricketts T, Dhar S. (1999). Comparison of performance across three directional hearing aids. *J Am Acad Audiol* 10:180–189.

Roberts M, Schulein R. (1997). *Measurement and Intelligibility Optimization of Directional Microphones for Use in Hearing Aid Devices.* Paper presented at the 103rd meeting of Audio Engineering Society; New York, NY.

Soli SD, Nilsson MJ. (1994). Assessment of communication handicap with the HINT. *Hear Instr* 45(2):12–16.

Studebaker GA, Cox RM, Formby C. (1980). The effect of environment on the directional performance of head worn hearing aids. In: Studebaker GA, Hochberg I, eds. *Acoustical Factors Affecting Hearing Aid Performance.* Baltimore: University Park Press, 81–105.

Sung SG, Sung RJ, Angelli A. (1975). Directional microphone in hearing aids: effects on speech discrimination in noise. *Arch Otolaryngol* 101:316–319.

Turner CW, Humes LE, Bentler RA, Cox RM. (1996). A review of past research on changes in hearing aid benefit over time. *Ear Hear* 17:14S–28S.

Valente M, Fabry DA, Potts LG. (1995). Recognition of speech in noise with hearing aids using dual microphones. *J Am Acad Audiol* 6:440–449.

Wolf R. (1999). Directional microphone hearing instruments: how and why they work. *Hear Rev* 3(1):14–25.