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Bone Conduction Communication: Research Progress and Directions

by Maranda McBride, Phuong Tran, and Tomasz Letowski

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14. ABSTRACT This report is a follow-on report to previous US Army Research Laboratory (ARL) work that served as a summary of bone conduction research that had been conducted to 2007 and provided a foundation for future research studies. Since then several more bone conduction communication studies—both external and by ARL—have been conducted to investigate the various characteristics of bone conduction communication systems. Progress has been made in understanding the nature of bone conduction hearing and speech perception, bone conduction psychophysics, and bone conduction technology. A number of bone conduction devices have been developed around the world, mostly outside of the United States; however, state-of-the-art bone conduction systems and bone conduction literature are not easily available due to their commercial limitations, trade restrictions, and military applications. However, there is still a scarcity of information about bone conduction in open literature and in trade magazines. In addition, information available in popular media outlets (e.g., TV, Internet, trade magazines) about the capabilities and physiological basis of bone conduction communication is frequently far from scientific scrutiny and leads to misinformation. This report provides a comprehensive summary of the state of the art in bone conduction communication technology applicable to the military. In addition, the report provides a list of current commercially available bone conduction devices, including pictures and short descriptions of their basic specifications.			
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1. Introduction

This report provides an update to an earlier report coauthored by Paula Henry and Tomasz Letowski in 2007 (ARL-TR-4138). Their technical report, *Bone Conduction: Anatomy, Physiology, and Communication*, provided a summary of bone conduction (BC) research that had been conducted to date to serve as a foundation for research studies to follow. The current report focuses on activities that took place from the year 2007 through 2015 with special focus on communication applications. Some general information provided in Henry and Letowski's report is briefly repeated here to allow the reader to follow this report without the need to consult the previous work to acquire new information.

1.1 Background

Both air conduction (AC) and BC pathways are used to transmit auditory signals for normal hearing and hearing impaired listeners. Although AC is the primary means by which individuals with normal hearing receive auditory signals, the transmission of sounds through BC is becoming more appealing in certain situations. This is because BC communication devices enable listeners to receive auditory communication messages concurrently with environmental hearing, allowing users to be alerted to potential dangers and enable them to estimate the distance and location of sound sources, which are critical components in situation awareness, safety, and spatial orientation processes. In addition, the BC pathway is a viable communication alternative for people wearing hearing protectors occluding their ears.

Since BC communication is a relatively new concept outside of the field of audiology, several field studies have been conducted to determine the effectiveness of devices used to transmit BC signals (Shachtman 2004). The results of these applied studies demonstrate the feasibility and viability of BC as a primary means of communication. More fundamental studies have also been performed to determine which head locations transmit BC pure tone signals to the cochlea the most efficiently (McBride et al. 2005; McBride et al. 2008) and identify BC perceptual differences that exist between male and female listeners (e.g., Hodges and McBride 2012). Since verbal communication is key to successful completion of many everyday tasks, most recent BC studies incorporated speech signals to assess speech intelligibility of various BC systems and system interfacings (McBride et al. 2008).

Most of the aforementioned studies suggest differences in the perception of bone conducted sound based upon where on the head the BC transducer is placed. For instance, McBride et al. (2005) and Tran et al. (2008) reported that out of 12 locations tested across the head, the locations closest to the ear and across the frontal region of the head resulted in the lowest pure tone hearing thresholds. The worst locations tended to be toward the back of the head and the fleshier regions of the head. The results of these studies also indicated differences based on the frequency of the sound transmitted. McBride et al. (2008) found that the intelligibility of bone-conducted vocal signals also tended to be affected by the location of the BC vibrator as well as the fundamental frequency of the voice being transmitted, particularly when the listener was located in a high noise environment.

1.2 Air Conduction vs. Bone Conduction Hearing

Hearing via AC is a sequential transmission process involving the outer ear, middle ear, and inner ear pathways. Initially, sound waves are captured by the pinnae and travel through the ear canal to the tympanic membrane separating the ear canal from the middle ear cavity. The tympanic membrane transforms sound waves into mechanical motion that cause the attached string of bones (a.k.a., ossicles) of the middle ear to vibrate. The sequential vibrations of the auditory ossicles (i.e., hammer, incus, and stapes) are transmitted to the inner ear through its oval window and ultimately create motion of the fluids within the cochlea. The movement of cochlear fluids causes the movement of the basilar membrane (BM) located within the cochlea and stimulates the sensory hair cells found inside the organ of Corti resting on top of the BM (Stenfelt and Håkansson 2002). The hair cells transduce the mechanical signals into electrical nerve impulses that travel through the auditory nerve to the brain.

The BC transmission process is more complex to describe than the AC process and involves several parallel pathways. Not all of the mechanisms involved in BC hearing are fully understood and there are disagreements in the literature regarding the dominant pathways of BC sounds; therefore, only a brief general overview is provided here. A more complete description of pathways and processes involved in BC hearing and related disagreements is given in Section 2, Bone Conduction Physiology.

When a person is in a strong acoustic sound field, sound waves arriving to the head can cause the skull bones to vibrate. These vibrations can be transmitted to the inner ear through the temporal, parietal, occipital, and frontal bones as well as through the jaw, cartilage, and soft tissue. As a result, the cochlea and vestibular system are mechanically stimulated (e.g., by compression and decompression of the cochlear cavity and the inertia of the inner ear fluids), which may cause displacements of the BM and activation of the hearing organ (von Békésy 1960; Tonndorf 1966). The additional processing of auditory information by the ear is the same as in the case of AC hearing, although direct vibratory stimulation of the cerebral cortex may also play a role (Stenfelt 2011).

Another mechanism to induce vibrations of the skull bones—aside from airborne sound waves impinging on the head—involves applying vibrations directly to the head using a BC transducer as a sound source. Such BC stimulation is frequently referred to as direct stimulation as opposed to indirect stimulation caused by a sound field. In this case, the vibrating device is either placed on the head using some type of headband or adhesive (transcutaneous coupling) or attached directly to the mastoid bone via a surgical procedure (percutaneous or bone-anchored coupling). Both types of coupling are commonly used in BC hearing aids—transcutaneous coupling since 1930s and percutaneous coupling since 1980s. Due to the invasive nature of percutaneous coupling, only transcutaneous coupling is used outside of the field of audiology. In both cases of coupling, vibrations from the BC vibrator cause all of the skull bones to vibrate similarly as in the case of sound field stimulation. However, when a BC vibrator is used, the relative strength and direction of vibrations in various parts of the head differ depending on the point upon which the transducer is placed.

1.3 Bone Conduction Sound Perception Research

Numerous BC sound perception studies have been conducted by various research groups within academia, government, and industry; however, the results of some of these studies, especially BC communication studies, have only been published in conference proceedings and documents with limited distribution such as internal industrial documents and military reports. Among such newer studies were those involving the investigation of the properties of signals transmitted via BC vibrators as well as those received from the skull using BC microphones. One of the first modern studies included in the Henry and Letowski (2007) review was McBride et al. (2005) (ARL-TR-3556). This study sought to find the optimal placement of a bone vibrator on the head, which was defined as the location on the skull that was most sensitive to bone vibrator signals (McBride et al. 2005). ARL-TR-3556 set the stage for many of the BC studies that followed.

Much of the nonmedical BC studies reviewed by Henry and Letowski (2007) used single frequency tones as signals. However, in the real world, most sounds are complex (i.e., composed of a spectrum of frequencies). One of the most important sounds transmitted between humans is speech. In BC radio communication, sound quality and intelligibility of speech depend not only on the technical parameters of the BC transducer but also on the placement of the vibrator at or on the head of the communicating person. For several of the speech communication studies that followed ARL-TR-3556 (McBride et al. 2005), the optimal BC vibrator locations identified in the US Army Research Laboratory (ARL) report (e.g., the mandibular condyle and mastoid) served as the primary locations tested (McBride et al. 2008; Osafo-Yeboah et al. 2009; Hodges and McBride 2012). Furthermore, several investigations have taken place over the last 9 years to investigate other factors that are believed to have an impact on the perception of BC sound. For instance, studies have been conducted to investigate the differences associated with the location of the BC transducer (Osafo-Yeboah et al. 2009), gender of the listener (McBride et al. 2008; Hodges and McBride 2012), gender of the talker (in the case of BC microphones) (Tran et al. 2008; McBride et al. 2011; Pollard et al. 2015), and type and level of background noise (Gripper et al. 2007; Osafo-Yeboah et al. 2009; Tran and Letowski 2010).

In addition to pure tone and speech intelligibility/quality studies, there have been studies investigating the ability of listeners to localize sound using virtual locations of BC signals (Walker et al. 2005; Stanley and Walker 2006; McBride et al. 2012a; McBride et al. 2015). Other studies have investigated the ability of listeners to differentiate and isolate the sound coming from a BC transducer (Blue et al. 2013; McBride et al. 2013), BC equal-loudness contours (Patrick et al. 2014), and equivalency ratios (Patrick et al. 2012). In addition, some studies addressed not only transmission of the BC signals to a listener's head but also from the talker's head and investigated effectiveness of various placements of a BC microphone on the head (Tran et al. 2008, 2013). The results of these studies can be used to determine the conditions under which BC communication devices can be used most effectively.

1.4 Purpose of this Report

The previous analysis of the state of the art in BC communication devices (Henry and Letowski 2007) revealed that there were several areas in both basic science and technology development that required further progress to develop robust, dependable, and sufficiently sensitive BC technology for military communication applications. Over the years some progress has been made in understanding the nature of BC hearing and BC psychophysics. A number of new BC devices have been developed around the world, mostly outside of the United States. However, relevant documentation is not easily available due to their linguistic diversity, commercial limitations, trade restrictions, and military applications. In addition, information available in popular media outlets (e.g., TV, Internet, trade magazines) about the capabilities and physiological basis of BC communication frequently has not undergone scientific scrutiny, which can lead to misinformation. Therefore, a serious roadblock for future progress in developing an effective and economical BC communication systems to be used by the US Army is the lack of an easily accessible, comprehensive source of scientific information about this technology. Having and sharing such an aggregated summary by US Army researchers, in collaboration with their academic and industrial partners after receiving feedback from Soldiers, who have used the technology is critical for full utilization of secure and dependable BC communication in military operations. In addition, since it is possible that some of the conclusions resulting from single studies could contradict one another, a thorough and critical discussion of the research conducted to date will aid in directing future research efforts. This report is intended to provide such a comprehensive and critical summary of various domains of BC research and development with special focus on the research that has taken place from 2007 through 2016.

2. Bone Conduction Physiology

Understanding the physiology of BC hearing is not only essential for hearing diagnosis and treatments but also for improving the effectiveness of BC communication technology. While it has been accepted that both AC and BC processes stimulate the hearing organ in the cochlea, BC is a complex mechanism that comprises a multitude of pathways and many elements of this mechanism are not yet clear (e.g., degree of nonlinearity of the transmission system, range of perceived frequencies, and degree to which BC transmitted information directly affects the auditory centers in the brain). Moreover, there is no consensus in the literature regarding the contribution of BC mechanisms in perception of microwave signals.

The anatomy of the auditory system as well as the knowledge about BC physiology that was available at the time has been described in the ARL technical report ARL-TR-4138 (Henry and Letowski 2007). This section summarizes information described in that technical report and provides updates regarding BC physiology based on new discoveries and on some older reports that have become more relevant with new discoveries.

2.1 Auditory System

The auditory system involves 2 ear mechanisms (right and left) that are connected to the brain through a network of neural fibers called auditory fibers. Auditory fibers form a pair of auditory nerves (left and right) with several crossover connections (bridges) at various levels of the nervous system. Each ear mechanism consists of 3 major parts: the outer (or external) ear, the middle ear, and the inner (or internal) ear. These 3 parts are sequentially connected and form the AC pathway of sound reception, which is the main auditory mechanism in humans. The AC pathway starts with the pinna (auricle) of the outer ear that collects the sound and directs it toward the ear canal (external auditory meatus) terminated by the tympanic membrane (eardrum). The pinna also alters the incoming sound depending on the angle of its incidence, modifying its spectrum and forming one of the major auditory localization mechanisms.

The ear canal is an S-shaped tube with an average length of about 22 mm and volume of about 1 cm^3 (Wever and Lawrence 1954). The structure of the ear canal has resonance capabilities and together with sound reflections from the upper torso provides about 5- to 20-dB amplification of the incoming sound in the frequency range between 1500 and 7000 Hz (Henry and Letowski 2007). The actual amount of amplification and the shape of the amplification function depend on the direction of incoming sound. The walls of the ear canal are lined with a layer of skin and the most external part is covered with hairs and mucous glands that protect the ear from small foreign objects entering the ear canal. The outer one-third of the canal is surrounded by cartilage, and the inner two-thirds of the canal is surrounded by the temporal bone. The cartilaginous portion of the ear canal has thick skin that is approximately 0.5–1 mm in thickness and contains a well-developed dermis and subcutaneous layer. The bony inner portion of the ear canal is lined with very thin skin that is continuous with the external layer of the tympanic membrane. The tympanic membrane closing the ear canal separates the outer ear from the middle ear. An airborne sound arriving to the ear travels along the ear canal toward the tympanic membrane and sets the membrane into mechanical vibrations that are transmitted into the middle ear.

The middle ear is an osseous (bony) cavity, 2 cm^3 in volume (Dallos 1973; Yost and Nielsen 1977), situated in the temporal bone and adjacent to the mastoid process. The cavity is filled with air and contains a chain of 3 ossicles (bones) called the malleus (hammer), incus (anvil), and stapes (stirrup) along with their supporting muscles and ligaments. The malleus is attached to the eardrum and the footplate of the stapes is suspended over the oval window of the inner ear. The air pressure in the middle ear cavity is controlled by the Eustachian tube, which is connected to the nasopharyngeal (nasal) cavity. It serves as a vent equalizing the air pressure in the middle ear to the outside atmosphere and as a drainage system for disposing excess middle ear secretions into the nasopharynx (throat).

The main function of the middle ear is to convert mechanical vibrations of the tympanic membrane into vibrations of the oval window, which is the entry point of the AC pathway to the fluid-filled inner ear. These vibrations are transmitted through the chain of ossicles, which together with different sizes of both membranes (eardrum and oval window) act as a matching transformer between the outer ear and the inner ear and provide about 35 dB of amplification of the pressure transmitted through the system (Henry and Letowski 2007; Møller 2013). The middle ear also constitutes some form of a protective mechanism for the inner ear. It dampens very loud sounds by contracting the muscles and making the ossicular chain more rigid and less able to transfer sound between the eardrum and the oval window of the inner ear. This response of the middle ear to loud sound is known as the acoustic reflex and it is most effective at reducing the transmission of low frequency sounds (Pickles 1988).

The inner ear is a home of 2 sensory organs: the organ of hearing and organ of balance (vestibular system). It consists of a complex series of connected bony tubes forming the bony labyrinth located in the petrous (hard) portion of the temporal bone. The bony labyrinth has an overall volume of about 200 mm^3 (Buckingham and Valvassordi 2001) and is filled with an incompressible fluid called perilymph that is similar to the intercellular fluid (i.e., fluid occupying space between cells). The bony labyrinth is filled with a series of membranous tubes called membranous labyrinth. The membranous labyrinth is filled with another incompressible fluid called endolymph that is similar to the intracellular fluid, (i.e., fluid filling the cells). The main parts of the inner ear (membranous labyrinth) are the semicircular canals, utricle, saccule, and cochlea. The utricle, saccule, and semicircular canals are part of the vestibular system responsible for balance. The cochlea serves as the end organ for hearing.

The cochlea is a snail-shaped shell twisted around a bony pillar called the modiolus through which the auditory nerves and blood vessels enter the cochlea. The larger end of the cochlea is called the base, which is terminated by the oval and round windows. The smaller end is called the apex. The diameter of the base is about 9 mm and the diameter of the apex is about 5 mm. The uncoiled length of the cochlea is about 32 mm. The cochlea is divided into 2 canals called scala vestibuli and scala tympani. The scala vestibuli originates at the oval window, and the scala tympani terminates by the round window. Both the scala vestibuli and scala tympani are filled with perilymph and are connected to each other at a narrow opening at the apex of the cochlea called helicotrema. Scala tympani is also connected to the cerebrospinal fluid (CSF) of the subarachnoid space of the brain by the cochlear aqueduc*t*. Between scala vestibuli and scala tympani also exists another parallel channel called the cochlear duct or scala media. The scala media is a triangular channel filled with endolymph (as opposed to the scala vestibule and scala tympani that are filed with perilymph) and terminates at the helicotrema. The scala media is separated from the scala vestibuli by the vestibular membrane and is separated from the scala tympani by the BM. The structure of the inner ear and the positions of all its channels (ducts) are shown in Fig. 1.

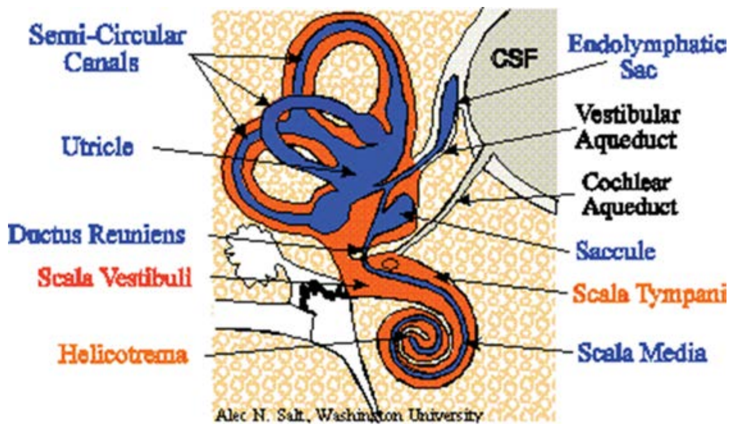

Fig. 1 The structures of the inner ear. Endolymph is in blue and perilymph is in orange color. Reprinted with permission from Washington University in St. Louis [accessed 2017 Mar 24] http://oto2.wustl.edu/cochlea/intro1.htm.

The BM is the anatomical base of the organ of Corti. The organ of Corti contains the vibration receptors (hair cells) distributed along the BM and connected to neural fibers. Individual hair cells and their associated nerves respond to one specific frequency with frequency scale tonotopically distributed along the BM. The cross section of the cochlea and the structure of the organ of Corti are shown in Fig. 2.

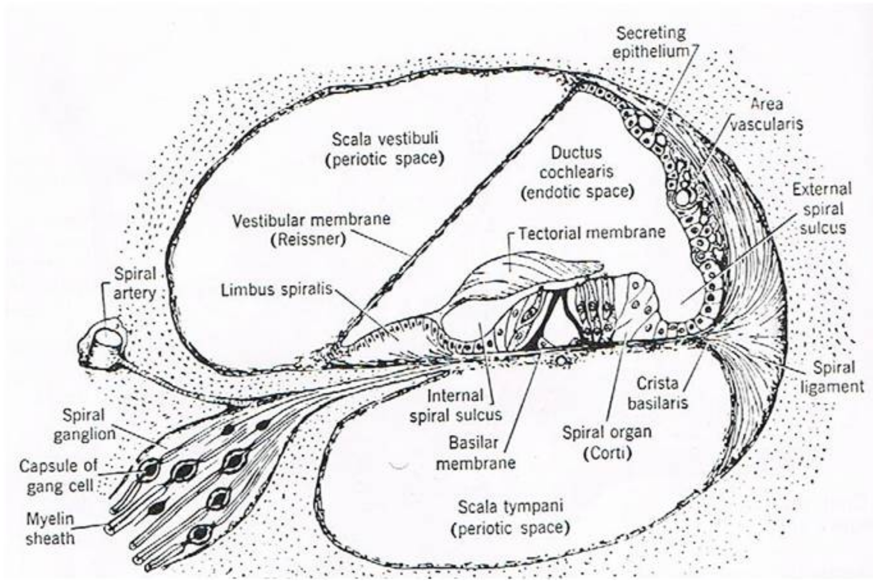

Fig. 2 Cross section of the cochlea. The organ of Corti is located on the basilar membrane in the Scala media ductus cochlearis. (Stevens 1951).

When an auditory stimulus arrives at the oval window, it sets the perilymph in the scala vestibule into motion. When the oval window is pushed toward the cochlea, the incompressible fluid in the scala vestibuli is pushed through the helicotrema to the scala tympani, which causes an outward motion of the round window. When the oval window is pulled away from the cochlea, the round window membrane of the scala tympani is moved inward toward the cochlea. The delayed movements of the fluid in the scala vestibuli and scala tympani create pressure differentials between the channels causing the BM to move perpendicularly back and forth to accommodate the push-pull action of both windows. The movement of the BM looks like a wave of varying amplitude—rising first and decaying later—moving along the length of the membrane and is called the traveling wave. The maximum displacement of the BM (traveling wave) along its length coincides with the location of the hair cells of the organ of Corti that are tuned to the frequency of the sound causing the movement. The movement of the hair cells results in a chemical action within the cell that triggers neural activity. The neural impulses are then transmitted to the brain through the auditory nerve to be perceived as sound. Thus, the BM together with the organ of Corti serves as the hearing mechanism that converts mechanical vibrations of the cochlear fluids (perilymph) into neural impulses.

2.2 Head Anatomy and Vibration Modes of the Skull

The human head can be approximated by a spherical shell with a radius of about 12.5 cm (Wismer and O’Brien 2010). The structure of the head comprises the skull (bony part), cartilage, and various types of soft tissue and fluids. The skull consists of 2 major parts: the cranium (cranial bones) that protects the brain and the facial bones that support the face and mouth. The cranium consists of 8 bones—1 occipital bone, 2 temporal bones, 2 parietal bones, 1 sphenoid bone, 1 ethmoid bone, and 1 frontal bone—that surround the fluid-filled space occupied by CSF and brain tissue. All cranial bones are covered with subcutaneous tissue and skin on the outside. The temporal bone, where the inner ear is located, forms the lower side of the skull and has a thicker and denser structure than other bones to protect the inner ear from damage. The facial skeleton consists of 14 bones that occupy the lower frontal part of the head. They are the vomer, 2 nasal (inferior) conchae, 2 nasal bones, 2 maxilla, the mandible, 2 palatine bones, 2 zygomatic bones, and 2 lacrimal bones. All of the cranial and facial bones of the skull, except for the mandible (jawbone), are connected together by flexible fibrous seams called sutures. The basic structure of human skull is shown in Fig. 3.

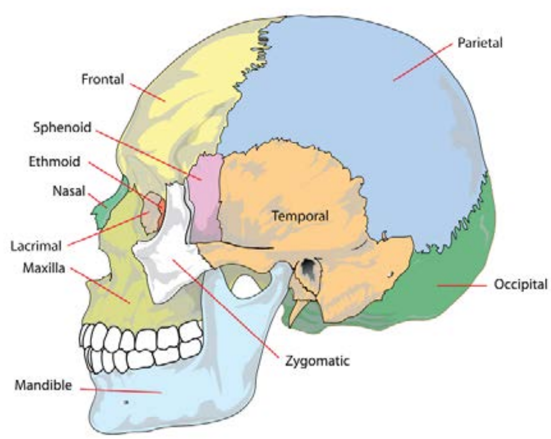

Fig. 3 Human skull bones. (Reprinted from LadyofHats Mariana Ruiz Villarreal; 2007 Jan 4 [accessed 2017 May 11]. https://commons.wikimedia.org/wiki/File:Human_skull_side_simplified_(bones).svg.

Soft tissue of the head is generally divided into head tissue and facial tissue. Based on this division, head tissue includes brain tissue, meninges tissue (dura mater), and scalp tissue, while facial tissue includes skin, face muscles, oral cavity, tongue, cartilage, and ligaments. Nerves and blood vessels support both types of soft tissue. Mechanical properties of soft tissue are very diverse and depend on a person’s age, gender, race, and body condition (Robetti et al. 1982). Together, the bones and soft tissue of the head form the musculoskeletal system of the head and all these elements are, to some degree, involved in processing BC signals.

It has been generally accepted that vibration of the skull is the main mechanism by which BC sounds are heard although there is recent evidence that transmission through soft tissue may be equally important. Due to complexity of the skull structure and the elasticity of the sutures connecting individual bones, skull vibrations are characterized by several modes of vibrations, resonances, and antiresonances (standing waves). The behavior of these characteristics depends on the direction of the applied force. von Békésy (1932, 1960) applied external vibration to the forehead and observed that at low frequencies where the wavelengths are longer than the dimension of the head, the skull moves as a whole in the direction of the applied force. In this frequency range, the skull behaved as a spherical shell with uniform wall thickness despite anatomical variation among all the skull bones. The back-and-forth movement of the skull as a rigid structure is referred to frequently as an inertial mode of skull vibrations. At higher frequencies, the skull vibrates with various compressional modes. The complexity of these modes increases with frequency. In a compressional mode the bones on the opposite sides of the head move toward and away from each other. Both von Békésy (1932) and Kirikae (1959) observed that at around 800 Hz the skull vibrates as 2 segments moving in opposite directions and at about 1600 Hz the skull vibrates as a combination of 2 perpendicular compression vibrations (as 4 segments). The frequencies 800 Hz and 1600 Hz correspond roughly to the 2 lowest resonances of the human head (Zwislocki 1953; Tonndorf and Jahn 1981; Håkansson et al. 1986) although a large variation among people regarding frequencies of these resonances exist (Håkansson et al. 1994). For a dry skull, Franke (1956) reported the lowest resonance frequency to be 820 Hz for 6 people with skin penetrating titanium implants while Håkansson et al. (1994) reported the average 2 lowest resonances as 972 and 1230 Hz.

