Published in final edited form as:

Hear Res. 2010 May ; 263(1-2): 85–92. doi:10.1016/j.heares.2009.11.002.

Middle-Ear Function At High Frequencies Quantified With Advanced Bone Conduction Measures

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Abstract

Auditory thresholds with standardized clinical procedures are obtained over a much narrower frequency range by bone conduction than by air conduction. As a result, diagnostic information for both sensorineural and conductive-mechanism function is incomplete for high frequencies. A new magnetostrictive bone-conduction transducer that has the potential for improved output in the high-frequency range was evaluated in the laboratory and in a variety of subjects with normal hearing (N=11) or sensorineural hearing loss (N=9). Laboratory results indicated that harmonic distortion and acoustic radiation were both sufficiently low to allow accurate threshold measurements. Auditory thresholds obtained with this magnetostrictive bone-conduction transducer can be measured accurately under conventional clinical conditions for frequencies up to 16 kHz and levels up to 85 dB HL. These measures can be used to accurately characterize sensorineural hearing sensitivity for high frequencies and, when combined with standard air-conduction measures for high frequencies, to accurately characterize conductive-mechanism function for frequencies higher than possible with current diagnostic bone-conduction technology.

Keywords

High frequency; bone conduction; air conduction; magnetostrictive; conductive; sensori-neural

Introduction

Standardized auditory thresholds are measured clinically for frequencies only through 6 kHz by bone conduction, but up to 16 kHz by air conduction (ANSI-2004). This discrepancy exists because of the limited high frequency output available with existing bone conduction transducers. As a result, diagnostic information for both sensorineural and conductive mechanism function is incomplete for frequencies greater than 6 kHz.

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Incomplete sensorineural information for frequencies greater than 6 kHz limits understanding of cochlear function in the basal region of the cochlea. This lack of information can influence decisions for setting the high-frequency gain for conventional hearing aids, and may also influence decisions for using frequency transposition hearing aids that transpose high-frequency information to lower-frequency regions. This limited information also may influence candidacy decisions for hybrid cochlear implants, which are devices that electrically stimulate only the basal region of the cochlea.

Incomplete conductive mechanism information for frequencies greater than 6 kHz also limits our understanding of middle-ear function, and may influence decisions on surgical intervention for middle-ear surgery. This incomplete information also may affect validity of outcome measures of middle-ear surgical intervention.

Understanding hearing function for the high frequencies, both for sensorineural and conductive mechanisms, is taking on more interest for several reasons. First, it is now known that speech contains more high-frequency information than previously thought (Moore et al., 2008). Second, speech localization ability is influenced by high-frequency perception (Best et al., 2005). Third, speech perception in noise is influenced by high-frequency perception when the noise originates either from a single source (Horwitz et al., 2008) or from spatially-separated sources (Puria et al., 2008). New methods that allow more comprehensive understanding of high-frequency hearing function, both sensorineural and conductive, will be necessary when considering strategies to implement high-frequency amplification and other treatments for high-frequency hearing loss.

At least three types of technology can be used for a practical, clinical bone conduction transducer. Electromagnetic transducers are based on the concept that an electrical current creates a magnetic field that moves a magnetic rod back and forth. This technology is the basis of all current standard bone conduction transducers (Radioear B-71, B-72). The high-frequency output of these transducers is limited because of the inherent mass of the rod (Hakansson, 2003).

Piezoelectric transducers are based on the concept that an electrical current bends a flat plate back and forth if the material that makes up the plate has piezoelectric properties such as certain non-conductive crystals and ceramics. No piezoelectric transducers suitable for bone conduction measures are currently available commercially. The output in the high-frequency range is potentially large for a piezoelectric transducer because the plate can be designed to have a low mass.

Magnetostrictive transducers are based on the concept that an electrical current creates a magnetic field that bends a flat plate back and forth if the material that makes up the plate has magnetostrictive properties. Common materials such as nickel, iron, and cobalt have small magnetostrictive properties, but alloys made from terbium, dysprosium, and iron can have large magnetostrictive properties. The output in the high frequency region is potentially large for a magnetostrictive transducer as well, because the plate can be designed to have a low mass.

