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Examining Force Level Output of Skin-Drive Bone Conduction Hearing Devices in Adults With Simulated Conductive Hearing Loss

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ABSTRACT

Purpose: Bone conduction hearing devices (BCDs) that deliver sound across the skin (i.e., transcutaneous) are suitable for some individuals who have conductive or mixed hearing losses. Prescriptive targets for percutaneous devices are available, for example, from the Desired Sensation Level–Bone Conduction Hearing Device (DSL-BCD) algorithm. These targets, however, may require modification for use with transcutaneous BCDs. The current study investigated three key variables that may inform target modification: (a) comparison of thresholds measured using an audiometric bone conduction (BC) transducer versus transcutaneous BCDs that offer in situ threshold measurement, (b) transcutaneous BCD default force level outputs versus recommended DSL percutaneous BC targets, and (c) the preferred listening levels (PLLs) of adults wearing transcutaneous BCDs in a laboratory setting.
Method: Bilateral conductive hearing loss was simulated in 20 normal-hearing adults via earplugs. Thresholds were measured using a B-71 BC transducer and two commercially available BCDs coupled to a soft headband. DSL percutaneous BC targets were generated, and PLLs were obtained for a 60-dB SPL speech stimulus. Force level outputs were measured using a skull simulator on the Audioscan Verifit2 at the hearing aids' default settings and at the participants' PLL for each device.
Results: On average, audiometric BC thresholds were significantly better than those measured in situ with each BCD. PLLs were similar to prescribed targets for one device with the smoother response shape and agreed in the high frequencies for both devices.
Conclusions: In situ thresholds are significantly higher than audiometric BC thresholds, suggesting that device-based in situ measurement more accurately accounts for the signal transmission from transcutaneous BCDs. PLLs differed from the percutaneous targets and varied between devices, which may indicate that either target modifications or manipulations of device frequency response shaping are needed to approximate PLL with transcutaneous BCD devices.

Bone conduction hearing devices (BCDs) are a management option for some individuals who have conductive or mixed hearing losses. BCDs fall into two broad categories: (a) direct-drive or active (percutaneous vibration or transcutaneous induction) devices that directly attach to the skull bone and (b) skin-drive or passive (transcutaneous vibration) devices that are placed over the intact skin (see Håkansson et al., 2019, for a comprehensive review). Some skin-drive BCD systems connect the processor onto a surgically implanted magnet underneath the skin. Nonsurgical transcutaneous BCD processors are coupled to the head using a soft headband (Håkansson et al., 2019) or adhesive adapter. Transcutaneous BCDs are often used with children who are too young to undergo surgical placement of a BCD due to softer bone tissue and thinner skulls (Bagatto et al., 2022; Gordey & Bagatto, 2021; Ricci et al., 2011; F. M. Snik et al., 2005; Willenborg et al., 2023).

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Past studies have indicated that air-conduction hearing aids may be more suitable for both adults and children over BCDs due to esthetics, better signal processing, and broader bandwidth (Mylanus et al., 1998; A. F. Snik et al., 1994). Recent advances in device size, form factor, connectivity, and signal processing in BCDs may have improved device acceptance. Regardless, it may not be possible to fit air-conduction hearing aids to some individuals who experience chronic middle ear infections, congenital aural atresia, or severe air–bone gaps that are not mitigated through the use of air-conduction hearing aids. Therefore, these patients may be candidates for BCDs (de Wolf et al., 2011; Mylanus et al., 1998).

Clinical Protocols for Fitting and Verification

In recent years, tools to support the objective verification of BCDs have become available. Desired Sensation Level (DSL) targets have been developed and validated for use with adults who wear unilateral percutaneous BCDs (Hodgetts & Scollie, 2017). They are available in some manufacturer fitting software and one hearing aid test system to support clinical fitting. The DSL-BCD targets can be verified clinically using a skull simulator. Skull simulators for use with research equipment have been available for some time (Håkansson & Carlsson, 1989), and clinical versions are also available (Audioscan, n.d.). Skull simulators are used in conjunction with hearing aid analyzers and measure device output on an abutment, in decibels Force Level (dB FL). These devices are conceptually analogous to the standardized coupler and coupler microphone sets used for air-conduction hearing aid fittings. One such system allows devices to be connected to the skull simulator abutment and to measure device output for speech and other stimuli, which permits comparison of device output to the DSL-BCD targets for fine-tuning of the frequency response of the device. This system was designed for use with percutaneously worn BCDs. Currently, it is unknown whether the current percutaneous DSL-BCD targets are appropriate for individuals who wear active or passive transcutaneous BCDs. One factor that is likely to produce differences between percutaneous and transcutaneous fitting is the skin transmission loss imposed by these devices (Gascon et al., 2022).