Håkansson et al. (1986) measured head vibrations in 7 people and found that the first skull antiresonance varies among people, ranging between 100 and 350 Hz. It is also the most prominent skull antiresonance that is most likely responsible for the lateralization effect observed in several studies (e.g., Stenfelt et al. 2000). The lateralization effect refers to situations where BC stimulation at a mastoid results in greater response in the contralateral than ipsilateral ear. Another antiresonance of the head observed by some investigators at around 2000 Hz is most likely attributable to the resonant properties of the ossicular chain. The decrease in BC threshold around 2000 Hz (called "the Carhart notch") is the clinical sign of stapes fixation (Carhart 1950, 1971; McConnell and Carhart 1952; Linstrom et al. 2001).

2.3 Bone Conduction Hearing

BC hearing is the other manner by which the hearing organ in the cochlea can be activated. It involves sound transmission in the head through the vibration of the skull, cartilage, soft tissues, and body fluids rather than only through the ears. Such head vibrations can be triggered globally by strong sound waves acting on the head or locally by one or more electromechanic actuators (vibrators) applied at some points to the head. In the case of airborne sound stimulation, BC is generally a secondary mechanism of sound transmission supplementing the AC mechanism since the impedance mismatch between the air and the skull makes the BC contribution negligible compared to that of AC. According to Reinfeldt et al. (2007), the sound field BC sensitivity is below AC sensitivity by about 50–60 dB at frequencies lower than 1 kHz or higher than 2 kHz and about 40–50 dB in the 1- to 2-kHz range.

The transmission process by which head vibrations are transmitted to the cochlea is typically referred to as the BC pathway and actually consists of several different mechanisms by which the head vibrations can reach and act on the cochlea. These mechanisms involve both osseous (bone) and non-osseous (soft tissue) pathways. Some authors have questioned the validity of the term BC for describing both types of transmission (de Jong et al. 2012; Adelman and Sohmer 2013). In addition, one form of sound conduction to the cochlea—cartilage conduction (CC)—was recently argued to be substantially different from both AC and BC transmission and proposed to be treated as the third main transmission pathway (Nishimura et al. 2014). In the present overview, all of these non-AC pathways are referred to together as the BC pathway regardless of the type of the physical matter involved in the transmission. One reason for such an approach is that the term BC pathway has been traditionally used as an overarching term for all auditory mechanisms other than the AC pathway alone (Barany 1938; Tonndorf 1966). Another reason is that some underlining BC processes are qualitatively the same in various transmitting matters. The use of a single term BC pathways for all non-AC mechanisms of auditory reception does not deter from discussion of all mechanisms involved in BC processes, but allows for a more comprehensive overview of all processes.

In theory, the cochlea and hearing organ may be stimulated by vibrations applied to any part of the human body. However, the attenuation of sound energy by the human body is very high—except for vibrations of very low frequencies (<100 Hz)—and effective stimulation of the hearing organ by vibrations applied at points distant from the cochlea is not very likely. Moreover, low frequency vibrations are primarily received as tactile stimulation and, at higher intensities, as harmful body vibrations (e.g., arm vibration or whole body vibration) before they activate the organ of hearing, if they activate it at all. In this context, while low-level tactile stimulation is not harmful, it can confound BC auditory perception in the low-frequency range of 20–100 Hz. In this frequency range, vibrations can produce both tactile and auditory sensations and it is important to differentiate between both types of sensations in studies of BC audition (Henry and Letowski 2007).

There is multifaceted experimental evidence that both AC and BC stimulation lead to the same general process in the cochlea where mechanical vibrations of the BM are converted into neural impulses (von Békésy 1932; Lowy 1942; Gelfand 1991). In one type of experiment, the cochlea was simultaneously stimulated by AC and BC stimuli of the same frequency and the effect caused by one stimulus was cancelled by the presence of the other stimulus by adjusting its intensity and phase (von Békésy 1932; Khanna et al. 1976; Stenfelt 2007, 2011; Ogiso et al. 2015). For example, Stenfelt (2007) conducted such cancellation experiments at 2 frequencies (0.7 and 1.1 kHz) and 3 levels (40, 50, and 60 dB [hearing level] HL). The results of these studies indicate that AC and BC pathways similarly excite the membrane and that both transmission systems, including BC skin transmission (Håkansson 1984), behave as linear systems (Håkansson et al. 1996). Nonlinear behavior of BC sound observed earlier by Khanna et al. (1976) and Arlinger et al. (1978) was most likely due to indirect rather than direct measurements of skull vibrations. In another type of experiment, direct measurements of the BM's motion revealed similar excitation patterns regardless of the pathway of sound transmission (Stenfelt et al. 2003). Further, electro-physiology measures, such as brainstem audiometry, give similar results for AC and BC stimulation despite global differences in latencies and amplitudes of evoked responses (Mauldin and Jerger 1979; Hernandez et al. 2008; Rahne et al., 2010). In still another type of experiment, recordings of distortion-product otoacoustic emissions generated in the ear were shown to be very similar for AC and BC stimulations in some subjects (Collet et al. 1989; Purcell et al. 1998; Clavier et al. 2010; Kandzia et al. 2011).

Although the basic mechanism of auditory perception by which vibrations of the BM are converted into electrical (neural) activity of the hair cells seems to be the same in AC and BC hearing, there are some differences in perception of both types of sound. The main difference between AC and BC hearing is the way the cochlea receives stimulation. In the AC pathway, sound travels through the ear canal and vibrates the tympanic membrane. The sound then travels across the ossicular chain, and moves the stapes against the oval window of the cochlea and subsequently vibrates the cochlear fluids and BM. In the BC pathway, the head components vibrate in various directions, depending on the direction of the excitation and mode of vibration, whereas the stapes remains steady or vibrates with an inertial time lag. Vibrations induced in the human head reach the cochlea through several BC mechanisms (pathways), which to a varying degree contribute to the final auditory sensation. The roles of specific mechanisms are the objects of several theories of BC hearing and are still a matter of debate.

The described difference in AC and BC pathways seems to also be responsible for some differences in perception of AC and BC sound. For example, there are reports (Watson and Frazier 1952; Stenfelt and Håkansson 2002; Stenfelt and Zeitooni, 2013b) indicating that at low and low-medium frequencies (<1000 Hz) the loudness of BC sound increases faster than that of AC sound. This difference has been credited to multipath transmission of BC sound as opposed to differences in the excitation of the BM. A similar multipath transmission explanation is offered for some differences observed in the AC and BC auditory brainstem response (ABR) and otoacoustic emissions despite the overall similarity in both types of transmission. Latencies of BC ABR are generally longer in the adult population—although shorter in infants (Yang et al. 1987)—than AC ABR responses due to delayed transmission of BC vibrations to the cochlea (Mauldin and Jerger 1979; Boezeman et al. 1983; Sohmer and Freeman 2001). The BC ABR is also dependent on the vibrator location on the skull (de Freitas et al. 2006; Small et al. 2007) and exhibits binaural interaction due to low intracranial attenuation of vibrations (Setou et al. 2001).

Another difference in auditory perception of AC and BC sounds is human ability to hear amplitude-modulated electromagnetic signals through BC. This phenomenon can be explained by the electrostrictive properties of skull bones that begin to vibrate when subjected to sufficiently strong alternating electric fields in frequency ranges from the tens to hundreds kHz (Deatherage, et al. 1954; Tonndorf and Kurman 1984; Lenhardt et al. 1991). Similarly, auditory perception of microwaves can be explained by the thermoelastic expansion of human tissue (Foster and Finch 1974; Röschmann 1991; Elder and Chou 2003). Much more puzzling is the human ability to hear through BC auditory signals of ultrasound frequencies up to about 100 kHz (Corso and Levine 1963; Lenhardt et al. 1991). Several hypotheses of bone-conducted ultrasound (BCU) perception have been proposed but there is no consensus yet regarding how these signals are ultimately received by humans. Some authors believe that ultrasound signals are received through the cochlea (Nishimura et al. 2003) while others argue that ultrasound stimuli are received by another separate reception mechanism such as the vestibular system (Lenhardt et al. 1991). More detailed discussion of BCU hypotheses is presented in Section 2.6.

In respect to the theories of BC hearing, most of the hypotheses are based on a seminal publication by Herzog and Krainz (1926) and subsequent work by von Békésy (1932), Barany (1938), Kirikae (1959), and Tonndorf (1966, 1968), although some BC mechanisms have been discussed in the literature even earlier (Rejtö 1914). Herzog and Krainz (1926) proposed that BC hearing results from the combined effects of the inertial motion of the middle ear ossicles caused by head vibrations and the compressional waves in the cochlea caused by vibrations through the skull. Georg von Békésy (1932) was the first to demonstrate that both AC and BC hearing result from the same excitation of the BM in the cochlea. He also emphasized the role of the ear canal in BC hearing when the ear canal is closed. In these cases, the ear canal serves as a sound amplifier.

Tonndorf (1966, 1968) conducted a series of comprehensive studies on animals and identified 8 specific mechanisms that contribute to auditory perception of BC sounds. These mechanisms are associated with direct transmission of vibrations to the inner ear and with indirect transmission of vibrations through AC sound involving the outer and middle ears. The 8 mechanisms identified by Tonndorf are as follows:

A. Direct mechanisms

    1) Alteration of the cochlear space

    2) Inertia of the cochlear fluid

    3) Mobility of the round window

    4) Mobility of the oval window

    5) Cochlear aqueduct compliance (“third window” effect)

B. Indirect mechanisms

    6) Acoustic radiation into the ear canal

    7) Inertia of middle ear ossicles

    8) Compliance of the middle ear cavity

Tonndorf (1968) considered mechanisms 1, 2, and 6–8 as the primary mechanisms of BC hearing and mechanisms 3–5 as playing some but a less important role in such hearing. The basic mechanisms identified by Tonndorf (1966) result from 2 basic modes of skull transmission that operate at low and high frequencies: inertial mode, in which the skull vibrates as a unit, making oscillatory movements in the direction of the force, and compressional mode, in which the skull is divided into parts that vibrate in opposite directions, making pulsating movements.

Later discoveries have shown that BC sound stimulates not only the sense of hearing but also sense of balance (saccule of the vestibular system) (Cazals et al. 1983; Welgampola et al. 2003) and this stimulation emphasizes the role of the vestibular aqueduct in BC hearing. Similarly, the discovery of pressure transmission from the CSF to the inner ear emphasizes the role of the cochlear aqueduct in the process of hearing BC sound. Finally, CC has been identified as a new useful mechanism for stimulation of the cochlea (Hosoi et al. 2010; Nishamura et al. 2014). The authors reported that clear sound can be heard when a vibrator is applied to the aural cartilage (e.g., tragus) and the CC auditory threshold is lower than the corresponding BC threshold.

The most recent comprehensive papers on BC physiology were by Stenfelt and Goode (2005a) and Stenfelt (2011). In these papers, the authors listed and summarized 5 mechanisms considered by them as the most important components of the BC pathway that contribute to sound perception. These mechanisms correspond to mechanism 1, 2, and 5–7 in Tonndorf's (1968) list if modern theory of mechanism 5 is taken into consideration. According to the authors, the 3 most important mechanisms among them are cochlear fluid inertia, middle ear ossicle chain inertia, and acoustic radiation in the ear canal when the ear canal is occluded.

Obviously, not everybody agrees regarding the relative importance of specific BC mechanisms or even their existence. For example, Brinkman et al. (1965) argued that the inertial movement of the ossicular chain is the main contributor to BC hearing while Allen and Fernandez (1960) believed that the only significant BC mechanism is the direct stimulation of the cochlea walls by vibrations. In addition, there is still confusion regarding how to classify some of the mechanisms contributing to BC hearing (Stenfelt and Goode 2005a), especially mechanisms involving the cochlear and vestibular aqueducts. Nevertheless, the complex and multipath character of BC is generally accepted. These multiple BC pathways sum up at the inner ear, resulting, as with the AC pathway, in the difference between the pressure in the scala vestibuli and the scala tympani causing motion of the BM and the organ of hearing, which is attached to it. This motion subsequently produces auditory neural impulses to be sent to the brain. A diagram of AC and BC pathways showing various BC mechanisms potentially involved in sound transmission is shown in Fig. 4. Neither feedback nor regulatory mechanisms are shown in the figure. The primary BC mechanisms are shown in Fig. 4 and described in Section 2.4

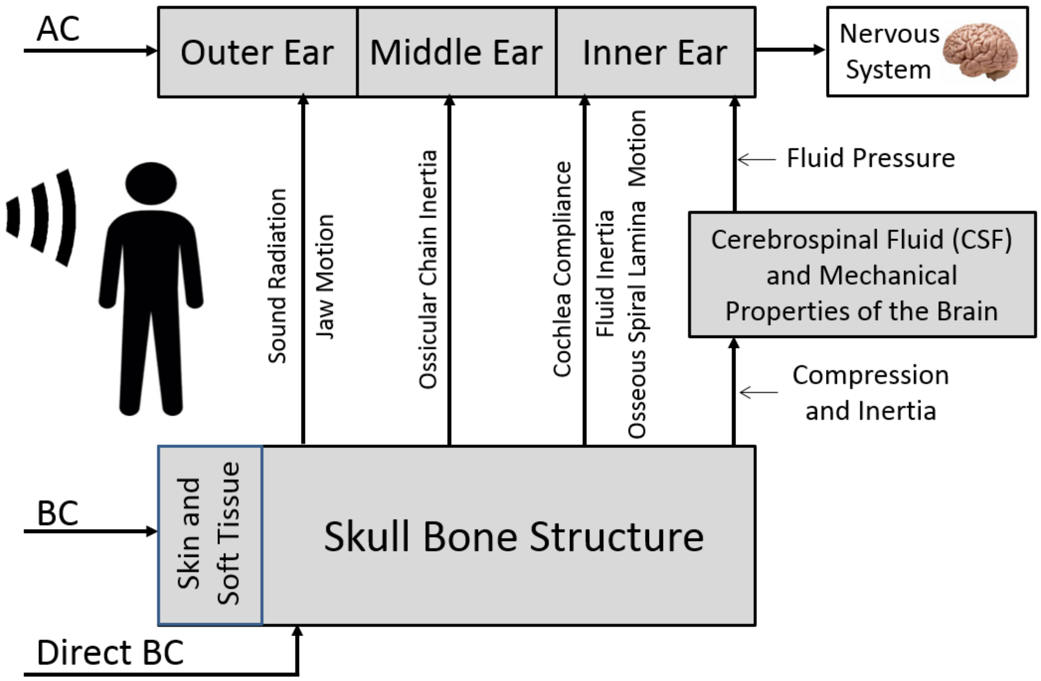

Fig. 4 AC and BC sound pathways

2.4 Bone Conduction Mechanisms

The main characteristics of specific BC mechanisms shown in Fig. 4 are summarized in Sections 2.4.1–2.4.7.

2.4.1 Acoustic Radiation into the Ear Canal

When the skull is stimulated by a BC signal, vibration of the bony and cartilaginous walls of the ear canal vibrate the air in the canal and produce sound pressure (pressure variation). When the ear canal is open, most of the sound energy leaks out. The resulting sound pressure that is transmitted through AC to the cochlea stimulates the cochlea at a level 10 dB below the level of other contributors for frequencies below 2 kHz and even less at higher frequencies (Stenfelt et al. 2003). When the ear canal is closed (occluded) the sound pressure generated in the ear canal impinges on the tympanic membrane and this pathway can increase BC stimulation of the cochlea at low frequencies by up to 40 dB depending on the type and position of the occluding device (Stenfelt and Reinfeldt 2007).

2.4.2 Inertia of the Middle Ear Ossicles

Most of the middle ear is occupied by the ossicular chain (the malleus, the incus, and the stapes) connecting the tympanic membrane to the oval window. The malleus is attached to the tympanic membrane, and the stapes footplate is suspended over the membrane of the oval window. Two supporting muscles connect the ossicles to the bony structure of the middle ear: the stapedius attaches to the head of the stapes and the tensor tympani attaches to the manubrium of the malleus. When the ear is exposed to intense sound, the stapedius contracts to tilt the base of the stapes in the oval window and reduce its range of movement, and the tensor tympani contracts to pull the handle of the malleus and limit the amplitude of tympanic membrane oscillations.

The inertial, or ossicular-inertial, mechanism of the middle ear is the effect of skull vibrations on position and relative movement of the ossicular chain. When the temporal bone surrounding the middle ear vibrates at low frequencies, the ossicles vibrate in-phase with the skull. At higher frequencies, however, the suspended character of the ossicular chain results in its delayed movement in response to vibrations of surrounding temporal bone. The contribution of the middle ear to BC sound is greatest when vibrations are induced in the horizontal plane along the lateral axis of the head, that is, along the in-and-out axis of the stapes (Bárány 1938; Stenfelt and Goode 2005a).

Stenfelt et al. (2002) reported the largest delay in the ossicles' motion during BC sound transmission at frequencies above the resonance frequency of the ossicular chain at about 1500–1700 Hz. In addition, a worsening of BC thresholds around 1500–1700 Hz (the Carhart notch) has been observed in patients with fixed ossicles due to otosclerosis of the stapes (Carhart 1950, 1971). Tonndorf (1971) provided a summary of the results of his studies of stapes fixation in various mammals (cats, dogs, guinea pigs, rats, and humans) and concluded that the magnitude of the Carhart notch depends on the extent of the middle ear contribution to the total BC response in each of the species tested. These findings were later confirmed by Homma et al. (2009). In this context, the resonance frequency of 1500–1700 Hz (Zwislocki 1953; Homma et al. 2009) reported previously is higher than the resonance frequency of the ossicular chain for AC stimulation, which is around 800–1200 Hz (Margolis et al. 1985). The difference between these 2 resonance frequencies results from differences in ossicle vibration behavior for both types of sound transmission. When comparing ossicle vibration at the hearing threshold for AC and BC stimulation, Stenfelt (2006) concluded that the ossicle inertia is the most important for BC perception in the normal ear in the 2- to 3-kHz range.

2.4.3 Compliance of the Middle Ear Cavity

Several authors have suggested that vibrating bones may radiate sound energy into the middle ear cavity causing compressions and decompressions of the cavity space. This energy would act on the ossicular chain in a way similar to the vibrations of the tympanic membrane. For example, Groen (1962) considered this mechanism to be a major contributor to BC hearing around 2500 Hz. However, Tonndorf (1966), Stenfelt et al. (2002), and Stenfelt (2013) considered the effects of this mechanism to be insignificant, if this mechanism is present at all.

2.4.4 Alteration of the Cochlear Space

Alteration of the cochlear space, referred also to as compression of the cochlear walls, is the compressional inner ear mechanism resulting from alternating compression and expansion of the cochlear shell in synchrony with the driving vibratory signal. When a transversal wave propagates in the skull, the bone structure compresses, expands, and alters the cochlear space, resulting in fluid motion that produces sound pressure. This mechanism, called inner-ear compression by Tonndorf (1966), is the common explanation for BC perception. Tonndorf (1966) considered this to be a sum of 2 mechanisms, both due to the incompressible cochlear fluid yielding to the movements of the cochlear shell: one is a result of the difference in compliance between the oval and round windows and the other, which operates in phase with the first mechanism, is a result of the difference in fluid volumes of the scala tympani and the scala vestibuli. The change in the shape of the bony labyrinth causes movements of the BM, which tries to compensate for imbalances in volume and compliance of the scala vestibuli and scala tympani. The scala vestibuli space is about 50% greater than the scala tympani and the impedance of the oval window is greater than that of the more compliant round window (Tonndorf 1966). Hence, when the cochlea compresses, excess fluid is forced from the vestibuli side to the tympani side and the round window; and when the cochlea expands, fluid flows from the tympani towards the vestibuli creating a pressure gradient across the BM and moving it perpendicularly and causing auditory reactions as a result. However, based on the dimension of the cochlea, the lowest frequency where the compressional response would result in effective excitation of the cochlea would be around 4000 Hz and, therefore, alteration of cochlear space by BC sound does not appear to be an important factor for BC hearing at frequencies below 4000 Hz (Stenfelt and Goode 2005a; Sabbe et al. 2015).

2.4.5 Inertia of the Cochlear Fluids

During AC sound transmission, vibration of the stapes in the oval window causes the cochlear fluid (perilymph) in the scala vestibuli to move. When the stapes is pushed medially, incompressible inner-ear fluid is pushed through the helicotrema to the scala tympani, causing the round window to bulge outward. When the stapes is pulled away from the cochlea, the round window membrane is moved inward. Because of different sizes and mobilities (stiffness) of the windows, the round window displacements are about 10 dB smaller than the oval window displacements (Maspétiol 1963). The movements of the windows create a pressure gradient across the BM that set the membrane into motion.

When the bone surrounding the cochlea vibrates, the cochlea fluids are subjected to inertia forces resulting in similar vibration of the BM as in the case of AC stimulation (Stenfelt and Goode 2005a, Stenfelt 2011). Since the oval window and round window are only loosely connected to the temporal bone, they lag in their motion behind the motion of the bony walls of the cochlea during BC sound transmission. The resulting inertial lag in the movement of the cochlear fluids constitutes another BC mechanism creating a pressure gradient moving the BM.

2.4.6 Cochlear Aqueduct Compliance

When the stapes footplate becomes immobilized, the AC sound transmission is severely attenuated while BC transmission is only minimally affected and BC sounds, especially low-frequency sounds, are heard almost normally. For example, Perez et al. (2011) observed that normal ABRs to both AC and BC stimulation did not change when the oval window was immobilized or the round window widely perforated. In a similar experiment, Minor (2000) showed that improving the fluid flow between the cochlea and the cranial space improves low-frequency BC sensitivity. With no or minimal transmission of sound from the middle ear to the inner ear, the only BC mechanisms that are still operational are those that act directly on the cochlea. Since alteration of the cochlear space mechanism does not work at low frequencies when the head moves as a rigid body, the only remaining mechanisms are inertia of the cochlear fluids and direct pressure transmission from the CSF (described later). Stenfelt and Goode (2005a) provided strong arguments for the presence and effectiveness in such cases of the inertial mechanism of the cochlear fluids. Such a mechanism can still operate when the oval or round window is blocked because of several other ear structures, collectively called the "third window" (Ranke et al. 1952), which can facilitate the inertial mechanism of the cochlear fluids. These structures include the vestibular and cochlear aqueducts, nerve fibers, veins, and microchannels in the cochlea (Kücük et al. 1991). However, for the inertial mechanism of the cochlear fluids to operate, there must be compliant structures (leaks) on both sides of the BM. On the other hand, according to Stenfelt and Goode (2005a), only very small compliance is needed on both sides of the BM to facilitate fluid flow between both scalas of the cochlea.

Conductive hearing loss (air-bone gap hearing threshold) is sometimes found in patients with no explicit middle ear pathology. Apparently, many such cases are caused by some form of inner ear pathology resulting in an additional third window to the cochlea. Merchant and Rosowski (2008) examined inner ear lesions causing conductive hearing loss (CHL) via the fluid interaction mechanism between the inner ear and the cranial cavity. They found that some hearing disorders (e.g., X-linked stapes gusher syndrome [DFN3 with large vestibule aqueduct connected the vestibuli to CSF] or superior canal dehiscence) always produce an effect indicating an existence of a mobile window on the scala vestibuli side of the cochlea. This effect could be explained as the result of an increased perilymphatic pressure that restricts the movement of stapes but increases the direct pressure transmission from CSF to the vestibuli. The CHL then results from both degraded AC thresholds and improved BC thresholds.

2.4.7 Pressure Transmission from CSF

There are several reports that both static pressure and sound pressure existing in the CSF can be transmitted to the cochlear fluids (Yoshida and Uemura 1991; Freeman et al. 2000). The CSF space and the inner ear are connected by the internal auditory meatus and 2 inner ear aqueducts that can facilitate such transmission. For example, Tonndorf (1966) observed that the cochlear aqueduct plays a role in transmitting BC sound but has no effect on AC sound. This mechanism may be a part of the "third window" mechanism described previously.

The pressure transmission from CSF space is frequently considered the primary non-osseous mechanism of BC transmission. Watanabe et al. (2008) studied several transmission pathways for BC sound and concluded that "an effective contribution to the transmission of vibratory energy to the inner ear is through non-osseous rather the osseous transmission mechanism" (p. 672). They further discussed sound transmission from the CSF to the inner ear as the main non-osseous mechanism of transmission for BC sound. However, Stenfelt and Goode (2005a) argued that transmission of sound through the CSF is not a significant pathway for BC sound since it fails to explain several BC experimental findings.

2.5 Transcranial Attenuation and Transcranial Time Delay

When an acoustic wave arrives at the human ears, the head geometry and structure provide some isolation between the ears. This isolation is called the interaural attenuation. In the case of BC, the isolation between ears is called transcranial attenuation. The amount of transcranial attenuation depends on the frequency of the BC stimulus, location of the point of stimulation on the head, and the mechanical properties of the individual head such as head size, gender, age, and health of a person (Kirikae 1959; Silman and Silverman 1991; Stenfelt et al. 2000; Stenfelt and Goode 2005a; Rowan and Gray 2008).

