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Kimberly A. Pollard,[a)] Phuong K. Tran, and Tomasz R. Letowski
U. S. Army Research Laboratory, 520 Mulberry Point Road, Aberdeen Proving Ground, Maryland 21005-5425

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Bone conduction communication systems employ a variety of transducers with different physical and electroacoustic properties, and these transducers may be worn at various skull locations. Testing these systems thus requires a reliable means of transducer calibration that can be implemented across different devices, skull locations, and settings. Unfortunately, existing calibration standards do not meet these criteria. Audiometric bone conduction standards focus on only one device model and on limited skull locations. Furthermore, while mechanical couplers may be used for calibration, the general human validity of their results is suspect. To address the need for more flexible, human-centered calibration methods, the authors investigated a procedure for bone transducer calibration, analogous to free-field methods for calibrating air conduction headphones. Participants listened to1s third-octave noise bands (125–12 500 Hz) alternating between a bone transducer and a loudspeaker and adjusted the bone transducer to match the perceived loudness of the loudspeaker at each test frequency. Participants tested two transducer models and two skull locations. Intra- and inter-subject reliability was high, and the resulting data differed by transducer, by location, and from the mechanical coupler. The described procedure is flexible to transducer model and skull location, requires only basic equipment, and directly yields perceptual data. [http://dx.doi.org/10.1121/1.4774273]

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I. INTRODUCTION

Bone conduction involves the use of skull bone and tissue vibrations to transmit acoustic information to the listener. As a communication technology, bone conduction offers many advantages over traditional air-conduction audio communication (Gripper *et al.*, 2007, Henry and Letowski, 2007). Bone receivers (also known as bone microphones or contact microphones) can provide favorable signal-to-noise ratios for persons speaking in environments with high background noise. Bone transmitters (bone vibrators) can be worn inconspicuously and can deliver signals with little sound leakage. Bone conduction transducers can also be used without obstructing a listener's ears and without interfering with hearing protection devices. These benefits make bone conduction an attractive means for radio communication, and several laboratories have conducted investigations using a variety of bone conduction transducer devices placed at various skull locations (e.g., McBride *et al.*, 2008a; McBride *et al.*, 2008b; Osafo-Yeboah *et al.*, 2009; Stanley and Walker, 2009; Tran and Letowski, 2010; McBride *et al.*, 2011).

The diversity of transducers and locations that can be used for bone-conducted speech communication and other commercial and military applications requires a means to compare and calibrate bone conduction systems. In communications research, it is essential to be able to compare and predict the performance of different bone conduction transducers. It is also essential to compare the performance of these transducers when placed at different skull locations and used under different operational conditions. To meet these goals, a simple and robust calibration method is needed.

Bone conduction technology is already in wide use in audiology and in commercial hearing aids, and there are device calibration standards related to these applications (ANSI, 2007; IEC, 2007; ANSI, 2010). However, the standards are aimed toward clinical use rather than communication applications (Henry and Letowski, 2007; McBride *et al.*, 2008b). The focus of the standards is on only one bone transducer model (RadioEar B-71) and on only two skull locations (forehead and mastoid process). The limited coverage of devices and skull locations in current standards presents challenges for communications research and other non-clinical purposes (Walker and Stanley, 2005). In communication and other non-clinical applications, a wide array of different bone transducer devices may be used including a range of manufacturers and models. A variety of different skull locations may also be used. For example, the mandibular condyle has been shown to be an effective location for bone-conducted speech communication (Gripper *et al.*, 2007; McBride *et al.*, 2008b; Stanley and Walker, 2009), but it is not included in the calibration standards.

