2013

The effectiveness of the directional microphone in the Oticon Medical Ponto Pro in participants with unilateral sensorineural hearing loss

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J Am Acad Audiol 24:701–713 (2013)

The Effectiveness of the Directional Microphone in the Oticon Medical Ponto Pro in Participants with Unilateral Sensorineural Hearing Loss

DOI: 10.3766/jaaa.24.8.7

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Abstract

Background: Current bone anchored hearing solutions (BAHSs) have incorporated automatic adaptive multichannel directional microphones (DMs). Previous fixed single-channel hypercardioid DMs in BAHSs have provided benefit in a diffuse listening environment, but little data are available on the performance of adaptive multichannel DMs in BAHSs for persons with unilateral sensorineural hearing loss (USNHL).

Purpose: The primary goal was to determine if statistically significant differences existed in the mean Reception Threshold for Sentences (RTS in dB) in diffuse uncorrelated restaurant noise between unaided, an omnidirectional microphone (OM), split DM (SDM), and full DM (FDM) in the Oticon Medical Ponto Pro. A second goal was to assess subjective benefit using the Abbreviated Profile of Hearing Aid Benefit (APHAB) comparing the Ponto Pro to the participant's current BAHS, and the Ponto Pro and participant's own BAHS to unaided. The third goal was to compare RTS data of the Ponto Pro to data from an identical study examining Cochlear Americas' Divino.

Research Design: A randomized repeated measures, single blind design was used to measure an RTS for each participant for unaided, OM, SDM, and FDM.

Study Sample: Fifteen BAHS users with USNHL were recruited from Washington University in St. Louis and the surrounding area.

Data Collection and Analysis: The Ponto Pro was fit by measuring in-situ bone conduction thresholds and was worn for 4 wk. An RTS was obtained utilizing Hearing in Noise Test (HINT) sentences in uncorrelated restaurant noise from an eight loudspeaker array, and subjective benefit was determined utilizing the APHAB. Analysis of variance (ANOVA) was used to analyze the results of the Ponto Pro HINT and APHAB data, and comparisons between the Ponto Pro and previous Divino data.

Results: No statistically significant differences existed in mean RTS between unaided, the Ponto Pro's OM, SDM, or FDM ($p = 0.10$). The Ponto Pro provided statistically significant benefit for the Background Noise (BN) ($p < 0.01$) and Reverberation (RV) ($p < 0.05$) subscales compared to the participant's own BAHS. The Ponto Pro (Ease of Communication [EC] [$p < 0.01$], BN [$p < 0.001$], and RV [$p < 0.01$] subscales) and participant's own BAHS (BN [$p < 0.01$] and RV [$p < 0.01$] subscales) overall provided statistically significant benefit compared to unaided. *Clinically* significant benefit of 5% was present for the Ponto Pro compared to the participant's own BAHS and 10% for the Ponto Pro and the participant's own BAHS compared to unaided. The Ponto Pro's OM ($p = 0.05$), SDM ($p = 0.05$), and FDM ($p < 0.01$) were statistically significantly better than the Divino's OM. No significant differences existed between the Ponto Pro's OM, SDM, and FDM compared to the Divino's DM.

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The Hearing Aid Research Laboratory at Washington University in St. Louis School of Medicine received funding from Oticon Medical to offset some of the direct and indirect costs associated with completing this study. In addition, Oticon Medical provided loaner Ponto Pros and reimbursement of $100 or the Ponto Pro at a significantly reduced cost to participants upon completion of the study.

Portions of this article were presented at a poster session at the annual meeting of the American Auditory Society, March 2012, Scottsdale, AZ, and at a poster session at the 12th International Conference on Cochlear Implants and Other Implantable Auditory Technologies, May 2012, Baltimore, MD.

Conclusions: No statistically significant differences existed between unaided, OM, SDM, or FDM. Participants preferred the Ponto Pro compared to the participant's own BAHS and the Ponto Pro and participant's own BAHS compared to unaided. The RTS of the Ponto Pro's adaptive multichannel DM was similar to the Divino's fixed hypercardioid DM, but the Ponto Pro's OM was statistically significantly better than the Divino's OM.

Key Words: Bone anchored hearing aid, directional microphone, Ponto Pro, single sided deafness, unilateral sensorineural hearing loss

Abbreviations: APHAB = Abbreviated Profile of Hearing Aid Benefit; AV = Aversiveness of Sounds; BAHS = bone anchored hearing solution; BN = Background Noise; DM = directional microphone; EC = Ease of Communication; FBR = front-to-back ratio; FDA = Food and Drug Administration; FDM = full directional microphone; HINT = Hearing in Noise Test; HRPO = Human Research Protection Office; MIL = most intelligible level; OM = omnidirectional microphone; PTA = pure-tone air conduction average; RTS = Reception Threshold for Sentences; RV = Reverberation; SDM = split directional microphone; SLM = sound level meter; SNR = signal-to-noise ratio; USNHL = unilateral sensorineural hearing loss; WRS = word recognition score

The use of the bone anchored hearing solution (BAHS) as an amplification option for patients with unilateral sensorineural hearing loss (USNHL) has increased in popularity over the last few years. Since the introduction of BAHS as an amplification option for USNHL in 2002 (United States Food and Drug Administration [FDA], 2002), significant advances have occurred. For the purposes of this study, USNHL is defined according to FDA guidelines (FDA, 2002), which is normal hearing in one ear (pure-tone air conduction average [PTA] ≤ 20 dB HL at 500, 1000, 2000, and 3000 Hz) and a sensorineural hearing loss in the opposite ear (profound sensorineural hearing loss, poor word recognition, and/or an inability to tolerate amplified sound) (Valente, 2007). In the past, BAHSs have had either an omnidirectional microphone (OM) or a fixed single-channel hypercardioid directional microphone (DM). Current BAHSs incorporate technology that is similar to modern conventional hearing aids, including automatic adaptive multichannel DM, digital signal processing, and feedback cancellation, and devices are now programmed via NOAH fitting software rather than via potentiometers.

The major goal of a BAHS for persons with USNHL is to overcome the head shadow effect when speech is presented to the side of the poorer ear. When a person is talking on the side of the poorer ear, the speech signal must travel around the head to reach the better ear. By the time the speech signal reaches the better ear, it has been attenuated overall by 6 dB for spondee words (Tillman et al, 1963) and as much as 20 dB in the high frequencies (Feddersen et al, 1957). To overcome this detriment, the BAHS amplifies sound on the side of the poorer ear and sends an amplified bone conduction signal to the cochlea of the better ear so the person does not have to position someone on the side of the better ear or have to turn his or her head. Previous studies comparing OM performance in BAHS to unaided performance for participants with USNHL have reported significant benefit with a BAHS using a wide variety of loudspeaker arrays. When examining the situation of the head shadow effect with speech to the side of the poorer ear and noise presented from either 0° (Bosman et al, 2003; Hol et al, 2004, 2005; Dumper et al, 2009; Linstrom et al, 2009; Desmet et al, 2012) or to the side of the better ear (Newman et al, 2008; Yuen et al, 2009), it has been well established that the BAHS overcomes the head shadow effect and performs better than unaided. One exception, however, is when speech arrives from 0° (Niparko et al, 2003; Wazen et al, 2003; Hol et al, 2004, 2005; Lin et al, 2006; Dumper et al, 2009; Linstrom et al, 2009; Desmet et al, 2012) and noise is presented to the side of the BAHS. In these studies, the BAHS, on average, performed equal to or 2.5 dB *poorer* than unaided. In this listening condition, the BAHS amplifies the unwanted noise, which is then sent to and received by the cochlea of the better ear and interferes with the wanted speech signal arriving to the side of the head with normal hearing. The next challenge and goal, therefore, of fitting a BAHS on a patient with USNHL is to determine how to prevent a deterioration in signal-to-noise ratio (SNR) and allow the patient to wear the BAHS when noise is on the side of the poorer ear so that he or she does not have to turn off the BAHS. One feature to help reduce the detrimental effects of background noise is a DM. A fixed hypercardioid DM was offered as an optional accessory for the Cochlear Americas' Compact BAHS and later was incorporated into a BAHS with the introduction of the Cochlear Americas' Divino.