The typical transcranial attenuation for frequencies above 1000 Hz is between 0.5 and 1.5 dB/cm based on skull vibrations measured in one specific direction (Stenfelt and Goode 2005b). However, the skull vibrations are generally largest in the direction perpendicular to the transducer surface, and vibration levels in any other direction were less than 10% of the perpendicular levels (Khalil et al. 1979). Stenfelt et al. (2000) and Stenfelt and Goode (2005b) reported that for low frequencies up to 500 Hz, the direction of greatest head excitation coincided with the direction of stimulation. At high frequencies, the directional effect of stimulation gradually disappeared except for the region close to the cochlea where the direction of stimulation still dominated the direction of maximum excitation. The authors hypothesized that the overall response of the cochlea resulting from the specific placement of the vibrator on the skull may be proportional to the summation of excitations in all 3 Cartesian directions. Overall response can also be affected by the directional sensitivity of the cochlea (Stenfelt and Goode 2005b). Nolan and Lyon (1981) conducted a psychoacoustic assessment of transcranial attenuation and reported an average transcranial attenuation value of 10 dB in the 250- to 4000-Hz frequency range, with rather large variability (–10 dB to 40 dB). Hurley and Berger (1970) investigated BC in monaurally deaf individuals and reported average transcranial attenuation values of 5 dB between 500 and 2000 Hz. Frequency-specific transcranial attenuation data reported by Snyder (1973) for 250, 500, and 1000 Hz were about 7–8 dB with standard deviations (SDs) from 6 to 7 dB and for 2000 and 4000 Hz, transcranial attenuation values were 11 and 13 dB, respectively, with SD of 8 dB. In general, for a lateral location of a vibrator at the head, the average transcranial attenuation is less than 5 dB in the 25- to 500-Hz range but increases with frequency to about 15–20 dB in the 2000- to 4000-Hz range and above. At resonance and anti-resonance frequencies, the transcranial attenuation values measured in skulls in vitro (postmortem) can be quite different from the average values; however, in vivo (live human), soft tissue attenuates these frequencies quite substantially and they seem to have a relatively minor effect on BC sound transmission (Stenfelt et al. 2000).

The relatively large attenuation of the skull to BC sound minimizes overstimulation by bodily noises and speech (Dirks 1985). When sound pressure levels (SPLs) in the laryngeal cavity reach 140 dB, speech self-perceived through a low-attenuating head structure could damage hearing. Under very loud conditions hearing must be protected against sound coming through both pathways. Most BC energy is in the 1.5- to 2-kHz range, probably because of the middle ear's resonance. A possible way to moderate such midfrequency transmission is by producing static pressure in the ear canal, known to reduce both AC and BC perception. Homma et al. (2010) found that negative pressures reduced BC sensitivity more than did positive pressures. This result may be due to a difference in the distribution of stiffening among the components of the middle ear, depending on pressure polarity. The BC sensitivity reduction, generally consistent with psychoacoustic data, shows how the middle ear is relatively important for BC hearing.

The velocity of in vivo BC sound in the temporal bone has been reported to be approximately 200–400 m/s, (i.e., similar to the velocity of sound in air [von Békésy 1932; Stenfelt and Goode 2005b]). Therefore, the BC transcranial time delay (TTD) should be expected to be comparable to the AC time delay between the ears. The BC TTD depends on the mechanical properties of the head and the point of stimulation. The latter is analogous to the effect of direction of an incoming sound in case of AC. If AC is not present or excluded, the TTD is strictly determined by the speed of sound through the structures of the head. Wigand (1964) measured the phase velocity of sound in a dry skull and reported the speed of sound through bones to be about 2600 m/s, whereas von Békésy (1948) measured speed of sound through the head of a live person with 2 different methods and reported the values of 540 and 570 m/s. Zwislocki (1953) and Tonndorf and Jahn (1981) used phase cancellation and reported 260 m/s (f > 500 Hz) and 330 m/s (f > 2000 Hz). Assuming that the distance from the mastoid process to the distal cochlea is about 22 cm, the transcranial time delay for BC transmission is about 600–800 μs (Tonndorf and Jahn 1981). This delay is almost identical to that for air-conducted pathways in an open field. Franke (1956) also reported similar phase velocity of 300 m/s (f > 1000 Hz). Additionally, Stenfelt and Goode (2005b) also reported phase velocities of 250 and 400 m/s at the cranial vault and the skull base of the cadaver head, respectively. They also noted a frequency-dependent group velocity.

A study from Boezeman et al. (1984) indicated that when simultaneously stimulating the ear by airborne sound and by vibration with the same signal, the bone-conducted sound arrives at the cochlea later than the airborne sound. The time lags were 2.0 ms at 500 Hz and 0.8 ms at 2000 and 4000 Hz with the vibrator at the forehead. When the vibrator was placed on the mastoid process, the time lag decreased to 1.5 ms at 500 Hz and zero at 2000 Hz. These results show that the speed of sound transmitted through the skull is location and frequency dependent.

2.6 Bone Conduction Ultrasonic Hearing

The term ultrasound refers to sound waves with frequencies above 20 kHz. Several studies have indicated that ultrasonic hearing is possible by humans but only through BC stimulation (Gavreau 1948; Pumphrey 1950; Combridge and Ackroyd 1951; Corso 1963). One of the earliest reports on “upper limit of frequency for human hearing”, Combridge and Ackroyd (1951) cited the work and demonstration of Dr Maass, a physicist and laboratory manager of Atlas Werke at Bremen, performed in December 1945. Dr Maass' work appears to be the earliest discovery on ultrasonic hearing that has been reported (Lenhardt 2003). Another early investigation on ultrasound perception was conducted by Deatherage et al. (1954). They demonstrated the perception of ultrasound by generating 50-kHz ultrasound waves in water. In the first study, the listener's jaw was placed in contact with a container filled with water in which the ultrasound was produced, in another study the listener was submerged in a container of water. The hearing threshold was 140 and 134 dB SPL, respectively. Later, several researchers pursued measurement of the sensitivity and discrimination ability of the human auditory system in the ultrasonic range using direct stimulation on the neck or skull (Corso 1963; Dieroff and Ertel 1975; Lenhardt et al. 1991; Hosoi et al. 1998; Imaizumi et al. 2001). It has been shown that some individuals with profound hearing loss could hear ultrasound, although at a higher level than those of normal hearing listeners, and frequency discrimination is possible although it is far poorer than in the audio range (Lenhardt 2003). Practical applications using ultrasound hearing have been proposed by various authors (e.g., treatment of tinnitus [Carrick et al. 1986; Lenhart 2003], diagnosis of hearing loss [Dieroff and Ertel 1975; Abramovich 1978], hearing aids [Lenhardt et al. 1991; Hosoi et al. 1998], and auditory orientation-echolocation [Lenhardt 2003]). However, the use of ultrasonic stimulation is not without its contraindications. Deatherage et al. (1954) warned of the potential high-frequency hearing loss and tinnitus that can be caused by high-intensity ultrasonic listening. Several investigators have noted tinnitus for several days after being exposed to ultrasonic BC stimulation (Deatherage et al. 1954; Corso 1963).

Several hypotheses have been presented to explain the phenomenon of ultrasonic hearing, including 1) perception by the saccule within the vestibular system based on its hair cells' response to 20–100 kHz stimuli (Lenhardt et al. 1991; Dobie et al. 1992), 2) demodulation of the ultrasonic stimulus through the skull that results in an auditory frequency sound perceived by the cochlea (Lenhardt et al. 1991; Dobie et al. 1992), 3) direct stimulation of the brain matter and CSF (Oohashi et al. 2000), and 4) direct stimulation of the cochlea through the brain (Freeman et al. 2000; Sichel et al. 2002). However, until now, there has been no general agreement among researchers on the actual mechanism of ultrasonic hearing and its perceptual form. The following is a summary of some recent reports on studies conducted to understand the perceptual mechanism of ultrasonic hearing and improve the performance of the ultrasonic hearing applications (e.g., ultrasonic hearing aids).

Lenhardt et al. (1991) reported that even people with profound hearing loss could hear bone-conducted ultrasound. They confirmed that speech discrimination in deaf subjects was possible using modulated ultrasound and proposed to use ultrasound for hearing aids. Lenhardt (2003) also suggested the use of BC high-frequency maskers for tinnitus treatment and supported his theory with modeling and psychoacoustic data. He proposed using high audio frequencies (10–20 kHz) and low-frequency ultrasound to mask tinnitus (20–40 kHz). The author hypothesized that the mechanisms involved in reception and perception of both low-frequency sound and ultrasound are identical with the exception that ultrasound interacts with an intermediary site: the brain. He proposed brain ultrasonic demodulation by place-mapping ultrasound on the first few millimeters of the BM. The rationale was that masking and long-term inhibition may involve inducing plastic changes in the brain at the central level. The neural reprogramming in tinnitus possibly can be reversed by increasing high-frequency stimulation to expand the frequency map (Menning et al. 2000), mask tinnitus, and produce varying degrees of residual inhibition (Meikle et al. 1999; Goldstein et al. 2001).

Fujimoto et al. (2005) explored the psychoacoustic characteristics and the perceptual mechanism of ultrasonic hearing by measuring the difference limens for frequency (DLF) using pure tones from 0.125 to 8 kHz modulated with 30-kHz ultrasonic carriers. Two types of carriers (30-kHz sine wave and a band pass Gaussian noise with rectangular window of 30 ± 4 kHz) and 2 types of amplitude modulations (AMs) (double-side band transmitted carrier [DSB-TC] and double side band suppressed carrier [DSB-SC]) were used. Five normal hearing volunteers participated in this study. Experiments were conducted in a fully anechoic chamber. Subjects were presented 2 pulsed tones with slightly different frequency and asked which one had higher pitch. The result showed that DLFs were increased with increased center frequencies under all modulation conditions. It also showed that ultrasonic AM DSB-TC signals produced the resolution of pitch perceptions (DLF) that were the same as those from air-conducted pure tones in the range of 0.250–4 kHz. However, it yielded a larger DLF at 0.125 and 6–8 kHz. Such perception was essentially identical between sinusoidal and Gaussian noise carriers. The authors also observed that the DLF produced by AM DSB-SC signals had the same value as the DLF produced by AM DSB-TC signals at double the frequency (e.g., DLF of AM DSB-SC at 0.5 kHz was the same as the DLF of AM DSB-TC at 1 kHz). The authors concluded that the results of their study confirmed the nonlinear origin of bone-conducted ultrasonic hearing. Based on the conventional theory that the cochlea is the fundamental organ for processing sound frequencies within the audible range, the authors speculated that the nonlinear conduction demodulates the ultrasounds into audible signals and provides inputs directly to the cochlea, which in turn sends neural inputs to the auditory cortex so that speech is recognized.

Nishimura et al. (2003) investigated ultrasonic perception by masking the air-conducted sounds in the 8- to 18-kHz frequency range at 1-kHz intervals by the

BCU produced at 27, 30, and 33 kHz. Eight normal hearing volunteers participated in the study. Prior to the experiment, each subject's BCU threshold was measured. This threshold was used to represent the sensation level (SL) of the BCU. The authors then measured the thresholds of the air-conducted high-frequency sounds without any masking and with the masking of BCU at 5-dB SL or 10-dB SL. They also measured the dynamic ranges (i.e., the difference between the uncomfortable loudness level and the threshold level).

The results showed that the air-conducted sounds from 10 to 14 kHz were strongly masked by ultrasonic maskers. When the BCU intensity increased from 5 to 10 dB SL, the air-conducted sound intensity had to be increased more than 10 dB in the frequency range of 9–15 kHz. The masking intensity spreads more for low-frequency and less for high-frequency air-conducted sounds. It was observed that while the amount of masking depended on the BCU masker intensity, it was nearly independent of the masker frequencies. In the case of BCU, the dynamic ranges were 13–23 dB among all subjects. For air-conducted sound, all subjects had the uncomfortable loudness level that exceeded the limit of the equipment at 100 SPL, but the minimum dynamic range was found to be at least 60 dB. Thus, the dynamic range of BCU was clearly much lower than the dynamic range of air-conducted sounds. From other studies, for air-conducted sound, when compared with normal hearing subjects, a narrower dynamic range was observed in people with cochlea impairments (Davis 1983); similarly, a narrow dynamic range was also observed in individuals with cochlea implants (Shannon 1983). In the first case, the subjects were lacking outer hair cell activity and in the second case, the stimulation was sent directly to the inner hair cells or the cochlear nerves; thus, it bypassed the outer hair cells. Nishimura et al. (2003) hypothesized that the perception of BCU does not depend on the enhancement of outer hair cells but by a direct stimulation of the inner hair cells. BCU is perceived by activating inner hair cells with passive vibrations of the BM. They argued that since the outer hair cells do not enhance the BC ultrasound at low-intensity level, the ultrasound cannot activate the inner hair cells and thus cannot be perceived. At high intensities, the BM vibrates more strongly in the cochlea basal turn, and sufficient intensity activates inner hair cells to create the sensation. Thus, it produces the characteristics that differ from those of air-conducted sound in terms of masker level and frequency of the masking pattern.

Another study eluding to ultrasonic perception caused by direct activation of the inner hair cells was conducted by Ito and Nakagawa (2010). The authors investigated the contribution of the external ear and middle ears to the BCU perception mechanism by measuring the acoustic field in the ear canal and tympanic membrane vibrations caused by ultrasonic stimulations. BC ultrasonic tones at 27, 30, and 33 kHz were delivered through a transducer (MA40E7S) attached to the mastoid. The audible air pressure inside the ear canal was measured with a probe microphone (BandK type 4182) at positions 10, 15, and 20 mm from the entrance of the ear canal. The intensity of the ultrasound was set to 15 dB SL (sensation level), which was sufficiently loud to be heard (Nishimura et al. 2003). The stimuli were 2 s in duration. Each subject also underwent a pitch matching test for bone conducted ultrasounds. The tympanic membrane vibrations were measured using a laser Doppler vibrometer (Ono Sokki LV1720). The results showed that there was evidence of the presence of ultrasonic signals (peak at 27, 30, and 33 kHz) but no signals in the audible range corresponding to the perceived pitch (13–15 kHz) or in the first subharmonic tones (13.5, 15, and 16.5 kHz) were detected. Thus, the results suggested that the inertia of the middle ear does not cause nonlinear distortions producing subharmonics of the delivered ultrasounds; in other words, the nonlinear distortion of the middle ear does not contribute to the hearing of ultrasound. Moreover, because the reverse directional flow of cochlea activities, such as otoacoustic emissions, generated by low-frequency bone conducted sound was observed and no frequency of perceived pitch or subharmonic frequency was observed at the tympanic membrane in this study, it is suggested that the ultrasonic BC perception is created in the inner ear itself without causing any traveling wave at audible frequencies in the BM of the cochlea (Ito and Nakagawa 2010).

Okayasu et al. (2013) also assessed BCU sensitivity at 27, 30, and 33 kHz in 20 patients who were scheduled to undergo cisplatin chemoradiation therapy. In addition, 7 healthy individuals with normal hearing also participated in a control group. The sensitivity threshold of air-conducted sound and BCU were measured before and after the treatment. For air-conducted sound, sensitivity measurements were obtained for high-frequency sounds (9, 10, 11, 12, 14, 16, 18, and 20 kHz) and also in conventional frequencies (0.125, 0.25, 0.5, 1, 2, 4, and 8 kHz). After the treatment, 62.5% of the 40 patients' ears were diagnosed with hearing loss. There were significant increases in sensitivity thresholds for air-conducted sounds in frequencies ranging 8–14 kHz. However, the BCU thresholds significantly decreased after the treatment. This is a surprising result. None of the patients had heard about BCU before the study. The improvement in the ultrasound hearing thresholds was not the result of familiarization due to repetitive listening to BC sounds since no improvement was observed in the control group. It shows that BCU does not rely on the same basal turn in the cochlea as air-conducted sound nor is it perceived as a low-frequency sound generated by skull demodulation. This finding indicates that ultrasound is directly perceived in the cochlea. The different effects in threshold between air-conducted sound and BCU can be explained by the damage of the outer hair cells during the treatment causing the upward shifting in air-conducted hearing threshold. It also supports the suggestion of the previous studies that the BCU stimulates the inner ear directly without enhancement of the outer hair cells (Nishimura et al. 2003; Ito and Nakagawa 2010).

Okamoto et al. (2005) studied the intelligibility of the BCU by exploring how well listeners can understand ultrasonic speech and confusion patterns to evaluate and improve bone conducted ultrasonic hearing. The intelligibility of Japanese words classified as familiar (encountered often in everyday life) and Japanese monosyllables modulated with ultrasound were investigated. A 30-kHz ultrasonic carrier amplitude modulated by speech signals was presented using a custom-made ceramic vibrator. The vibrator was applied at the left or right mastoid of the subject and was held in place by a hairband-like supporter. Before the speech intelligibility test, hearing threshold was determined with a 30-kHz sinusoidal carrier modulated by a 1-kHz sinusoidal tone. The ultrasonic speech was presented at sound levels 20, 25, and 30 dB HL greater than hearing threshold. These levels corresponded to the range for which the listener can understand speech signals without feeling any discomfort based on observations from a pilot study. Listeners were instructed to write down what they heard on a prepared answer sheet. A monosyllabic intelligibility test with air-conducted sound was also performed. The average sound levels of the stimuli were set at 20, 25, and 30 dBA. Ten normal hearing Japanese adults participated. The results showed that the intelligibility of the more familiar words was significantly higher than that of the unfamiliar words. A comparison of monosyllabic intelligibility tests with BCU and air-conducted sound showed similar patterns of speech recognition. The speech intelligibility of BCU did not increase with sound level as opposed to the intelligibility of air-conducted sounds.

It has been reported that bone conducted ultrasonic signals modulated by speech signals can be heard not only by normal hearing people but also to some extent by profoundly deaf individuals (Lenhart et al. 1991). This discovery led to the development of the BC ultrasonic hearing aid (BCUHA) by Nakagawa et al. (2002, 2006). In this device, the ultrasonic 30-kHz signal is modulated by speech signals and presented at the mastoid by a vibrator. Generally, 2 sounds are perceived from the device: one is a high-pitch tone of the ultrasonic carrier, with a pitch corresponding to 8–16 kHz and the other is the envelope of the modulated sound. AM DSB-TC was used. From the hearing tests for 24 profoundly deaf subjects using this prototype device, 42% of the subjects were able to perceive some tone bursts and 17% were able to recognize the words (Nakagawa et al. 2006). After this encouraging result, Nakagawa and his colleagues conducted a number of studies to investigate the mechanism of BCU and developed methods to improve the BCUHA (Nakagawa 2007; Hotehama and Nakagawa 2012; Nakagawa et al., 2013; Okayasu et al. 2013).

Nakagawa (2007) investigated the capability to discriminate multichannel inputs of BC ultrasonic hearing aids by using magnetoencephalography, or MEG. Two-channel BCU signals were presented to the left and right mastoids of 10 normal and 4 profoundly deaf subjects. The lateralities of the auditory evoked cortical activities were evaluated. Three forms of a 1-kHz tone were presented: a 30-kHz carrier amplitude modulated with a 1-kHz tone presented at 10 dB SL, 1-kHz BC sound presented at 50 dB SL, and 1-kHz air-conducted sound presented at 50 dB SL. The results showed that in the case of normal hearing subjects, the most prominent deflections after the sound onset, N1m responses, evoked by contralateral stimuli were larger in amplitude and shorter in latency than those deflections evoked by ipsilateral stimuli for BCU as well as audible sounds. These phenomena were also observed in profoundly deaf subjects. It suggested that 2-channel BCUs were separately localized and provided a rationale to develop a multichannel BCU hearing aid (Nakagawa 2007).

In another study, Nakagawa et al. (2013) compared the articulation, intelligibility, and sound quality of different modulation techniques. The authors speculated that a high-pitch tone of the ultrasonic carrier is the key factor in the degradation of the articulation and sound quality, such that it increases the discomfort of the speech and decreases articulation (Okamoto et al, 2005). Three AM techniques, DSB-TC, DSB-SC, and so-called “transposed modulation”, were investigated. Transposed modulation is similar to the DSB-SC modulation in the sense that the carrier frequency was suppressed; however, in the transposed modulation, the speech signal was half-wave rectified and low-pass filtered. In this study, the authors chose a low-pass filter at 8 kHz to avoid impairing speech information. The study comprised 31 normal hearing Japanese subjects, 1 female and 1 male voice, and 4 levels of familiarity with each level chosen from the midrange of familiarity levels to avoid ceiling and floor effects. Four sessions with different stimulus types including AC were performed. In each session, 100 words were used (50 words were from the female speaker and 50 words were from the male speaker). The results showed that DSB-SC speech was less intelligible than other forms of modulated speech. The authors’ rationale was that in this type of modulation, even though the carrier frequency was suppressed, the maximum of the envelope was twice as large as that of the original speech. In addition, the modulated signal contained some distortion. No statistically significant difference was observed between intelligibility and articulation of DSB-TC and transposed speech, but the transposed modulation tended to show lower articulation. Both methods had identical peak envelopes of the original speech; however, the DSB-TC speech had relatively strong high-pitch tones due to high amplitude of the carrier. Since BCU masked AC sounds of 10–14 kHz but did not mask AC sound below 8 kHz (Nishimura et al. 2003), it is reasonable to consider the high-pitch tone of the carrier did not affect the perception of speech below 8 kHz in the DSB-TC speech. The results also indicated that transposed sound contains more distortion than DSB-TC. With respect to sound quality, the sound quality of the transposed speech was generally closer to the sound quality of AC speech than the sound quality of other methods and was particularly more pleasant than the sound quality of DSB-TC.

To verify the feasibility of a binaural BCU hearing aid, Hotehama and Nakagawa (2012) investigated whether listeners can use interaural time differences in the signal envelope (envelope-ITD) and the interaural intensity difference (IID) as cues for bilateral BCU presentation. They measured the thresholds for detecting changes in these parameters of bilateral BCU stimuli and the interaction between envelope-ITD and IID on the lateralization of BCUs. The results showed that listeners could detect changes in both the envelope-ITD and IID of BCUs. In addition, they observed that there is a trade-off between time and intensity in BCU perception. These results indicated that the binaural BCU hearing aid could be effective by controlling the envelope-ITD and the IID between the left and right channels. However, the direction of the sound image of BCUs is not always ipsilateral as is the case with low-frequency BC and AC sounds, but sometimes it is contralateral to the source of stimulation and the perception direction shifts with slight changes in the location of the transducer. A previous computer-simulation study (Sakaguchi et al. 2002) somewhat explained this phenomenon. In this study, several peaks in the spatial distribution of the maximal sound pressure were observed both ipsilaterally and contralaterally when a BCU is presented. This effect is due to the relationship between the size of the head and the wavelength of the sound wave.

Regarding the paralinguistic information, Kagomiya and Nakagawa (2010a, 2010b) reported that hearing impaired patients using BCUHA could effectively perceive paralinguistic information, especially for information on the intension of the speaker's emotion such as admiration, suspicion, and disappointment coded with changes in fundamental frequency F_o pattern and duration of the whole utterance. However, the listeners could be confused on the intension of focused and neutral voices. In the most recent report (Kagomiya and Nakagawa 2016) on the same topic, the authors compared the effectiveness of DSB-TC and DSB-SC AM on the transmission of emotional states of speakers (i.e., anger, disgust, fear, joy, sadness, surprise, and neutral). They also asked the participants to subjectively evaluate the voice quality, including voice clarity, comfortableness, and preference. The results showed that while DSB-SC was superior in comfortableness and preference, DSB-TC was more effective in the transmission of voice emotion.

In summary, with direct contact stimulation, human listeners can perceive ultrasound up to around 100 kHz. The mechanism of ultrasonic hearing is still not clear; however, most researchers agreed that the perception of ultrasound sensation is the result of direct stimulation at the cochlea through the head without any involvement of the outer ear and middle ear. The most recent studies indicated that the hearing sensation probably does not cause any traveling waves at audible frequencies in the BM or involve the outer hair cells in the cochlea (Ito and Nakagawa 2010; Okayasu et al. 2013). Thus, ultrasound might directly stimulate the inner hair cells. Furthermore, the sound intensity needed to be heard for ultrasound is high. Lenhardt (2003) reported that, on average, 5 dB sensational level of ultrasound at 26 kHz in water is equal to 150 dB SPL and at 39 kHz is equal to 155 dB SPL (re: 1 micro Pascal). The dynamic range of ultrasound is narrow compared to audible air-conducted sound and it is narrower in hearing impaired persons. For normal hearing listeners, the dynamic range is from 13 to 23 dB according to Nishimura et al. (2003) or about 30 dB according to Okamoto et al. (2005). The pitch perception resolutions of low frequencies (0.125–8 kHz) modulated onto ultrasonic carriers depend on AM types DSB-TC or DBS-SC. For DSB-TC modulation, they were compatible to those from air-conducted pure tones in the range of 0.250–4 kHz but larger at 125 Hz and above 4-kHz frequencies modulated sounds (Fujimoto et al. 2005). In addition, the investigations on the ultrasonic perception by masking the ultrasounds at 27, 30, and 33 kHz with audible air-conducted sounds at high frequencies (8–18 kHz) indicated that these ultrasounds were masked with 9–15 kHz and quite strongly with 10–14 kHz frequencies but weren't masked with 8-kHz signals (Nishimura et al. 2003). Thus, the high pitch of carriers probably does not affect the perception of speech signals below 8 kHz (Nakagawa et al. 2013). Even though many researchers saw the potential applications of ultrasounds in hearing aids, the ultrasonic hearing aid technology is still in the developing stage and needs more research. So far, we are not aware of any ultrasonic device in the market that delivers a practical application for hearing assistance.

2.7 Bone Conduction Modeling

In general, it may be assumed that all the BC transmission mechanisms described in the previous section are involved in BC transmission of external auditory stimuli to the cochlea. However, due to the complexity of the skull, modeling has produced only limited insight regarding the relative importance of various BC transmission mechanisms. In a recent effort, Kim et al. (2011) developed 3-D finite-element (FE) models of the human middle ear and cochlea to gain some new insights into the fundamental BC hearing mechanism. The researchers examined a variety of cochlear responses such as fluid pressure, BM vibration, and oval and round window volume velocities for both AC and BC excitation. The results of these examinations were validated by comparing them with the experimental data from the literature. BC excitations were simulated in the form of rigid body of vibrations (inertia) of surrounding bone structures in 3-D directions. Based on the previous research (Peterson and Bogert 1950; Olson 1998, 2001), the authors decomposed the fluid pressure in the scala vestibuli and scala tympani into 2 components: an in-phase "symmetric wave" (also called the "fast" wave) and an out-of-phase "asymmetric wave" (also called the "slow" wave). The results show that the BM vibrates in response only to the lower-magnitude asymmetric (slow) component of the cochlear fluid wave, which is generated by asymmetric components of the oval and round window volume velocities. It does not respond to the dominant symmetric fast-wave component, regardless of AC or BC excitation and the direction of the BC excitation. The same result was also observed when they modified the middle ear to alter the out-of-phase component of both volume velocities. These results show that the BM vibrational pattern remains essentially the same for AC and BC stimulation of the cochlea.