One commercially-available magnetostrictive transducer appropriate for bone conduction testing in humans is the TEAC HP-F100. This transducer is intended to be an alternative to high-quality stereo earphones for listening to music with an open external ear canal. Because of this it was designed to produce high vibratory output levels in the high-frequency range in a form factor appropriate for humans.

The purpose of this study was to determine if auditory thresholds by bone conduction for high frequencies can be measured accurately using this new commercial magnetostrictive technology. The intent was to determine if the technology could be used to accurately

characterize sensorineural hearing sensitivity for high frequencies and, when combined with standard air-conduction measures for high frequencies, to accurately characterize conductive-mechanism function for frequencies higher than possible with current diagnostic bone-conduction technology.

Materials and Methods

Laboratory Measures

Figure 1 shows the TEAC bone conduction transducer, its associated headband, and battery-operated electronics. Because this device was designed as a consumer product for listening to music, it does not match exactly the physical dimensions of the most widely used electromagnetic transducer (Radioear B-71) for standard bone conduction measures (ANSI-2004), also shown in Figure 1. The physical differences between the two transducers may be significant. First, the contact area of the TEAC is larger than the B-71 (4.15 cm² vs. 1.75 cm²). Second, the contact surface is slightly convex, not flat as specified by the standard. Third, the coupling force provided by the headband is controlled in a different way than the B-71 headband. Fourth, the TEAC transducer was designed to be applied to the zygomatic process rather than mastoid process. Finally, the TEAC transducer employs a specific battery-operated amplifier with an external input, as opposed to the Radioear transducers, that are passive and designed to be connected directly to any audiometer.

Because of these differences, the output force of the device should not be measured validly with a standard accelerometer called an “artificial mastoid”, nor can it even be properly coupled to our particular artificial mastoid, so an alternative measurement approach had to be devised. Figure 2 illustrates the laboratory apparatus that was used to measure the vibratory output of the transducer. The measurement setup employed a standard auditory research manikin (KEMAR). This manikin has removable pinnae and a hollow head, making it possible to couple the TEAC transducer over one ear position and aim a laser Doppler vibrometer (PolyTec OFV-3000/OFV-302) from the contralateral ear position, through the hollow head, and directly onto the surface of the transducer. A stiff plastic plate with a central hole (15 mm diameter) smaller than the contact surface diameter of the TEAC, along with a soft rubber plate (Shore OO Gauge, 70 Duro; www.sorbothane.com) having the consistency of skin, were placed between the transducer and the KEMAR opening. This arrangement allowed the transducer surface velocity to be measured under conditions somewhat similar to those of a human skull.

The transducer velocity was measured in a typical laboratory room (no sound treatment), using a custom measurement system (SYSid version 7.0) that both sent test signals to the TEAC transducer and measured responses with the laser Doppler vibrometer. Tones were generated at a constant voltage of −19.5 dB re 1-volt p (110 mV p) or −40.5 dB re 1 volt p (9.4 mV p), and the levels of the primary tone, 2nd harmonic, and 3rd harmonic were recorded.

All bone conduction transducers produce acoustic as well as vibratory energy. If the acoustic energy radiating from the bone conduction transducer can be detected by air conduction at a level above the bone conduction threshold, then the bone conduction threshold measures will be better than they should be, and therefore invalid. A calibrated probe tube (ER-7c) was placed near the body of the transducer to measure the acoustic radiation of this transducer under the laboratory measurement conditions. These acoustic measures were made only to determine if acoustic radiation was sufficiently low to proceed with measures on humans.