A standardized mechanical coupler, such as the B&K 4930 artificial mastoid, may be used as a reference device to test and calibrate bone transducers (ANSI, 2007). Although mechanical couplers generally yield repeatable results (e.g., Wilber and Goodhill, 1967a), they are not intended to model the response of multiple skull locations (see also Stenfelt and Goode, 2005), and the human validity of their response curves for different transducer models is limited (Richter and Brinkmann, 1976; Henry and Letowski, 2007; Weece and Allen, 2010; Margolis and Stiepan, 2012). Acoustic

[a)]Author to whom correspondence should be addressed. Electronic mail: kpollard@ucla.edu

calibration methods—capitalizing on air-conducted leakage from transducers—are promising (Margolis and Stiepan, 2012), but these methods do not represent the human perceptual experience with bone conduction. A more flexible means of transducer calibration is needed to accommodate a variety of nonstandard configurations that may be used for communication purposes or other non-clinical functions (Richter and Brinkmann, 1976; Henry and Letowski, 2007). It is therefore desirable to develop a reliable and versatile, yet operationally simple, method of calibrating and comparing bone conduction transducers for communication applications.

Previous studies have described perceptual methods for calibrating bone conduction transducers for clinical use. The three basic methods include hearing threshold (Roach and Carhart, 1956; Hedgecock, 1961; Wilber and Goodhill, 1967b), phase cancellation (Békésy, 1932; Kapteyn *et al.*, 1983; Stenfelt, 2007), and loudness balance (Carlisle *et al.*, 1947; Barry and Vaughan, 1981; Hedgecock, 1961) methods. The most promising of these methods for general use is the loudness balance method, developed originally by Beranek (1947) for the calibration of air conduction earphones. In the bone conduction variant of this method (Hedgecock, 1961; Barry and Vaughan, 1981), a bone transducer is placed on the skull near one ear, and an air conduction earphone is placed at the other ear. This arrangement can be problematic at low frequency ranges due to the occlusion effect (Franks *et al.*, 2003). Blocking the ear canal with an earphone creates a resonant chamber that alters the perceived loudness of the bone conducted signal (see also Keidser *et al.*, 2000; Stenfelt *et al.*, 2003; Reinfeldt *et al.*, 2007). This difficulty may to some extent be reduced by repeatedly removing the air conduction earphone, measuring the occlusion effect separately, or using tubing or leaky transducers (Barry and Vaughan, 1981; Stenfelt, 2007). However, the repeated placement of these devices introduces undesired data variability and imposes time gaps that make loudness balancing difficult for the listeners (Olsen, 1967; Zera *et al.*, 1997). Additionally, in-the-ear measurements are appropriate only for clinical sites or specialized laboratories but not for general application. The occlusion effect is negligible for frequencies at or above 2 kHz, and loudness balancing of bone vibrators with occluded ears has been performed at 2 kHz as a means of testing the performance of hearing protective devices (Rimmer and Ellenbecker, 1997; McKinley, 2009). Unfortunately, this limited frequency range is not useful for calibrating bone vibrators for communication purposes.

These various limitations can be alleviated by leaving the ears unoccluded and having listeners balance the loudness of bone transmitted signals against sound presented in the free field. Such a technique was first proposed by Richter and Brinkmann (1976) but has not since been refined and is seldom referenced in the literature. Richter and Brinkmann (1976) used a free-field loudness balance method to calibrate bone conduction transducers for clinical applications and compared obtained response curves to those generated on a B&K 4930 mechanical coupler. The B&K 4930 is intended to calibrate transducers with circular contact areas of 1.75 cm^2 when applied with 5.4 N static force (ANSI, 2007; IEC, 2007). Under these conditions, the B&K 4930 mimics the impedance of the human forehead over a limited frequency range (250-4000 Hz, Richter and Brinkmann, 1976). To best compare loudness balance data with the coupler data, Richter and Brinkmann (1976) used only bone transducers with the standard contact area of 1.75 cm^2 and placed these on the foreheads of volunteers with 5.4 N static force. These conditions yielded robust results but are not appropriate for bone conduction communication. People typically find a static force of 5.4 N highly uncomfortable even after short periods of wear, so a lower static force would be more realistic for testing bone transducers for communications or other long-wear applications (see also Toll *et al.*, 2011). Similarly, the forehead is just one location, and generally not the most practical or efficient location, for bone transducers in communications. Most commercially available headsets rest the bone transducers against the mandibular condyle or the mastoid process. Communications headsets also employ transducer models with a range of contact areas, so a calibration method must be flexible to this variation.