In another recent paper, Kim et al. (2014) used a modeling approach to investigate the importance of the hook region of the cochlea on BC hearing. This region is located at the basal part of the cochlea where the vestibule meets the scala vestibuli. The authors' hypothesis was that despite the fact that the coiled shape of the cochlea is not very important for AC hearing (Viergever 1978; Steele and Zais 1985), it could play an important role in BC hearing. The human cochlea has 2.5 turns around the modiolus with tighter turns at the apex to looser turns at the base. Thus, the curvatures of the spiral shape of the cochlea and the BM change with the distance from the oval window. In their study, the authors used the 3-D FE model of coupling the human middle ear and inner ear (as in their previous modeling study) but with more realistic geometry obtained from the microcomputed tomography images of the temporal bone from a human cadaver ear. The model results for both AC and BC stimuli were consistent with the results of the previous modeling study indicating that regardless of the type of excitation or direction (as in the case of BC excitation) the asymmetric fluid pressure was highly correlated with BM velocity (Kim et al. 2011). BC excitations were simulated by applying rigid-body (inertia) vibrations normal to the BM surface at locations 0.8, 5.8, 15.6, and 33.1 mm from the base of the cochlea. The applied frequency range was from 0.5–10 kHz with 0.1-kHz steps from 0.5 to 1 kHz and 0.5 kHz steps from 1 to 10 kHz. The simulated results showed that the vibrational direction that was normal to the BM at the hook region (0.8 mm from the base of the cochlea) produced the highest BM velocities across all tested frequencies. These BM velocities were higher than the BM velocities excited at other locations even at the location that matched with the frequency map of the cochlea. This indicates that the directional BC vibrations normal to the BM in the basal hook region of the cochlea affect the BM responses more significantly when compared to those of BC excitation at other regions of the cochlea. The authors hypothesized that due to the large and asymmetric cross-sectional areas of the scala vestibuli and scala tempani in the hook region, the directional BC vibrations normal to the BM in this region end up producing the largest asymmetric fluid pressure waves, which in turn produced the largest BM velocity regardless of the frequency of stimulation. In other words, the BC excitation normal to the BM surface applied at the base region (hook's region) was more effective than that applied at other locations on the BM regardless of the applied frequencies. However, both modeling efforts described in Kim et al.'s (2011, 2014) studies considered only the inertial mode of BC transmission.

2.8 Bone Conduction Correlational Research

Based on the assumption that the vibrations of the cochlea result in an auditory perception, the extent of cochlear vibration may be used as a physiological measure of the strength of the perceived sound. Eeg-Olofsson et al. (2013) investigated the correlation between hearing perception and cochlear vibration by using a laser Doppler vibrometer to measure vibration velocity of the lateral semicircular canal and the cochlear promontory in persons with a unilateral middle ear common cavity syndrome. One contralateral and 3 ipsilateral positions were used. BC pure tone thresholds and vibration data were obtained at frequencies between 0.3 and 5 kHz. The results showed a large variability in the measured relationship among the people participating in the study. The cochlea velocity resulting from BC stimulation depended on the frequency of the stimulating tone while the threshold of hearing showed a tendency to decrease with the stimulation closer to the cochlea. The correlation between bone vibration velocities at 2 measuring sides were significant and relative median data showed similar trends for both methods. However, low correlation between the vibration velocity and hearing threshold was found at the individual level.

In another effort, Reinfeldt et al. (2013) estimated the effectiveness of BC transmission through the skull by investigating the correlation between ear canal sound pressure (ECSP) and hearing threshold. Three positions of stimulations (ipsilateral mastoid, contralateral mastoid, and forehead) were used. With the ear canal open, the estimates were similar at most frequencies; however, statistically significant differences were seen at 0.5, 0.75, 2, and 3 kHz. Thus, even if ECSP could be used to predict BC effectiveness for most frequencies, this technique could result in errors as large as 10 dB at some frequencies. In addition, statistically significant differences between open and occluded cases were seen due to ear occlusion. Thus, the authors concluded that normal BC perception should not be estimated using occluded measurements. However, the ECSP measurements provided results similar to previously reported measurements of cochlear promontory vibration supporting the hypothesis of similar relative vibrations at the canal and cochlea. Moreover, the results show that BC perception depends on stimulation positions and vibration direction with better sensitivity of the cochlea at the ipsilateral compared to contralateral and forehead positions.

2.9 Summary

The anatomy and physiology of BC were quite extensively reviewed in the previous ARL technical report on BC sound perception by Henry and Letowski (2007). The focus of that report was on psychoacoustics and the medical and military applications of BC. Therefore, some aspects of BC physiology, such as physiology of BC ultrasound reception, that were considered at that time less relevant to real-world applications were not discussed. The present updated review of BC research conducted after 2007 required some review of basic anatomy and physiology of BC to allow the reader to follow its text without the need to consult the older Henry and Letowski report. Consequently, some basic information on anatomy and physiology of BC, including BC ultrasound perception physiology, has been summarized from older and newer literature and is presented in this section.

While a number of newer studies contributed to a better understanding of BC mechanisms and transmission pathways, there is still a lack of uniform theory of BC perception. There is no consensus among researchers regarding the importance of various BC mechanisms as well as some of the general aspects of BC transmission (e.g., transcranial sound velocity). In addition to several mechanisms reviewed by Tonndorf (1966, 1968) some new mechanisms have been proposed on the basis of recent studies (e.g., pressure transmission from the cerebrospinal fluid to the inner ear and cartilage conduction). It is quite possible that all of the proposed mechanisms contribute to some extent to BC hearing but the challenge remains to determine whether their contributions are invariant or they depend on a form of BC stimulation (location of transducer, type of signal, etc.).

The review of the BC ultrasound perception literature leads to the conclusion that such perception is real and not an artifact resulting from measurement limitations or observation bias. However, many unanswered questions remain regarding the actual mechanism of BC ultrasound perception as well as the perceptual effects of BC ultrasound stimulation. Two of the main questions are the efficacy of ultrasound speech perception and health limitations associated with ultrasound stimulation.

3. Bone Conduction Loudness

The term “loudness” is used to describe the magnitude of an auditory sensation. While it is related to sound intensity (an objective measure of sound strength), the two are not equivalent because loudness is a subjective measure that is based on an individual's perception of the sound.

It is well known that loudness perception not only varies substantially across signal types but it also varies across individuals (Schneider 1980; Algom and Marks 1984). The same applies to both AC and BC sounds. However, while loudness of AC sounds has been an object of numerous studies (Ham and Parkinson 1932; Robinson and Dadson 1956, 1957; Moore et al. 1997), only a few studies have been conducted regarding the loudness of BC sounds and much is still unknown.

In general, the loudness of BC sounds can be studied by comparing BC sounds to AC sounds or by comparing various BC sounds among themselves. The former studies can be divided into 1a) sound cancellation studies and 1b) equal-loudness studies. The latter studies can be divided into 2a) equal-loudness frequency (or sound type) studies and 2b) equal-loudness placement studies. However, no equal-loudness placement type study has yet been reported. Similarly, no direct loudness scaling studies, such as fractional studies (Geiger and Firestone 1933; Stevens and Poulton 1956; Brand and Hohmann 2002; Al-Salim et al. 2010) using AC and BC or exclusively BC signals have been found in our literature search. Therefore, to summarize what we have learned to date about loudness of BC sounds, the following discussion is divided into 2 parts summarizing the sound cancellation studies (1a) and the equal-loudness studies (1b and 2a).

3.1 Sound Cancellation Studies

The oldest studies intended to compare human perception of AC and BC sounds were sound cancellation studies in which both sounds were presented simultaneously—from a loudspeaker (AC) and bone vibrator (BC). In these studies, the intensity and phase of an AC signal was adjusted by a listener to cancel the effect of BC signal and minimize the resulting sound loudness. Over the years, several cancellation studies have been conducted primarily to further explore factors associated with BC physiology; however, they were also used to determine the extent of linearity between AC and BC sound levels (von Békésy 1932; Lowy 1942; Wever and Lawrence 1954; Khanna et al. 1976). In von Békésy's study, the BC signal was delivered using a BC vibrator coupled to the forehead. Two phone receivers situated about 2 cm away from the head were used to deliver the AC sound to each ear. A 400-Hz tone was presented through BC at 57 dB higher than the individual's threshold. Cancellation was achieved by allowing the individual to adjust the amplitude and phase of the AC stimuli delivered by the phone receivers.

The subjects for Lowy's (1942) study were 5 cats with BC vibrators attached directly to an exposed bone above the auditory meatus. A tube was used to connect a loudspeaker to the outer meatus. Pure tone signals from 250 to 3000 Hz were sent one at a time via AC and then BC independently and the signals were adjusted in each instance until the cochlear response to both, as displayed through oscillography, were equivalent. Then the AC and BC signals were played simultaneously and the phase of the BC signal was adjusted until complete cancellation was achieved. Lowy also discovered that the whole BM contribution was cancelled when local cancellation was achieved via this method (Lowy 1942). Weaver and Lawrence (1954) extended Lowy's study by expanding the range of the frequencies tested. The results of their studies using signals from 0.1 to 15 kHz were similar to those found by Lowy.

In Khanna et al.'s (1976) study, a bone vibrator was coupled to the forehead and an AC transmitter was inserted into the right ear. The left ear received a narrowband masking noise. BC and AC signals from 0.5 to 6 kHz were presented alternately and the listener used the method of adjustments to match the loudness of the 2 signals. After the loudness match was complete, the 2 signals were presented simultaneously and listeners used phase and voltage controls to cancel out the signals (Khanna et al. 1976).

While not all of these studies were performed with human participants, they all generally established that the relationship between the intensities of each BC stimulus and the AC stimulus needed to cancel out each BC stimulus of the same frequency was essentially linear. In other words, if an AC and BC signal were set to an intensity whereby they cancel each other out and the intensity of the BC signal was increased 10 dB, the AC signal necessary to cancel out the louder BC signal also had to be increased 10 dB.

Up until 2007, most of these cancellation studies focused on comparing AC and BC tones of the same frequency. However, Stenfelt (2007) extended these studies by investigating the cancellation of tones of 2 different frequencies presented at the same time. In the first set of trials consisting of 6 experimental conditions, the listener was presented with BC and AC signals of one frequency at a time (either 700 or 1100 Hz). In the second set of trials consisting of 3 experimental conditions, 2 pairs of AC and BC tones (one 700 Hz and one 1100 Hz) were presented simultaneously via BC and AC for the cancellation task. There was also a third set of trials consisting of 3 experimental conditions during which only the 1100-Hz BC signal was to be cancelled by an 1100-Hz AC tone; however, a 700-Hz AC tone was also presented as a disturbance. The intensities of the BC signals that were cancelled in this study were 40, 50, and 60 dB HL. The results of the study supported the linearity conclusions reported in previous sound cancellation studies (Stenfelt 2007).

In the most recent cancellation study, Clavier et al. (2010) performed a 2-part study on the linear relationship between AC and BC sounds using a psychoacoustic sound cancellation technique and distortion product otoacoustic emission (DPOAE) measurement technique that evaluates the cochlear response of the listener. During the cancellation process, listeners first were instructed to adjust the loudness of the AC signal to match the perceived loudness of the BC signal as the 2 signals alternated. Once this match was achieved, both signals were presented simultaneously and the listener was asked to adjust the relative phase between the AC and BC stimuli so that they are no longer heard. During both parts of the study, listeners were fitted with an in-ear probe that was used to transmit the AC sound and could be used to take DPOAE measurements from one ear. A circumaural headset covered the other ear and transmitted masking noises during the cancellation technique, and the bone vibrator used to deliver the BC signal was coupled to the forehead. Frequencies between 0.25 and 4 kHz and sound levels ranging from 15 to 80 dB SPL were used in the study. The results of the psychoacoustic tests provided evidence of a linear relationship between the perceived AC and BC sound levels. However, the results of the DPOAE tests indicated a nonlinear cochlear response. Similar results were found during AC/AC linearity tests conducted concurrently by the authors.

3.2 Equal-Loudness Studies

Since linearity of AC/BC cancellation for signals of the same frequency has been fairly well established, the newer BC studies have been focused almost exclusively on equal-loudness comparisons between AC and BC sounds—typically of the same frequency—and most recently on loudness comparisons between BC sounds of various frequencies. Some of these studies were focused on delving deeper into the linearity of AC/BC signals while others concentrated more on the development of equal-loudness contours (ELCs) for bone conducted sounds.

The concept of ELCs for AC sounds was introduced in 1933 by Harvey Fletcher and Wilden Munson, 2 Bell Labs scientists, who wrote a paper documenting the results of a study in which they sought to investigate the differences in how people perceive various parts of the audible frequency spectrum (Fletcher and Munson 1933). Essentially, they performed a comparison of individuals' perceptions of the magnitude of 2 sounds that differ in frequency using a loudness matching process. Loudness matching, also called loudness balance, is a psychoacoustic technique in which a listener has to compare the loudness of the target signal to the loudness of the reference signal presented at a specific level. The loudness matching process requires the experimenter to present to a listener 2 alternating signals: the reference signals of specific frequency and intensity and the comparison signal of the same or a different frequency and adjustable intensity. Comparisons are made by alternating both sounds either monaurally or binaurally or alternating them between the ears. Both sounds may also be presented simultaneously like during matching loudness of a target signal to the loudness of the tinnitus. The listener is instructed to adjust the intensity of the comparison signal so the 2 signals are perceived to be equally loud. This is a very popular measuring technique that has been used to determine the shape of equal-loudness curves, perceptually calibrate electroacoustic transducers, assess sound attenuation provided by hearing protectors (Rimmer and Ellenbecker 1997; Franks et al. 2003), and assess loudness of tinnitus sound (Henry and Meikle 2000; Hoare et al. 2014), to name just a few common applications.

The results of the Fletcher and Munson (1933) study demonstrated that humans do not perceive the same intensity of a sound to be equally loud across all frequencies. In other words, if a 500-Hz tone is played at 40 dB SPL, it will not be perceived to be the same loudness as a 2-kHz tone also played at 40 dB SPL. Based on their studies, they developed the first set of ELCs for pure tones transmitted via AC. These ELCs show the SPLs of pure tones that are perceived to be equally loud. Subsequent data collected by other researchers have been used to update the curves over the years (e.g., Churcher and King 1937; Robinson and Dadson 1956; Fastl and Zwicker 1987; Watanabe and Moller 1990; Poulsen and Thøgersen 1994; Lydolf and Møller 1997; Takeshima et al. 1997, 2001, 2002; Bellman et al. 1999). The most recent set of the standardized AC ELCs is available in the ISO 226:2003 document.

The first attempts to measure ELCs for bone conducted sounds appear to have been made in the late 1940s in Vern Knudson’s laboratory in the Physics Department at the University of California, Los Angeles. However, the only trace of this work is an abstract by Watson and Frazier (1952) of their talk at the 42nd Acoustical Society of America Meeting in 1951. The authors measured BC ELCs (forehead) at 20 and 40 dB SL re 1-kHz BC threshold and reported that the BC ELCs were “definitely more sharply curved” than the corresponding AC ELCs.

The first fully reported study of BC ELCs was published by Corso and Levine (1965). The authors measured monaural (nontest ear occluded) AC ELCs in the 2- to 16-kHz frequency range and BC ELCs (both ears occluded) in the 2- to 94-kHz range at 0, 10, and 20 phon loudness level. They concluded that both AC and BC ELCs were essentially similar up to 14 kHz; however, the AC ELCs began to converge at about 16 kHz while BC ELCs did not converge until around 85 kHz.

A few researchers have measured ELCs indirectly to compare the effectiveness of AC and BC communication methods. In the first study of this kind, Stenfelt and

Håkansson (2002) used the loudness matching technique in their study to determine whether there were any differences in the perceived loudness of sounds delivered through AC and BC hearing aids. They alternated AC and BC signals delivered to the listener, and the listener adjusted the loudness of the BC signal until it matched the perceived loudness of the AC signal. There was no silent period between the alternating presentations. For the normal hearing participants of the study, they found that for the frequencies tested (0.25–4 kHz), perceived loudness over the intensity range of 30–80 dB HL is higher for signals transmitted through BC than those transmitted through AC. This means that to achieve a specific perceived loudness level, a less-intense signal is required to be delivered through the BC pathway than the AC pathway.

To determine how well the linearity characteristic holds for AC/BC signals under various listening conditions, McKinley (2009) conducted a study focused on determining whether there was a nonlinearity component associated with the AC/BC perceived sound level comparison when hearing protection was involved. The author was interested in determining the magnitude of any nonlinearity noted in the loudness perception of BC signals. In his study, the BC signals were transmitted via a sound field using loudspeakers in a reverberant chamber in lieu of a BC vibrator, and the AC signals were transmitted via deep insert earplugs or earphones.

The procedure used in McKinley's study required the listener to adjust the sound of the AC insert earphone signal (the target signal) to match the sound of the ambient noise BC signal (the reference signal). The study also involved 3 test frequencies (1, 2, and 4 kHz) and 5 sound levels between 70 and 110 dB SPL, inclusively, for the loudspeaker signals. The results of their study indicated a linear relationship between the perception of the AC and BC signals when the attenuation of the ambient noise reached or exceeded the BC limit, which ensures that the ambient signal was being transmitted primarily by the BC pathway.

While most of the equal-loudness studies conducted in the past focused on just one BC transducer location, Patrick et al. (2012) designed a study that included bone vibrator location as a factor that might influence the perceived loudness of BC signals. The goal of the study was to compare the spectral content of AC and BC sounds using conduction equivalency ratios (CERs). To accomplish this goal, the researchers compared the signal intensities of AC and BC sounds that resulted in equivalent perceived loudness levels. Their tests included 5 one-third octave narrowband frequencies (0.25, 0.5, 1, 2, and 4 kHz), 3 BC transducer locations (mastoid, condyle, and forehead), and 3 target AC free-field signal intensities (40, 60, and 80 dB SPL). The narrowband signals alternated between a pair of loudspeakers and a BC transducer. Listeners were instructed to adjust the intensity of the BC signals to match the perceived intensity of the AC signals.

To calculate the CERs, both the AC and BC signal intensities were converted into decibels HL and then the BC value was subtracted from the AC value. The results indicate that for all BC transducer locations, the CERs increased as the reference AC level increased. Additionally, BC signals generally did not have to be as intense (in terms of dB HL) to be perceived to be the same loudness as the AC signals. This finding agrees with that of Stenfelt and Håkansson (2002). Furthermore, the magnitude of the difference between the AC and BC intensities appeared to be dependent upon the location of the BC transducer. For instance, the forehead location resulted in BC intensities relatively close to the AC intensities, especially for the higher frequencies; however, the condyle intensities differed more dramatically from the AC intensities when compared with the other 2 locations tested (Patrick et al. 2012).

Pollard et al. (2013) compared perceptual data resulting from an equal-loudness study to the data obtained using a BandK 4930 artificial mastoid. The purpose of their study was to validate the BC data resulting from level calibrations using an artificial mastoid and to determine if an equal-loudness procedure would be appropriate for such calibration. The signals used in the study were 1-s long, one-third octave band of white noise. Participants in the study were asked to match the loudness of a signal presented through a BC vibrator to a 45-dB signal presented by a loudspeaker. The signal alternated smoothly between the BC vibrator and loudspeaker with no breaks in between. Several conditions were tested. First, 2 BC vibrator models were used—a RadioEar B-71 and an Oiido SD02. In addition, 2 locations were tested—mastoid and mandibular condyle. Six normal hearing listeners participated in the study.

The results of their study indicated the data obtained from the artificial mastoid did not correspond to the perceptual data obtained from the listeners for any of the conditions tested even though the intra- and inter-individual reliability was high (Cronbach's alpha > 0.90). Additionally, the RadioEar B-71 and Oiido SD02 bone vibrators performed relatively the same for the 0.63- to 3-kHz frequencies. However, the Oiido transducer performed better at frequencies below 630 Hz, and the RadioEar transducer outperformed the Oiido transducer for frequencies above 3 kHz. Lastly, according to the results, the mandibular condyle location was more sensitive to the vibrations than the mastoid, which corresponds with previous studies.

Stenfelt and Zeitooni (2013b) performed a follow-up study to the Stenfelt and Håkansson (2002) study to determine whether the procedures used in the initial study had an impact on the BC loudness functions resulting from the older study. In the 2002 study, a bracketing procedure was used, while an adaptive categorical scaling method was used in the 2013 study. In both studies, the signal alternated between the AC and BC device with no breaks in between. However, the bracketing procedure required listeners to first adjust the BC sound so that it was louder than the AC sound, then adjust the BC signal so that it was softer than the AC sound. This process was repeated as the range of the BC signal was decreased until the AC and BC signals were perceived to be equally loud.

An adaptive categorical scaling procedure similar to the one documented by Brand and Hohmann (2002) was used in the 2013 study. The procedure incorporated 11 loudness category response alternatives ranging from inaudible (0 categorical units [cu]) to too loud (50 cu) and each loudness category was 5 cu higher than the previous category. When a signal was presented, listeners rated the loudness using a mouse to click on one of the loudness categories displayed on the computer screen. Once the response was received and recorded, another signal was presented until all signals were tested for each condition.

In addition to the different loudness estimation procedures, there were some other differences between the 2002 study and 2013 study. For instance, in the 2002 study, the AC signals were presented bilaterally, while the BC signals were presented unilaterally. In the 2013 study, both the AC and BC signals were presented bilaterally. Also, in the 2002 study, the signals ranged from 30 to 80 dB HL, while in the 2013 study, the range of the signals was from 10 to 90 dB SPL.

The results of the Stenfelt and Zeitooni (2013b) study provided no evidence that the procedure had an impact on the results. There was a statistically significant difference between the AC and BC loudness function slopes for the low-level signals. The same was true for the high-level signals. Just as in Stenfelt and Håkansson (2002), the slopes for the BC functions were steeper than for the AC functions in both cases even when a different method was used. In the case of the low-level signals, there was also a significant difference between the low- and high-frequency stimulations as well as the interaction between modality (AC vs. BC) and the stimulation frequency. There was no significant difference between the low- and high-level frequency stimulations for the high-level sound. As in the 2002 study, nonlinearity was detected in the functions resulting from the 2013b data. However, the source of the nonlinearity could not be irrefutably determined.

In 2014, Patrick et al. published a paper comparing results of their study with the results of the Stenfelt and Håkansson's 2002 study. In addition to the mastoid used in the Stenfelt and Håkansson's study, Patrick et al. (2014) included the forehead and condyle locations. This investigation used the same 5 narrowband signals and

3 signal intensities as were used in the Patrick et al. (2012) study. Another deviation from the Stenfelt and Håkansson study involved the use of loudspeakers to deliver the AC sound instead of headphones, transforming the listening environment from closed-ear to open-ear. As the AC and BC signals alternated between the speakers and BC transducer, listeners adjusted the intensity of the BC signal until it was perceived to be as loud as the AC signal. Once the adjustment was completed, the experimenter recorded the voltage necessary to produce the BC intensity before the next signal was presented.

Once all test conditions were completed, the recorded voltages were converted to decibels HL before the equal-loudness curves were created. The curves revealed nonlinear patterns for the AC/BC loudness comparisons. This means that while the intensity of the AC signals differed by 20 dB HL, the corresponding BC signal intensities did not illustrate a constant intensity change, much less a 20-dB change. In most cases, a 20-dB HL change in AC intensity resulted a BC intensity change of less than 20- dB HL indicating listeners were essentially more sensitive to the BC signals than the AC signals. Similar trends were also found in the closed-ear environment study (Stenfelt and Håkansson 2002); however, in the Patrick et al. (2014) study, the BC signals in the open-ear environment were perceived to be louder on average when compared with the BC signals in the closed-ear environment of Stenfelt and Håkansson's study.

In one of the most recent papers, Patrick et al. (2015) performed a follow-up analysis using the data obtained from the Patrick et al. (2012) study to determine if predictive equations can be constructed to calculate a person's conduction equivalency. Although the data collected in the previous study included 5 frequencies and 3 BC vibrator locations, the 2015 study was performed only on the data for the 1-kHz signal at the mastoid location. Multiple regression was used to create the predictive function. In this case, the dependent variable was the BC intensity while the independent variables were the AC signal intensities. Two sets of models were developed. The first one used each listener's AC threshold for both the right and left ear and the BC threshold at 1 kHz as the independent variables. In the second model, the right and left AC thresholds were averaged, and the average AC and the BC threshold were used as the independent variables.

Based on the results from the analysis, only the models for the lowest target AC signal were considered to be predictive whereby the model was significant at the alpha = 0.05 level. In the case of the first model, about 51% of the variation in the BC signal intensity was accounted for by the model. For the second model, approximately 40% of the variation in BC signal intensity was accounted for by the model. The models for the middle and high target AC signals were not statistically significant. The results of this study indicate that while it may be possible to develop a predictive model for calculating an individual's conduction equivalency, additional factors need to be considered when developing such a model.