Results from studies examining the benefits of a fixed single-channel DM in BAHSs have varied. Studies have examined benefit using different loudspeaker arrays, and only a few have examined participants with USNHL. In Linstrom et al (2009), results using the Hearing in Noise Test (HINT) (Nilsson et al, 1994) were examined comparing unaided and the Compact's OM and DM with HINT noise presented at 65 dBA from 0° and HINT sentences presented to ±90°. A second condition examined HINT sentences presented from

0° and HINT noise presented at 65 dBA from ±90°. Of particular interest are the results of the most difficult listening condition with HINT sentences from 0° and HINT noise presented to the poorer ear. While OM performance was statistically significantly poorer than unaided by an average of 2.5 dB ($p < 0.01$), the DM, on the other hand, performed poorer, but not significantly poorer, than unaided by an average of 1.7 dB. Compared to OM performance, the DM performed slightly, but not significantly, better by an average of 0.9 dB. Lin et al (2006) also reported significantly poorer performance with an OM compared to unaided but reported no statistically significant differences between a DM and unaided for the Compact when HINT sentences were presented from 0° and 65 dBA of white noise was presented to the side of the poorer ear. In Lin et al (2006), three of 14 participants evaluated with the DM performed better than unaided; however, this study did not report the overall mean or any differences between the means, and this was not statistically significant. In addition, differences between OM and DM were not reported. In Oeding et al (2010), the Divino's OM and DM were examined with HINT sentences from 0° and uncorrelated Lou Malnati's restaurant noise at 65 dBA presented from either 180° or from eight surrounding loudspeakers (e.g., diffuse), including the front loudspeaker. Across these two loudspeaker array conditions, overall the DM performed statistically significantly better than the OM by 2.3 dB ($p < 0.001$). A mean Reception Threshold for Sentences (RTS in dB) advantage of 2.5 dB was reported for the DM compared to OM when noise was from 180°, and a mean advantage of 2.1 dB was reported for the DM compared to OM in the diffuse listening condition.

Several studies examined the performance of a fixed DM in BAHSs in participants with conductive and mixed hearing loss. Hodgetts (2005) reported a mean directional advantage of 7 dB for the Divino's DM compared to the Cochlear Americas' Classic OM and a mean 5 dB directional advantage for the Divino's DM compared to the Divino's OM when HINT sentences were from 0° and 65 dBA of HINT noise was presented to the side of the BAHS. Statistical analysis was not provided to determine if these differences were statistically significant. In Kompis et al (2007), unaided, the Compact's OM and the Divino's OM and DM were compared using Basler sentences (Tschopp and Züst, 1994) presented at 70 dB SPL from 0° and noise (type undefined) presented from 180°. Results revealed a mean advantage of 6 dB for the Compact's OM, 7 dB for the Divino's OM, and 8 dB for the Divino's DM relative to unaided ($p = 0.03$). A mean advantage of approximately 1 dB was reported for the Divino's DM compared to the Divino's OM, which was not statistically significant. Finally, a statistically significant mean advantage of 2.3 dB ($p = 0.04$) was reported for the Divino's DM compared to the Compact's OM.

Compared to the previous fixed single-channel hypercardioid DM, current BAHSs have an automatic adaptive multichannel directional microphone that will theoretically create a polar plot in each specific channel providing the best SNR based on the listening environment. Few studies, however, have examined the performance of the adaptive multichannel DM in current BAHSs. Flynn et al (2011) compared the Divino to the Cochlear Americas' BP-100 using the Swedish version of the HINT (Hällgren et al, 2006) with HINT sentences from 0° and 65 dB SPL of HINT noise presented from 180°. A subgroup of participants with USNHL was examined, and the Divino's OM was compared to the BP-100's OM and DM. Results revealed a mean advantage of approximately 1 dB for the BP-100's DM compared to the BP-100's OM and a mean advantage of 2.7 dB ($p < 0.01$) with the BP-100's DM compared to the Divino's OM. The BP-100's OM also performed, on average, 1.7 dB ($p < 0.01$) better than the Divino's OM. This may be due to the position compensation algorithm of the BP-100, which attempts to compensate for the placement of the BAHS behind the pinna (Flynn et al 2011). Pfiffner et al (2011) examined the Divino's OM and DM and the BP-100's OM and DM in participants with conductive and mixed hearing losses with Oldenburger sentences (Kollmeier and Wesselkamp, 1997) presented from 0° and 65 dB SPL of speech babble noise presented from 180°. The DM of the BP-100 and Divino revealed a mean advantage of 2.2 dB compared to their respective OM ($p < 0.001$). While not compared statistically, the Divino's DM and the BP-100's OM were found to provide equal benefit, and the DM of the BP-100 provided a mean 2.2 dB improved RTS compared to the Divino's DM.

Olsen et al (2011) evaluated differences between the BP-100 BAHS and the Oticon Medical Ponto Pro BAHS in participants with conductive, mixed, and USNHL. The study examined the two BAHSs with Dantale II sentences (Wagener et al, 2003) arriving from 0° and noncorrelated noise at 70 dB SPL presented from ±90°. The BP-100's OM performed, on average, 0.4 dB better than the BP-100's DM, which was not statistically significant. This is an interesting finding, particularly for the BP-100, as the more advanced DM performed poorer than OM. This is contrary to the aforementioned studies examining a DM compared to OM, which reported a mean directional advantage of 0.9 to 7 dB (Hodgetts, 2005; Kompis et al, 2007; Linstrom et al, 2009; Oeding et al, 2010; Flynn et al, 2011; Pfiffner et al, 2011). This difference may be due to differences in participant population, loudspeaker arrangements, speech material, and output level and type of noise. Also, a statistically significant ($p < 0.01$) mean advantage of 2.5 dB was reported for the DM of the Ponto Pro compared to the OM of the Ponto Pro. Although not compared statistically, the DM of the Ponto Pro performed, on average, 3.1 dB better than the DM of the BP-100.

As can be seen, results of current BAHS DM technology have been mixed with few reporting results for patients with USNHL, and the loudspeaker arrays reported in these studies did not approximate a more real-world listening environment with background noise surrounding a participant. A previous study completed at the researchers' facility (Oeding et al, 2010) examined the performance of the fixed single-channel hypercardioid DM of the Divino in a more real-world listening environment with HINT sentences from 0° and uncorrelated Lou Malnati's restaurant noise at 65 dBA from an eight loudspeaker array. The current study was initiated to evaluate whether the adaptive multichannel DM in current BAHS technology provides improved benefit in diffuse background noise by replicating the Oeding et al (2010) study. The Ponto Pro was examined, which has 15 channels of processing with ten bands that can be adjusted in Oticon Medical's Genie Medical fitting software. Some features of the Ponto Pro include feedback cancellation, a program button with the capability of adding four programs, a volume control wheel, and an automatic adaptive multichannel directional microphone that has three microphone modes: OM, a split DM (SDM), and a full DM (FDM). It is important to emphasize that the OM in the Ponto Pro is not a traditional OM where the output for sounds from the front is equal to the output for sounds from the sides and behind. Rather, the OM front-to-back ratio (FBR) provides high frequency (above 2000 Hz) attenuation for sounds from behind, and greater output is provided to sounds from the front (Fig. 1A) to compensate for the position of the BAHS behind the pinna. The two DM options in the Ponto Pro provide a different polar plot in four channels that change based on the listening environment with the goal to provide the best SNR. These two DMs also provide differing FBR. The SDM maintains an OM FBR in the low frequencies, and directionality is provided in the mid-to-high frequencies (Fig. 1B). The FDM maintains a DM FBR across the entire frequency range (Fig. 1C) (R. Sockalingam, pers. comm.). Currently, no peer-reviewed studies have examined the differences between these three microphone modes (i.e., OM, SDM, and FDM) or compared the Ponto Pro to a fixed single-channel hypercardioid DM measured in a diffuse listening environment.

The primary goal of this study was to determine if statistically significant differences were present in the RTS (in dB) in uncorrelated diffuse restaurant noise for HINT sentences between unaided, OM, SDM, and FDM microphone modes of the Ponto Pro. A second goal was to assess perceived subjective benefit for the Ponto Pro compared to the participant's own BAHS and the Ponto Pro and the participant's own BAHS compared to unaided performance utilizing the Abbreviated Profile of Hearing Aid Benefit (APHAB) questionnaire (Cox and Alexander, 1995). The third goal was to compare HINT data of the Ponto Pro's OM, SDM, and FDM to data reported by Oeding et al (2010) examining the same listening conditions with the OM and DM of the Divino.