The aim of the current study is thus to investigate the use of a free-field loudness balance method for calibrating communication and general-use bone vibrators. The current study expands on the work of Richter and Brinkmann (1976) to develop a free-field loudness balance calibration method that is flexible to transducer type, skull location, and operational conditions and that provides reliable results in an extended frequency range. The proposed free-field loudness balance method is conceptually analogous to free-field loudness balance methods for calibrating air-conduction earphones (see Beranek, 1949, pp. 738–739), as mentioned in IEC 60268-7 (IEC, 2010b). In free-field loudness balance calibration of air-conduction earphones, human subjects adjust the output of the earphones to perceptually match the loudness of acoustic stimuli being played in the free field from a loudspeaker (e.g., Bauer and Torick, 1966; Villchur, 1969; Morgan and Dirks, 1974; Brinkmann and Richter, 1989). The standard IEC 60645-2 (IEC, 2010a) suggests that a similar method could be used for calibrating bone conduction transducers. The present study aims to describe and test such a method.

II. MATERIALS AND METHODS

A. Devices and stimuli

1. Bone conduction transducers

Two bone conduction transducers were used in this study: the RadioEar B-71, which is the standard bone transducer for audiometric work, and the Oiido SD02, which has been used in a variety of communication studies (Tran *et al.*, 2008; McBride *et al.*, 2010; Tran and Letowski, 2010; McBride *et al.*, 2011). During the experiment, each participant wore one transducer at a time. The transducers were held in place using an Oiido headset adjusted to the participant's comfort in the range of 2-2.9 N (200–300 g) static force.

2. Skull locations

Bone conduction involves sound transmission through the bone and soft tissue of the head, so the placement of bone conduction devices is likely to have strong influence on signal transmission (Snidecor *et al.*, 1959; Acker-Mills *et al.*, 2005; Stenfelt and Goode, 2005; Gripper *et al.*, 2007; McBride *et al.*, 2008a; McBride *et al.*, 2008b; Osafo-Yeboah *et al.*, 2009; Stanley and Walker, 2009; McBride *et al.*, 2011). Two skull locations were investigated in this study: the mastoid process, which is a common transducer location for hearing aids and clinical applications and is also useful for communications (McBride *et al.*, 2008a; McBride *et al.*, 2008b; Osafo-Yeboah *et al.*, 2009; McBride *et al.*, 2011), and the mandibular condyle, which is a commonly used and effective location for bone conduction communication (McBride *et al.*, 2008a; McBride *et al.*, 2008b; Osafo-Yeboah *et al.*, 2009; Stanley and Walker, 2009; McBride *et al.*, 2011).

3. Stimuli

Stimuli were 1 s long, one-third-octave wide bands of digitally generated white noise. The noise bands were centered around the standard one-third octave frequencies extending from 100 to 12 500 Hz (22 test frequencies). These frequencies include standard audiometric test frequencies plus additional high and low frequencies to test the limits of the bone conduction devices. The stimuli were set up as two-channel sound files (Microsoft Windows .wav file format, 16-bit depth, with 44.1 kHz sampling rate), where the signal from one channel was sent to the loudspeaker, and the signal from the other channel was sent to the bone transducer. The noise bands alternated between channels with no time in between and were played on loop to the participants (Fig. 1) using ADOBE AUDITION 3.0 software.

B. Participants and procedure

Six volunteers (five females and one male) participated in the study. Their ages ranged from 23 to 46 yr (mean 32.3, sd 8.1). Air conduction and bone conduction hearing thresholds were obtained for each volunteer using standard hearing testing methods (American Speech-Language-Hearing Association, 2005). All volunteers had air and bone conduction thresholds of 20 dB HL (hearing level) or below in both ears at all test frequencies (ANSI, 2010) and had no reported otologic problems.