Recently, a clinical consensus document was developed to describe the selection and fitting of transcutaneous BCDs to children and highlights a need to further develop prescriptive targets and clinical protocols (Bagatto et al., 2022). Children under the age of about 5 years are not eligible for surgical BCDs in many jurisdictions, so nonsurgically placed BCDs are provided to support early speech access. Hearing aid fitting and verification protocols are known to support optimal speech access for individuals with hearing loss, especially for children who are developing speech and language skills (Tomblin et al., 2014). For example, studies with air-conduction hearing aids indicate that high speech recognition scores and long-term speech and language development are achieved in children when hearing aids are fitted using objective verification strategies that incorporate in situ measures with fine-tuning to prescriptive targets (American Academy of Audiology, 2013; Amri et al., 2022; Marriage et al., 2018; Tomblin et al., 2014). Use of prescriptive targets is also intended to provide an amplified listening level that approximates the user's preferred listening level (PLL), at least for midlevel speech (Cox & Alexander, 1994; Polonenko et al., 2010; Scollie et al., 2000, 2005; Van Eeckhoutte et al., 2020).

The clinical consensus document also recommends obtaining device-specific BCD in situ thresholds using age-appropriate procedures whenever possible (Bagatto et al., 2022). In a survey of 144 pediatric audiologists who routinely fit BCDs to children, approximately 65% reported conducting BCD in situ audiometry in addition to measuring audiometric bone conduction (BC) thresholds (Gordey & Bagatto, 2021). The authors speculated that these in situ measures are motivated by the desire to individualize the BCD fitting in the absence of verification procedures. Also, within this survey, more than 86% used aided thresholds to verify BCD performance (Gordey & Bagatto, 2021). This strategy has known limitations especially for young infants who may not have further task compliance for aided tests on the same day as in situ thresholds. Also, aided thresholds have known limitations in objectively describing the performance of hearing devices for speech- and high-level signals (Stelmachowicz et al., 2002; Wiseman et al., 2023). For these reasons, use of aided thresholds is not recommended for verifying hearing aids. However, it may be conducted when a validated prescription and methods for verification and fine-tuning to target are not yet available, which is currently the case with transcutaneous BCDs.

Comparisons between behavior-based verification and BCD targets can lend insight toward the development of targets. Hodgetts et al. (2011) compared outcome measures of patients fitted with percutaneous BCDs using a patient-derived and prescriptive approach. The patient-derived approach consisted of subjective measures such as perception of overall loudness, perception of voice "echo," and perceived distortion in response to loud sounds. The prescriptive approach used a modified version of the DSL target. The authors found improved outcomes with the prescriptive approach for measures of speech recognition in quiet and in noise, as well as consonant recognition in noise compared to the patient-derived approach. They concluded that a more systematic approach to verifying BCDs would be beneficial (Hodgetts et al., 2011). Later work on percutaneous BCD prescription has led to the

development of prescriptive targets for percutaneous BCD devices (Hodgetts & Scollie, 2017). Adaptation of this approach for transcutaneous devices is necessary but requires adaptation for sound transmission through soft tissue.

Sound Transmission Across Soft Tissue

Transmission of sound across soft tissue varies with skin thickness in transcutaneous BCD fittings (Mattingly et al., 2015; Stenfelt, 2012). Mattingly et al. (2015) examined input signals with soft tissue thickness varying from 0 (no soft tissue) to 9 mm. This was accomplished by manipulating skin tissue on cadaveric heads and placing pressure sensors between the tissues to measure equivalent sound pressure level (SPL) values. Signal attenuation occurs first in the high-frequency region, and with increases in soft tissue thickness, attenuation extends into the mid- to low-frequency regions (Mattingly et al., 2015). The authors concluded that skin thickness–related effects on cochlear response magnitudes should be considered for patients receiving implants that use transcutaneous signal delivery (Mattingly et al., 2015).