In 2015, another BC equal-loudness study was performed by 3 doctoral candidates at Towson University (Andreaggi 2015; Arvindekar 2015; Lasman 2015). The researchers collected data jointly but analyzed them separately. Each of the 3 researchers collected data from 10 participants using the same procedures and combined their data prior to analysis. The goal of the study was to establish equal-loudness contours for specific conditions: bone-to-bone, sound field-to-sound field, and sound field-to-bone. For each of the conditions, the same 7 frequencies (0.25, 0.5, 1, 2, 3, 4, and 6 kHz) were tested except for the sound field-to-sound field condition in which 8 kHz was also tested. In the sound field-to-sound field and sound field-to-bone conditions, only one intensity (40 dB HL) was used; however, in the bone-to-bone condition, both 20 and 40 dB HL were used. In the bone-to-bone condition, the mastoid and condyle contact points were used but in the sound field-to-bone condition, only the right mastoid was used. A loudness matching procedure similar to the one used by Stenfelt and Håkansson (2002) was used in the study whereby the target and reference signals alternated. The listener used gestures to instruct the experimenter to either increase or decrease the test signal until it was perceived to be the same intensity as the reference signal. The auditory signals for these studies were 1 s long, one-third-octave band noises delivered through a loudspeaker located in front of the listener.

In performing data analysis, each researcher focused on different aspects of the equal-loudness contours. Arvindekar (2015) investigated the differences between previously developed sound field equal-loudness contours and the contours developed from her team's data collection process. She also compared the previous sound field equal-loudness contours to her team's sound field and BC equal-loudness contours. Lasman (2015) compared the data from the mastoid and condyle locations and evaluated differences in the data obtained for the 2 intensity levels. She also did a comparison between sound field and BC loudness contours. The foci of Andreaggi's (2015) analyses were the differences between unilateral and bilateral BC conditions and between-participant variability.

The analysis of data included in Arvindekar's (2015) thesis indicates that no statistically significant differences between the equal-loudness contours were found regardless of differences in the signal intensity (20 vs. 40 dB HL), transducer location (mastoid vs. condyle), or laterality condition (unilateral vs. bilateral). When the BC contours were compared to the AC contours listed in ISO 2003, the BC curve typically fell slightly below the corresponding ISO curve. The BC curves were approximately equal to the ISO curves for all of the frequencies except 250 and 6 kHz. The experimental BC curves were also compared to those reported in

Stenfelt and Håkansson (2002), Patrick et al. (2012), and Pollard et al. (2013). The results of these comparisons showed that the Stenfelt and Håkansson curves as well as the Patrick et al. curves were relatively the same as those reported by Arvindekar (2015) except for slight differences at 250 and 500 Hz. Pollard et al.'s curves deviated more considerably from the others and were between 2 and 6 dB higher than the values reported by Arvindekar (2015).

Lasman's (2015) data analysis included comparisons between the sound field and BC data collected for each frequency tested. The results of the analysis indicated the BC data were significantly higher at 250 Hz and significantly lower at 1 kHz than the sound field data. There were no statistically significant differences between the 2 sets of data at the other frequencies. These findings contradict those documented in previous studies by Stenfelt and Håkansson, (2002), Patrick et al. (2012), and Pollard et al. (2013).

Andreaggi (2015) focused his data analysis on the placement of the vibrator and the laterality condition. He also looked at the variability across participants based on their gender and the tester. No significant differences were detected between the condyle and mastoid locations. Additionally, the results of the laterality analysis indicated no significant differences between the unilateral and bilateral BC vibrator placement. This remained true even when the analysis was performed on each condition broken down by frequency and intensity. There were, however, differences between the BC bone-to-bone equal-loudness contours and previously established air-to-air contours such that the BC contours were higher for the lowest 2 frequencies tested (250 and 500 Hz) and lower for one of the highest frequencies tested (6 kHz).

The gender variability analyses included comparisons of both of the BC vibrator positions combined. At the 20-dB HL level, gender differences were observed at both 250 and 500 Hz whereby the adjusted loudness values for the male participants at each of these frequencies was close to 5 dB higher than the adjusted loudness values for the female participants. Significant gender differences were also detected at 250 Hz for the 40-dB HL level whereby the male participant values were about 4 dB higher than the female's values.

When evaluated by tester separated by gender, significant main effects for tester were found at 2, 3, and 6 kHz for 20 dB HL, and at all frequencies for 40 dB HL. The loudness data variations differed both in respect to the values reported by each tester as well as the magnitude of the difference between the listeners; therefore, interactions between subject's gender and tester were observed. Significant interactions between gender and tester were found at 0.5, 2, 3, and 4 kHz for 20 dB HL and 500, 3, and 4 kHz for 40 dB HL.

3.3 Summary

Loudness is a difficult perceptual variable to measure because of its tendency to substantially vary across both individuals and signals. The studies reported in this section describe several attempts to evaluate the loudness characteristics of bone conducted signals but the results are not consistent. Since measuring the loudness of a BC signal is difficult to achieve by attaching a sound measuring device directly to the BC vibrator, sound cancellation or loudness matching procedures are commonly employed to obtain the desired measurements. In general, the sound cancellation studies summarized in this section reported linear relationships between perceived AC and BC sound levels for sound levels between 15 and 80 dB SPL and frequencies between 0.25 and 4 kHz. The loudness matching procedures produced different results. In most of the loudness matching studies discussed, the loudness of the BC sounds was higher than that of the AC sounds when comparing the same frequency and intensity combinations. In other words, it typically took less energy for a BC signal to achieve the same loudness level (in dB HL) of an AC signal of the same frequency. The same was true when different bone vibrator locations were tested and when unilateral and bilateral conditions were compared. These results indicate that listeners generally appear to be more sensitive to vibrator-delivered BC signals than AC signals.

The mixed results from the BC loudness matching studies clearly indicate that additional research should be performed to develop an effective predictive model for calculating conduction equivalencies for various populations as well as individuals. Such models would need to take into consideration factors not included in the studies summarized in this section, such as variations in head dimensions and skull thickness as well as individual just noticeable differences associated with auditory signal perception. In addition, since in some studies gender differences were detected for signals of certain frequencies, this aspect of BC hearing should also be explored more thoroughly to identify the gender-related factors that influence BC loudness perception. Several of the reported studies indicated a presence of a nonlinear component in BC sound perception but the actual factor(s) causing the nonlinearity could not be conclusively identified. Therefore, future studies should also aim to confirm or deny the presence of the factor(s) and in the former case isolate the source of nonlinearity to improve the model.

4. Bone Conduction Spatial Auditory Perception

One of the major concerns regarding the use of BC devices for communication purposes has been the ability of the devices to transmit spatialized auditory signals in such a way that they can be used to isolate and localize the origin of a sound.

While some spatiality of BC sound within the head of the listener is easy to demonstrate with a binaural BC system, the resulting perceptual image is quite diffused and no specific sound source locations can be determined beyond some sense of lateralization. This is generally attributed to the fact that sound typically travels much faster through bones than through air, thus decreasing the listener's ability to use ITDs and interaural level differences (ILDs) as localization cues, which are the primary means by which we localize air-conducted sounds in the horizontal plane. However, several studies demonstrated the presence of lateralization effects in bilaterally delivered BC signals and possibility of spatial perception of spectrally processed BC signals.

4.1 Lateralization Studies

Several older studies, published before Henry and Letowski (2007), have already reported that time and intensity (or level) differences (ITD and ILD) delivered through a pair of bone vibrators exist and result in perceived sound source lateralization. For instance, Jahn and Tonndorf (1982) successfully used interaural time and intensity differences to produce lateralization cues for BC pure tone signals. Kaga et al. (2001) achieved BC lateralization effects in hearing impaired children using interaural time and intensity differences of a continuous narrow band noise. Stanley and Walker (2006) used ILDs of pure tones in their study and were able to create the lateralization effects from their bone vibrator headphones (i.e., bonephones) similar to those obtained with headphones. The authors presented 3 normal hearing listeners with auditory signals consisting of 8 pulses. The first 3 pulses had no interaural difference but the last 5 pulses had ILDs of 4, 8, 12, 16, or 20 dB. The frequencies of the signals were 500, 3000, and 8000 Hz. Participants were asked to listen to each signal and identify where inside the head they perceived the signal to be located by using a diagram of the head presented on a computer screen. The computer display contained a slider that could be moved straight across from the left ear to the right ear. The task was completed with both a stereo BC headset and a pair of circumaural headphones, and the data from the 2 devices were compared. The results of the study indicated that as the ILD increased, the perceived spatial separation increased. In addition, the perceived lateralization for the BC headset was similar to those for the headphones for all frequencies.

These and similar studies confirmed that ITD and ILD can be used to achieve sound source lateralization using BC transmission when the ITD and ILD values are sufficiently large. While this finding is important on its own merit, it does not indicate that BC sounds can be localized within the whole head or—which is really much more desirable—in the space outside the head like it is in case of 3-D headphone sound reproduction.

4.2 Localization Studies

The first study that actually demonstrated the possibility of discrete spatial localization (not only lateralization within the head) of BC sounds was the study by MacDonald et al. (2006). The authors used individualized head-related transfer functions (HRTFs) to achieve spatialization of Gaussian noise bursts presented from a binaural BC system. Localization accuracy of BC transmitted sounds was about the same as in the case of 3-D headphone sounds, and this study is described in Henry and Letowski (2007). In a similar study, Lindeman et al. (2007, 2008) investigated how well 24 listeners could identify the origin of spatialized augmented reality (AR) auditory signals that were either stationary or moving. They looked at 3 means of delivering the computer-generated AR signals: loudspeaker array, headphones, and BC headset. For all 3 methods, they wanted to include the transformative effects of sounds in the real world to present signals in a more realistic environment. This was easy to accomplish in both the loudspeaker array and BC headset conditions. Since the ears remained open in both of these conditions, the listener simultaneously received both the real-world sounds directly from the environment and the computer-generated sounds presented through the loudspeakers or BC headset. In the headphone condition, however, the real-world sounds could not be delivered directly from the environment since the ears were occluded. Therefore, they were captured from the environment before the experiment using microphones positioned at the opening of the ear canal of one of the investigators. The sounds were recorded and then combined with the computer-generated sound before being presented through the headphones.

Their study utilized 3 frequencies (200, 500, and 1000 Hz), 5 stationary signals (left, center-left, center, center-right, and right), and 2 moving signals (left-to-right, right-to-left). In the case of the stationary trials, listeners were asked to identify the location of the signal and for the moving trials, they were asked to identify the direction the signals were moving. Based on percent accuracy, the results for the stationary trials indicated the best performance was obtained for the speaker array followed by the headphones and then the BC headset. However, for the moving signals, the loudspeaker array resulted in the best performance and the headphones had the worst performance. The percent accuracy for the BC headset was higher than that for the headphones and less than that for the loudspeakers, but these differences were not significantly different based on the statistical analyses.

In 2012, McBride et al. (2012a) conducted a study designed to identify the best location to present localized signals. This study investigated how well listeners could identify the virtual location of bone conducted signals delivered to 3 vibrator positions (i.e., directly in front, behind, and above the ear). Seven normal hearing listeners participated in the study. Their task was to listen to a stream of eight 250-ms white noise bursts. The noise bursts were presented in 300-ms intervals. To create individualized signals that took into account the effect of the head on the directional perception of the signal, an HRTF-based filtering process was used. In this process, small microphones were placed into the listener's ears and signals were presented from 16 locations around the listener's head. The recordings were then processed to eliminate distortions potentially caused by the bone vibrators. The individualized signals recorded for each location were then randomly presented to the listener multiple times through a stereo bone vibrator headset, and the listener identified the location from which they perceived the signal to originate by clicking the perceived location on a circle displayed on a computer screen. The results of the study indicated the 3 vibrator positions performed relatively the same; however, the location right above the ear appeared to outperform the locations behind and in front of the ear when differentiating the extreme front (0°), back (180°), left (–0°), and right (90°) directions.

A more comprehensive study was performed by McBride and a team of ARL researchers in 2014 (McBride et al. 2015). In this study, listeners' individualized HRTFs were captured and used to compare the ability of listeners to localize sounds from a loudspeaker array, a set of AC headphones, and a BC headset positioned so that the vibrators made contact with 3 different symmetric positions around the ear (front, top, and back). The signal used was a stream of five 250-ms white noise bursts presented in 300-ms intervals. A similar HRTF process used in the 2012 study was used for this study. The interface used in this study consisted of a swiveling chair with a laser pointer attached to a front bar. After a signal was presented, listeners' were required to turn the chair and point to the direction from which they perceived the sound to have originated. Results of the study suggest that localization performance for the top and front BC vibrator positions were essentially the same and just as good as performance with the headphones. The best performance occurred with the loudspeaker condition while performance for the back BC vibrator position was the worst.

4.3 Spatialized BC Modeling Studies

Walker et al. (2007) experimented with FE models to develop a computer model that can be used to predict and improve spatialized speech signals presented through a BC headset. The initial version of the model, developed by Fluid Dynamics Research Corporation, included models of the soft tissue and fluids in the skull as well as the cochlea and basil membrane. Two phenomena lead to the belief that more-detailed knowledge of the skull will facilitate the improvement of the intelligibility of bone conducted speech signals. First, the time it takes for a vibration to move from the initial point of contact to the cochlea is believed to differ based upon the structures within the skull. Second, during the time it takes for a vibration to travel to the cochlea, transmission changes to the spectral components of the signal can occur that can impact its intelligibility. The authors hoped that future versions of the model would be able to provide guidance to help identify ways in which bone conducted auditory signal detectability can be improved through spatialization and facilitate the development of a bone-related transfer function (BRTF). However, no new or improved model has been published as of yet.

4.4 Summary

Recent studies focused on spatial auditory perception were primarily focused on comparing listener's localization and lateralization abilities between AC and BC devices. As expected, for the studies that included a sound field condition, sound field spatial auditory perception (i.e., loudspeaker-based sound presentation) was best in this condition when compared with headphones and BC devices. However, when headphone- and BC-based performances were compared, the BC devices were as effective as, and in some instances better than, headphones in delivering spatialized sound. In terms of BC device location, recent studies indicate relatively small differences in performance for BC vibrator positions around the ear, with the location right above the ear having a slight edge over the others.

Since previous studies have shown that BC devices have the potential to effectively transmit spatial auditory signals, future research should focus on improving localization accuracy of such signals in both the horizontal and vertical plane. Initial attempts at developing a FE model that can be used to predict and increase the effectiveness of spatialized BC signals were enlightening; however, additional research is needed to develop a BRTF that can be used to individualize spatial auditory BC signals.

5. Bone Conduction Speech Intelligibility

Over the past decade, BC devices have been employed in various types of military and commercial communication tasks. In both cases, communication was in the form of tones, pulses, or speech signals. In the case of tone and pulses, they just need to be audible and sufficiently different to convey intended code (meaning) and to be easily differentiated. In the case of speech communication, the speech signals that are sent and received must be clear and easy to understand (i.e., unambiguous and make sense). In technical terms, such speech signals need to have high intelligibility (for transmitted signals) or recognition rate (for received signals).

Typically, when speech communication is assessed in nonmilitary applications, word tests such as the modified rhyme test (MRT) (House et al. 1965), diagnostic rhyme test (DRT) (Voiers et al. 1973), Northwestern University Test Number 6 (NU6) (Tillman and Carhart 1966), phonetically balanced word lists (Egan 1948), and Central Institute for the Deaf (CID) W-22 test (Hirsh et al. 1952) are commonly used. The word tests entail the presentation of single syllable words, most of which are commonly found in the English language. Alternatives include various, less common, sentence tests.

In an effort to use speech signals that have a greater level of validity for military applications, another speech intelligibility test was developed by the Auditory Research Team at ARL. This test is called the callsign acquisition test (CAT) and instead of using single syllable words common to any English layperson, military callsigns and numbers are presented together as 3-syllable phrase test items (Letowski 2002; Rao 2003). Regardless of the test used, speech intelligibility is determined based on how often the listener can correctly identify the words presented and is usually reported as the percent of correctly identified test items.

The military has demonstrated a special interest in the use of BC devices for tactical operations. The small size and light weight of these devices makes them easy to conceal inside military helmets and other types of tactical headgear and impose minimal obstruction when the user is required to maneuver within confined spaces such as crawl spaces and underbrush. Due to the high utility of BC devices in tactical operations, the military has funded several studies to investigate the ability of BC devices to effectively transmit communication signals under various operational conditions.

Since BC communication devices generally have different technical parameters than AC communication devices, the signals that are produced have different acoustic properties. To assess whether these differences detract from their ability to be used effectively in communication tasks, several studies have taken place since the publication of ARL-TR-4138 (Henry and Letowski 2007). Most of these studies involved the use of BC technologies to deliver a signal to the listener, but some studies also investigated the use of BC microphones to capture the talker's speech. These studies are summarized in this section.

5.1 Bone Conduction Transmission (Vibrator) Studies

Since the primary means of transmitting speech communication is through AC, one of the first studies used to assess the viability of using BC devices in lieu of AC devices was conducted by Gripper et al. (2007). In their study, the CAT was used to compare the speech intelligibility performance of 12 normal hearing listeners presented speech signals through both AC headphones and a BC vibrator. The AC headphones used in this study were a pair of TDH 39 earphones and the BC device used was a Radioear B-71 bone vibrator. The vibrator was coupled to the listener's mandibular condyle using a headband. The test was conducted under 3 speech-to-noise ratios (SNRs) (–6, –9, and –12 dB) and the loudness of the signals from both devices were matched prior to initiating the CAT. The resulting speech intelligibility data showed that the listeners performed better (i.e., had higher speech recognition scores) with the headphones than with the bone vibrator regardless of the SNR. This was true for the entire callsign (letter-number combination) recognition as well as when the results of letter recognition were evaluated independently and when the results of number recognition were analyzed independently.

In addition to the perceptual assessment of speech intelligibility, Gripper et al. (2007) also performed a subjective evaluation of the 2 modes of listening. This was accomplished using a brief posttest questionnaire. Based on the questionnaire responses, over half of the listeners preferred the AC listening condition while only a quarter preferred the BC listening condition. Surprisingly a significant number of listeners (about 42%) indicated the clarity of the signals transmitted via BC was better than the clarity of the air-conducted signals, while 50% felt the air-conducted signals were clearer. In terms of comfort, most of the participants (67%) felt comfortable while wearing the bone vibrator, while 33% felt uncomfortable.

Another AC-BC speech intelligibility comparison study was conducted by Stanley and Walker (2009). In their study, the DRT was used to evaluate the intelligibility of speech delivered by AC and BC. In addition to the mandibular condyle, they assessed 2 additional contact points, the mastoid and vertex. The task in which their 17 normal hearing listeners participated required them to identify 96 words from the DRT word list for each of the 4 experimental conditions. The words were recorded in a reverberant chamber with Black Hawk helicopter background noise. The intensity of the noise was 106 dBA. In addition to the background noise in the recordings, 60 dB of pink background noise was also present in the room in which the listening task took place. The 2 devices they used to transmit the air and bone conducted signals, respectively, were a Radioear B-71 bone vibrator held in place by a headband and a set of Sennheiser HD 465 supra-aural headphones. The intensity of the signals for the 2 devices and 3 BC contact points were matched by 5 pilot listeners before the experiments began. As with Gripper et al.'s (2007) study, the results of Stanley and Walker's study also showed that the best performance occurred with the headphones. In addition, the test scores for the condyle were better than the scores for the vertex. They did not find a significant difference between the condyle and mastoid conditions.

Osafo-Yeboah et al. (2009) also looked at speech intelligibility performance of multiple BC vibrator contact points. As in Gripper et al. (2007), they also used items from the CAT. During the experiment, they exposed their 20 normal hearing listeners to background noise and delivered the test signals through a Radioear B-71 bone vibrator coupled to both the condyle and mastoid locations using a headband, similar to Stanley and Walker (2009). A digital force gauge was used to measure the static force being exerted on the skull by the vibrator. Four background noise conditions were utilized in their study: white noise, pink noise, multitalker babble, and quiet. The noise intensity was 89 dB SPL and was mixed in with the speech recordings. Since the speech signals were presented at 80 dB SPL, the resulting SNR was –9 dB. The results of their study showed no difference between the speech intelligibility scores for the 2 bone vibrator locations regardless of the background noise type used.

Subjective assessments were also obtained in this study as well. Based on the postexperiment survey administered, 95% of the listeners felt comfortable while wearing the bone vibrator and 5% were uncomfortable during its use. In addition, the majority of listeners (55%) favored the condyle location over the mastoid location when asked which contact location was more comfortable. However, other studies suggest that a key factor in the level of comfort is the static force applied by the bone vibrator against the skull, which is often determined by the type of headset used, not just the contact location (Toll et al. 2011; Tran et al. 2012). For this study, the static force for each listener was between 3.5 and 3.9 N.

In 2016, Manning, Mermagen, and Scharine published a study in which the effects of using a BC device to transmit speech signals to individuals with tinnitus were investigated. Since many military personnel, particularly Soldiers, suffer from some form of sensorineural hearing loss due to exposure to extremely loud noises, Manning's team was interested in determining whether the devices would be effective for those with hearing loss. This study focused on individuals with tinnitus since sound masking devices are often used to treat tinnitus sufferers because the external noise from the device can inhibit the internal noise produced inside the individual's head. This study was designed to determine if the speech intelligibility performance of individuals with sensorineural hearing loss, including tinnitus, differed from the performance of individuals with sensorineural hearing loss alone when either an AC or BC headset was used. While overall the individuals with tinnitus performed better than the individuals with hearing loss without tinnitus, the results of the study did not indicate any significant benefits or impairments between the 2 groups for either the AC or BC headset condition. Those with hearing loss also did not demonstrate noticeable differences within each headset condition when compared with normal hearing listeners (Manning et al. 2016).

5.2 Bone Conduction Reception (Microphone) Studies

In addition to bone vibrator assessments, experiments have been conducted to investigate the performance of BC microphones, although there is no research in this area prior to 2010. In the first study of this kind Tran and Letowski (2010) compared intelligibility of speech picked up by a bone microphone with intelligibility of speech picked up by a traditional boom microphone. The authors used an Oiido noise-cancelling AC boom microphone positioned about 1 cm from the left side of the talker's lips and a Sensory Devices HCM/A25 BC microphone coupled to the talker's left mastoid. In addition, 2 Oiido BC vibrators coupled to the participants' mandibular condyle bones were also used to deliver BC signals. Eight normal hearing participants whose native language was English took part in the study. Each participant was paired with another and the pair took turns serving as both the talker and the listener while located in separate rooms. The words spoken by the talkers in this study were items from the CAT. One of 2 background noise conditions (less than 30 dB(A) or 100 dB(A)) was used in the room containing the talker during the task. The noise used in the 100 dB(A) condition was from the inside of a Bradley Fighting Vehicle. Each participant was exposed to the 2 microphone conditions and 2 background noise conditions as both the talker and the listener. Based on the results of this study, the speech intelligibility of the AC microphone was higher than that for the BC microphone. However, both microphones met the speech intelligibility performance criteria for military communication equipment used in operational settings (MIL-STD-1472). In addition, the authors pointed out that a poor-fitting BC microphone might have caused some of the lower intelligibility scores experienced during some trials.

In a later study conducted by McBride et al. (2011), a Temco HG-17 BC microphone was used to make recordings from 8 contact points on the head of 1 female and 1 male talker. The contact points used in this study were the right mastoid, collarbone, chin angle, forehead, vertex, inion, Fz (located between the forehead and vertex), and right above the temple. Ten words used in the CAT were spoken by each talker and recorded at each contact point. To assess the bone microphone speech recordings, the words were played back to 33 normal hearing listeners through AKG K 240 DF circumaural earphones. The listeners were asked to rate each recording based on speech intelligibility and sound quality. Based on the results of this experiment, the location of the bone microphone does have an impact on the intelligibility and quality of the speech transmitted. This study provided evidence that the best contact point for the bone microphone is the forehead followed by the bone above the temple.

McBride et al. (2011) used the same 10 signals as those used in the earphone study for a second study incorporating a bone vibrator. This time the listeners rated only the intelligibility of the signals transmitted to them, not the quality of the signals. Twelve normal hearing listeners were fitted with an Oiido stereo BC headset so that one bone vibrator was coupled to the left condyle and another was couple to the right condyle. Based on the ratings provided, placing the BC microphone on the forehead again produced the most intelligible speech signals.

Tran et al. (2013) conducted an assessment that went beyond the relatively subjective speech intelligibility rating tests. In their study, they looked at the spectral characteristics of bone microphones and then compared them to the intelligibility ratings of the speech produced. Twelve bone microphone contact points were used in this study. These were the same contact points used in the loudspeaker study documented in McBride et al. (2011). Twelve talkers of both genders whose native language was American English were used to create the recordings. Instead of actual words, the 5 signals used in this study were individual vowel and consonant sounds. In addition to the two Temco HG-17 BC microphones, a Bruel and Kjaer 4133 AC microphone was also used for comparison purposes. The recordings were simultaneously recorded by both BC microphones and the AC microphone. One of the BC microphones was used for reference purposes only and remained coupled to a single contact point on the forehead throughout the duration of a talker's recordings. The sensitivity of each contact point was determined by calculating the difference between the sound levels of the recording produced at that location and those made at the reference location.

The results of the location comparisons performed by Tran et al. (2013) indicated the chin, chin angle, and collarbone were the most sensitive locations based on higher intensity recordings. However, when these results were compared to the intelligibility results from McBride et al. (2011), which used the same bone microphone contact points, the significant negative correlation between intensity and intelligibility indicated the contact points with the higher intensity recordings (such as the collarbone and chin) did not necessarily produce more intelligible signals. One explanation of this effect could be spectral differences in signals observed at the discussed locations. According to the results of spectral analyses that looked at the sound spectrum for the recordings from 6 of the test locations (chin, collarbone, condyle, forehead, temple, and mastoid), the recordings from the collarbone and chin had relatively high content of low-frequency energy but had noticeably lower high-frequency energy when compared with the AC microphone recordings. Those locations that had similar spectral patterns as the AC microphone (such as the forehead and temple) had a tendency to have relatively high intelligibility ratings. Since the AC microphone recordings resulted in perfect intelligibility scores, the difference between the AC and BC microphone spectral patterns are believed to serve as an indicator of the level of intelligibility associated with the BC microphone.