The tests were conducted in an anechoic room meeting free-field conditions above 120 Hz (no reflections) with a background noise level below 25 dB A-weighted. Each participant was fitted with one bone transducer at a time, held in place with an Oiido headset adjusted to the participant's comfort in the range of 2–2.9 N (200–300 g) static force. This static force range has been shown to be both effective and comfortable for bone conduction hearing (Toll *et al.*, 2011). The participant was seated in the center of the anechoic room facing a concealed loudspeaker. A headphone amplifier was connected to the bone transducer and placed on the participant's lap, and a microphone was available for speaking to the experimenter. All free-field signals were presented at 45 dB SPL (re: 20 μPa), measured at the location of the participant's head with the participant absent. Both free-field and bone-conduction test signals were played from a battery-powered laptop computer located outside the test chamber and routed to the loudspeaker and bone transducer inside the chamber. Stimuli were presented alternating between the loudspeaker and the bone transducer, and the participant was instructed to adjust the volume on the bone transducer (via the amplifier) to perceptually match the loudness of the signal from the loudspeaker. The amplifier dial moved smoothly and allowed a continuous, analog range of responses from the participant. The marks on the dial were obscured with masking tape to prevent visual assessment of amplifier volume. Once satisfied with the signal level chosen, the participant would inform the experimenter by speaking into the microphone. The experimenter then documented the signal level from an audio voltmeter that was located outside the chamber but connected directly to the input of the bone transducer (see schematic in Fig. 2).

After the experimenter documented the participant's chosen volume, the next stimulus would then be played, and the procedure would be repeated for each stimulus and each device-location combination. To obtain data on within-subject repeatability, one participant repeated all device/location conditions six times, and two other participants

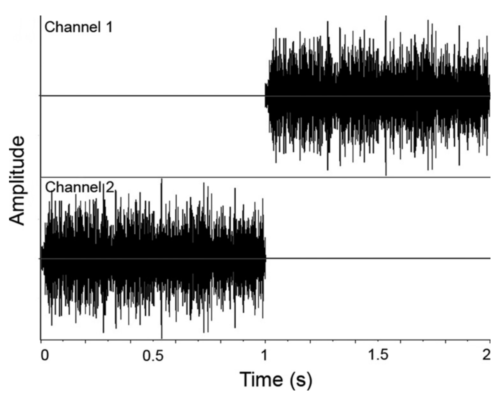

FIG. 1. Waveform of a test stimulus. The top channel plays to the bone transducer and the bottom to the loudspeaker. Both channels contain the same noise sample. In the actual test stimuli sound files, the loudspeaker channel was attenuated by 45 dB because the loudspeaker requires lower voltage input than the bone transducers to produce a sound of similar perceived loudness. The loudspeaker channel attenuation is not shown in this figure.

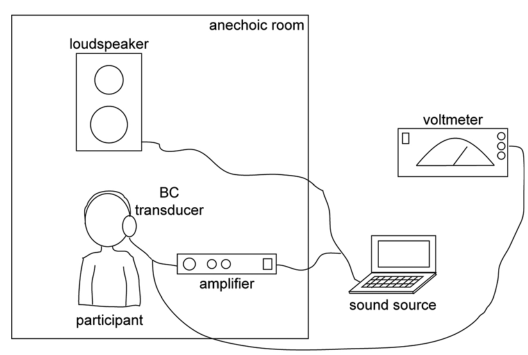

FIG. 2. Schematic of experimental set-up.

repeated the B-71/mastoid condition six times. For all participants, the headset was removed, adjusted, replaced, and readjusted after each device-location block and each repetition.

The participant's task in this study differed slightly from that of the study of Richter and Brinkmann (1976) in which the experimenter adjusted the volume level until participants indicated that a satisfactory loudness match had been achieved. The current study had the participants adjust the volume themselves, with the expectation that this would allow finer control, streamline the procedure, and make the participants feel less pressured to make a rapid response.