Kurz et al. (2014) compared the sound transmission of an abutment-worn percutaneous BCD to a passive transcutaneous BCD using artificial skin. Similarly, they found a predominately high-frequency attenuation (20–25 dB) due to skin transmission loss (Kurz et al., 2014). The authors suggested that such attenuation can be compensated with adjustments to the BCD during the fitting, particularly in the frequency range up to 3 kHz (Kurz et al., 2014). In a more recent study by Gascon et al. (2022), the authors investigated BC thresholds in normal-hearing (NH) adults and a clinical sample of adult percutaneous BCD users. For the NH group, in situ thresholds with a BCD coupled to a soft headband were obtained, as well as with the B71 audiometric bone oscillator. For the clinical group, in situ thresholds were obtained using their own percutaneous BCD and a BCD coupled to a soft headband in addition to thresholds measured with a B71 transducer. Results revealed that BCD thresholds were on average higher (worse) compared to audiometric BC thresholds for both the NH and clinical groups. In addition, the clinical BCD users had lower (better) thresholds with their percutaneous BCD compared to their audiometric and BCD on soft headband thresholds. The authors concluded that in addition to calibration and BCD device differences, attenuation across the skin was a contributing factor.

PLLs

Within the hearing aid fitting process, the listener's preference for the hearing aid settings is an important consideration. The PLL is a measure of the overall level of sound that an individual chooses while listening to speech (Cox & Alexander, 1994). The PLL has been used to cross-check the overall listening levels of prescriptive targets (Dekok, 1999; Scollie et al., 2005; Van Eeckhoutte et al., 2020). It does not crosscheck the device's frequency response shape but is sensitive to adult–child differences (Scollie et al., 2005), headband tension in transcutaneous BCDs (Hodgetts et al., 2006), and varying audible bandwidth of hearing aid fittings (Van Eeckhoutte et al., 2020). PLL measurement may provide a useful starting place for understanding the preferred suprathreshold levels of force output for transcutaneous BCD fittings.

In Situ Thresholds

To account for variations in soft tissue transmission of sound, some BCDs offer threshold measurement with the device using the manufacturer's fitting software to deliver the stimuli at various frequencies. These in situ thresholds measure sound transmission to the listener, including soft tissue effects and any device-specific frequency response characteristics. Measurement of these behavioral thresholds with young children requires that the child be developmentally capable of providing reliable in situ threshold responses, as well as the use of age-appropriate procedures such as visually reinforced audiometry and/or conditioned play audiometry using recommended strategies (Bagatto et al., 2022). If in situ thresholds cannot be measured from a young child, audiometric thresholds are measured with a BC transducer (B-71 or B-81; Håkansson, 2003).

Although audiometric BC thresholds are commonly used in substitution for in situ thresholds, the two threshold types differ (Gascon et al., 2022), and the differences may be device specific. It is unknown how thresholds gathered using an audiometric BC transducer compared to a BCD processor differ and what impact that may have on the provided output versus PLLs of transcutaneous BCD fittings.

Purpose of the Study

Accurately defining hearing levels so that appropriate selection and fitting of BCDs can be achieved is recommended to facilitate accurate calculation of targets. For transcutaneous BCDs, the loss of force level to the cochlea due to sound traveling across the skin is an important consideration of a BCD fitting that has yet to be integrated into the process. Understanding the effects of both individual and/or device-dependent skin transmission is required as a first step toward prescription of transcutaneous BCDs. As such, this study aimed to investigate threshold level and suprathreshold sound transmission with transcutaneous BCDs by investigating the following questions:

1. What are the differences among thresholds obtained using an audiometric BC transducer versus in situ threshold measurement using two commercially available BCDs?
2. What are the differences in force level output from passive transcutaneous BCD devices when programmed to default manufacturer settings, compared to DSL-BCD adult targets for percutaneous BCDs?
3. What are the PLLs of adults with simulated conductive hearing loss (CHL) wearing nonsurgical passive transcutaneous BCDs in a laboratory setting, and how do these compare to the DSL-BCD adult targets for percutaneous devices?