5.3 BC-to-BC Sound Transmission Studies

The studies described in the previous 2 sections involved cases where either a BC vibrator or BC microphone were used. Pollard et al. (2015) performed a study that incorporated both BC microphones and BC vibrators to determine what factors might influence the intelligibility of BC-to-BC speech. In this study, there were 8 talkers and 24 listeners. Both the talkers and listeners were selected in such a way to ensure diversity within the groups. Two locations (i.e., the forehead and mandibular condyle) were used as bone microphone contact points. The left and right mandibular condyles were used as bone vibrator contact points. Two background noises (i.e., quiet and pink noise) were used for both the talkers and the listeners. Several participant characteristics were recorded and their effects on speech intelligibility were assessed. For both listeners and talkers, these characteristics included gender, age, and regional origin. For the talkers, additional characteristic vocal traits such as fundamental frequency, spectral tilt, jitter, and shimmer were also measured and recorded. The test signals were words from the MRT spoken by the talker.

The findings from this study support the results of McBride et al. (2011) that indicated the forehead resulted in signals of higher intelligibility than the condyle. One possible reason for these results is the relatively flat surface of the forehead makes it a more suitable contact point for the BC microphone. Another factor that could potentially contribute to the findings is that the forehead location provides a stronger vibratory signal than the condyle location for frequencies from 1,000 to 16,000 Hz and the frequencies in a 1- to 5-kHz range are the most critical for speech intelligibility. Additionally, the authors found that signals recorded from the condyle were more intelligible when pink background noise was present than in the absence of background noise. It is believed that this might be caused by the Lombard effect whereby individuals increase their vocal fundamental frequency and frequency distribution when talking to compensate for interference that might be caused by background noise. Pollard et al. (2015) also found that voices with higher fundamental frequencies produced more intelligible signals for condyle recordings than voices with lower fundamental frequencies. Furthermore, when takers and listeners were from the same region, the speech intelligibility scores for the condyle recordings were higher. However, none of these "condyle effects" were observed for the forehead recordings. Spectral tilt, jitter, shimmer, and age did not appear to affect speech intelligibility in any case (Pollard et al. 2015). In a follow-up study, Pollard et al. (2016) examined the influence of craniofacial morphology on BC sound transmission using the morphological data of the participants from the previous study. They reported that 1) individual morphological and vocal differences in talkers affect how endogenous sounds are transmitted to recording locations on the skull and 2) individual morphological differences in listeners affect how external sounds are transmitted from skull locations to the internal hearing organs. These morphological effects explained the collected data better than individual demographic traits such as gender, which may primarily serve as a proxy for morphological traits.

5.4 Sound Source Separation Studies

Walker et al. (2005) performed a study to compare the ability to spatially separate dichotic signals presented through a set of AC headphones and a BC headset (referred to as bonephones in their paper). In their study, 8 normal hearing listeners performed a task in which they were asked to identify elements in the Coordinate Response Measure (CRM) corpus. This task is similar to the Synchronized Sentence Set (S^3) (Abouchacra 2000; Abouchacra et al. 2009) whereby 2 or more talkers are speaking the same carrier phrase simultaneously and the elements to be identified are imbedded in that phrase. In the case of the CRM, listeners had to identify the color and number spoken by the same voice that spoke the target call sign “Baron”. They tested 6 ITDs between the values of 0 and 1600 µs and 6 ILDs between 0 and –16 dB to create the effect of the target phrase being presented to either the left or right of the listener. Their results indicated that the listeners were able to provide the correct response more often with the headphones than with the BC headset. They also noted that the increase in performance as the ITD and ILD increased was more drastic with the headphones than with the BC headset, which could potentially indicate an upper limit on the amount of spatial separation possible with BC headsets. However, spatial separation was shown to be possible with a BC headset using these methods.

In 2011, a study was conducted at ARL to investigate the ability of listeners to isolate speech signals transmitted through a 2-channel BC headset (McBride et al. 2012b). In this study, 24 normal hearing listeners were presented dichotic vocal signals to the left and right side of the head via a BC headset or a set of headphones using the S^3 task. In this listening task, the 2 different male voices spoke a sentence (i.e., carrier phrase) at the same time so that their words completely overlapped one another. The carrier phrases were exactly the same except for 4 token words on which the listener was asked to focus their attention. The first word was a name, the second word was a number, the third word was a color, and the fourth word was an object. Their task was to listen for a specific name (i.e., Troy) and identify the other 3 words spoken by the same voice that said the target name. One voice was presented to the left ear and the other to the right ear. The target voice was randomly presented to either the left or the right ear throughout the experiment. The listeners' performance using the BC headset was compared to the performance under the same conditions using traditional AC headphones. The results indicated that the performance using the 2 types of listening devices were comparable.

Blue et al. (2013) performed a multichannel communication systems study using a BC vibrator as one of the sound sources. In this study, 18 normal hearing listeners were asked to distinguish between 3 spatially separated communication channels. A multichannel amplifier was used to create the 3 different listening configurations associated with the communication systems tested. The first system consisted of 3 loudspeakers, the second used a set of headphones, and the third used a set of earphones and a BC vibrator. Again, the S^3 listening task was used where a different voice was presented randomly to each of the 3 channels. Each listener was required to isolate the elements of the target sentence, which was transmitted to only one of the communication channels. Based on the results of the study, overall performance was best using the system that consisted of the headphones and bone vibrator even though statistically there was not a significant difference between this system and the system using just the headphones. These results indicate that incorporating a bone vibrator as one of the channels is an effective method to increase the number of communication channels and a viable alternative to using 3-D headphones.

In a parallel study, McBride et al. (2013) investigated the impact of left/right presentation of auditory signals on speech intelligibility. The study sought to determine whether the same summation effect present in AC hearing was present with BC hearing since intracranial attenuation is low and a single vibrator can stimulate the hearing structures on both sides of the head. This time the bone vibrators were assessed based on listener performance in a monotic/diotic speech recognition task. In this study, 12 normal hearing listeners were asked to complete the CAT using 4 different listening conditions achieved using 4 amplifier channels. In one condition, the speech signals were presented to the bone vibrator coupled to the bone in front of the left ear only (monotic). Another condition presented signals to the bone vibrator coupled to the bone in front of the right ear only (monotic). The other 2 conditions were diotic conditions in which the same signal was presented simultaneously to both ears; however, in one of the diotic conditions, the intensity of the signal was adjusted to compensate for the diotic summation effect and in the other no adjustments to the signal intensity was made. The improved speech recognition scores resulting in this study for the diotic condition without level compensation provide evidence of a diotic summation effect; however, the effect was not as strong as that typically seen in AC monotic/diotic listening tasks.

5.5 Summary

When comparing the clarity of speech transmitted through headphones and BC devices, the former still tends to outperform the latter. However, several studies have demonstrated the ability of BC devices to transmit high quality, intelligible speech as well, even in noisy environments. The primary challenge with bone conducted speech communication has been identifying the optimal contact point for these devices that will result in the clearest speech signal possible. In the case of BC listening devices, the mastoid and mandibular condyle locations typically result in the most intelligible signals and generally can be used interchangeably. However, the most effective contact point for bone microphones appears to be the forehead followed by the temple. This proved to be the case regardless of whether an AC or BC listening device was used. When evaluating the spectral content of bone microphone recordings, the locations closest to the mouth, such as the chin and collarbone, had higher intensity recordings. However, these recordings proved not to be more intelligible than recordings from the forehead and temple, which had spectral characteristics similar to a traditional AC microphone.

Additionally, reported studies have shown that BC listening devices produce results comparable to AC listening devices in terms of the listener's ability to separate sound sources. In fact, the results of one study even suggests that multichannel communication systems can actually benefit from the inclusion of a BC device as one of the sound sources since it improved the listener's ability to isolate sentence elements in comparison to binaural earphone transmission of the same number of channels.

Future BC speech intelligibility studies should incorporate the use of a wider array of BC devices. As technology advances, the performance of BC devices is likely to improve and the number of available and technically diverse BC devices is rapidly growing. Despite the fact, based on the discussed studies, that BC devices do not quite currently measure up to AC devices when it comes to the intelligibility and quality of speech signals, technological improvements are likely to result in device characteristics that enable the production of BC speech signals that are practically indistinguishable from those produced by AC devices.

6. Bone Conduction Gender Differences

The transmission of bone conducted signals is known to be affected by several anatomical and physiological factors. The factors most commonly discussed include the density of the skull bone, thickness of the skin tissue, and the amount of hair a person has on his/her head at the point where the BC transducer makes contact. Men and women are known to differ in each of these areas; however, other gender-differentiated factors might also have an impact on the transmission of BC signals. Hodges (2007) investigated several of these factors, some of which are discussed in this section along with additional studies that were conducted to investigate how these gender differences impact BC communication.

6.1 Air Conduction Studies

Several researchers have documented results of studies that indicate gender differences in hearing overall. For instance, the Nord-Trondelag survey conducted from 1995 to 1997 presented data illustrating differences in AC hearing thresholds based on gender. In this study, 51,975 Norwegians were tested using pure tone frequencies from 250 to 8000 Hz. The study showed that significantly more males than females reported a history of noise exposure (75.4% vs. 25.2%, respectively) and symptoms of hearing loss (15.4% vs. 11.1%, respectively). However, there was not a noticeable differences between the percentage of men and women reporting a history of ear-related diseases and disorders (24.2% vs. 25.7%, respectively) nor between the percentage of men and women reporting unilateral conductive hearing loss (both 48.8%). When participants reporting ear-related disorders, ear-related diseases, and a history of noise exposure were removed from the sample population, the data showed that females (especially those within the age range of 20–29 years old) had lower hearing thresholds for frequencies 3000 Hz and above. This gender difference had a tendency to increase with age. Additionally, males appeared to have lower thresholds than females overall at 500 Hz (Engdahl et al. 2005).

Some researchers have suggested that the gender-related threshold differences might be revealed by the presence of spontaneous otoacoustic emissions (SOAEs) (sounds emitted in the absence of acoustic stimuli). For instance, researchers have found that females tend to experience SOAEs more often than males (Bilger et al. 1990; McFadden and Loehlin 1995). The results of a study conducted by McFadden and Mishra (1993) showed that the hearing sensitivity of people who experienced SOAEs more frequently were more likely to have lower hearing thresholds for frequencies from 1000 to 6000 Hz. Overall, those people tested who did not experience SOAEs at all had hearing thresholds that averaged about 3 dB higher than those people who did experience SOAEs. Additionally, Schmuziger et al. (2005) conducted a similar study using a higher frequency range and found that people who experienced SOAEs more often had lower hearing thresholds for frequencies in the 8000- to 16,000-Hz range as well. In another study, McFadden and Loehlin (1995) tested 242 people using a low-noise microphone system and found that 63% of the 133 females tested exhibited at least one SOAE while only 43% of the 109 males tested exhibited at least one SOAE during the 2-h test session. The results of these studies provide further support for the theory that the presence of robust SOAEs may indicate the ability of females to hear higher frequency ranges at lower intensity levels than males regardless of the mode of hearing (AC or BC).

Another factor believed to have an impact on hearing sensitivity is the length of the cochlea. In a study conducted by Sato et al. (1991) the cochlea of 9 men and women were measured. Based on the data collected, the average cochlea length for women is about 5 mm shorter than it is for men (32.3 mm vs. 37.1 mm, respectively). It is believed that a shorter cochlear length allows the cochlea to process stimuli more quickly, which may in turn result in lower auditory thresholds (Hunter et al. 2005).

In addition to the presence of SOAEs and cochlea length differences, head size has also been suggested as a contributing factor to differences seen in male and female auditory signal processing. Research shows that females tend to have smaller head dimensions than males. For instance, Aoyagi et al. (1990) performed head measurements using 3 different parameters: ear-to-ear, nasion-to-inion, and head circumferences. For all 3 parameters, the dimensions for the male participants were significantly larger than those dimensions for the female participants. Based on these external differences in the skull size, it is suggested that the length of the central auditory pathway might also be shorter for women whereby the female auditory pathway may be as much as 2.16–5.40 mm shorter than the males (Aoyagi et al. 1990). The shorter auditory pathway is believed to result in shorter ABR latencies. Since ABR latencies tend to increase as the intensity of a signal approaches a listener's hearing threshold, shorter ABR latencies typically correspond to higher hearing sensitivities (i.e., lower hearing thresholds).

Still another theory suggests that hormonal differences between genders contribute to differences in hearing. A study conducted by Dehan and Jerger (1990) used an EEG, or electroencephalogram, to measure the ABR latencies for both male and female participants presented 100-µs clicks through tubephones inserted into the ears. They found that even when there were no differences between the head sizes of the males and female participants, the latencies for the females were still shorter. They did find, however, that the hearing latencies changed depending on the stage in which the women were in their menstrual cycle. For instance, after ovulation and before menses when the progesterone levels were higher, the latencies were at their shortest. The latencies of postmenopausal women did not change and remained similar to those of the men.

All of the previous studies were designed to investigate gender differences in AC hearing. In respect to BC hearing, very little research has been conducted to investigate the differences between genders. This could be due to the belief that the results will be similar to those found for AC hearing. However, Sohmer and

Freeman (2001) performed a study that showed that the ABR latency periods for bone conducted stimuli transmitted through skull bone might actually be longer than those from air-conducted stimuli. It was postulated that the extended latency period for transmission through the skull was likely due to the time required to transmit the vibration from the skull to the relevant structures within the cranium that impact auditory perception. Sohmer and Freeman's results supported those found by other researchers such as Durant and Hyre (1993) and by the normal hearing participants in a study conducted by Maudlin and Jerger (1979); but contradict results found by other researchers such as Hooks and Weber (1984), Stuart et al. (1993), and Yang et al. (1993). However, the studies in which the BC ABRs were shorter than the AC ABRs, the measurements were taken from infants, whereas in the other studies, the measurements were taken from teenagers or adults. The results from these studies justify the need to specifically assess whether or not gender differences exist in BC hearing since the psychophysical response for air- and bone-conducted stimuli differ in some respects.

Since bone structure plays such a vital role in BC signal transmission, gender differences in bone structure may also result in significant differences in BC hearing. For instance, in a study conducted by Trune et al. (1988), the bones of male participants were found to be thicker than the bones of females. In addition, researchers have found that when looking at the body as a whole, males have higher bone mineral content and bone mineral density (BMD) when compared to females (Henry and Eastell 2000; Maynard et al. 1998). However, when it comes to the skull, studies have shown that women have higher BMDs presumably because they have smaller heads (Maynard et al. 1998). Therefore, since lower bone density is believed to facilitate the transmission of BC signals, it was believed that the lower BMD values for men should result in them having lower BC hearing thresholds.

In addition to hearing thresholds, speech intelligibility of male and female voices may also differ but the data presented in the literature are not consistent. For example, some authors have found that the difference in intelligibility of male and female voices in low to moderate noise levels is negligible (Ellis et al. 1996, 2002). However, according to Nixon et al. (1998) the female voice is not as easy to decipher as the male voice in some of the most commonly experienced loud noise environments. This could be because the pitch of the female voice is perceived to be higher than their male counterparts and the fundamental frequency of female voices actually doubles that of male voices (250 vs. 124 Hz, respectively) (Nixon et al. 1998). Furthermore, according to Bergeijk et al. (1960), the average vocal frequency of females also tends to be higher than males (727 vs. 500 Hz, respectively). However, based on a study by Letowski et al. (1993), when speaking in noise, the Lombard effect for females tends to result in smaller changes in vocal pitch when compared with males (vocal pitch shift of 2.5 and 18 Hz for women vs. 16 and 28.5 Hz for men when comparing the shift between quiet to 70 dB SPL background noise and quiet to 90 dB SPL background noise, respectively). These characteristics could impact the effectiveness of BC communication devices.

6.2 Bone Conduction Transmission (Vibrator) Studies

To investigate whether threshold differences present in AC hearing also appear in BC hearing, Hodges and McBride (2012) conducted a study investigating the hearing thresholds of male and female participants. In their study, 30 normal hearing participants between the ages of 18 and 25 years old were subjected to a standard BC hearing test using pure tone frequencies from 250 to 8000 Hz. A Radioear B71 bone vibrator was coupled to 4 different contact points in their study (mandibular condyle, mastoid, vertex, and temple). Prior to conducting the hearing test, 2 head measurements were taken for each participant. The first measurement identified the distance from inion to nasion, and the second measurement determined the distance from left to right mastoid. Based on the inion to nasion measurements, the male participants had significantly larger heads than the female participants did (mean = 36.07 cm and 33.40 cm, respectively; p-value < 0.001). The left-to-right mastoid difference for the male participants was slightly higher than for the female participants, but the difference was not statistically significant (mean = 39.27 cm and 38.13 cm, respectively; p-value = 0.07).

The results of this study showed that the female participants had lower hearing thresholds than the male participants over all of the frequencies tested. However, 6000 and 8000 Hz were the only frequencies where these differences were statistically significant, and these differences were only present at the mastoid location. There were no significant differences at the lower frequencies or the other bone vibrator contact points (Hodges and McBride 2012).

One of the gender studies that was included in the Hodges (2007) BC thesis was designed to investigate the potential intelligibility differences between male and female voices transmitted through a BC headset. During this investigation, 2 BC vibrator contact points were used to deliver items from the MRT to 12 normal hearing participants between the ages of 18 and 25 years, inclusively. Each participant was exposed to 2 versions of the MRT speech intelligibility test presented through a Radioear B71 bone vibrator. One version of the test used a female voice and the second version used a male voice. Pink noise at 4 different levels ranging from 0–103 dB(A) was used during the study. The results of this study indicated performance on the test appeared to be significantly impacted not only by the location of the vibrator (which was expected due to previous studies) but also by the gender of the speaker. Contrary to what was found in previous AC listening studies, the female voice transmitted via BC was found to be more intelligible than the male voice when there was no background noise present. However, in the presence of background noise, the male voice was statistically more intelligible than the female voice at each of the 4 noise levels tested (McBride et al. 2008).

In another speech intelligibility study, Osafo-Yeboah et al. (2009) reported that when it comes to deciphering speech components, females tend to perform slightly (but not significantly) better than males. In this study, the CAT was used to see how well male and female participants are able to discern speech in different background noises. Ten male and 10 females were asked to identify both the letter and number associated with the military callsign presented via BC vibrator (Radioear B-71) to either the mandibular condyle or mastoid. The results of their study showed that from a statistical standpoint, female and male participants had practically the same speech intelligibility scores for the quiet environment. When pink or white noise was present, the females had slightly higher speech intelligibility scores than males, but the differences were not statistically significant. However, for multitalker babble, the male participants had statistically higher speech intelligibility scores than the female participants (p-value = 0.039). In a later study, Pollard et al. (2015) instructed 12 male and 12 female participants to listen to recordings of MRT words. The words were recorded with a BC microphone located at 2 different contact points (i.e., the forehead and mandibular condyle). Four female and 4 male talkers vocalized 300 target words from the MRT within the following carrier phrase: "Mark the _____ again". The signals were delivered to the listeners' left and right mandibular condyle. The results for the forehead recordings supported the findings of Osafo-Yeboah et al. (2009) whereby the female listeners had higher speech intelligibility scores than the male listeners; however, no gender differences were noted for the condyle recordings.

6.3 Bone Conduction Reception (Microphone) Studies

Gender differences have also been discovered in a couple of BC microphone studies (Tran et al. 2008; McBride et al. 2011). In all these studies, the listening task took place in quiet without any masking noise. In one study, one male and one female voice were used to record 10 words from the CAT. The words were recorded from 8 bone microphone contact points (right mastoid, collarbone, chin angle, forehead, vertex, inion, Fz [located between the forehead and vertex] and right above the temple) using a Temco HG-17 BC microphone. The recordings were played back to 33 normal hearing listeners using AKG K 240 DF headphones. The assessment results favored the male voice over the female voice whereby the male voice was rated higher in terms of intelligibility and quality. However, since only one talker of each gender was utilized in the study, the authors recommended further studies be conducted in which speech signals from multiple talkers of each gender are assessed before attempting to make any generalizations (Tran et al. 2008).

A follow-on study conducted by McBride et al. (2011) used 2 male and 2 female talkers. This time only 3 words from the CAT were recorded for each talker and 12 bone microphone contact points were used. In addition to the 8 mentioned previously, the chin, left mastoid, condyle, and Pz (located between the vertex and inion) were included. The same Temco HG-17 BC microphone was used to make the recordings; however, this time the recordings were played for 22 listeners through a loudspeaker and the listeners rated each recording based on speech intelligibility and quality. The results of this study showed that the female voices were typically rated higher for both intelligibility and quality for all locations except for the chin angle and Pz.

The study by Pollard et al. (2015) drew some different conclusions regarding the impact of gender on the intelligibility of BC recorded MRT speech signals. In their study, they not only recorded the gender of their 8 talkers (4 male and 4 female) but also the fundamental frequency of their voices. While the condyle recordings results supported the findings of the McBride et al. (2011) study, whereby female speech resulted in higher intelligibility scores than male speech, there were no differences found between the 2 types of voices for the forehead recordings. The same was true for the fundamental frequency: higher fundamental frequencies resulted in higher intelligibility scores. Since female voices tend to have higher fundamental frequencies than male voices, Pollard et al. performed an additional analysis using a general linear model to determine the contribution of both gender and fundamental frequency on the intelligibility of the speech signals recorded at the condyle. The analysis revealed that fundamental frequency is the main contributor and the gender of the talker did not provide any additional information that can be used to predict the level of intelligibility.

6.4 Summary

In terms of BC gender differences, the location of the BC device and the background noise appear to play a part in how signals are perceived by male and female listeners. For instance, male listeners tend to be able to decipher speech signals in multitalker babble background noise better than females. However, in pink and white noise, male and female listeners perform practically the same. In terms of voices transmitted via a BC device, studies have shown that female voices are more intelligible in quiet environments while the male voice tends to be more intelligible when background noise is present. When evaluating hearing thresholds, differences between male and female listeners were detected for certain frequencies when the BC device was located on the mastoid, but not when it was located on the mandibular condyle. Location differences were also demonstrated between genders for speech intelligibility, whereby female listeners scored higher than male listeners but only for the condyle location, not the forehead.

Evaluations of gender differences associated with bone microphone recordings provided mixed results. In one study, the male voice was deemed more intelligible and of higher quality; however, in a follow-up study, the female voices tested were found to be more intelligible and higher in quality but only for certain locations. It is believed that the gender of the talker recorded is less of a factor in the intelligibility and quality assessments than is their fundamental frequency.

While these studies provide evidence of gender differences in BC communication, the actual cause of these differences is still unknown. Several theories have been presented over the past 30 years but none have been confirmed. Results of a recent study by Pollard et al. (2016) suggest that morphological differences among people may explain observed results better than general demographic traits as gender. Future studies should focus on effectively isolating and testing specific individual gender differences to identify which differences truly have an impact on BC communication.

7. Conclusion

In 2007, ARL-TR-4138 (Henry and Letowski 2007) provided one of the first comprehensive reports on the anatomical, physiological, and communication characteristics of BC. By doing so, it has served as a key source of information for researchers performing BC research. The current report continues where ARL-TR-4138 left off by providing an update on the research that took place between 2007 and 2015, inclusively. In addition, the current report includes studies that took place prior to 2007 that were not included in ARL-TR-4138.

BC research has come a long way but there are many components of BC that are not well understood. This report is designed to serve as a quick-reference guide for researchers interested in continuing the investigation into BC to determine the applications for which the technology is best suited as well as to identify means by which the technology can be optimized. The results of such studies will aid in the development of communication systems that are not only functionally effective but cost-effective as well.

8. References

Abouchacra KS. Synchronized sentence set (S^3) CD3. Aberdeen Proving Ground, (MD): Human Research and Engineering Directorate, Army Research Laboratory (US); 2000.

Abouchacra KS, Letowski T, Besing J, Koehnke J. Clinical application of the synchronized sentence set (S^3). In: Proceedings of the 16th International Congress of Sound and Vibration; 2009 July 5–9; Kraków, Poland.

Abramovich SJ. Auditory perception of ultrasound in patients with sensorineural and conductive hearing loss. Journal of Laryngology and Otology. 1978;92(10):861–867.

Adelman C, Sohmer H. Threshold to soft tissue conduction stimulation compared to bone conduction stimulation. Auditory Neurotology. 2013;18(1):31–35.

Al-Salim SC, Kopun JG, Neely ST, Jesteadt W, Stiegemann B, Gorga MP. Reliability of categorical loudness scaling and its relation to threshold. Ear and Hearing. 2010;31(4):567.

Algom D, Marks LE. Individual differences in loudness processing and loudness scales. Journal of Experimental Psychology. 1984;113(4):571–593.

Allen G, Fernandez C. The mechanism of bone conduction. Annals of Otology, Rhinology and Laryngology. 1960;69(1):5–28.

Andreaggi DS. Bone conduction equal loudness contours [unpublished AuD dissertation]. [Towson (MD)]: Towson University; 2015.

Aoyagi, M, Kim Y, Yokoyama J, Kiren T, Suzuki Y, Koike Y. Head size as a basis of gender differences in the latency of the brainstem auditory-evoked response. Audiology. 1990;29(2):107–112.

Arlinger S, Kylen P, Hellquist H. Skull distortion of bone conducted signals. Acta Otolaryngologica. 1978;85(1–6):318–323.

Arvindekar S. Bone conduction equal loudness contours: placement, frequency, and intensity [unpublished AuD dissertation]. [Towson (MD)]: Towson University; 2015.

Bárány E. A contribution to the physiology of bone conduction. Acta Otolaryngologica, Supplement. 1938;26:1–129.

Bellmann MA, Mellert V, Reckhardt C, Remmers H. Perception of sound and vibration at low frequencies. In: Collected papers from the joint meeting “Berlin 99” of ASA, EAA, and DAGA, Berlin Germany (1999). Journal of the Acoustical Society of America. 1999;105:1297.