METHODS

Participants

Twenty participants were recruited from Washington University in St. Louis School of Medicine's Center for Advanced Medicine and surrounding clinics via either a telephone script or letter approved by the Human Research Protection Office (HRPO). Each participant

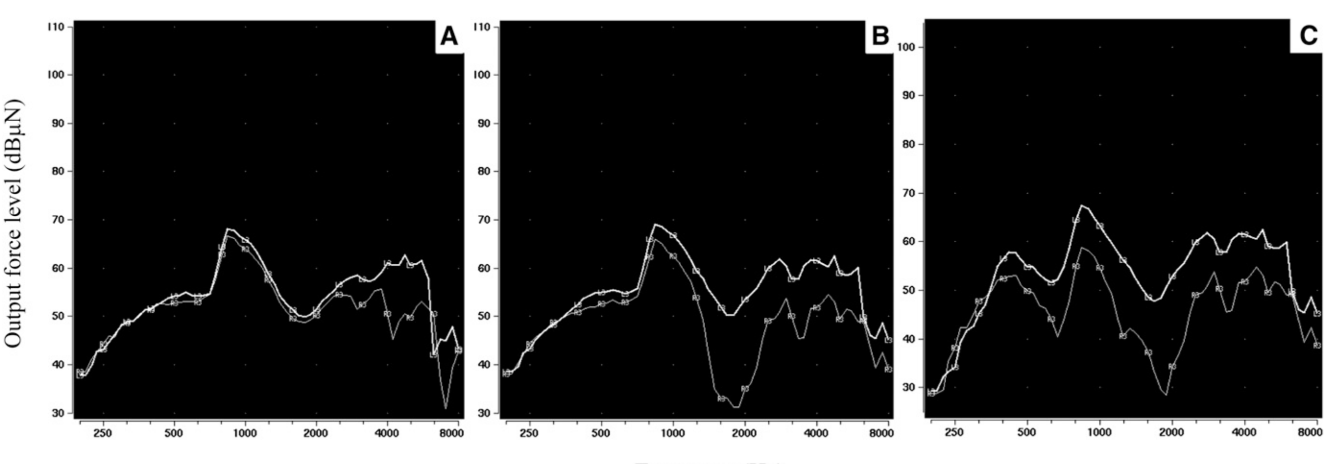

Figure 1. Front-to-back frequency response of the OM *(A),* SDM *(B),* and FDM *(C)* of the Ponto Pro coupled to a TU-1000 skull simulator in the Verifit test box using 65 dB SPL dual noise. The top line represents ouput force level for signals from the front and the lower line output for signals from behind.

signed an informed consent form approved by HRPO's Institutional Review Board either prior to or at the initial visit. In order to qualify for entrance into the study, each participant was required to (a) be 18 yr of age or older; (b) be a current BAHS user; (c) have an abutment that is compatible with the Ponto Pro; (d) have USNHL, which is defined as normal hearing (PTA ≤20 dB HL at 500, 1000, 2000, and 3000 Hz) with a word recognition score (WRS) of 90–100% in the better ear and a profound sensorineural hearing loss, poor WRS (<50%), and/or an inability to tolerate amplified sound in the poorer ear; (e) be a native English speaker; and (f) be willing to attend each visit and capable of completing the APHAB questionnaire.

Otoscopy, pure-tone air conduction (at 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz) and bone conduction audiometry, and WRS testing, utilizing the compact disc recording of the female version of the Northwestern University Auditory Test No. 6 (NU-6) word lists (Tillman and Carhart, 1966) at the participant's most intelligible level (MIL), were performed to determine if a participant qualified for the study. The MIL was determined using monitored live voice presentation (voice peaking at 0 dB on the VU meter) by talking to the participant and asking the participant to indicate when the presentation level was most intelligible and comfortably loud. A full list was presented if the participant missed more than two words, otherwise a half list was presented. An a priori sample size calculation using G*Power 3.0.10 determined that 11 participants were appropriate to determine statistical significance based on the means, standard deviations, and correlations determined from the open ear, diffuse environment condition for OM and DM from Oeding et al (2010), a two-tailed test, alpha of 0.05 and power of 0.80. Five potential participants could not participate: one participant had poorer hearing thresholds than the inclusion criteria in the better ear; two participant's abutments were not compatible with the Ponto Pro; one participant had swelling around the abutment site and was not medically cleared to participate; and one participant developed an infection around the abutment site during the study and had to discontinue participation. This left 15 participants that completed the study. A post hoc sample size analysis determined that 15 participants were appropriate to determine statistical significance.

Mean hearing thresholds in the better and poorer ear and ±1 SD are reported in Figure 2. The mean PTA (at 500, 1000, 2000, and 3000 Hz) for the better ear was 9.1 dB HL (SD = 5.3 dB HL) and 91.4 dB HL (SD = 33.4 dB HL) for the poorer ear. The mean WRS was 98.4% (SD = 3.0%) for the better ear and 3.7% (SD = 7.7%) for the poorer ear. Six participants were male and nine were female with a mean age of 58.8 yr (SD = 10.6 yr). Hearing loss etiology in the poorer ear included Ménière's disease (n = 4), acoustic neuroma (n = 5), petroclival meningioma (n = 1), congenital deafness (n = 1), sudden sensorineural hearing loss (n = 2), noise induced hearing loss (n = 1), and herpes zoster oticus (n = 1). Five participants wore the BP-100, six the Divino, three the Cochlear Americas' Intenso, and one the Compact. Participants' mean years of experience with the BAHS was 4.0 yr (SD = 1.8 yr). Nine participants wore the BAHS on the right side, and six wore the BAHS on the left side.

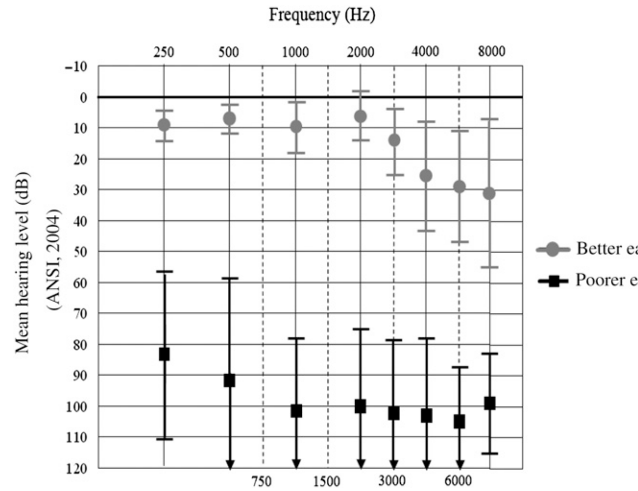

Figure 2. Audiogram reporting the mean and ±1 SD for pure-tone air conduction thresholds (dB HL) in the better ear and poorer ear. Arrows indicate SDs beyond the limits of the audiometer and audiogram.

Electroacoustic Verification of Microphone Performance

A TU-1000 skull simulator was utilized to perform electroacoustic measures of the output force level (dBμN) of the Ponto Pro's automatic program and to test the FBR of the OM (Fig. 1A), SDM (Fig. 1B), and FDM (Fig. 1C) programs between 250 and 8000 Hz. The TU-1000 skull simulator simulates properties of the average mastoid bone and overlying tissues (International Electrotechnical Commission [IEC], 1990). The TU-1000 skull simulator connects to an Audioscan Verifit (which measures output force level in dB SPL), and the Ponto Pro connects to the TU-1000 skull simulator via an abutment similar to the titanium abutment implanted in the mastoid (see Håkansson and Carlsson, 1989, and Stenfelt and Håkansson, 1998, for more detailed descriptions).