Method

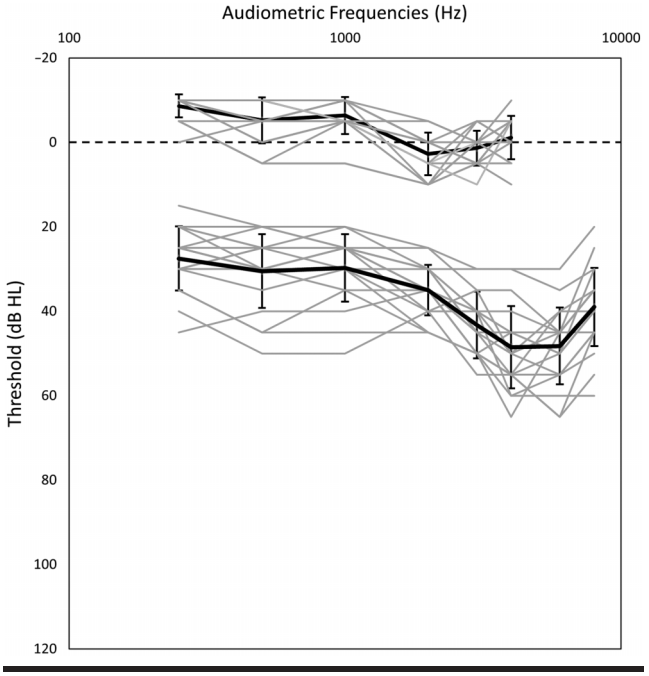
Twenty NH adults with an average age of 21 years (range: 19–25 years; female = 11; male = 9) were recruited from within Western University, in London, Ontario, Canada. Recruitment occurred through the National Centre for Audiology database, as well as posters across the university campus and word of mouth. The study was approved by Western University's Research and Ethics Board prior to recruitment (ID: 113162). Each participant read a letter of information and had any questions about the study addressed by the researcher prior to signing the consent form. The informed consent process was approved by the Western University Research Ethics Board. To be included in the study, participants completed a standardized questionnaire (International Organization for Standardization, 2009) to screen for NH followed by threshold testing in the sound field.

Assessment

Otoscopic examination was completed in each ear and cerumen cleared from the ear canal(s), as necessary. For each participant, unaided sound field thresholds were obtained using warbled pure tones in a double-walled sound-treated room with sound delivered at 0° azimuth. Frequencies tested ranged from 250 to 8000 Hz with thresholds equal to or less than 20 dB HL considered to be within the normal range (International Organization for Standardization, 2009). A bilateral CHL was simulated using E-A-R 3M Classic foam ear plugs placed in both ear canals. Sound field thresholds were repeated in the occluded condition to verify the simulated bilateral CHL (see Figure 1).

With the earplugs in place binaurally, BC thresholds were obtained using a B-71 audiometric BC transducer, as well as in situ using two different commercially available BCDs. The order of transducer-specific testing was randomized across participants. The B-71 was coupled to the standard metal headband, and the BCDs were coupled monaurally to their respective soft headbands. Transducers were placed posterior to the pinna on the superior mastoid. Each BCD soft headband was adjusted on each participant's head to allow the experimenter's first and second fingers to slide comfortably under the headband (Hodgetts et al., 2006). Audiometric BC thresholds were obtained at interoctave frequencies from 250 to 4000 Hz and up to 6000 Hz with each BCD connected to the respective manufacturer's software.

Figure 1. Simulated conductive hearing loss measured from 20 participants. The solid thick line represents the average sound field air-conduction thresholds, and the dashed line represents the average bone conduction thresholds. Error bars are standard deviations. Thin lines represent individual participant thresholds.



Default Manufacturer BCD Setting

Each participant's in situ thresholds were entered into the manufacturers fitting software to derive default settings for each transcutaneous BCD. For the Oticon Ponto 3 SP, Adult DSL-BCD prescriptive targets were available in the manufacturer software used to generate default DSL-BCD settings. For the Cochlear BAHA 5 P, the manufacturer's proprietary prescriptive method was used to generate the default settings. For both BCDs, monaural fitting was chosen within the fitting software which, when measured, resulted in an approximately 3-dB force level increase across frequencies compared to choosing a binaural fitting. All other features such as coupling (Softband), compression ratio, directionality, and noise management were set to default software recommendations.

For the Oticon Ponto 3 SP, directionality was set to automatic and noise reduction was turned on. For the Cochlear BAHA 5 P, directionality was set as fixed directional and noise reduction was set to automatic. These settings were saved and force level outputs were measured for each device using the verification procedure described below.