Bergeijk WA, van Pierce, JR, David EE Jr. Waves and the ear. Garden City (NY): Anchor Books/Doubleday; 1960.

Bilger RC, Matthies ML, Hammel DR, Demorest ME. Genetic implications of gender differences in the prevalence of spontaneous otoacoustic emissions. Journal of Speech and Hearing Research. 1990;33(3):418–432.

Blue M, McBride M, Weatherless R, Letowski T. Impact of a bone conduction communication channel on multi-channel communication system effectiveness. Human Factors. 2013;55(2):346–355.

Boezeman E, Bronkhorst A, Kapteyn T, Houffelaar A, Snel A. Phase relationship between bone and air conducted impulse signals in the human head. Journal of the Acoustical Society of America. 1984;76(1):111–115.

Boezeman E, Kapteyn T, Visser S, Snel A. Comparison of latencies between bone and air conduction in the auditory brain stem evoked potential. Electroencephalography and Clinical Neurophysiology. 1983;56(2): 244–247.

Brand T, Hohmann V. An adaptive procedure for categorical loudness scaling. Journal of the Acoustical Society of America. 2002;112(4):1597–1604.

Brinkman W, Marres E, Tolk J. The mechanism of bone conduction. Acta Otolaryngologica. 1965;59(2–6):109–115.

Buckingham R, Valvassordi G. Inner ear fluid volumes and resolving power of magnetic resonance imaging: can it differentiate endolymphatic structures? Annals of Otology, Rhinology, and Laryngology. 2001;110(2):113–117.

Carhart R. Clinical applications of bone conduction. Archives of Otolaryngology. 1950;51(6):798–808.

Carhart R. Effects of stapes fixation on bone-conduction response. In: Ventry IM, Chailkin JB Dixon RF, editors. Hearing measurement: a book of readings. New York (NY): Appleton-Century-Crofts; 1971 .p. 116–129.

Carrick DG, Davies WM, Fielder CP, Bihari J. Low-powered ultrasound in the treatment of tinnitus: a pilot study. British Journal of Audiology. 1986;20(2):153–155.

Cazals Y, Aran J, Erre J, Guihaume A, Aurosseau C. Vestibular acoustic reception in the guinea pig: a saccular function? Acta Otolaryngologica. 1983;95(1–4):211–217.

Churcher BG, King AJ. The performance of noise meters in terms of the primary standard. Journal of the Institution of Electrical Engineers. 1937;81(487):57–81.

Clavier OH, Norris JA, Dietz AJ. A comparison of the nonlinear response of the ear to air and to bone-conducted sound. Hearing Research. 2010;263(1):224–232.

Collet L, Chanal JM, Hellal H, Gartner M, Morgon A. Validity of bone conduction stimulated ABR, MTR and otoacoustic emissions. Scandinavian Audiology. 1989;18(1):43–46.

Combridge JH, Ackroyd JO. Upper limit of frequency for human hearing. Nature. 1951;167:438.

Corso JF. Bone-conduction thresholds for sonic and ultrasonic frequencies. Journal of the Acoustical Society of America. 1963;35(11):1738–1743.

Corso JF, Levine M. Pitch discrimination by air and by bone conduction for sonic and ultrasonic frequencies (A). Journal of the Acoustical Society of America. 1963;35(5):804.

Corso JF, Levine M. Sonic and ultrasonic equal-loudness contours. Journal of Experimental Psychology. 1965;70(4):412–426.

Dallos P. The auditory periphery. New York (NY): Academic Press; 1973.

Davis H. An active process in cochlear mechanics. Hearing Research. 1983;9(1):79–90.

Deatherage B, Jeffress L, Blodgett H. A note on the audibility of intense ultrasonic sound. Journal of the Acoustical Society of America. 1954;26(4):582.

Dehan CP, Jerger J. Analysis of gender difference is in the auditory brainstem response. Laryngoscope 1990;100(1):18–24.

de Jong M, Perez R, Adelman C, Sohmer H. Experimental exploration of the soft tissue conduction pathway from skin stimulation site inner ear. Annals of Otology, Rhinology, and Laryngology. 2012;121(9):625–628.

Dieroff HG, Ertel H. Some thoughts on the perception of ultrasound by name. Archives of Oto-Rhino-Laryngology. 1975;209:277–290.

Dirks D. Bone-conduction testing. In: Katz J, editor. Handbook of clinical audiology. 3rd ed. Baltimore (MD): Williams and Wilkins; 1985.

Dobie R, Wiederhold M, Lenhardt M. Ultrasonic hearing. Science. 1992;255(5051):1584–1585.

Durrant JD, Hyre R. Observations on temporal aspects of bone-conduction clicks: real head measurements. Journal of the American Academy of Audiology. 1993;4(3):213–219.

Eeg-Olofsson M, Stenfelt S, Taghavi H, Reinfeldt S, Håkansson B, Tengstrand T, Finizia C. Transmission of bone conducted sound - correlation between hearing perception and cochlear vibration. Hearing Research. 2013;306:11–20.

Egan JP. Articulation testing methods. The Laryngoscope. 1948;58(9):955–991.

Elder JA, Chou CK. Auditory response to pulsed radiofrequency energy. Bioelectromagnetics. 2003;24(S6):S162–S173.

Ellis L, Reynolds L, Fucci D, Benjamin B. Effects of gender on listeners' judgments of speech intelligibility. Perceptual and Motor Skills. 1996;83(3):771–775.

Ellis LW, Spiegel B, Benjamin B. Effects of speakers' augmented characteristics and listeners' sex on intelligibility and acceptability of synthesized speech. Perceptual and Motor Skills. 2002;94(3 suppl):1081–1088.

Engdahl B, Tambs K, Borchgrevink HM, Hoffman HJ. Screened and unscreened hearing threshold levels for the adult population: results from the Nord-Trondelag hearing loss study. International Journal of Audiology. 2005;44(4):213–230.

Fastl H, Zwicker E. Lautstärkepegel bei 400 Hz; psychoakustische messung und berechnung nach ISO532B. Fortschritte der Akustik, DAGA. 1987;87:189–193.

Fletcher H, Munson WA. Loudness, its definition, measurement and calculation. The Bell System Technical Journal. 1933;12(4):377–430.

Foster KR, Finch ED. Microwave hearing. evidence for thermoacoustic auditory stimulation by pulsed microwaves. Science. 1974;185(4147):256–258.

Franke EK. Response of human skull to mechanical vibrations. Journal of the Acoustical Society of America. 1956;28(6):1277–1284.

Franks JR, Murphy WJ, Harris DA, Johnson JL, Shaw PB. Alternative field methods for measuring hearing protector performance. American Industrial Hygiene Association (AIHA) Journal. 2003;64(4):501–509.

Freeman S, Sichel JY, Sohmer H. Bone conduction experiments in animals: evidence for a non-osseous mechanism. Hearing Research. 2000;146(1):72–80.

de Freitas VS, Alvaranga KF, Morettin M, de Souza EF, Costa-Filho OA. Bone conduction auditory brainstem responses in normal hearing individuals. Pró-Fono Revista de Atualização Cientifica, Barueri (SP). 2006;18(3):323–330.

Fujimoto K, Nakagawa S, Tonoike M. Nonlinear explanation for bone-conducted ultrasonic hearing. Hearing Research. 2005;204(1):210–215.

Gavreau V. Audibilite de sons de frequence elevee. Comptes Rendus de L'Academie des Sciences de Paris. 1948;226(25):2053–2054.

Geiger PH, Firestone FA. The estimation of fractional loudness. Journal of the Acoustical Society of America. 1933: 5(1): 25-30.

Gelfand S. Hearing. New York (NY): Marcel Dekker, Inc.; 1991.

Goldstein BA, Shulman A, Lenhardt ML, Richards DG, Madsen AG, Guinta R. Long-term inhibition of tinnitus by ultraquiet therapy: preliminary report. International Tinnitus Journal. 2001;7(2):122–127.

Gripper M, McBride M, Osafo-Yeboah B, Jiang X. Using the callsign acquisition test (CAT) to compare the speech intelligibility of air versus bone conduction. International Journal of Industrial Ergonomics. 2007;37(7):631–641.

Groen J. The value of the Weber test. In: Schuknecht H, editor. Otosclerosis. Boston (MA): Little, Brown and Company; 1962. p. 165–174.

Håkansson B. The bone-anchored hearing aid – engineering aspects.. Göteborg (Sweden): School of Electrical Engineering, Chalmers University of Technology; 1984. Technical Report TR-144.

Håkansson B, Carlsson P, Tjellström A. The mechanical point impedance of the human head with and without skin penetration. Journal of the Acoustical Society of America. 1986;80(4):1065–1075.

Håkansson B, Brandt A, Carlsson P. Resonance frequencies of the human skull in vivo. Journal of the Acoustical Society of America. 1994;95(3):1474–1481.

Håkansson B, Carlsson P, Brandt A, Stenfelt S. Linearity of sound transmission through the human skull in vivo. Journal of the Acoustical Society of America. 1996;99(4):2239–2243.

Ham LB, Parkinson JS. Loudness and intensity relations. Journal of the Acoustical Society of America. 1932;3(4):511–534.

Henry YM, Eastell R. Ethnic and gender differences in bone mineral density and bone turnover in young adults: Effect of bone size. Osteoporosis International. 2000;11(6):512–517.

Henry P, Letowski T. Bone conduction: anatomy, physiology, and communication. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2007. Report No.: ARL-TR-4138.

Henry JA, Meikle MB. Psychoacoustic measures of tinnitus. Journal of the American Academy of Audiology. 2000;11(3):138–155.

Hernandez MC, Perez MC, Gaya JA, Charro L, Rodriguez E, Rioja L. 188. Bone conduction audiometry with multiple auditory steady state responses: a study in normal hearing subjects. Clinical Neurophysiology. 2008;119(9):e145.

Herzog H, Krainz W. Knochenleitungsproblem. Theoretische erwägungen. Zeitschrift für Hais-, Nasen-, und Ohrenheilkunde. 1926;15:300–313.

Hirsh I, Davis H, Silverman S, Reynolds E, Eldert E, Benson R. Development of materials for speech audiometry. Journal of Speech and Hearing Disorders. 1952;17(3):321–337.

Hoare DJ, Edmondson-Jones M, Gander PE, Hall DA. Agreement and reliability of tinnitus loudness matching and pitch likeness rating. PloS one. 2014;9(12):e114553.

Hodges H. Gender differences in auditory perception of pure tone frequencies and speech intelligibility via bone conduction transducers. [Unpublished thesis.] Daytona Beach (FL): Embry-Riddle Aeronautical University; 2007.

Hodges ML, McBride ME. Gender differences in bone conduction auditory signal processing: communication equipment design implications. International Journal of Industrial Ergonomics. 2012;42(1):49–55.

Homma K, Du Y, Shizmu Y, Puria S. Ossicular resonance modes of the human middle ear for bone and air conduction. Journal of the Acoustical Society of America. 2009;125(2):968–979.

Homma K, Shimizu Y, Kim N, Du Y, Puria S. Effects of ear-canal pressurization on middle-ear bone- and air-conduction responses. Hearing Research. 2010;263(1):204–215.

Hooks RG, Weber BA. Auditory brain stem responses of premature infants to bone-conducted stimuli: a feasibility study. Ear and Hearing. 1984;5(1):42–46.

Hosoi H, Imaizumi S, Sakaguchi T, Tonoike M, Murata K. Activation of the auditory cortex by ultrasound. Lancet. 1998;351(9101):496–497.

Hosoi H, Yanai S, Nishimura T, Sakaguchi T, Iwakura T, Yoshino K. Development of cartilage conduction hearing aid. Archives of Material Science and Engineering. 2010;42:104–110.

Hotehama T, Nakagawa S. Psychoacoustic studies for development of the "binaural" bone conducted ultrasonic hearing aids. Proceedings of the 2012 ICME International Conference on Complex Medical Engineering; 2012 July 1–4; Kobe, Japan. Piscataway (NJ): IEEE; c 2012. p. 412–417.

House A, Williams C, Hecker M, Kryter K. Articulation testing methods: consonantal differentiation with a closed-response set. Journal of Acoustical Society of America. 1965;37(1):158–166.

Hunter MD, Phang S, Kwang-Hyuk L, Woodruff PWR. Gender-specific sensitivity to low frequencies in male speech. Neuroscience Letters. 2005;375(3):148–150.

Hurley R, Berger, K. The relationship between vibrator placement and bone conduction measurements with monaurally deaf subjects. Journal of Auditory Research. 1970;10(2):147–150.

Imaizumi S, Hoso H, Sakaguchi T, Watanabe Y, Sadato N, Nakamura S, Waki A, Yonekura Y. Ultrasound activates the auditory cortex of profoundly deaf subjects. NeurorReport. 2001;12(3):583–586.

International Organization for Standardization. ISO 226: 2003: Acoustics–normal equal-loudness-level contours. International Organization for Standardization; 2003.

Ito K, Nakagawa S. Perception mechanisms of bone-conducted ultrasound assessed by acoustic characteristics in the external auditory meatus. Japanese Journal of Applied Physics. 2010;49(7S):1–7.

Jahn AF, Tonndorf J. Lateralization of bone-conducted sounds. American Journal of Otolaryngology. 1982;3(2):133–140.

Kaga K, Setou M, Nakamura M. Bone-conducted sound lateralization of interaural time difference and interaural intensity difference in children and a young adult with bilateral microtia and atresia of the ears. Acta Oto-Laryngologica. 2001;121(2):274–277.

Kagomiya T, Nakagawa S. An evaluation of bone-conducted ultrasonic hearing aid regarding perception of paralinguistic information. Proceedings of the Speech Prosody 2010 Conference; 2010a May 10–14; Chicago, IL.

Kagomiya T, Nakagawa S. Evaluation of bone-conducted ultrasonic hearing aid regarding perception of paralinguistic information: a comparison with cochlear implant simulator. Proceedings of Interspeech 2010 Conference; 2010b Sep 26–30; Chiba, Japan.

Kagomiya T, Nakagawa S. Development and evaluation of bone-conducted ultrasonic hearing aid regarding transmission of speaker emotion: Comparison of DSB-TC and DSB-SC amplitude modulation method. Proceedings of the Speech Prosody 2016 Conference; 2016 May 31–Jun 2; Boston, MA.

Kandzia F, Oswald J, Janssen T. Binaural measurement of bone conduction click evoked otoacoustic emissions in adults and infants. Journal of the Acoustical Society of America. 2011;129(3):1464–1474.

Khalil T, Viano D, Smith D. Experimental analysis of the vibrational characteristics of the human skull. Journal of Sound and Vibration. 1979;63(3):351–376.

Khanna SM, Tonndorf J, Queller J. Mechanical parameters of hearing by bone conduction. Journal of the Acoustic Society of America. 1976;60(1):139–154.

Kim N, Homma K, Puria S. Inertial bone conduction: symmetric and anti-symmetric components. Journal of the Association for Research in Otolaryngology. 2011;12(3):261–279.

Kim N, Steele C, Puria S. The importance of the hook region of the cochlea for bone conduction hearing. The Biophysical Journal. 2014;10(1):233–241.

Kirikae I. An experimental study on the fundamental mechanism of bone conduction. Acta Otolaryngologica, Supplement. 1959;145:1–110.

Küçük B, Abe K, Ushiki T, Inuyama Y, Fukuda S, Ishikawa K. Microstructures of the bony modiolus in the human cochlea: a scanning electron microscopic study. Journal of Electron Microscopy. 1991;40(3):193–197.

Lasman J. Bone conduction equal loudness contours: placement, frequency, and intensity. [unpublished AuD dissertation]. [Towson (MD)]: Towson University; 2015.

Lenhardt ML. Ultrasonic hearing in humans: applications for tinnitus treatment. International Tinnitus Journal; 2003;9(2):69–75.

Lenhardt ML, Skellett R, Wang P, Clarke AM. Human ultrasonic speech perception. Science. 1991;253(5015):82–85.

Letowski T. Performance intensity function for the callsign acquisition test (CAT). Unpublished research protocol. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2002.

Letowski T, Frank T, Caravella J. Acoustical properties of speech produced in noise presented through supra-aural earphones. Ear and Hearing. 1993;14(5):332–338.

Lindeman RW, Noma H, and de Barros PG. Hear-through and mic-through augmented reality: Using bone conduction to display spatialized audio. In: Proceedings of the 2007 6th IEEE and ACM International Symposium on Mixed and Augmented Reality; 2007 Nov 13–16; Nara, Japan. Piscataway (NJ): IEEE Computer Society; c2007. p. 173–176.

Lindeman RW, Noma H, de Barros PG. An empirical study of hear-through augmented reality: Using bone conduction to deliver spatialized audio. In: Proceeds of the 2008 IEEE Virtual Reality Conference VR'08; 2008 Mar 8–12; Reno, NV. Piscataway (NJ): IEEE Computer Society; c2008. p. 35–42.

Linstrom C, Silverman C, Rosen A, Meiteles L. Bone-conduction impairment in chronic ear disease. Annals of Otology, Rhinology, and Laryngology. 2001;110(5):437–441.

Lowy K. Cancellation of the electrical cochlear response with air- and bone-conduction. Journal of the Acoustical Society of America. 1942;4(2),156–158.

Lydolf M, Møller H. New measurements of the threshold of hearing and equal loudness level contours at low frequencies. In: Proceedings of the 8th International Meeting on Low Frequency Noise and Vibration; 1997 June 3–5; Gothenburg, Sweden.

MacDonald JA, Henry PP, Letowski TR. Spatial audio through a bone conduction interface. International Journal of Audiology. 2006;45(10):595–599.

Manning C, Mermagen T, Scharine A. The effect of sensorineural hearing loss and tinnitus on speech recognition over air and bone conduction military communications headsets. Hearing Research [accessed 2017 Apr 26] http://dx.doi.org/10.1016/j.heares.2016.10.019.

Margolis RH, Van Camp J, Wilson RH, Creten WL. Multifrequency tympanometry in normal ears. Audiology. 1985;24(1):44–53.

Maspétiol R. L'audiométrie et son interprétation clinique. Revue du Praticien – Médecine Général*e*. 1963;13:2539–2547.

Mauldin L, Jerger J. Auditory brain stem evoked responses to bone-conducted signals. Archives of Otolaryngology. 1979;105(11):656–661.

Maynard LM, Shumei SG, Chumlea WC, Roche WA, Zeller CM, Towne B, Siervogel RM. Total-body and regional bone mineral content and areal bone mineral density in children aged 8-18y: the Fels longitudinal study. American Journal of Clinical Nutrition. 1998;68(5):1111–1117.

McBride M, Fasanya B, Tran P, Letowski T. Monotic and diotic speech recognition of bone conducted speech. Proceedings of the 2013 Industrial and Systems Engineering Research Conference (ISERC); 2013 May 18–22; San Juan, Puerto Rico.

McBride M, Hodges M, French J. Speech intelligibility differences of male and female vocal signals transmitted through bone conduction in background noise: Implications for voice communication headset design. International Journal of Industrial Ergonomics. 2008;38(11–12):1038–1044.

McBride ME, Letowski TR, Tran PK. Bone conduction head sensitivity mapping: bone vibrators. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2005. Report No.: ARL-TR-3556.

McBride M, Tran P, Letowski T, Patrick R. The effect of bone conduction microphone locations on speech intelligibility and sound quality. Applied Ergonomics. 2011;42(3):495–502.

McBride M, Tran P, Pollard KA, Letowski T, McMillan G. Effects of bone vibrator position on auditory spatial perception tasks. Human Factors. 2015;57(8):1443–1458.

McBride M, Tran T, Weatherless R, Letowski T. Effects of bone vibrator locations on auditory localization in the horizontal plane. Proceedings of the XXIVth Annual International Society for Occupational Ergonomics and Safety Conference; 2012a June 7-8; Fort Lauderdale, FL.

McBride ME, Weatherless R, Letowski T. Effectiveness of a bone conduction audio communication system in a two-channel speech recognition task. Proceedings of the 4th International Conference on Applied Human Factors and Ergonomics; 2012b July 21–25; San Francisco, CA.

McConnell F, Carhart R. Influence of fenestration surgery on bone conduction measurements. Laryngoscope. 1952;62(12):1267–1292.

McFadden D, Loehlin JC. On the heritability of spontaneous otoacoustic emissions: a twins study. Hearing Research. 1995;85(1):181–198.

McFadden D, Mishra R. On the relation between hearing sensitivity and otoacoustic emissions. Hearing Research. 1993;71(1):208–213.

McKinley RL. Bone conducted noise and mitigation techniques. Wright Patterson Air Force Base (OH): Air Force Research Laboratory (US); 2009. Report No.: AFRL-RH-WP-TR-2009-0061. p. 1–14.

Meikle MB, Edlefsen LL, Lay JW. Suppression of tinnitus by bone conduction of ultrasound. Paper presented at the Twenty-First Annual Meeting of the Association for Research in Otolaryngology; 1999 Feb 13-18; St. Petersburg Beach, FL.

Menning H, Roberts LE, Pantev C. Plastic changes in the auditory cortex induced by intensive frequency discrimination training. NeuroReport, 2000;11(4):817–822.

Merchant S, Rosowski J. Conductive hearing loss caused by third-window lesions of the inner ear. Otology and Neurotology. 2008;29(3):282–289.

MIL-STD 1472F. Department of Defense design criteria standard: human engineering. Washington (DC): Department of Defense; 1999 Aug 23.

Minor LB. Superior canal dehiscence syndrome. American Journal of Otology. 2000;21(1):9–19.

Møller AR. Hearing: anatomy, physiology, and disorders of the auditory system. San Diego (CA): Plural Publishing; 2013.

Moore BC, Glasberg BR, Baer T. A model for the prediction of thresholds, loudness, and partial loudness. Journal of the Audio Engineering Society. 1997;45(4):224–240.

Nakagawa S. Objective assessments of bone-conducted ultrasonic hearing-aid (BCUHA) by magnetoencephalography: a study on discrimination capability of multi-channel inputs. 2007 IEEE/ICME International Conference on Complex Medical Engineering; 2007 May 23–27; Beijing, China. Piscataway (NJ): IEEE Computer Society; c2007. p. 1379–1383.

Nakagawa S, Fujiyuki C, Kagomiya T. Development of a bone-conducted ultrasonic hearing aid for the profoundly deaf: evaluation of sound quality using a semantic differential method. Japanese Journal of Applied Physics. 2013;52(7S):07HF06.

Nakagawa S, Okamoto Y, Fujisaka Y. Development of a bone conducted ultrasonic hearing aid for the profoundly sensorineural deaf. Transactions of Japanese Society for Medial and Biological Engineering. 2006;44(1):184–189.

Nakagawa S, Yamaguchi M, Tonoike M, Watanabe Y, Hosoi H, Imaizumi S. Development of bone-conducted ultrasonic hearing aid for profoundly deaf. Proceedings of the 41st SICE Annual Conference, 2002 Aug 5–7; Osaka, Japan. Tokyo (Japan): The Society of Instrument and Control Engineers (SICE); c2002. Vol. 5 p. 2859–2862.

Nishimura T, Hosoi H, Saito O, Miyamae R, Shimokura R, Matsui T, Yamanaka T, Levitt H. Is cartilage conduction classified into air or bone conduction? The Laryngoscope. 2014;124(5):1214–1219.

Nishimura T, Nakagawa S, Sakaguchi T, Hosoi H. Ultrasonic masker clarifies ultrasonic perception in man. Hearing Research. 2003;175(1):171–177.

Nixon CW, Morris LJ, McCavitt AR, McKinley RL, Anderson TR, McDaniel MP, Yeager DG. Female communications in high levels of aircraft cockpit noises – part i: spectra, levels, and microphones. Aviation, Space, and Environmental Medicine. 1998;69(7):675–683.

Nolan M, Lyon DJ. Transcranial attenuation in bone conduction audiometry. Journal of Laryngology and Otology. 1981;95(06):597–608.

Ogiso S, Mizutani K, Zempo K, Wakatsuki N. Measurement of the differential transfer function between bone-conduction and air-conduction for sound localization. 2015 IEEE 4th Global Conference on Consumer Electronics (GCCE); 2015 Oct 27–30; Osaka, Japan. Piscataway (NJ): IEEE Computer Society; c2015. p. 135–138.

Okamoto Y, Nakagawa S, Fujimoto K, Tonoike M. Intelligibility of bone-conducted ultrasonic speech. Hearing Research. 2005;208(1):107–113.

Okayasu T, Nishimura T, Yamashita A, Saito O, Fukuda F, Yanai S, Hosoi H. Human ultrasonic hearing is induced by a direct ultrasonic stimulation of the cochlea. Neuroscience Letters. 2013;539:71– 76.

Olson ES. Observing middle and inner ear mechanics with novel intracochlear pressure sensors. Journal of the Acoustical Society of America. 1998;103(6):3445–3463.

Olson ES. Intracochlear pressure measurements related to cochlear tuning. Journal of the Acoustical Society of America. 2001;110(1):349–367.

Oohashi T, Nishina E, Honda M, Yonekura Y, Fuwamoto Y, Kawai N, Maekawa T, Nakamura S, Fukuyama H, Shibasaki H. Inaudible high-frequency sounds affect brain activity: hypersonic effect. Journal of Neurophysiology. 2000;83(6):3548–3558.

Osafo-Yeboah B, Jiang X, McBride M, Mountjoy D, Park E. Using the callsign acquisition test (CAT) to investigate the impact of background noise, gender, and bone vibrator location on the intelligibility of bone-conducted speech. International Journal of Industrial Ergonomics. (2009);39(1):246–254.

Patrick R, Kring J, McBride M, Letowski T. Conduction equivalency ratios: a means for comparing the frequency response of bone and air conduction auditory displays. Proceedings of the 56th Annual Meeting of the Human Factors and Ergonomic Society (HFES); 2012 Oct 22–26; Boston, MA. Thousand Oaks (CA): SAGE Publications; c2012.