Measures on Humans

Hearing thresholds were measured behaviorally in a typical clinical setting (Acoustic Systems sound-attenuating test booth) with a conventional audiometer (GSI-61 with the high-frequency

option) by an experienced audiologist with a conventional method (5-dB step size). Thresholds were measured by air conduction from 250 – 16 kHz (Sennheiser HDA200 circumaural earphone, ANSI-2004, calibrated with a Larson Davis system with AEC101 IEC318 coupler), by bone conduction from 500 – 6 kHz (Radioear B-71, ANSI-2004, calibrated with a Larson Davis system with AMC493 coupler with an 11.4 dB correction at 4000 Hz to compensate for a well-known error in the standard for this transducer), and by bone conduction from 8 kHz – 16 kHz (TEAC). Because no standard existed for the new transducer, normal hearing subjects (N=5) were used to provide an initial estimate of 0 dB HL for the TEAC by varying both the gain of the TEAC electronics and the output of the audiometer. Once this value was obtained, the gain control on the TEAC electronics was fixed, and all signal levels were varied using only the attenuator on the audiometer.

The experimental subjects (N=9) consisted of patients in an Audiology clinic expected to have no conductive mechanism pathology, defined as having normal otoscopic findings, normal tympanograms at 226 Hz, and no conductive audiometric component from 250 Hz through 6 kHz as measured with standard procedures and the B-71 transducer. Because of these measures it was presumed that there was also no conductive component for frequencies greater than 6 kHz. No other restrictions were made in subject selection, so a wide range of sensorineural hearing levels, at least above 6 kHz, and a wide range of hearing sensitivity through 16 kHz were obtained.

An additional group of normal hearing subjects was used for control conditions. To verify the laboratory acoustic radiation measures, acoustic radiation directly from the transducer was measured again as subjects (N=3) wore the transducer while seated in a sound-attenuating booth (Acoustic Systems). The microphone of a precision sound level meter (Bruel & Kjaer, type 2235, with type 4176 1/2 inch microphone, and a 1/3 octave filter set) was located ~1 cm from the transducer on the side closest to the entrance to the external ear canal. To determine if the transducer signal reached the cochlea via pathways other than bone conduction, thresholds were measured both with and without blocking the external canal with either the circumaural earphone used for air conduction measures (N=3) or a foam, noise attenuating ear plug (N=2).

The Institutional Review Board of Stanford University under Protocol # 10676 approved the experiments involving humans.

Results

Transducer Electroacoustics

Figure 3 shows the output of the TEAC transducer (velocity in dB re 1 mm/s) as a function of frequency for a constant voltage at the two input levels of -19.5 dB re 1-volt p (110 mV p) and -40.5 dB re 1-volt p (9.4 mV p), as well as the noise floor of the laboratory measurement system. Because the two output curves were parallel and 21 dB apart as expected, the transducer is linear with input level over this range. The transducer output has a smooth response rising with frequency up to a primary resonant peak at ~7 kHz, and a smooth decreasing response (at least -30 dB/octave) above the primary resonant peak. Despite the rapid decrease in output above the resonant frequency, substantial output remained at higher frequencies, at least up to 16 kHz.

Measurement reliability was determined by repeating measurements made before and after removal and replacement of the transducer at the same location on the manikin. The velocity measures were repeatable to within 3 dB above 3 kHz, to within 5 dB between 800 Hz – 3 kHz, and greater than 5 dB below 700 Hz.

Figure 4 shows the levels of the 2nd and 3rd harmonics of the TEAC as a function of frequency for the same two input signal levels as in Figure 3. The maximum harmonic level was ~32 dB lower than the level of the primary, at ~2.3 kHz for the 3rd harmonic and at ~9 kHz for the 2nd harmonic, and much lower at other frequencies and for the lower input signal. This equates to a distortion level of less than 3%, and well within the specification of the ANSI standard for transducers used for auditory testing.

Range of Bone Conduction Thresholds

Figure 5 shows the individual hearing threshold results for each of the experimental subjects, in standard audiometric format. In general, the bone-conduction thresholds were similar to the air-conduction thresholds for either transducer. The specific pattern or shape of the bone conduction threshold curves obtained with the TEAC followed very closely the specific pattern or shape of the corresponding air-conduction threshold curves in the high-frequency region. The TEAC had sufficient output to measure thresholds up to 85 dB HL for at least some high frequencies.