PLLs

PLLs were obtained from participants while wearing each programmed BCD fitted on a soft headband (Cox & Bisset, 1982). BCDs were fitted using the participants' device-specific in situ thresholds and programmed as described in the previous section and then turned down approximately 10 dB as a starting point. One of 32 sentences from a modified version of the Connected Speech Test (Cox et al., 1987; Saleh et al., 2020) was presented at 60 dB SPL in the sound field. Participants were instructed to listen to the sentence while wearing the BCD and press a response button when they perceived the speech to "sound the best." BCD levels were increased in 1-dB increments until the participant indicated that the device had reached PLL. This PLL procedure was repeated for one participant who requested a second trial to confirm their PLL. When the second response did not align with the first, the two levels were replayed and the participant chose their preference between the two. The PLL for each participant was recorded and force level outputs were measured for each device using the verification procedure described below.

Verification of Fit to Targets and PLLs

DSL-BCD targets for percutaneous devices were derived within the Audioscan Verifit2 (Software Version 4.23.3) by entering the participant's in situ thresholds for each BCD. The BCDs were connected to the Verifit2 skull simulator within the test box to measure force level output across frequency and compared to targets from 250 to 8000 Hz. Aided frequency responses for each device were measured using standardized simulated speech stimuli at 60 dB SPL. This procedure was completed for the default BCD fittings generated within the manufacturer software and at the participant's PLL. The force level output for each input and the DSL-BCD targets generated within the Verifit, across frequency, were stored and imported from the Verifit into a spreadsheet for analysis.

Results

Detection Thresholds

Unaided sound field thresholds ranged from −10 to 15 dB HL in the unoccluded condition and from 15 to 65 dB HL in the occluded condition. The frequency-specific differences between unoccluded and occluded thresholds were computed for each participant to estimate the simulated CHLs per frequency. The average difference between plugged and unplugged conditions was 27.5 dB for the four-frequency pure-tone average (SD = 6.6 dB). Across frequencies, these CHLs ranged from 19 dB at 250 Hz to 40 dB HL at 6000 Hz. These results indicate that a mild–moderate CHL was successfully simulated for all participants in this study (see Figure 1).

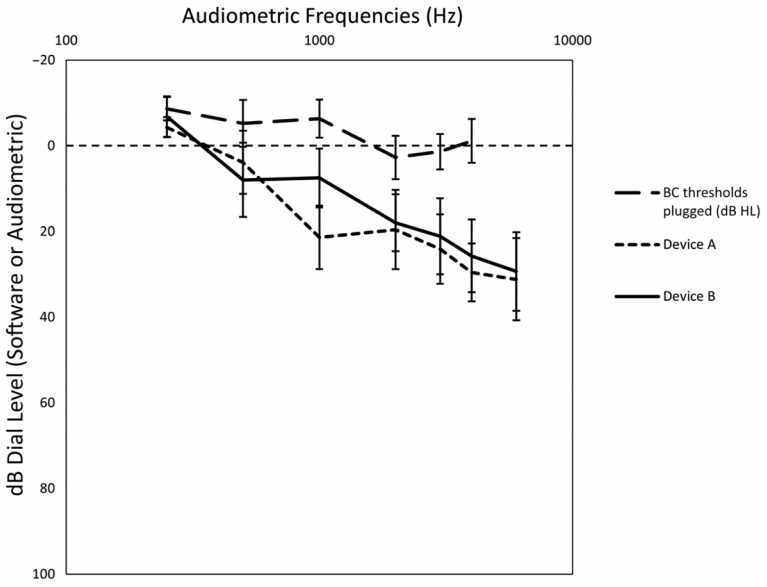
In situ thresholds were also obtained with the two transcutaneous BCDs worn on a soft headband. Values ranged from −5- to 55-dB dial level for Device A (Oticon Ponto 3 SP) and −10- to 50-dB dial level for Device B (Cochlear BAHA 5 P). The in situ thresholds for each BCD were compared to average BC thresholds obtained with the audiometric BC transducer (see Figure 2). The audiometric and in situ thresholds were submitted to a repeated-measures analysis of variance, with test frequency (six levels) and transducer type (three levels) as within-subjects factors (SPSS, Version 28). Greenhouse–Geisser epsilon was used to correct for lack of sphericity in the data for all tests, and Bonferroni corrections were used to correct alpha rates during post hoc contract testing.