C. Mechanical coupler

The human responses were also compared to frequency response curves generated on the B&K Type 4930 mechanical coupler. The frequency response of each transducer on the mechanical coupler was obtained using standard pure tone signals (for verification purposes) and using 1/3 octave noise bands (to mimic conditions experienced by this study's human participants). To mimic the human conditions, each bone transducer was placed on the mechanical coupler with 2.9 N (300 g) static force, and the same 1/3 octave band noise stimuli were played. The sound source volume was held constant with 200 mV sent to the transducer during the 1 kHz noise band. To verify that static force and signal bandwidth did not have any unexpected effects on the transducers or mechanical coupler, the frequency response of the transducer on the coupler was checked against curves derived from standard coupler conditions [i.e., using pure tone signals at 100 mV input with a static force of 5.4 N (550 g); ANSI, 2007; IEC, 2007]. One-third octave noise band curves are expected to be similar to but smoother than pure tone curves because a wider bandwidth signal is used. The general shape of the curves was as expected, confirming that static force and bandwidth did not generate any unexpected effects on the transducer or mechanical coupler performance.

III. RESULTS

The output voltages chosen by the participants (in dB re: 1 mV) at each frequency were compared within subjects, across subjects, and across devices and skull locations. The data averaged across all participants are shown in Figs. 3 and 4.

A. Intra- and inter-individual reliability

To assess reliability, intraclass correlations (two-way random, absolute agreement) were performed across runs of each subject who did multiple runs and across the different subjects. Results are reported as coefficients of reliability, Cronbach's α, which is a measure of internal consistency (Cronbach, 1951).

One subject was run six separate times on each device-location combination. Intra-individual reliability for this subject was high under each condition. Intraclass correlations (Cronbach's α, 22 frequencies) were 0.983 for the B-71 on the condyle; 0.974 for the B-71 on the mastoid; 0.987 for the SD02 on the condyle; and 0.990 for the SD02 on the mastoid. The condition with the lowest intra-individual reliability (B-71 on the mastoid) was then run six separate times each on two more subjects. These subjects' intra-observer reliability (Cronbach's α, 22 frequencies) was also high, with $\alpha = 0.967$ for one subject and $\alpha = 0.952$ for the other.

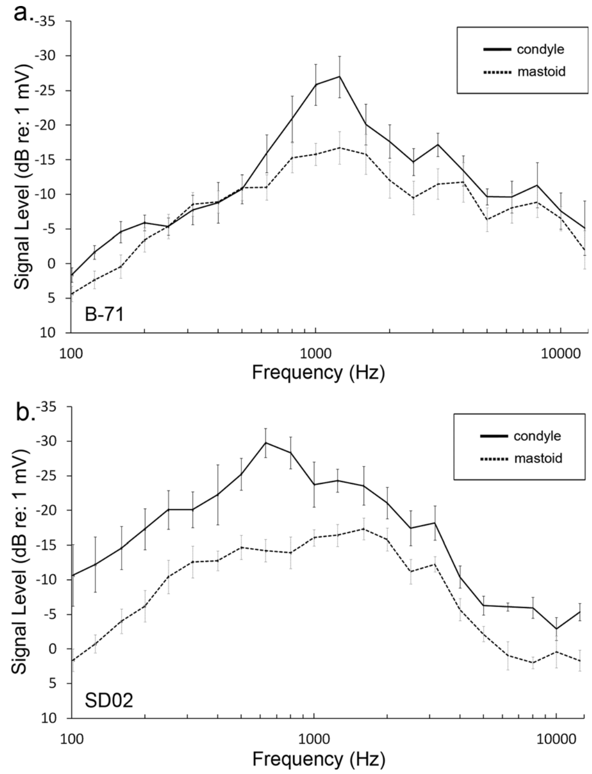

FIG. 3. Comparison of mandibular condyle (solid line) and mastoid process (dashed line) skull locations for the B-71 transducer (a) and the SD02 transducer (b). Lines depict the mean response for six subjects at each test frequency, ± se. The vertical axis indicates the signal level (dB re: 1 mV) that the human subjects selected to perceptually match the bone conducted sound to 45 dB of air-conducted sound in the free field.

To compare inter-subject reliability, all runs were averaged first within subjects, and then intraclass correlations were run across subjects. Intraclass correlations (Cronbach's α, 22 frequencies in each case) were 0.940 for the B-71 on the condyle; 0.907 for the B-71 on the mastoid; 0.947 for the SD02 on the condyle; and 0.961 for the SD02 on the mastoid.