The TU-1000 skull simulator was utilized to verify that the Ponto Pro was operating properly and to quantify the magnitude of the OM, SDM, and FDM FBRs prior to fitting the Ponto Pro, at user settings after the fitting, and before HINT testing was performed. Prior to electroacoustic measures, the participant's

Ponto Pro was dehumidified, and the microphone ports were cleaned using a MedRx Ultra Vac. A new #13 zinc air battery was used to ensure the battery was fully charged prior to testing. The reference microphone of the Audioscan Verifit was calibrated according to the Audioscan Verifit User's Guide version 3.0 (Etymonic Design Inc., 2007). Next, the Ponto Pro was coupled to the TU-1000 skull simulator, and the volume control of the Ponto Pro remained at the default setting of the volume control range for electroacoustic testing.

The Ponto Pro was placed in the OM, SDM, and FDM modes via the program button to measure performance of each program using "dual noise" presented at 65 dB SPL (Etymonic Design Inc., 2009). The microphones were deemed to be working properly when the front measure (top line in Figs. 1A–C) and the back measure (bottom line in Figs. 1A–C) provided the appropriate FBR for the respective microphone mode. As can be seen in Figure 1A, the OM program is not a traditional OM in that directionality is provided above 2000 Hz. SDM provides an OM response below 1000 Hz and directionality above 2000 Hz (Fig. 1B), and FDM maintains directionality above 300 Hz (Fig. 1C).

Ponto Pro Fitting

The Ponto Pro was connected to Oticon Medical's Genie Medical fitting software version 2011.1, and the single sided deafness (SSD) box was selected on the appropriate side. The Ponto Pro was fit using in-situ bone conduction measures. A pulsed pure-tone was presented at 250 to 8000 Hz at all octave and interoctave frequencies via the Ponto Pro on the participant's abutment. The participant indicated to the investigator each time he or she heard the pulsed pure-tone. In-situ bone-conduction threshold measures were determined utilizing standard audiometric procedures for determining pure-tone thresholds. Next, a feedback test was performed, and four programs were programmed into the Ponto Pro. The first program was an automatic program for everyday use; the second program was OM; the third program was SDM; and the fourth program utilized the FDM. Noise reduction was turned off in all four programs, and the learning volume control function was disabled.

The indicator tones for the volume control, program button, and low battery warnings were played to ensure each was sufficiently audible. Participants practiced placing and removing the Ponto Pro on their abutment, using the volume control and program button, and opening and closing the battery door. They were counseled on the differences between the four programs in the Ponto Pro and their appropriate use and were encouraged to try each program in different listening environments. Participants wore the Ponto Pro for 4 wk prior to final testing in the R-Space™ system.

R-Space System

The R-Space system consists of eight Boston Acoustics CR-65 loudspeakers (dimensions: 257 mm × 162 mm × 200 mm; frequency response [±3 dB]: 65–20,000 Hz; crossover frequency: 4200 Hz; woofer: 135 mm copolymer; tweeter: 20 mm dome; nominal impedance: 8 ohms) in a circular array, with each loudspeaker separated by 45° in a 1.97 × 2.54 × 2.73 m double-walled sound suite (volume = 14.05 m^3) with a reported reverberation time of 0.19 sec (pers. comm. with Industrial Acoustics Company). The radius of the circle was 2 ft plus the depth of the loudspeaker (200 mm). Nine discrete audio channels (sentences from 0° and noise from all eight loudspeakers) were delivered from a Macintosh-driven digital audio workstation, using MOTU Digital Performer 6 software and a MOTU Model 828 eight-channel FireWire A/D-D/A converter. All loudspeakers were driven by the individual channels of a QSC CX168 eight-channel amplifier.

Before calibration of the loudspeaker array, a QC-20 calibrator was used to check the calibration of a Quest 1900 precision sound level meter (SLM) with a 1-in pressure microphone. The calibrator output was measured through the SLM and was determined to be within ±0.1 dB of the targeted 94 dB SPL. To calibrate the loudspeaker system, the pressure microphone was placed at ear level, with the participant absent, at grazing incidence (pointing up), at the center of the loudspeaker array. A prerecorded, "nearly" pink noise signal was presented through each loudspeaker, one at a time, and the gain of the corresponding amplifier channel was adjusted so that the SLM registered 84 dBA ± 0.2 dB. Once calibration was ascertained in this way, software attenuators within the digital audio programming provided the necessary attenuations to produce the desired nominal presentation level of 65 dBA.

The eight channels of restaurant noise used as competing noise in this study were recorded simultaneously at Lou Malnati's restaurant in Elk Grove Village, IL, using the patented R-Space recording method. Eight high-order directional microphones were placed pointing outward in a horizontal circular array (one microphone at every interval of 45°), capturing restaurant sounds at points 2 ft from the center of the microphone array. During playback, the natural signal paths were completed in the laboratory by the array of loudspeakers pointing inward from 2 ft from the center of the array (see Revit et al, 2007 for a complete description of the R-Space recording and playback methods). As expected in a crowded, partially reverberant restaurant, the eight simultaneous channels of restaurant noise consisted mostly of naturally uncorrelated elements. At times during the restaurant recording when a nearby talker may have been located between the pickup patterns of two adjacent microphones in the recording array, the playback of that talker would be correlated across the corresponding adjacent channels, presented as a "phantom center" image between the corresponding adjacent loudspeakers. Except for such isolated cases of adjacent-channel correlation (reflecting what occurred naturally in the restaurant), the signals in the restaurant simulation were effectively uncorrelated (Compton-Conley et al, 2004). Compton-Conley et al (2004, fig. 4, p. 447) reported that the average long-term speech spectrum of the R-Space restaurant noise was similar to the average long-term speech spectrum of the HINT sentences.

The purpose for using this continuous noise rather than the gated noise provided by the HINT recording was because this continuous noise more closely approximates a "real-world" listening condition. Finally, a lavaliere microphone was placed near the participant's mouth so the examiner could hear the participant's responses to the HINT sentences. The R-Space system was calibrated prior to each test session.

Hearing in Noise Test (HINT)

The HINT consists of 250 sentences (25 lists of 10 sentences per list) read by a male speaker. The first 200 sentences (20 lists) were utilized in this study. The sentences are of approximately equal length (six to eight syllables) and difficulty (first-grade reading level) and have been digitally recorded for standardized presentation. The HINT estimates the RTS (in dB) at which sentences, embedded in uncorrelated restaurant noise, can be repeated correctly 50% of the time.

The administration of the HINT required presentation of two lists (10 sentences per list) to obtain an RTS for each of the four experimental conditions. Four lists were presented for each experimental condition, and the two RTS values were averaged. The first sentence was presented at 0 dB SNR with the noise fixed at 65 dBA. The first sentence was repeated, increasing the level of presentation by 4 dB, until repeated correctly by the participant. Subsequently, the intensity level was decreased by 4 dB and the second sentence was presented. The stimulus level was raised (incorrect response) or lowered (correct response) by 4 dB after the participant's response to the second through fourth sentences. The first four sentences are used to acclimatize participants to the task and are not included in the calculation of the final RTS. The step size was then reduced and fixed at 2 dB after the fourth sentence, and a simple up-down stepping rule was continued for the remaining 15 sentences. Calculation of the RTS is based on averaging the presentation level of sentences 5 through 20, plus the calculated intensity for a 21st presentation, which is determined by the response for sentence 20. HINT sentence lists were counterbalanced for each participant.

A repeated measures design was utilized in which each participant completed testing for each of the four treatment levels (unaided, OM, SDM, and FDM), and the order of testing of the four treatment levels was counterbalanced. Participants were blinded to the three aided conditions by removing the Ponto Pro from the abutment and changing programs outside the sound suite. The volume control remained at the default setting for the three aided conditions, and the Ponto Pro remained at a vertical position to obtain maximum benefit from the DM for the entire test session. The participant was seated in the center of the R-Space system facing the front (0°) loudspeaker, and head placement was level with the eight loudspeakers. Each participant was instructed to face a dot in the center of the front loudspeaker throughout the entire test session and told that sentences would be arriving from the front loudspeaker and restaurant noise would be heard from all eight loudspeakers. Participants were asked to repeat the sentence exactly as heard, and if unsure, participants were instructed to take a guess. Two HINT RTSs were obtained for each of the four treatment levels and averaged. The final test session was approximately 1.5 hr in length. At the conclusion of the study, participants were presented with the option to purchase the Ponto Pro at a significantly reduced cost or be compensated $100 for participation.