There was a statistically significant effect of transducer on the level of thresholds averaged across frequencies, $F(1.72, 36.18) = 161$, $p < .001$, $\eta^2 = .885$, as well as an interaction of Transducer Type × Test Frequency, $F(6.2, 130.3) = 22.1$, $p < .001$, $\eta^2 = .513$. Post hoc comparisons using Bonferroni corrections indicated that the average audiometric BC transducer thresholds were statistically significantly lower than the in situ thresholds of each BCD by approximately 20 dB, collapsed across frequencies ($p < .05$). Per frequency, the audiometric thresholds were lower than BCD in situ thresholds at all frequencies, although the specific amounts varied per frequency with audiometric-to-in situ differences ranging between 10.5 and 34 dB (see Figure 2). There were also a statistically significant differences between in situ thresholds for the two BCDs at 250 Hz (M = 2.5 dB, $p = .04$) and 1000 Hz (M = 13.9, $p < .001$). All other differences were nonsignificant.

PLLs

PLLs were obtained for all participants using Device A. Due to audible feedback from Device B, PLLs could not be obtained for five of the 20 participants. PLL data for these participants were not included in the analysis. The overall force level output was compared for (a) software-generated default settings, (b) DSL-BCD targets within the Verifit for percutaneous devices, and (c) the participants' PLLs as described above (see Figures 3 and 4).

Figure 2. Average in situ and audiometric bone conduction (BC) across frequencies.



Overall force level output was determined by calculating the power of the force level at each one-third octave band, for each participant, using power sum averaging:

$$\text{POWER}(10, (\text{frequency force level}/10)) \quad (1)$$

The sum of the overall level for each participant was calculated using the following equation:

$$\log \times 10(\text{SUM of all frequency force levels}) \quad (2)$$

Once this was calculated for each participant, the overall force level for each BCD in each condition was calculated using the same equation. The resulting overall levels were submitted to a repeated-measures analysis of variance (SPSS, Version 27) with device setting as a three-level within-subjects factor (default, target, PLL). Greenhouse–Geisser corrections for lack of sphericity were implemented. Bonferroni-corrected post hoc contrasts were used to locate any pairs of device settings that differed and

Figure 3. Average force level output (dB) of Device B across frequency for three conditions: DSL-BCD targets from the Verifit 2 are for adults for percutaneous devices. Standard deviations were < 5 dB at all frequencies for all conditions (error bars are not shown). DSL = Desired Sensation Level; BCD = bone conduction hearing device.

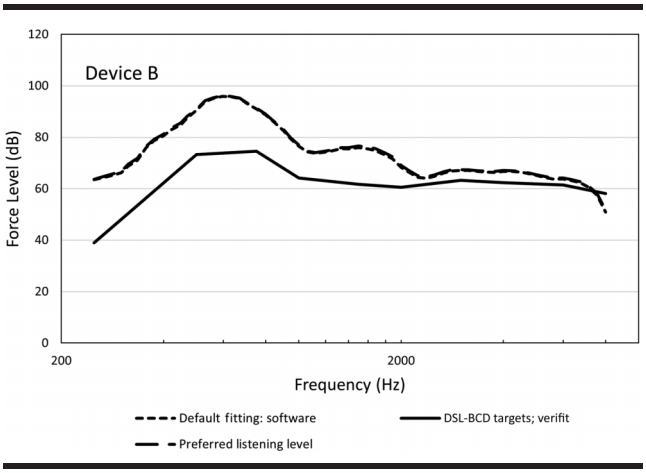
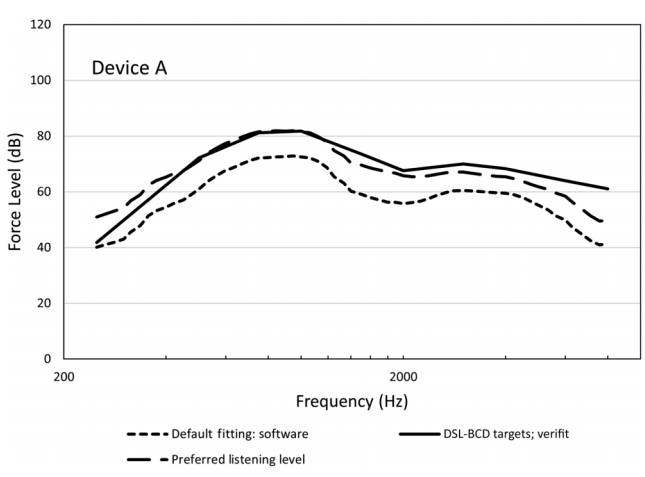


Figure 4. Average force level output (dB) of Device A across frequency for three conditions: DSL-BCD targets from the Verifit 2 are for adults for percutaneous devices. Standard deviations were < 5 dB at all frequencies for all conditions (error bars are not shown). DSL = Desired Sensation Level; BCD = bone conduction hearing device.



to estimate the mean differences between conditions. This analysis was completed for each brand of BCD.