B. Comparison of skull locations

As shown in Fig. 3, the condyle location was more sensitive to bone vibration stimulation than the mastoid. This held for both the RadioEar B-71 bone transducer [Fig. 3(a)] and for the Oiido SD02 bone transducer [Fig. 3(b)] although the difference was more noticeable for the SD02. When adjusted for the overall difference in sensitivity between condyle and mastoid (i.e., after shifting curves vertically so they could be placed on top of one another), it is clear that the shape of the calibration curves is highly similar across skull locations at frequencies above approximately 2000 Hz. This held true for both the B-71 and the SD02.

C. Comparison of bone transducers

When worn on the mastoid, both transducer models were similarly effective in the mid-frequency range (approximately 630–3000 Hz) with the Oiido SD02 transducer performing better at frequencies below that range and the RadioEar B-71 performing better at higher frequencies [Fig. 4(a)]. When worn on the condyle, the Oiido SD02 transducer was generally more effective than the RadioEar B-71 especially at low frequencies (up to 800 Hz) although the B-71 was somewhat more effective at frequencies above 4000 Hz [Fig. 4(b)].

D. Comparison with mechanical coupler

As shown in Fig. 5, the mechanical coupler (B&K 4930) output did not align well with the human perceptual data for any of the transducer/location combinations. High and low sensitivity regions for the mechanical coupler response did not match with those of the human mastoid or human condyle. Regardless of skull location or device model, the results of the perceptual calibrations are closer to each other than any of them are to the mechanical coupler curve.

IV. DISCUSSION

The presented study described a free-field loudness balance method to calibrate bone conduction transducers. Participants were asked to adjust the volume of a bone

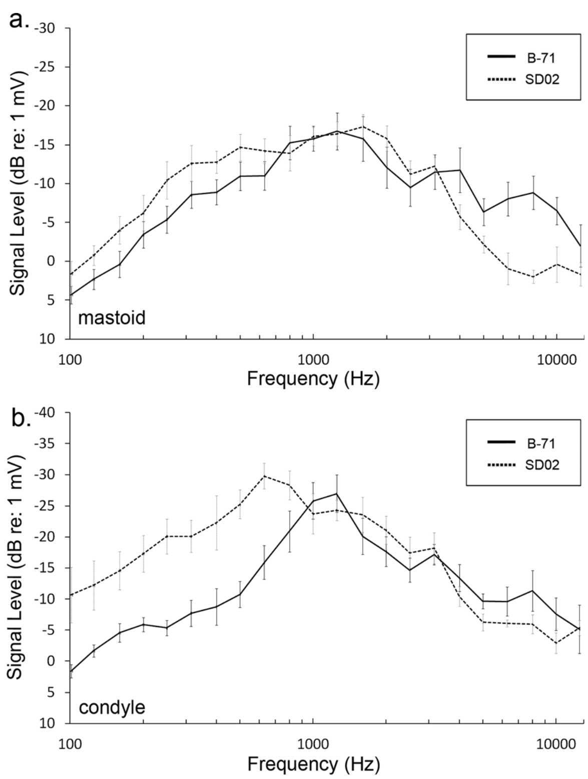

FIG. 4. Comparison of the B-71 (solid line) and SD02 (dashed line) bone transducers on the mastoid process (a) and mandibular condyle (b). Lines depict the mean response for six subjects at each test frequency, $\pm$ se. The vertical axis indicates the signal level (dB re: 1 mV) that the human subjects selected to perceptually match the bone conducted sound to 45 dB of air-conducted sound in the free field.