Air-Bone Gap

A quantitative measure of conductive mechanism function is the difference between the thresholds for air- and bone-conduction, the “air-bone gap”. Figure 6. shows the air-bone gaps at each frequency for each subject, also in the standard audiometric format. Also shown are two horizontal lines, one representing the average air-bone gap when using the standard bone conduction transducer (frequencies through 6 kHz) and one representing the average air-bone gap when using the TEAC transducer (frequencies greater than 6 kHz).

The average air-bone gap for the standard transducer up through 6 kHz was +1.1 dB. This value is very close to zero dB, as expected for subjects with no conductive abnormalities.

The average air-bone gap for the TEAC transducer for frequencies greater than 6 kHz was -7.2 dB. This value is slightly larger in the negative direction than the expected 0 dB. This indicates that the initial calibration level for the high frequencies was fairly accurate. A reduction of 7.2 dB in the gain control on the TEAC electronics would bring this value to the expected 0 dB.

The standard deviation of the air-bone gaps across subjects for the thresholds less than 6 kHz (conventional transducer) was 3.6 dB. This value is less than the 5-dB step size used to obtain the thresholds. This level of variability is completely expected for conventional clinical measures.

The standard deviation of the air-bone gaps across subjects for the thresholds greater than 6 kHz (TEAC) was 6.7 dB. This value was almost twice as large as that for the lower frequencies. This increased variability may be due to a variety of factors. First, the air-bone gap measures may be influenced by the inherently more variable air-conduction measures. Second, there were several uncontrolled variables for the TEAC, such as contact surface area, coupling force, and a different location on the skull compared to the standardized measures. Regardless, this variability was still fairly small, and adequate for clinical purposes.

Transducer Acoustic Radiation

Figure 7 shows the direct acoustic radiation results for bone conduction signals delivered to the TEAC (filled circles) at 65 dB HL (except at 16 kHz where 45 dB HL was used) while worn by subjects (N=3). This signal level to the bone conduction transducer was selected to be high enough to produce measurable acoustic radiation above the much lower acoustic noise floor in the environment where the behavioral measures would be conducted. The mean acoustic radiation levels (open circles, ± 1 standard deviation) and noise floor (dashed line)

were measured in dB SPL, but converted to dB HL using minimal audible field values for 0 degree azimuth (ANSI-2004). The level of the acoustic radiation was 15 dB lower than the delivered bone conduction signal at 4 kHz, and much lower at all other frequencies. These acoustic radiation data measured in a quiet test booth were consistent with the acoustic radiation data measured in the laboratory and adds validity to the laboratory measures.

Acoustic radiation from the body of a bone conduction transducer can enter the external ear canal directly and, if at a sufficient level, can be detected via the normal air conduction route and result in an overestimate of the threshold and thus invalid bone conduction threshold. The acoustic radiation measures in Figure 7 suggest that the level of the acoustic radiation from the TEAC was not sufficient to cause this effect. To directly assess this route of acoustic radiation, bone conduction thresholds from 8 kHz through 16 kHz again were measured in normal hearing subjects (N=3) without conductive pathology under two conditions. In the first condition bone-conduction measures were made while the acoustic radiation from the transducer was allowed to enter the open external canal. In the second condition, the transducer acoustic radiation was blocked with the circumaural earphone used for air conduction testing. Compared to other types of earphone, a circumaural earphone is not expected to alter bone conduction sensitivity so the bone conduction thresholds were expected to be similar for the two conditions if the TEAC acoustic radiation did not influence the measures.

The results of blocking direct acoustic radiation are shown in Figure 8. The bone conduction thresholds were nearly identical for the two conditions in all three subjects. These results suggest that any direct acoustic radiation from the TEAC transducer did not substantially influence the measured bone-conduction thresholds in the high-frequency range.