Overall force level output ranged from 77.1 dB FL for Device A's default fitting to 98.2 dB FL for Device B's PLL. For Device A, there was a statistically significant effect of device setting type (default, target, PLL) on the overall level, $F(1.8, 34.9) = 30.83$, $p < .001$, $\eta = .62$, with the manufacturer's default setting being statistically significantly lower than the PLLs and the DSL-BCD targets by about 9 dB ($p < .001$). The difference between the prescribed percutaneous target and PLL was not significantly different ($M = 0.9$ dB, $p > .05$). For Device B, there was a statistically significant effect of device setting on the overall level, $F(1.5, 28.9) = 413$, $p < .001$, $\eta^2 = .96$, with the DSL-BCD targets being statistically significantly lower than the PLLs and software-generated setting by about 19 dB ($p < .001$). The differences between PLL and the device default settings were nonsignificant ($M = 0.5$ dB, $p > .05$).

Discussion

This study investigated some components of fitting transcutaneous BCDs in order to better understand underlying factors in objective fitting of these devices, which requires estimation of in situ thresholds and prescription of suprathreshold levels of speech in force level.

In Situ Thresholds

In this study, detection thresholds were compared in the clinical units used to obtain them, which were dB HL for audiometric data and software-specific dial levels for thresholds measured in situ with two BCD devices. When comparing audiometric BC thresholds to in situ thresholds for the two BCDs on a soft headband, results revealed that audiometric (B-71) BC thresholds were statistically significantly lower (better) than in situ thresholds. Differences between the devices ranged on average from 2 dB at 250 Hz to 28 dB at 4000 Hz. Differences between the in situ thresholds by brand of BCD were also noted, with differences ranging between 1.59 dB at 2000 Hz and 13.86 at 1000 Hz. In particular, statistically significant differences were noted at 250 Hz and 1000 Hz. At 250 Hz, a difference of 2.5 dB may not be clinically significant as it is less than a 5-dB audiometric step size compared to 1000 Hz, which is different by about two audiometric step sizes. Recall that the internal transducers, external form factors, and head coupling methods (steel band vs. soft band) differ between these devices. However, Hodgetts et al. (2006) found that force level measurements across soft headband tension settings indicated that tension manipulations between 2 and 5 N did not result in significant changes in measured output force levels. Therefore, differences in tension may not have contributed significantly to the variation in our results. However, skin thickness changes force level, with poorer signal transmission associated with thicker skin, which may have contributed to between-listener variation in our data, although it is not a likely explanation of variation between transducers (Mattingly et al., 2015). Overall, the significant difference between in situ and audiometric BC thresholds in the current study suggests a need to account for skin transduction and for device/coupling differences between audiometric and in situ BC thresholds when computing targets for transcutaneous BCDs. This can be accomplished either by measuring in situ thresholds directly or by applying a correction to convert audiometric BC thresholds to estimate in situ thresholds. This latter approach could offer convenience, while the former option is a more direct representation of hearing limits associated with a specific BCD. One consensus document recommends the in situ approach whenever possible (Bagatto et al., 2022).

Suprathreshold Output Levels of Speech

We also compared the output levels at PLL with transcutaneous BCD with existing percutaneous DSL-BCD targets and device-specific default settings. The results were mixed, suggesting that when the device frequency response shape and target shape are similar, like in the case of Device A, differences between the percutaneous target and the transcutaneous PLL were small. Therefore, once skin attenuation and device characteristics are accounted for in addition to in situ thresholds and the BCD is programmed accordingly, skin attenuation does not seem to impact signal output. In contrast, the second device had a markedly different frequency response shape than was prescribed, due to a large low-frequency peak. This observation of device-specific peaks for some BCD devices has been noted previously (Hodgetts & Scollie, 2017). For this device, agreement between target and PLL was poorer. It appears that device frequency response shape may have played a role in these results. Specifically, when examining the PLL responses for each device (see Figures 3 and 4), it appears that listeners preferred the high-frequency response at similar levels in both devices. The large peak in the low frequencies in Device B was not adjusted to the listener's PLL. Rather, they adjusted the high frequencies to a similar level as for Device A, which had a flatter frequency response. In fact, the agreement between PLLs was within an audiometric step size between devices from 2000 to 4000 Hz (see Figures 3 and 4). This may be consistent with striking a balance between clarity of speech with overall comfort, as per the instructions for PLLs. Had listeners been able to adjust