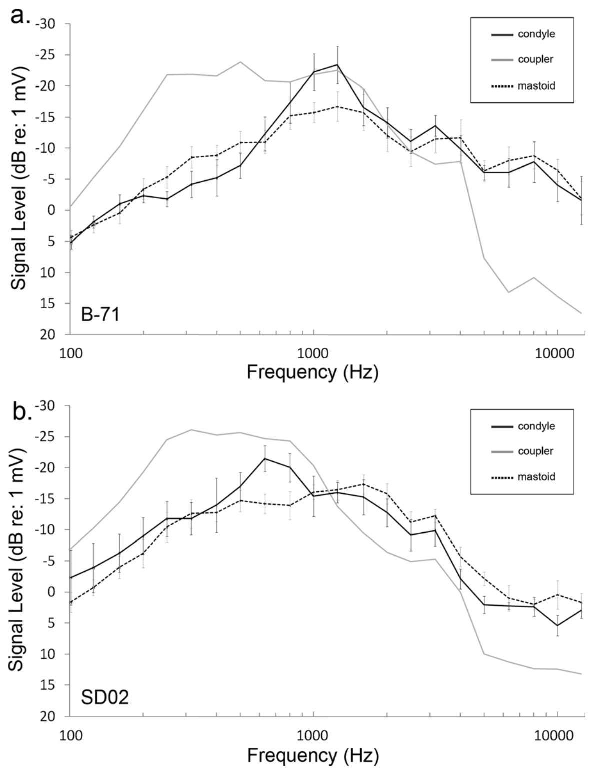

FIG. 5. Comparison of the human mastoid response (dashed black line) to the mechanical coupler response (solid gray line) and human condyle response (solid black line) for the B-71 transducer (a) and the SD02 transducer (b). Lines depict the mean response for six subjects at each test frequency, $\pm$ se. The vertical axis indicates the signal level (dB re: 1 mV) that the human subjects selected to perceptually match the bone conducted sound at the mastoid to 45 dB of air-conducted sound in the free field. For ease of comparison, the mechanical coupler curve and human condyle curve have been overlaid on the human mastoid curve (vertically shifted by the average difference between each curve and the human mastoid curve).

transducer to perceptually match the loudness of 45 dB noise bands presented in the free field from a loudspeaker. The study tested the method using two bone transducer models (RadioEar B-71 and Oiido SD02) and two skull locations (mastoid process and mandibular condyle) and compared these data to those generated on a mechanical coupler, the B&K 4930 artificial mastoid. The results indicate that the proposed loudness balance method is sufficiently accurate and reliable to be used as a calibration method for bone conduction communication transducers. Furthermore, the obtained results can be used to select either the device model (for a given location) or the skull location (for a given device model) that might be the most suitable for a specific bone conduction communication application. The relatively smooth frequency responses measured in this study also suggest that the number of test frequencies used for calibration can be reduced without sacrificing the accuracy and validity of the calibration procedure.

Intra- and inter-subject reliability was high with this calibration method (Cronbach's $\alpha > 0.9$ in all cases) although repeatability varied somewhat by device model and skull location. Both within and among subjects, the B-71 mastoid condition yielded the least repeatable data. This may be due to the slim rounded shape of the mastoid process combined with the smaller surface area of the B-71 compared to the

SD02; it may be more difficult with this configuration to achieve similar levels of contact both across subjects and across repeated sessions with the same subject.

As expected, reliability across subjects was lower than within subjects (see also Richter and Brinkmann, 1976). However, the difference was relatively small, indicating that although individual differences may play a role in how listeners experience bone conducted sounds, these differences may not be practically important for the purposes of device calibration.

Skull location comparisons confirmed that the condyle location is more sensitive than the mastoid location for bone conduction stimulation, and this was true for both transducer models (Fig. 3). These results are consistent with those of McBride *et al.* (2008b), who found the condyle to be more sensitive than the mastoid location for pure tones, and Stanley and Walker (2009), who found the same relationship for speech sounds. This suggests the condyle may be a preferable location for use in communication applications (see also McBride *et al.*, 2008a), although another study found no differences in speech intelligibility between the mastoid and condyle (Osafo-Yeboah *et al.*, 2009).