Soft Tissue Acoustic Radiation

The transducer directly transmits mechanical energy to the cochlea but also can vibrate surrounding soft tissues in the lateral portion of the ear canal (Stenfelt, et al., 2003). The vibrating soft tissues in the external ear canal can produce acoustic signals that can then be transmitted to the cochlea by the usual air-conduction path. To directly assess this route, bone-conduction thresholds from 8 kHz through 16 kHz were measured in two subjects under two conditions. In the first condition the bone conduction measures were made while acoustic radiation from ear canal soft tissues was allowed to develop in the external canal. In the second condition the external ear canal was blocked with a typical foam, noise-attenuating plug that was expected to block the air-conduction signals resulting from the vibrating soft tissues in the canal. Though blocking the ear canal with this method does potentially increase bone-conduction sensitivity (the occlusion effect, e.g.), the effect is much more likely in the low frequencies than in the high frequencies. The bone conduction thresholds were expected to be similar for the two conditions if any acoustic radiation caused by the soft tissue vibration in the external canal was not influencing the measures. The results of blocking soft-tissue acoustic radiation are shown in Figure 9.

As expected, the plug worsened the air conduction thresholds by ~30 dB. However, the bone conduction thresholds again were nearly identical for the two conditions. Blocking the air-conduction energy resulting from vibration of the soft tissues in the external canal did not change the bone-conduction thresholds in the high-frequency range.

These limited preliminary data suggest that the TEAC transducer is capable of providing accurate high-frequency bone-conduction sensitivity measures that are not negatively influenced either by acoustic radiation directly from the transducer directly or from the vibrating surrounding soft tissues.

Discussion

Technology

Patents exist for magnetostrictive vibratory transducers (United States Patent 4986808, e.g.), and commercial versions are often used in many different disciplines such as acoustics, mechanical vibration, sonar, and underwater applications. However, there has been only a single report of their use for measures of bone conduction hearing sensitivity. An experimental magnetostrictive transducer was used to measure auditory brainstem responses in a rat model (Sakai et al., 2006). This study showed measures of skull vibration velocity using laser Doppler vibrometry that indicated that the magnetostrictive transducer was linear with signal input at 1 kHz and 4 kHz, and that the harmonic distortion was less than 0.1% at all frequencies. For this research application on small mammals, the high-frequency vibratory output was much greater compared to the traditional electromagnetic bone conduction transducer, with useable vibratory signals as high as 30 kHz. For a constant input voltage (1 V p) at 8 kHz, e.g., the vibratory output of the magnetostrictive transducer was over 30 dB greater than that of an electromagnetic transducer. Of course, the mass of the rat skull, and therefore its vibratory characteristics, is very different from that of a human skull, so these results may not be directly applicable to humans.

The laboratory measures on the magnetostrictive transducer used in the present studies indicated that the harmonic distortion and direct acoustic radiation were low enough to allow valid bone-conduction thresholds to be obtained. The thresholds obtained with the magnetostrictive transducer should represent only bone-conduction function, and not be influenced by the air-conduction sensitivity of the patient.

In subjects with no conductive abnormality, as reported here, the air-conduction sources will not affect the bone-conduction measures, because any effect automatically would be accounted for during calibration. The preliminary measures reported here indicate that acoustic radiation directly from the transducer body was not a major factor in cases with a normal conductive mechanism.

In subjects with a conductive mechanism abnormality (Stenfelt et al., 2002) however, any air-conduction signal from the soft tissues of the ear canal will reach the cochlea at a lower level, make the bone-conduction threshold worse than expected, and incorrectly reduce the air-bone gap. The preliminary measures reported here indicated that acoustic radiation from the soft tissues in the external ear canal also should not be a major factor.

These limited preliminary data suggest that the TEAC transducer is capable of providing accurate high-frequency bone-conduction sensitivity measures that are not negatively influenced either by acoustic radiation from the transducer directly or from the vibrating surrounding soft tissues.