Abbreviated Profile of Hearing Aid Benefit (APHAB)

The APHAB questionnaire measures the participant's impressions of his or her performance in 24 listening environments for four subscales (with six listening environments per subscale): Ease of Communication (EC), Background Noise (BN), Reverberation (RV), and Aversiveness of Sounds (AV). Participants rate how much difficulty they have in each environment when unaided and/or aided on a seven-point scale, with responses ranging from "always" to "never." The resulting problem scores are subtracted from each other to determine the amount of benefit the participant perceives from the aided condition compared to unaided or between two aided conditions. The unaided and two aided portions (Ponto Pro and the participant's own BAHS) of the APHAB were completed at the last visit in an interview format with the investigator reading the questions while the participant followed along. One participant did not complete the unaided portion of the APHAB as the participant could not remember a time when a hearing aid was not worn on the poorer ear until a BAHS was obtained.

RESULTS

Hearing in Noise Test (HINT)

The mean RTS (in dB) and ±1 SD for the four listening conditions of unaided, OM, SDM, and FDM is reported in Figure 3. A lower RTS indicates better performance in background noise. The mean RTS provided

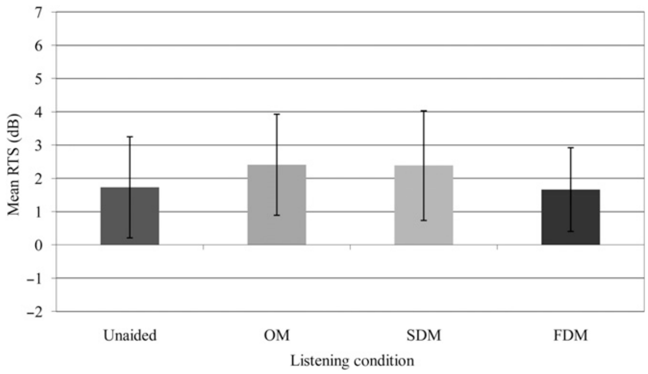

Figure 3. Mean RTS (dB) (±1 SD) for the four listening conditions. A lower RTS indicates better performance in background noise. Note: There were no statistically significant differences between unaided, OM, SDM, and FDM ($p = 0.10$).

for unaided was 1.7 dB (SD = 1.5 dB), 2.4 dB for OM (SD = 1.5 dB), 2.4 dB for SDM (SD = 1.7 dB), and 1.7 dB for FDM (SD = 1.3 dB). A repeated measures analysis of variance (ANOVA) revealed that the mean differences in RTS for the four listening conditions were not statistically significant ($F(3, 42) = 2.3$; $p = 0.10$).

Abbreviated Profile of Hearing Aid Benefit (APHAB)

Mean benefit scores and ±1 SD for the EC, BN, and RV subscales of the APHAB are reported in Figure 4. The higher the benefit score (%), the greater the perceived benefit for the respective condition. The results for the AV subscale were not reported because this subscale has not been found to be as clinically relevant as the EC, BN, and RV subscales (Cox and Alexander, 1995). A repeated measures ANOVA was performed for each subscale separately to compare problem scores, of which the difference between the two problem scores created a benefit score, between (a) the Ponto Pro and the participant's own BAHS, (b) the Ponto Pro and unaided, and (c) the participant's own BAHS and unaided. Results revealed statistically significant differences for the main effects of the EC ($F(2, 26) = 9.3$, $p < 0.01$), BN ($F(2, 26) = 35.6$, $p < 0.001$), and RV ($F(2, 26) = 18.8$, $p < 0.001$) subscales.

Ponto Pro versus Participant's Own BAHS

The difference between the aided problem scores for the Ponto Pro and for the participant's own BAHS on the EC, RV, and BN subscales was calculated to determine an aided benefit score between the two hearing aids. Participants perceived improved mean benefit with the Ponto Pro compared to their own BAHS on the EC (7.3%), BN (15.2%), and RV (9.7%) subscales and Bonferroni-adjusted pairwise comparisons revealed statistically significantly improved perceived benefit for the Ponto Pro compared to the participant's own BAHS for the BN ($p < 0.01$) and RV ($p < 0.05$) subscales, however, not for the EC subscale ($p = 0.37$). According to Cox and Alexander (1995), results on the APHAB are considered to be *clinically* significant if benefit scores are 5% or greater on the three subscales of EC, BN, and RV, which means there is a less than 11% chance that the observations occurred by chance (Cox and Alexander, 1995). If a 10% or greater difference is present on all three subscales, there is a less than 4% chance that observations occurred by chance (Cox and Alexander, 1995). Thus, the Ponto Pro provided a *clinically* significant improvement in perceived benefit compared to the participant's own BAHS of 5% or greater on the EC, BN, and RV subscales. When individual benefit scores are examined, seven reported *clinically* significant benefit with the Ponto Pro compared to

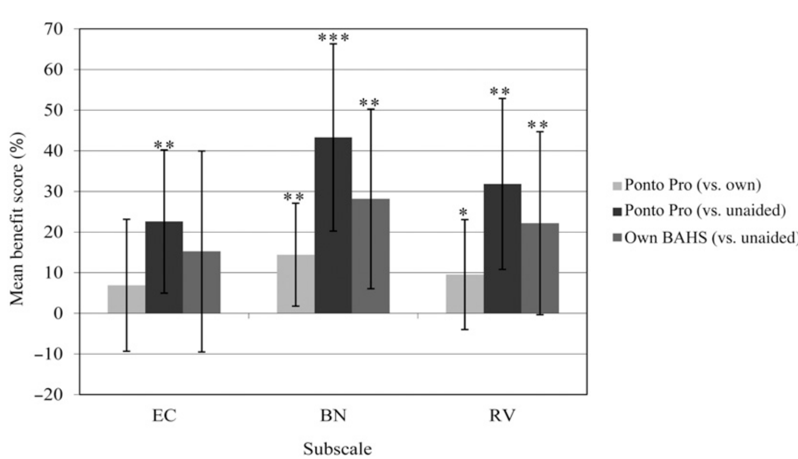

Figure 4. Mean benefit scores (%) (±1 SD) for the three APHAB subscales reporting the benefit score for the Ponto Pro compared to the participant's own BAHS, the Ponto Pro compared to unaided, and the participant's own BAHS compared to unaided. The higher the percentage benefit score, the greater the perceived benefit. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

the participant's own BAHS, and one reported *clinically* significant benefit with the participant's own BAHS.

Ponto Pro and Participant's Own BAHS versus Unaided

Participants perceived improved mean benefit with the Ponto Pro compared to unaided for the EC (22.6%), BN (43.3%), and RV (31.9%) subscales. Bonferroni-adjusted pairwise comparisons revealed statistically significantly improved perceived benefit with the Ponto Pro compared to unaided for the EC ($p < 0.01$), BN ($p < 0.001$), and RV ($p < 0.01$) subscales. Participants also perceived improved mean benefit with their own BAHS compared to unaided for the EC (15.2%), BN (28.1%), and RV (22.2%) subscales. Bonferroni-adjusted pairwise comparisons revealed statistically significantly improved perceived benefit with the participant's own BAHS compared to unaided for the BN ($p < 0.01$) and RV ($p < 0.01$) subscales. There were no statistically significant differences on the EC subscale ($p = 0.12$). The Ponto Pro and the participant's own BAHS provided a *clinically* significant improvement in perceived benefit compared to unaided of 10% or greater on the EC, BN, and RV subscales. When individual benefit scores are examined, nine reported *clinically* significant benefit with the Ponto Pro and eight with their own BAHS compared to unaided.