frequency-specific channels in the hearing aid, it may have provided additional information regarding their preference for the low- to midfrequencies. Tested with fixed frequency responses, the results are in agreement with previously reported listening levels in the high frequencies (Hodgetts & Scollie, 2017). Overall, the results in this study suggest that both soft tissue transmission and device-specific characteristics may impact both measured thresholds and suprathreshold levels of speech for transcutaneous BCDs.

Limitations and Future Directions

The results of this study may be limited to the specific devices used, so further data on a broader range of transcutaneous BCD would inform whether these results are generalizable. Further, participants judged the overall level of the device during the PLL task rather than different frequency responses. Studies that facilitate adjustment of the frequency response shape, as has been done for air-conduction devices (see review in Vaisberg et al., 2021), would provide insight into the agreement between prescribed or default shapes and listener preferences. A related issue is that, due to audible feedback, five participants could not adjust the volume of Device B to a comfortable level. Upon further examination, the default setting of the device demonstrates a level increase at certain frequencies that may have contributed to the noted feedback. Had the participants been able to manipulate particular frequency regions, PLLs may have been obtainable for all participants and all devices in this study.

An important limitation in our participants is that all were adults with NH status, while the typical clinical population for transcutaneous BCDs are individuals who have external ear structures that impact sound transmission by air conduction. We attempted to overcome this, in part, by successfully simulating a CHL with earplugs, verifying the earplug effect and testing devices with that loss in place. However, we used adult test procedures including testing with 5-dB step sizes and testing without limits of minimum response levels that are well known to limit testing to 15 to 25 dB in young children (e.g., Sabo et al., 2003) for air-conduction methods at least. Further testing in children to determine typical differences between audiometric BC thresholds and in situ thresholds is necessary. Fortunately, almost 70% of the pediatric audiologists surveyed (Gordey & Bagatto, 2021) indicated that they gathered both audiometric BC thresholds and device-specific in situ thresholds when fitting their young patients with BCDs. This means that the gold-standard in situ data (Bagatto et al., 2022) may be available in the majority of fittings, which likely would contribute positively to accuracy in fitting. Preference for a wider range of signal than only speech may also be needed to understand optimal fittings across test signal types (Toll & Dingemanse, 2022). The final limitation to note is that listeners were not asked to rate the quality of their own voice. This is an important factor in the verification of BCDs to reduce the impact of the "barrel effect" (Hodgetts & Scollie, 2017).

Conclusions

Currently, there is a lack of validated strategies for computing prescriptive targets for transcutaneous BCDs, particularly for use with children. Recent survey data indicate that almost 80% of the clinicians used the manufacturer's default settings when fitting BCDs to young children (Gordey & Bagatto, 2021), and clinical consensus indicates that validated tools for prescription and verification are needed (Bagatto et al., 2022). As such, basing transcutaneous BCD targets on in situ BCD thresholds may be feasible. In this study with transcutaneous BCDs, we completed a preliminary investigation of device-specific thresholds and device-specific transmission of aided speech, in order to inform future directions for modification of a percutaneous BCD target. Thresholds measured in situ differed from thresholds measured audiometrically, which strengthens the existing recommendations for in situ approaches whenever possible. Suprathreshold speech levels were preferred at similar levels to those currently recommended by percutaneous targets, particularly when the BCD device provided a smoother response shape. Future directions include gathering audiometric and BCD thresholds from a sample of infants and children with conductive or mixed hearing losses to determine whether audiometric-to-in situ corrections are feasible and to better understand these variables in children. Similarly, understanding children's PLLs associated with transcutaneous listening is necessary to understand how recommended levels from percutaneous BCD prescriptions can be modified.

Data Availability Statement

Data generated during the current study are not publicly available due to ethical restrictions. Data may be available from the corresponding author on reasonable request.

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