Middle Ear Function

Standardized clinical measurements are adequate for assessing conductive-mechanism function for frequencies 6 kHz and below, but do not presently allow conductive-mechanism function to be evaluated at frequencies above 6 kHz. Though air-conduction measurements up to 16 kHz are already well established, bone-conduction measurements are limited to frequencies of 6 kHz and below, largely because of current bone-conduction transducer limitations. These limitations mean that measurements of the air-bone gap, which is the difference in dB between the air- and bone-conduction thresholds, are limited to frequencies 6 kHz and below. Given that the air-bone gap is a critical measurement for quantifying the functional status of the conductive mechanism, it is important to extend the frequency range of current bone-conduction measurements. With valid high-frequency air-bone gap

measurements as shown here, it will be possible to determine the functional status of the middle ear related to contemporary myringoplasty and tympanoplasty procedures, and test our hypothesis that guided surgical intervention may optimize air-bone gap deficits for frequencies above 6 kHz. Even if a small proportion of the transducer signal can reach the cochlea via pathways other than bone conduction and affect the absolute magnitude of the conductive component, relative changes in magnitude of the conductive component would still be useful for comparison of different surgical interventions.

An air conduction signal, particularly one originating in the sound field, also can reach the cochlea by bone conduction. However, based on direct measures (Reinfeldt et al., 2007), this bone conduction component is at least another 40 dB lower in this frequency range. The air conduction thresholds in the high frequencies measured with an ear phone are not likely to be artificially influenced by this bone conduction component. The data in Figure 9 suggest that a 30 dB change in hearing sensitivity in the high-frequency region, induced by an ear plug, was correctly attributed to a change in conductive mechanism function for the high frequencies.

Auditory thresholds obtained with a commercial magnetostrictive bone conduction transducer can be measured accurately under conventional clinical conditions for frequencies from 8 kHz up to 16 kHz, and for levels up to 85 dB HL. Though the variability of the resulting air-bone gaps was larger in this high-frequency region compared to the variability of the air-bone gaps measured with a conventional transducer at lower frequencies, it was still small enough to be useful clinically. A reasonable interpretation of the audiometric data in Figure 5 allows the conclusion that these subjects had no conductive component for frequencies greater than 6 kHz, as expected. Stated another way, conductive-mechanism function for the high frequencies was normal.

Speech has significant energy above the traditional 4 kHz range (Moore et al., 2008), and this energy is important for localizing speech (Best et al., 2005). It has been suggested that the high-frequency cues are important for hearing speech in the presence of spatially separated speech maskers (Puria et al., 2008), more commonly known as the “cocktail party” problem (Cherry, 1953). The ability to accurately determine high-frequency hearing capability should be very useful for explaining differences in spatial hearing ability.

Normally, the middle ear is well suited to transmit high-frequency cues to the cochlea (Ruggero and Temchin, 2002), largely due to the uniquely mammalian radial- and circumferential-fiber layers of the eardrum (Lim, 1970; Funnell and Laszlo, 1982; Fay et al., 2006), and the three middle-ear bones (Colbert and Morales, 1991). When the radial-fiber layer is interrupted, such as occurs from pathology or from surgical intervention, transmission at frequencies above 4 kHz is attenuated (O'Connor et al., 2008). With this understanding of how the middle-ear mechanism affects sound transmission, including at frequencies above 4 kHz, it is now possible to consider modifications of surgical procedures to better restore both low- and high-frequency middle-ear function.

Future Studies

The auditory performance of the magnetostrictive transducer for frequencies below 8 kHz was not investigated. If it were equal to the performance of the conventional bone conduction transducer in this frequency range, and it should be given the laboratory measures, then the magnetostrictive transducer could be used for the entire frequency range. If the auditory performance were not as good, then two transducers would be necessary to measure the entire frequency range clinically. More comprehensive studies are necessary to determine the feasibility of using this magnetostrictive transducer for the entire frequency range in actual human subjects with various known middle-ear conditions.