Comparison between the Ponto Pro and Divino Data

Two separate one-way ANOVAs were utilized to compare the results of the OM and DM of the Divino with the better ear unoccluded in diffuse noise from the Oeding et al (2010) study to the results reported in the current study for the OM, SDM, and FDM of the Ponto Pro (Fig. 5). This comparison was made to determine differences between a fixed single-channel DM and an adaptive multichannel DM in BAHS, and the studies were completed using identical methodology. Note that the comparisons need to be interpreted with caution as there may be some unforeseen differences between the two studies that could have contributed to different outcomes, and some participants participated in both studies. The Ponto Pro's OM, SDM, and FDM performed, on average, 1.6, 1.7, and 2.4 dB better than the Divino's OM, respectively, and results from the ANOVA revealed the Ponto Pro's OM ($F(1, 29) = 4.1$; $p = 0.05$), SDM ($F(1, 29) = 4.1$; $p = 0.05$), and FDM ($F(1, 29) = 9.3$; $p < 0.01$) provided a statistically significantly lower (better) RTS than the mean RTS of the Divino's OM. The Ponto Pro's OM and SDM performed, on average, 0.5 dB and 0.4 dB poorer than the Divino's DM, respectively, and the FDM performed, on average, 0.3 dB better than the Divino's DM. Results from the ANOVA, however, revealed no statistically significant differences between the Ponto Pro's OM ($p = 0.57$), SDM ($p = 0.60$), and FDM ($p = 0.70$) compared to the Divino's DM.

DISCUSSION

HINT results for the Ponto Pro revealed no statistically significant differences in RTS between unaided and the three aided microphone conditions. Unaided and FDM provided a nearly equal RTS (1.7 dB) when rounded to the nearest tenth, and OM and SDM provided an equal RTS (2.4 dB) when rounded to the nearest tenth. The mean unaided RTS was, on average, 0.7 dB better than the OM RTS, which is in close agreement to the lower end of the range of results from previous studies that reported the OM performed, on average, equal to or 2.5 dB poorer than unaided when noise was presented to the BAHS side (Niparko

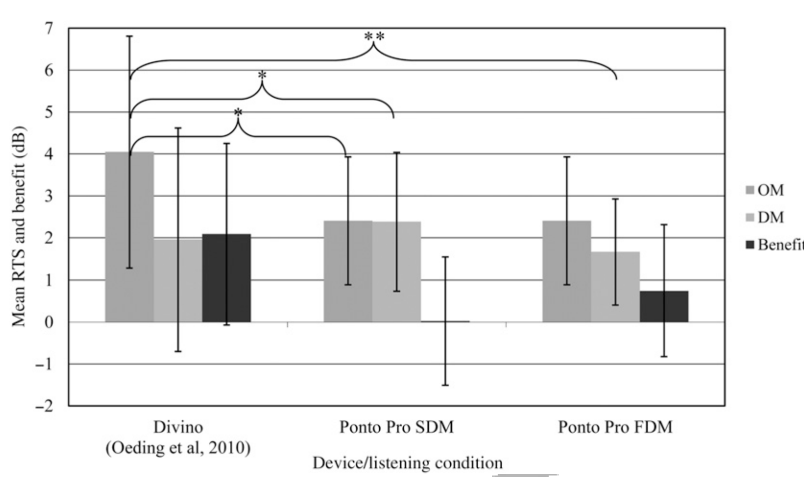

Figure 5. Mean RTS (dB) (±1 SD) for the OM, DM, and directional benefit comparing results from the Divino Oeding et al (2010) study and the current Ponto Pro study. A lower mean RTS indicates better performance in background noise. $*p = 0.05$; $**p < 0.01$.

et al, 2003; Wazen et al, 2003; Hol et al, 2004, 2005; Dumper et al, 2009; Linstrom et al, 2009; Desmet et al, 2012). For the studies comparing OM to unaided that examined only participants with USNHL and stated the model of BAHS used, the Classic (Hol et al, 2004, 2005) and Compact (Niparko et al, 2003; Hol et al, 2004, 2005; Linstrom et al, 2009) performed poorer by 0.8 dB to 2.5 dB, and the Divino and BP-100 (Desmet et al, 2012) performed equal to or 0.3 dB poorer. These results suggest that the OM microphone of more recent models (e.g., Divino and BP-100) performs better in background noise, which may be due to differences in the frequency response (compensation for position behind the pinna) and digital signal processing. The OM of the Ponto Pro may have performed closer to unaided than what was reported in the past due to the directionality provided in the high frequencies (see Fig. 1A), which previous BAHS OMs did not provide. It is also important to emphasize that while the results are similar, the listening environment of the current study was significantly more difficult with eight surrounding loudspeakers presenting uncorrelated restaurant noise compared to one loudspeaker presenting noise to the side of the BAHS. The Ponto Pro, therefore, appears to perform equally and in some cases better than results reported in previous studies examining the OM that were obtained in a significantly less difficult listening environment.

When examining the SDM and FDM performance compared to unaided, SDM performed, on average, 0.7 dB poorer, whereas FDM performed, on average, equally as well as unaided. A previous study reported a mean advantage for unaided compared to the DM of the Compact of 1.7 dB (Linstrom et al, 2009) when speech was from 0° and noise was presented to the poorer ear. Kompis et al (2007) reported a mean 8 dB directional advantage with the DM of the Divino compared to unaided when speech was presented from 0° and noise from 180°. The results of the Ponto Pro were slightly better with SDM (mean difference = 0.7 dB poorer than unaided) and FDM (mean difference = 0 dB) compared to the mean 1.7 dB advantage for unaided reported by Linstrom et al (2009). Again, considering that the current study utilized a more difficult listening environment indicates an improvement with the Ponto Pro compared to the Compact. The results from Kompis et al (2007) are significantly better (mean advantage of 8 dB for DM compared to unaided) than the results reported for the SDM (mean difference = 0.7 dB poorer than unaided) and FDM (mean difference = 0 dB), which may be due to differences in loudspeaker arrangement (noise from 180° compared to eight loudspeakers), participant population (conductive and mixed compared to USNHL), test materials (Basler sentences compared to HINT sentences), and level and type of noise (undefined compared to uncorrelated Lou Malnati's restaurant noise at 65 dBA).

Results from the current study comparing OM to DM revealed equal performance between SDM and OM and a directional advantage, on average, of 0.7 dB for FDM compared to OM. Previous studies reported a mean directional advantage of 0.9 to 7 dB relative to OM, and the lower end of this range is close to the results reported in the current study (Hodgetts, 2005; Kompis et al, 2007; Linstrom et al, 2009; Oeding et al, 2010; Flynn et al, 2011; Olsen et al, 2011; Pfiffner et al, 2011).

When compared to Olsen et al's (2011) study, the Ponto Pro mean directional advantage was greater (2.5 dB) than the current study (0.7 dB). Differences between the current and previous studies may be due to differences in: (a) loudspeaker arrangement (noise to the BAHS side [Hodgetts, 2005; Linstrom et al, 2009], 180° [Kompis et al, 2007; Flynn et al, 2011; Pfiffner et al, 2011] or from ±90° [Olsen et al, 2011] compared to eight loudspeakers), (b) different participant populations (conductive and mixed hearing loss [Hodgetts, 2005; Kompis et al, 2007; Olsen et al, 2011; Pfiffner et al, 2011] compared to only USNHL), (c) speech material (Basler sentences [Kompis et al, 2007], Oldenburger sentences [Pfiffner et al, 2011], Swedish HINT sentences [Flynn et al, 2011], or Dantale II sentences [Olsen et al, 2011] compared to HINT sentences), and (d) level and type of noise (speech babble [Pfiffner et al, 2011] or noncorrelated noise [at 70 dB SPL; Olsen et al, 2011] compared to uncorrelated Lou Malnati's restaurant noise at 65 dBA).

Compared to studies that only examined participants with USNHL, the DM of the Compact (Linstrom et al, 2009) performed 1.7 dB poorer than unaided when speech was presented to the front and noise to the side of the BAHS, which is poorer than the current study. The DM of the Compact performed 0.9 dB better than OM when speech was from the front and noise to the side of the BAHS (Linstrom et al, 2009), the DM of the BP-100 performed 1 dB better than the OM of the BP-100, and the BP-100 DM performed 2.7 dB better than the Divino's OM (Flynn et al, 2011) when speech was from the front and noise from 180°. It is important to once more emphasize that although the results from the present study did not report as large a directional advantage compared to previous studies, the listening condition was significantly more difficult and the DM of the Ponto Pro performed equally well to unaided and slightly better than OM.