Upon comparison of transducers, the SD02 model was found to be more effective than the B-71 at lower frequencies (100–630 Hz). This was the case for either skull location, but especially for the condyle (Fig. 4). At both skull locations, the B-71 outperformed the SD02 at higher frequencies above 4000 Hz. At both skull locations, the transducer models performed similarly within the critical speech range of 1000–4000 Hz. This suggests that either model would be suitable for general-purpose speech communication. Specific applications that rely heavily on low or very high frequency signals might be better suited for the SD02 or B-71, respectively.

Human response curves for both transducers were also compared to those generated on a B&K Type 4930 mechanical coupler. The coupler did not accurately reproduce the human response to either transducer device at either skull location. It is noteworthy that the B-71's frequency response on the B&K 4930 coupler largely agreed with the B-71 B&K 4930 data reported in other studies (e.g., Dirks *et al.*, 1979). A B&K 4930 or other mechanical coupler is a helpful device for comparing the vibrational output of different bone transducers, but users should note that the resulting unprocessed curves do not accurately reflect the human perceptual experience (see also Richter and Brinkmann, 1976; Margolis and Stiepan, 2012). In fact, the shapes of perceptual frequency responses obtained in this study are more similar across different skull locations and across different transducer models than any of these frequency responses are to the B&K 4930 coupler data. The B&K 4930 coupler output overestimates the bone conduction transducer's ability to impart low frequency energy (below 1000 Hz) to the head while underestimating transmission of high frequency energy (above 3000 Hz) to the head. This discrepancy warrants further consideration.

A variety of factors likely contribute to the fact that the mechanical coupler response curve does not match the human perceptual data. First, the coupler is designed to mimic the impedance of the human skull, but it is not designed to mimic any subsequent auditory filtering that arises in the cochlea or perceptual processing in the brain. Audiologists account for the perceptual filtering/processing steps by adding transfer factors (ISO, 1994) to the raw coupler output at standard audiometric frequencies to generate a curve that mimics human bone conduction threshold levels. The present study, however, was not conducted at threshold sound levels. The present study instead used a sound level that is more appropriate for communications applications, i.e., a supra-threshold level. The standard transfer factors would therefore not be appropriate. Equal loudness curves for bone conduction have not yet been established, but it is well known that equal loudness curves for air conduction are not parallel. That is to say, a loudness balance study at 45 SPL would yield a curve that differs in shape from a curve at threshold level. Because equal loudness curves are not yet available for bone conduction, caution should be exercised when trying to extrapolate mechanical coupler data to human experience at supra-threshold bone-conducted sound levels. Future perceptual studies should be conducted at a variety of bone-conducted sound levels to determine how these curves compare to one another and to determine how well these curves agree with those produced on mechanical couplers.

V. CONCLUSIONS

This paper described a free-field perceptual loudness calibration method for use with bone conduction transducers. The method was developed to address the needs of bone conduction calibration for communications applications, but it is flexible enough to be used for other applications as well. Intra- and inter-subject reliability was high, and data revealed sensitivity differences between the condyle and mastoid and between two different transducer models. The curves generated by the human subjects were, unsurprisingly, not well-represented by a standard mechanical coupler—a device designed to mimic skull impedance for a single transducer model at a single skull location. Human-generated curves are direct perceptual data and thus may give a more accurate representation of the human experience of bone conduction signals, especially for signals at supra-threshold levels, such as typical signals from bone conduction communication devices.

The free-field calibration method described in this paper appears both effective and simple to implement for calibration of communication bone conduction transducers. The method uses commonly available equipment, and the listener's task is straightforward. The method is flexible and can allow comparison among multiple skull locations and various bone transducer devices. Furthermore, the method yields data that directly represent the human perceptual experience. This practical and intuitive calibration method provides a means of comparing the effectiveness of different devices and locations and should facilitate the transfer of knowledge across different studies, researchers, and labs investigating bone conduction communication.

Future research could examine different playback levels and include other skull locations and bone conduction devices, perhaps with the aim of developing a body of human-focused data relevant to the use of bone conduction in communications. A better understanding of how different locations and devices compare is important for future development of optimized transducers for specific applications, headsets, and head locations. Future studies could also focus on individual differences to identify physiological features that need to be taken into consideration for efficient bone conduction communication.

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