We did not control for sources of variability known to affect conventional bone-conduction measures, such as transducer contact surface area and coupling force. It is likely that these factors will be similar for magnetostrictive transducers compared to electromagnetic transducers. More comprehensive studies are necessary to determine the effects of these variables.

Variability in air-conduction thresholds is greater for high frequencies compared to the lower frequencies, and this increased variability was seen in the individual air-conduction thresholds in this study. More comprehensive studies are necessary to isolate the inherent variability of the high-frequency air-conduction thresholds from the variability of the high-frequency bone-conduction thresholds.

Patient selection was intentionally limited in this initial study. Future studies will involve measures on individuals with a more extensive range of hearing levels for sensorineural hearing loss, as well as a wide variety of conductive losses.

The air-conduction radiation component from the ear-canal soft tissue will be assessed in future studies that will involve subjects with known conductive pathology, and include direct measures of the acoustic signal at the tympanic membrane and in the ear canal due to vibration of the soft tissues in the external ear-canal.

Conclusions

Bone conduction thresholds obtained with a commercial magnetostrictive bone conduction transducer can be measured accurately under conventional clinical conditions for frequencies from 8 kHz to 16 kHz and levels up to 85 dB HL. Comparison of these thresholds to air-conduction thresholds allows accurate statements of sensorineural and conductive mechanism function for the high frequencies.

Acknowledgments

Supported by R-01 Grant No. DC 005960 from the National Institute on Deafness and Other Communication Disorders (NIDCD) of the National Institutes of Health (NIH)

Abbreviations

dB SPL	decibels sound pressure level re 20 μ Pa
HL	hearing level re ANSI-2004
V	volt
p	peak
Hz	Hertz

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Figure 1.

Left Panel: Commercially-available magnetostrictive bone conduction transducers mounted on a headband, with the associated electronics module. Right Panel: Standard bone conduction transducer (Radioear B-71) placed next to the magnetostrictive transducer for comparison.

Figure 2.
Setup for laboratory measures of the magnetostrictive transducer on KE-MAR.

Figure 3.

The output of the TEAC (velocity in dB re 1 mm/s) as a function of frequency for a constant voltage at two input levels, -19.5 dB re 1 V p (110 mV p) and -40.5 dB re 1 V p (9.4 mV p) as well as the noise floor of the measurement system.

Figure 4.
Levels of the 2nd and 3rd harmonics of the TEAC as a function of frequency for the same two constant input signals as in Figure 3.

Figure 5. Air-conduction thresholds (circles) and bone-conduction thresholds (triangles) for the nine individual experimental subjects. A standard bone conduction transducer (B-71) was used for frequencies up to 6 kHz (red triangles) and a new magnetostrictive bone conduction transducer (TEAC) was used for frequencies greater than 6 kHz (blue triangles).

Figure 6. Air-Bone gaps for the individual experimental subjects, using the standard bone conduction transducer (B-71), and the new magnetostrictive bone conduction transducer (TEAC).

Figure 7.

Signals at 65 dB HL (except at 16 kHz where 45 dB HL was used) were delivered to the TEAC (filled circles) while worn by subjects (N=3). The mean acoustic radiation (open circles, ± 1 standard deviation) and noise floor (dashed line) were measured in dB SPL, but converted to dB HL using minimal audible field values for 0 degree azimuth (ANSI-2004).

Figure 8. Effects of transducer acoustic radiation on air conduction (filled circles) and bone conduction (filled triangles) thresholds in three subjects with normal hearing. The bone-conduction measures were made while the acoustic radiation from the transducer was allowed to enter the external canal (red triangles), or was blocked with a circumaural earphone (blue triangles).

Figure 9.

Effects of soft tissue acoustic radiation on air conduction (filled circles) and bone conduction (filled triangles) thresholds in two subjects with normal hearing. Bone conduction measures were made while acoustic radiation from ear canal soft tissues either remained in the external canal (red triangles), or was blocked with a foam, noise-attenuating ear plug.