Results for the APHAB revealed a statistically significant improvement for the Ponto Pro on the BN and RV subscales compared to the participant's own BAHS. The Ponto Pro provided statistically significant improvement on the EC, BN, and RV subscales compared to unaided and the participant's own BAHS provided statistically significant improvement on the BN and RV subscales compared to unaided. The current study reported a 5% or greater improvement in benefit on the EC, BN, and RV subscales for the Ponto Pro compared to the participant's own BAHS and a 10% or greater improvement in benefit for the Ponto Pro and the participant's own BAHS compared to unaided. These results are similar to previous studies that have also reported a 5% (Bosman et al, 2003; Niparko et al, 2003; Wazen et al, 2003; Baguley et al, 2006; Desmet et al, 2012) or 10% (Hol et al, 2004, 2005; Newman et al, 2008; Dumper et al, 2009; Linstrom et al, 2009; Yuen et al, 2009; Desmet et al, 2012) improvement in benefit with a BAHS compared to unaided for participants with USNHL. Results were also similar to the Oeding et al (2010) study, which reported statistical and clinical significance (>10%) for the Divino compared to unaided on the EC, BN, and RV subscales. Overall, these results suggest that participants perceive improved benefit with a BAHS compared to unaided and that the current technology may provide even greater improved benefit compared to previous BAHS technology.

Of particular interest to the authors were differences between the current study and a previous study examining the fixed DM of the Divino that utilized an identical protocol (Oeding et al, 2010). After acquiring the results for the Ponto Pro, the researchers were surprised by the differences between the results of the Ponto Pro compared to the Divino because in Oeding et al (2010), the Divino reported a 2.1 dB mean directional advantage relative to OM. The Ponto Pro, however, did not report a significant directional advantage with the best DM condition (FDM with a mean directional advantage of 0.7 dB) relative to OM. To examine these differences, the results for the OM and DM from the Oeding et al (2010) Divino study with the similar condition (better ear unoccluded in diffuse noise) were compared to the results of the OM, SDM, and FDM in the current study (Fig. 5). Statistical analysis revealed statistically significant improved performance with the Ponto Pro's OM, SDM, and FDM compared to the Divino's OM. No statistically significant differences were reported between the Divino's DM and the Ponto Pro's OM, SDM, or FDM. The Ponto Pro's OM, SDM, and FDM performed 1.6, 1.7, and 2.4 dB better than the Divino's OM. While there were no significant differences between the OM and DM of the Ponto Pro as was reported in the Oeding et al (2010) study for the Divino, the reason for this may be related to the mean improvement in performance of the Ponto Pro's OM, as well as differences in frequency response and individualized programming of the Ponto Pro compared to a non-individualized programming of the Divino.

When the OM FBR frequency response of the Divino (Fig. 6) and Ponto Pro are compared (Fig. 1A), some significant differences appear. The OM of the Ponto Pro provides directionality above 2000 Hz, whereas the OM of the Divino does not provide any directionality. The frequency response of the two devices is also different as they both have a peak around 1000 Hz, however,

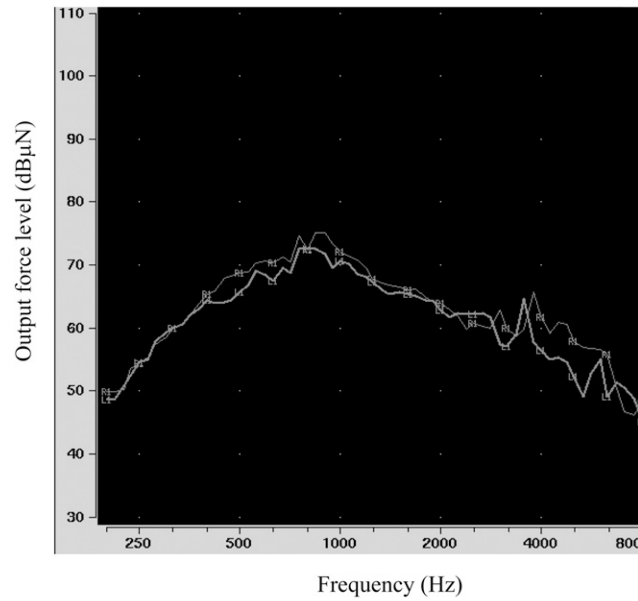

Figure 6. Front-to-back frequency response of the OM of the Divino measured on a TU-1000 skull simulator in the Verifit test box using 65 dB SPL dual noise. The thicker line represents output provided to signals from the front, and the thinner line represents output provided to signals from behind.

the Divino provides a gradually sloping response beyond this peak in the low and mid-to-high frequencies, while the Ponto Pro provides a sharply sloping decrease below 1000 Hz and provides increased output from 2000 to 6000 Hz for signals arriving from the front. The directionality of the Ponto Pro's OM along with the increased output in the mid-to-high frequencies may account for the improved sentence recognition performance of the Ponto Pro's OM (2.4 dB) compared to the Divino's OM (4.1 dB). Because the Ponto Pro's OM provided a significantly lower RTS than the Divino's OM, the differences between the Ponto Pro's OM and SDM and FDM were much smaller relative to those reported for the Divino. When the *absolute* RTS values are examined rather than the *relative* directional advantage, the Ponto Pro's DM performed equally as well as the Divino's. This indicates that the adaptive multichannel DM of the Ponto Pro performed equally as well as the fixed single-channel hypercardioid DM of the Divino. This finding is in agreement with previous studies that examined differences in HINT RTS between a fixed (cardioid or hypercardioid) DM and an adaptive DM in conventional hearing aids (Ricketts and Henry, 2002; Bentler et al, 2004; Bentler et al 2006). Overall, these studies reported that the fixed DM performed equally as well as an adaptive DM in diffuse noise. When noise is outside of the null of the fixed DM, however, the adaptive DM performed better. For example, in Ricketts and Henry (2002), a fixed cardioid DM was compared to an adaptive DM in the Phonak Claro 211 dAZ behind-the-ear hearing aid. The two DMs performed equally well in diffuse noise and when noise was presented from 180°, but when noise was presented to the side the adaptive DM performed significantly better than the fixed cardioid. This is because the prominent null of the cardioid microphone is from 180° and not from the side. These results could be similar for the adaptive DM in BAHS in that certain environments may benefit an adaptive DM compared to the previous fixed DM depending on where noise is arriving in the environment. This could be an advantage for BAHS users as they could potentially have a more favorable SNR in different listening environments with an adaptive DM compared to a fixed DM. Future research should examine whether different noise azimuths cause significant differences in RTS between a fixed DM versus an adaptive DM in a BAHS.

CONCLUSION

There were no significant differences in the RTS using the HINT in diffuse uncorrelated restaurant noise between unaided and the Ponto Pro's OM, SDM, or FDM, and there were no significant differences between the three aided conditions. Results on the APHAB revealed statistically significantly improved perceived benefit for the Ponto Pro compared to the participant's own BAHS on the BN and RV subscales as well as clinical significance on all three subscales. No statistically significant differences were present for the EC subscale. The Ponto Pro also provided a statistically significant improvement on the EC, BN, and RV subscales as well as clinical significance on all three subscales compared to unaided. The participant's own BAHS provided a statistically significant improvement on the BN and RV subscales and a clinically significant improvement on all three subscales compared to unaided. No statistically significant differences were present for the EC subscale. While the HINT RTS results for the Ponto Pro did not report a significant directional advantage for Ponto Pro compared to the Divino (Oeding et al, 2010), these differences are likely due to the directionality and improved output in the mid-to-high frequencies of the Ponto Pro's OM compared to the Divino's OM. These results show that the adaptive multichannel DM of current BAHS technologies is at least equal to or slightly (but not significantly) better than previous BAHS fixed hypercardioid single-channel DMs. Also, the OM of the Ponto Pro also provides improved performance in background noise compared to the Divino's OM.

Of the 15 participants in this study, eight participants decided to purchase the Ponto Pro. Of these eight participants, two wore the BP-100, four the Divino, and two the Intenso. Reasons for purchasing the Ponto Pro included improvement in feedback management, sound quality, and decreased static noise from the microphones. This suggests an improvement in perceived benefit for some of the participants compared to previous BAHS and even the newer BP-100. Future studies should examine the BP-100's adaptive multichannel DM in a similar diffuse listening environment to determine differences between the BP-100 and Ponto Pro in a difficult listening environment. Another area for future research is to examine differences in RTS between a fixed and adaptive DM in a BAHS using different noise azimuths.

Acknowledgments. Thanks to Ravi Sockalingam, Ph.D., for support throughout the study; Laura Phelps, M.S., for support with programming and participant recruitment; Oticon Medical for their support; Michael Strube, Ph.D., Professor of Psychology at Washington University in St. Louis, for completing the statistical analysis and providing advice on appropriate interpretation of the data; colleagues at surrounding clinics for their help in recruiting participants; and to the participants for their time.

REFERENCES

American National Standards Institute (ANSI). (2004) *Methods for Manual Pure-Tone Threshold Audiometry. ANSI S3.21-2004.* New York: ANSI.

Baguley DM, Bird J, Humphriss RL, Prevost AT. (2006) The evidence base for the application of contralateral bone anchored hearing aids in acquired unilateral sensorineural hearing loss in adults. *Clin Otolaryngol* 31(1):6–14.

Bentler R, Palmer C, Mueller HG. (2006) Evaluation of a second-order directional microphone hearing aid: I. Speech perception outcomes. *J Am Acad Audiol* 17(3):179–189.

Bentler RA, Tubbs JL, Egge JL, Flamme GA, Dittberner AB. (2004) Evaluation of an adaptive directional system in a DSP hearing aid. *Am J Audiol* 13(1):73–79.

Bosman AJ, Hol MK, Snik AF, Mylanus EA, Cremers CW. (2003) Bone-anchored hearing aids in unilateral inner ear deafness. *Acta Otolaryngol* 123(2):258–260.

Compton-Conley CL, Neuman AC, Killion MC, Levitt H. (2004) Performance of directional microphones for hearing aids: real-world versus simulation. *J Am Acad Audiol* 15(6):440–455.

Cox RM, Alexander GC. (1995) The abbreviated profile of hearing aid benefit. *Ear Hear* 16(2):176–186.

Desmet JB, Wouters K, De Bodt M, Van de Heyning P. (2012) Comparison of 2 implantable bone conduction devices in patients with single-sided deafness using a daily alternating method. *Otol Neurotol* 33(6):1018–1026.

Dumper J, Hodgetts B, Liu R, Brandner N. (2009) Indications for bone-anchored hearing aids: a functional outcomes study. *J Otolaryngol Head Neck Surg* 38(1):96–105.

Etymonic Design Inc. (2007) *Verifit Hearing Instrument Fitting System User's Guide Version 3.0.* Dorchester, ON, Canada: Etymonic Design Inc.

Etymonic Design Inc. (2009) *Audio Note 2: Verifit and RM500SL Test Signals and Analysis.* http://audioscan.com/news/Audionotes/audionote2.pdf.

Feddersen W, Sandel T, Teas D, Jeffress L. (1957) Localization of high-frequency tones. *J Acoust Soc Am* 29(9):988–991.

Flynn MC, Sadeghi A, Halvarsson G. (2011) Benefits of directional microphones and noise reduction circuits for improving Baha® hearing performance. *Cochlear Implants Int* 12(Suppl. 1):S139–S141.

Håkansson B, Carlsson P. (1989) Skull simulator for direct bone conduction hearing devices. *Scand Audiol* 18(2):91–98.

Hällgren M, Larsby B, Arlinger S. (2006) A Swedish version of the Hearing In Noise Test (HINT) for measurement of speech recognition. *Int J Audiol* 45(4):227–237.

Hodgetts B. (2005) Directional capabilities of the Baha divino: preliminary objective results. *Bone Anchored Appl* 2:11–14.

Hol MK, Bosman AJ, Snik AF, Mylanus EA, Cremers CW. (2004) Bone-anchored hearing aid in unilateral inner ear deafness: a study of 20 patients. *Audiol Neurootol* 9(5):274–281.

Hol MK, Bosman AJ, Snik AF, Mylanus EA, Cremers CW. (2005) Bone-anchored hearing aids in unilateral inner ear deafness: an evaluation of audiometric and patient outcome measurements. *Otol Neurotol* 26(5):999–1006.

International Electrotechnical Commission (IEC). (1990) *Mechanical Coupler for Measurements on Bone Vibrators.* IEC 60373. 2nd ed. Geneva, Switzerland: IEC.

Kollmeier B, Wesselkamp M. (1997) Development and evaluation of a German sentence test for objective and subjective speech intelligibility assessment. *J Acoust Soc Am* 102(4):2412–2421.

Kompis M, Krebs M, Häusler R. (2007) Speech understanding in quiet and in noise with the bone-anchored hearing aids Baha Compact and Baha Divino. *Acta Otolaryngol* 127(8):829–835.

Lin LM, Bowditch S, Anderson MJ, May B, Cox KM, Niparko JK. (2006) Amplification in the rehabilitation of unilateral deafness: speech in noise and directional hearing effects with bone-anchored hearing and contralateral routing of signal amplification. *Otol Neurotol* 27(2):172–182.

Linstrom CJ, Silverman CA, Yu GP. (2009) Efficacy of the bone-anchored hearing aid for single-sided deafness. *Laryngoscope* 119 (4):713–720.

Newman CW, Sandridge SA, Wodzisz LM. (2008) Longitudinal benefit from and satisfaction with the Baha system for patients with acquired unilateral sensorineural hearing loss. *Otol Neurotol* 29(8):1123–1131.

Nilsson M, Soli SD, Sullivan JA. (1994) Development of the Hearing in Noise Test for the measurement of speech reception thresholds in quiet and in noise. *J Acoust Soc Am* 95(2):1085–1099.

Niparko JK, Cox KM, Lustig LR. (2003) Comparison of the bone anchored hearing aid implantable hearing device with contralateral routing of offside signal amplification in the rehabilitation of unilateral deafness. *Otol Neurotol* 24(1):73–78.

Oeding K, Valente M, Kerckhoff J. (2010) Effectiveness of the directional microphone in the Baha® Divino™. *J Am Acad Audiol* 21(8):546–557.

Olsen SØ, Glad H, Nielsen LH. (2011) Comparison of two bone anchored hearing instruments: BP100 and Ponto Pro. *Int J Audiol* 50(12):920–928.

Pfiffner F, Caversaccio MD, Kompis M. (2011) Comparisons of sound processors based on osseointegrated implants in patients with conductive or mixed hearing loss. *Otol Neurotol* 32(5): 728–735.

Revit L, Killion M, Conley C. (2007) Developing and testing a laboratory sound system that yields accurate real-world results. *Hear Rev* 14(10):54–63.

Ricketts T, Henry P. (2002) Evaluation of an adaptive, directional-microphone hearing aid. *Int J Audiol* 41(2):100–112.

Stenfelt SP, Håkansson BE. (1998) A miniaturized artificial mastoid using a skull simulator. *Scand Audiol* 27(2):67–76.

Tillman TW, Carhart R. (1966) An Expanded Test for Speech Discrimination Utilizing CNC Monosyllabic Words. Northwestern University Auditory Test No. 6. USAF School of Aerospace Medicine Technical Report SAM-TR-66-55. Brooks Air Force Base, TX: USAF School of Aerospace Medicine, Aerospace Medical Division (AFSC).

Tillman T, Kasten R, Horner J. (1963) Effect of head shadow on reception of speech. *ASHA* 5(10):778–779.

Tschopp K, Züst H. (1994) Performance of normally hearing and hearing-impaired listeners using a German version of the SPIN test. *Scand Audiol* 23(4):241–247.

United States Food and Drug Administration (FDA). (2002) Section 2 Summary and Certification (510(k) number K021837). www.accessdata.fda.gov/cdrh_docs/pdf2/k021837.pdf.

Valente M. (2007) Fitting options for adults with unilateral hearing loss. *Hear J* 60(8):10, 14–16, 18.

Wagener K, Josvassen JL, Ardenkjaer R. (2003) Design, optimization and evaluation of a Danish sentence test in noise. *Int J Audiol* 42(1):10–17.

Wazen JJ, Spitzer JB, Ghossaini SN, et al. (2003) Transcranial contralateral cochlear stimulation in unilateral deafness. *Otolaryngol Head Neck Surg* 129(3):248–254.

Yuen HW, Bodmer D, Smilsky K, Nedzelski JM, Chen JM. (2009) Management of single-sided deafness with the bone-anchored hearing aid. *Otolaryngol Head Neck Surg* 141(1): 16–23.