Patrick R, Kring J, McBride M, Letowski T. Bone conduction equal-loudness: a comparison of AC/BC equal-loudness curves in an open vs. closed ear listening environment. Proceedings of the 2014 Industrial and Systems Engineering Research Conference (ISERC); 2014 May 31–June 3; Montreal, Canada.

Patrick RN, Veroneze G, Benedict B, Jiang S. Conduction equivalency ratios: an open-ear regression model of air and bone conduction equal-loudness. Proceedings of the 2015 Industrial and Systems Engineering Research Conference; 2015 May30–June 2; Nashville, TN.

Perez R, Adelman C, Sohmer H. Bone conduction activation through soft tissues following complete immobilization of the ossicular chain, stapes footplate and round window. Hearing Research 2011;280:82–85.

Peterson LC, Bogert BP. A dynamical theory of the cochlea. Journal of the Acoustical Society of America. 1950;22(3):369–381.

Pickles J. An introduction to the physiology of hearing. New York (NY): Academic Press; 1988.

Pollard KA, Tran PK, Letowski TR. A free-field method to calibrate bone conduction transducers. Journal of the Acoustical Society of America 2013;133(2):858–865.

Pollard KA, Tran PK, Letowski T. The effect of vocal and demographic traits on speech intelligibility over bone conduction. Journal of the Acoustical Society of America. 2015;137(4):2060–2069.

Pollard KA, Tran PK, Letowski T. Morphological differences affect speech transmission over bone conduction. The Journal of the Acoustical Society of America; 2017;141(2):936-944.

Poulsen T, Thøgersen L. Hearing threshold and equal loudness level contours in a free sound field for pure tones from 1 kHz to 16 kHz. Proceedings of the Nordic Acoustic Meeting; 1994 June 6–8; Århus, Denmark; p. 195–198.

Pumphrey RJ. The upper limit of frequency for human hearing. Nature. 1950;166(4222):571.

Purcell D, Kunov H, Madsen P, Cleghorn W. Distortion product otoacoustic emissions stimulated through bone conduction. Ear and Hearing. 1998;19(5):362–370.

Rahne T, Ehelebe T, Rasinski Ch, Götze G. Auditory brainstem and cortical potentials following bone-anchored hearing aid stimulation. Journal of Neuroscience Methods. 2010;193(2):300–306.

Ranke O, Keidel W, Weschke H. Des hören beim verschluss des runden fensters. Zeitschrift Laryngologie. 1952;31:467–475.

Rao M. Speech intelligibility of the callsign acquisition test (CAT)-phase II. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2003. Unpublished report.

Reinfeldt S, Stenfelt S, Good T, Håkansson B. Examination of bone-conducted transmission from sound field excitation measured by thresholds, ear-canal sound pressure, and skull vibrations. Journal of the Acoustical Society of America. 2007;121(3):1576–1587.

Reinfeldt S, Stenfelt S, Håkansson B. Estimation of bone conduction skull transmission by hearing thresholds and ear-canal sound pressure. Hearing Research. 2013;299:19–28.

Rejtö A. Beiträge zur Physiologie der knochenleitung. Der 23d Verhandlungen der Deutschen Otologischen Gesellshaft. Jena (Germany): Fischer Verlag; 1914. p. 268–285.

Rimmer TW, Ellenbecker MJ. Hearing protection attenuation measurement by bone conduction loudness balance compared with real ear attenuation at threshold in a sound field. Applied Occupational and Environmental Hygiene. 1997;12(1):62–68.

Robetti I, Iorio M, Mascaro V. The thickness of the soft tissue of the face for person identification. Zeitschrift Rechtsmedizin. 1982;89(2):19–124.

Robinson DW, Dadson RS. A re-determination of the equal-loudness relations for pure tones. British Journal of Applied Physics. 1956;7(5):166.

Robinson DW, Dadson RS. Threshold of hearing and equal-loudness relations for pure tones, and the loudness function. Journal of the Acoustical Society of America. 1957;29(12):1284–1288.

Röschmann P. Human auditory system response to pulsed radiofrequency energy in RF coils for magnetic resonance at 2.4 to 170 MHz. Magnetic Resonance in Medicine. 1991;21(2):197–215.

Rowan D, Gray M. Lateralization of high-frequency pure tones with interaural phase difference and bone conduction. International Journal of Audiology. 2008;47(7):404–411.

Sabbe A, Verhaert N, Joossen I, Lammens A, Debruyne F. Otosclerosis: shift in bone conduction after stapedotomy. 2015;B-ENT,11(3):183–189.

Sakaguchi T, Hirano T, Watanabe Y, Nishimuta T, Hosoi H, Imaizumi S, Nakagawa S, Tonoike M. Inner head acoustic field for bone-conducted sound calculated by finite-difference time-domain method. Japanese Journal of Applied Physics. 2002;41(5B):3604–3608.

Sato H, Sando I, Takahashi H. Sexual dimorphism and development of the human cochlea: computer 3-D measurement. Acta Oto-Laryngologica. 1991;111(6):1037–1040.

Schmuziger N, Probst R, Smurzynsk, J. Otoacoustic emissions and extended high-frequency hearing sensitivity in young adults. International Journal of Audiology. 2005;44(1):24–30.

Schneider B. Individual loudness functions determined from direct comparison of loudness intervals. Perception and Psychophysics. 1980:28(6):493–503.

Setou; M, Kurauchi T, Tsuzuku T, Kaga K. Binaural interaction of bone-conducted auditory brainstem responses. Acta Otolaryngologica. 2001;121(4):486–489.

Shachtman N. Can you hear me now? Tech & Gadgets on NBC NEWS.com. New York (NY): NBC News; 2004 [accessed 2016 Jan 3]. http://www.msnbc .msn.com/id/6116399/.

Shannon RV. Multichannel electrical stimulation of the auditory nerve in man. I. Basic psychophysics. Hearing Research. 1983;11(2):157–189.

Sichel JY, Freeman S, Sohmer H. Lateralization during the Weber test: animal experiments. Laryngoscope. 2002;112(3):542–546.

Silman S, Silverman, C. Auditory diagnosis: principles and applications. San Diego (CA): Academic Press; 1991.

Small SA, Hatton JL, Stapelis DR. Effects of bone oscillator coupling method, placement location, and occlusion on bone-conduction auditory steady-state responses in infants. Ear and Hearing. 2007;28(1):83–98.

Sohmer H, Freeman S. The latency of auditory nerve brainstem evoked responses to air- and bone-conducted stimuli. Hearing Research. 2001;160(1):111–113.

Snyder J. Interaural attenuation characteristics in audiometry. Laryngoscope. 1973;83(11):1847–1855.

Stanley RM, Walker BN. Lateralizaton of sounds using bone-conduction headsets. Proceedings of the Annual Meeting of the Human Factors and Ergonomics Society (HFES 2006); 2006 Oct 16–20;San Francisco, CA. Thousand Oaks (CA): SAGE Publications; c2006. p. 1571–1575.

Stanley RM, Walker BN. Intelligibility of bone-conducted speech at different locations compared to air-conducted speech: Evaluation of bone-conduction transducers for use in radio communications. Proceedings of the Annual Meeting of the Human Factors and Ergonomics Society (HFES 2009); 2009 Oct 19–23; San Antonio, TX.

Steele CR, Zais JG. Effect of coiling in a cochlear model. Journal of the Acoustical Society of America. 1985;77(5):1849–1852.

Stenfelt S. Middle ear ossicles motion at hearing thresholds with air conduction and bone conduction stimulation. Journal of the Acoustical Society of America. 2006;119(5):2848–2858.

Stenfelt S. Simultaneous cancellation of air and bone conduction tones at two frequencies: extension of the famous experiment by von Békésy. Hearing Research. 2007;225(1):105–116.

Stenfelt S. Acoustic and physiologic aspects of bone conduction hearing. Advances in Oto-Rhino-Laryngology. 2011;7(1):10–21.

Stenfelt S. Bone conduction and the middle ear. In: Puria S, Fay RR, Popper AN, editors. The middle ear: science, otosurgery, and technology. New York (NY): Springer-Verlag; 2013. p. 135–169.

Stenfelt S, Goode RL. Bone conducted sound: physiological and clinical aspects. Otology and Neurotology. 2005a;26(6):1245–1261.

Stenfelt S, Goode R. Transmission properties of bone conducted sound: measurement in cadaver heads. Journal of the Acoustical Society of America. 2005b;118(4):2373–2391.

Stenfelt S, Håkansson B. Air versus bone conduction: an equal loudness investigation. Hearing Research. 2002;167(1):1–12.

Stenfelt S, Håkansson B, Tjellström A. Vibration characteristics of bone conducted sound in vitro. Journal of the Acoustical Society of America, 2000;107(1):422–443.

Stenfelt S, Hato N, Goode RL. Factors contributing to bone conduction: the middle ear. Journal of the Acoustical Society of America. 2002;111(2):947–959.

Stenfelt S, Puria S, Hato N, Goode RL. Basilar membrane and osseous spiral lamina motion in human cadavers with air and bone conduction stimuli. Hearing Research. 2003;181(1):131–143.

Stenfelt S, Reinfeldt S. A model of the occlusion effect with bone-conducted stimulation. International Journal of Audiology. 2007;46(10):595–608.

Stenfelt S, Zeitooni M. Binaural hearing ability with mastoid applied bilateral bone conduction stimulation in normal hearing subjects. Journal of the Acoustical Society of America. 2013a;134(1):481–493.

Stenfelt S, Zeitooni M. Loudness functions with air and bone conduction stimulation in normal-hearing subjects using a categorical loudness scaling procedure. Hearing Research. 2013b;301(1):85–92.

Stevens SS, editor. Handbook of experimental psychology. New York (NY): John Wiley and Sons, Inc.; 1951. p. 1117.

Stevens SS, Poulton EC. The estimation of loudness by unpracticed observers. Journal of Experimental Psychology. 1956;51(1):71.

Stuart A, Yang EY, Stenstrom R, Reindorp AG. Auditory brainstem response thresholds to air and bone conducted clicks in neonates and adults. Otology and Neurotology. 1993;14(2):176–182.

Takeshima H, Suzuki Y, Ashihara K, Fujimori T. Equal-loudness contours between 1 kHz and 12.5 kHz for 60 and 80 phons. Acoustical Science and Technology. 2002;23(2):106–109.

Takeshima H, Suzuki Y, Fujii H, Kumagai M, Ashihara K, Fujimori T, Sone T. Equal-loudness contours measured by the randomized maximum likelihood sequential procedure. Acta Acustica united with Acustica. 2001;87(3):389–399.

Takeshima H, Suzuki Y, Kumagai M, Sone T, Fujimori T, Miura H. Equal-loudness levels measured with the method of constant stimuli – equal-loudness level contours for pure tone under free-field listening conditions (II). Journal of the Acoustical Society of Japan (E). 1997;18(6): 337–340.

Tillman T, Carhart R. An expanded test for speech discrimination utilizing CNC monosyllabic words (N.U. Auditory Test No. 6). Brooks Air Force Base (TX): USAF School Aerospace Medical Division; 1966 Jun. Rep. No.: SAM-TR-66-55.

Toll LE, Emanuel DC, Letowski T. Effect of static force on bone conduction hearing thresholds and comfort. International Journal of Audiology. 2011;50(9):632–635.

Tonndorf J. Bone conduction. Studies in experimental animals. Acta oto-laryngologica. 1966;Suppl-213.

Tonndorf J. A new concept of bone conduction. Archives of Otolaryngology. 1968;87(6):49–54.

Tonndorf J. Animal experiments in bone conduction: clinical conclusions. In: Ventry IM, Chaiklin JB, Dixon RF, editors. Hearing measurement: a book of readings. New York (NY): Appleton-Century-Crofts; 1971. p. 130–141.

Tonndorf J, Jahn A. Velocity of propagation of none-conducted sound in a human head. Journal of the Acoustical Society of America. 1981;70(5):1294–1297.

Tonndorf J, Kurman B. High frequency audiometry. Annals of Otology, Rhinology, and Laryngology. 1984;93(6 Pt 1):576–582.

Tran PK, Binseel MS, Letowski TR. User evaluation of a bone conduction headset during the patriot 2008 joint field training exercise. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2012 May. Report No.: ARL-TR-5973.

Tran P, Letowski T, McBride M. Bone conduction microphone: head sensitivity mapping for speech intelligibility and sound quality. Proceedings of the

International Conference on Audio, Language and Image Processing (ICALIP); 2008 Jul 7–9; Shanghai, China. Piscataway (NJ): IEEE Computer Society; c2008. p. 107–111.

Tran P, Letowski T. Speech intelligibility of air conducted and bone conducted speech over radio transmission. The Journal of the Acoustical Society of America. 2010;127(3):1896–1896.

Tran P, Letowski T, McBride M. The effect of bone conduction microphone placement on intensity and spectrum of transmitted speech items. Journal of the Acoustical Society of America. 2013;133(6):3900–3908.

Trune DR, Mitchell C, Phillips DS. The relative importance of head size, gender and age on the auditory brainstem response. Hearing Research. 1988;32(2):165–174.

Viergever MA. Basilar membrane motion in a spiral-shaped cochlea. Journal of the Acoustical Society of America. 1978;64(4):1048–1053.

Voiers WD, Sharpley AD, Hehmsoth CJ. Research on diagnostic evaluation of speech intelligibility. Austin (TX): Tracor Inc.; 1973. Report No.: TRACOR-T73-AU-9010-U. .

von Békésy G. Zur theorie des hörens bei der schallaufnahme durch knochenleitung. Annalen der Physik. 1932;13:111–136.

von Békésy GV. Vibration of the head in a sound field and its role in hearing by bone conduction. Journal of the Acoustical Society of America. 1948;20(6):749–760.

von Békésy G. Experiments in hearing. New York (NY): McGraw-Hill; 1960.

Walker BN, Stanley R, Iyer N, Simpson BD, Brungart DS. Evaluation of bone-conduction headsets for use in multitalker communication environments. Proceedings of the Annual Meeting of the Human Factors and Ergonomics Society (HFES 2005), 2005 Sep 26–30; Orlando, FL. Thousand Oaks (CA): SAGE Publications; c2005. p. 1615–1619.

Walker BN, Stanley RM, Przekwas A, Tan XG, Chen ZJ, Yang HW, Wilkerson P, Harrand V, Chancey C, Houtsma AJM. High fidelity modeling and experimental evaluation of binaural bone conduction communication devices. Proceedings of the 19th International Congress on Acoustics (ICA 2007), 2007 Sep 2–7; Madrid, Spain.

Watanabe T, Betoli S, Probst R. Transmission pathways of vibratory stimulation as measured by subjective thresholds and distortion-product otoacoustic emissions. Ear and Hearing. 2008;29(5):667–673.

Watanabe T, Moller H. Hearing thresholds and equal loudness contours in free field at frequencies below 1 kHz. Journal of Low Frequency Noise, Vibration and Active Control. 1990;9(4);135–148.

Watson N, Frazier TV. Equal loudness contour for hearing by bone conduction. Journal of the Acoustical Society of America. 1952;24(1):114.

Wever E Lawrence M. Physiological acoustics. Princeton (NJ): Princeton University Press; 1954.

Welgampola MS, Rosengren SM, Halmagyi GM, Colebatch JG. Vestibular activation by bone-conducted sound. Journal of Neurology, Neurosurgery, and Psychiatry. 2003;74(6):771–778.

Wigand M. Unpublished results. Reported by Tonndorf and Jahn (1981); 1964.

Wismer MG, O'Brian W. Evaluation of the vibrational modes of the human skull as it relates to bone-conducted sound. Journal of the Acoustical Society of America. 2010;128(5):2792–2797.

Yang EY, Rupert AL, Moushegian G. A developmental study of bone-conduction auditory brain stem response in infants. Ear and Hearing. 1987;8(4):244–251.

Yang E, Stuart A, Mencher GT, Mencher LS, Vincer MJ. Auditory brain stem responses to air-and bone-conducted clicks in the audiological assessment of at-risk infants. Ear and Hearing. 1993;14(3):175–182.

Yoshida M, Uemura T. Transmission of cerebrospinal fluid pressure changes to the inner ear and its effect on cochlear microphonics. European Archives of Oto-Rhino- Otolaryngology. 1991;248(3):139–143.

Yost W, Nielsen D. Fundamentals of hearing: an introduction. New York (NY): Holt, Rinehart and Winston; 1977.

Zwislocki J. Acoustic attenuation between the ears. Journal of the Acoustical Society of America. 1953;25(4):752–759.

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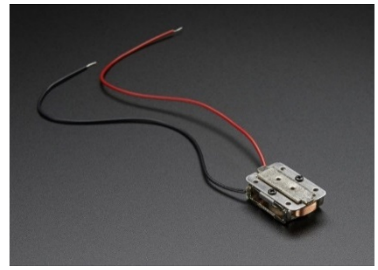
Appendix. Bone Conduction Communication Devices in Commercial Market

Manufacturers and existing models	General properties	Technical parameters	Sources
		Transducers	
Adafruit Adafruit bone conduction transducer 8 Ω, 1 W	Bare transducer Can be use with Adafruit audio amplifier TPA2012 or MAX98306	**Dimensions:** 14 mm × 21.5 mm / 0.6 inch × .8 inch **Weight:** 9.6 g **Power handling:** 1 watt RMS/2 watt max **Le:** 1.26 mH **Impedance:** 8 Ω **Re:** 5.8 Ω **Frequency response:** 300–19,000 Hz (vary with what you use as the transducer surface) **Fs:** 1600 Hz **SPL:** 90.1 dB 1 W/1 m (vary with what you use as the transducer surface)	https://www.adafruit.com/products/1674  Note: possible product of Dayton
Dayton BCE-1 22 × 14mm bone conduction exciter	Creates sound using bone conduction Leaves ears free for increased listener safety Can be used as a mini tactile transducer when attached to substrates or resonating plate Wide frequency response bandwidth Suitable for voice and music reproduction 8 Ω impedance with 1 W power handling or 4 Ω impedance with 3 W power handling	**Model number:** BCE-1- 4 Ω/3 W **Le at 1 kHz:** 0.56 mH **Impedance:** 4 Ω **Re:** 3.99 Ω **Power handling (RMS):** 3 W **Frequency response:** 300–19,000 Hz (change with the substrate and substrate materials) **Resonance frequency-uncoupled:** 2100 Hz **Dimensions (L × W × H):** 21.8 mm × 17.8 mm × 7.5 mm **Net weight:** 12.6 g	http://www.daytonaudio.com/index.php/bce-1-22-x-14mm-bone-conducting-exciter.html 

Manufacturers and existing models	General properties	Technical parameters	Sources
		Transducers	
Dayton BCT-2 45 ×2 5 mm Bone conducting transducer	Creates sound through vibration transmission Turns nearly any surface into a speaker Cushioned stand keeps your surface scratch-free Cushioned stand keeps your surface scratch-free Wide 300 to 20,000 Hz frequency response 4 Ω impedance and 10 W power handling	**Impedance:** 4 Ω **Power handling (RMS):** 10 W/max 20 W Frequency response: 300–20,000 Hz **Resonance frequency (Fs):** 530 Hz **Dimensions (Diameter×depth):** 45 mm × 25 mm **Net weight:** not available	http://www.daytonaudio.com/index.php/bct-2-45-x-25mm-bone-conducting-transducer.html 
Dayton DAEX13CT-8 Coin type exciter	13 mm Exciter 3 W, 8 Ω 8 Ω impedance for use with small class D amplifier Rare-earth neodymium motor Note: frequency response and sensitivity are completely dependent on the exciter's designated surface Thinner, smaller materials will tend to be louder and create a mid/tweeter response Thicker, larger materials (with multiple exciters) will be slightly quieter but result in a more full-range sound Pre-applied 3M™ VHB™ adhesive for quick, durable installation	**Impedance:** 8 Ω **Re:** 7.3 Ω **Le at 1 kHz:** 0.08 mH **Resonance frequency (Fs)-uncoupled:** 616 Hz **Voice coil diameter:** 13 mm **Overall outside diameter:** 26.3 mm **Net weight:** 12.5 g RMS power handling: 3 W	http://www.daytonaudio.com/media/resources/295-216-dayton-audio-daex13ct-8-spec-sheet.pdf 

Manufacturers and existing models	General properties	Technical parameters	Sources
		Transducers	
PerCom Teardrop Miniature Inertial Transducer	Can serve as both a receiver or vibrator Made from high impact ABS plastic Measures approximately 31mm x 24mm and is about 12mm thick Has provision for fitting a headband Can be supplied with or without a dome on the front face Allows user to hear radio messages clearly without their ears being covered or blocked by earpieces or a headset Transposes sound directly to the fluids in the cochlea, thus bypassing the eardrum and ossicular chain	**Impedance**: 68 or 500 Ω (nominal) **Sensitivity, free air**: 100 mW for 0.2 G at 500 Hz **Perceived sensitivity**: 25 mW for 110dB SPL **Max input power (continuous):** 250 mW **Max input power (50% duty cycle)**: 500 mW **Frequency response**: 400–14,000 Hz **Weight**: 13 g **Connector**: IEC No. 5 polarized or nonpolarized **Color**: Black or fleshtone	http://www.percom2000.com/teardrop%20brochure.pdf  
PerCom 31MIT Inertial Transducer	Can serve as both a receiver or vibrator Used in applications where a higher output is required than can be obtained from the teardrop transducer Can be attached to a lightweight helmet, effectively using the helmet shell as a loudspeaker	**Impedance**: 35 or 100 Ω (nominal) **Sensitivity, free air**: 100 mW for 0.35 G at 500 Hz **Perceived sensitivity**: 25 mW for 110 dB SPL **Max input power (continuous):** 200mW **Max input power** (50% duty cycle): 350 mW **Frequency response**: 250–12,000 Hz **Weight**: 18 g **Connector**: IEC No. 5 **Color**: Black	http://www.percom2000.com/31mit%20inertial%20transducers.htm 

Manufacturers and existing models	General properties	Technical parameters	Sources
		Transducers	
Radioear B70A Bone Conductor *	No acoustical tip on the case Available from 10 Ω up to 300 Ω impedances Other special order impedances and/or configurations are available upon request.	**Impedance:** 10 Ω at 1 kHz **Sensitivity:** Sensitivity: 80 dB re 1.0 Dyne and 1kHz **Max Input Voltage:** 1.0 V rms **Frequency Response:** 250-4000 Hz **Weight:** 16 g	http://www.radioear.us/bone-conductors.html 
Radioear B71 (B71W) Bone Conductor	Handmade and hand assembled to consistently perform to an exacting standard. Meets ANSI and ISO standard for Audiometric Testing interface Industry standard for bone conduction Available from 10 Ω up to 300 Ω impedances Other special order impedances and/or configurations are available upon request B71W same as B71 without lead	**Impedance:** 10 Ω at 1 kHz **Sensitivity:** 75.5 dB re 1.0 Dyne and 1 kHz **Max Input Voltage:** 20 dB re 1.0 mW **Frequency Response:** 250–4000 Hz **Weight:** 24 g	http://www.radioear.us/bone-conductors.html 
Radioear B72 Bone Conductor *	Low frequency enhanced version of the B71. A high mass, large cased, version of the B71 Originally designed to enhance and improve the bone conductors' capability for low frequency output Available from 10 Ω up to 300 Ω impedances Other special order impedances and/or configurations are available upon request	**Impedance:** 10 Ω at 1 kHz **Sensitivity:** 79 dB re 1.0 Dyne and 1 kHz **Max Input Voltage:** 1.0 V rms **Frequency Response:** 250–4000 Hz **Weight:** 47.7 g	http://www.radioear.us/bone-conductors.html 

Manufacturers and existing models	General properties	Technical parameters	Sources
		Transducers	
Radioear B81 Bone Conductor	High maximum output, low distortion Very robust product Secured plug concept RoHS compliance Has generally lower distortion and higher output at low frequencies Bone thresholds up to 50 dB HL to be more reliably measured at 250 Hz	**Dimensions of housing:** Height – 16 mm, Length –31.7 mm, Depth – 18.2 mm **Weight:** 20 g **Sensitivity**: 119 dB re.1 µN at 1 V rms and 1 kHz **Total Harmonic Distortion:** 1.1% at 1 V rms and 1 kHz **Impedance:** 12.5 Ω at 1 kHz	http://www.radioear.us/pdfs/RadioEarB81.pdf 
Radioear M10 Bone Conductor *	32 Ω "hard case" transducer with solid wire leads All seams and openings sealed with epoxy Used extensively in underwater speech communication applications Available from 10 Ω up to 300 Ω impedances Special order impedances and/or configurations available upon request Can be fully encapsulated	**Dimensions of housing:** Height – 1.49 cm, Length –2.95 cm, Depth – 1.83 cm **Weight:** 15.5 g **Impedance:** 10 Ω @ 1 kHz **D.C. Resistance:** 3.0 Ω nominal **Sensitivity:** 67 dB re 20 7 dB re 2	http://www.radioear.us/bone-conductors.html 

Manufacturers and existing models	General properties	Technical parameters	Sources
	Tactical headsets for radio communications		
3M 3M™ Peltor™ORA TAC in-Ear Tactical Communications Headset (obsolete)	Dual-sided in-ear tactical communications headset Lightweight, compact and provides hearing protection with comfortable, ambient listening Can be worn with eyewear, respirators, hard hats and welding helmets Delivers omnidirectional reception Offers direct connection to a variety of 2-way communications radios Provides clear communication with tactical features for more natural sound	Specifications unavailable per vendor's request	**http://solutions.3m.com/wps/portal/3M/en_US/3M-PPE-Safety-Solutions/Personal-Protective-Equipment/Products/Product-Catalog/~/3M-Peltor-ORA-TAC-In-Ear-Tactical-Communications-Headsets?N=3294529207+8690968+3294177941+7576577&rt=rud 
3M 3M™ Peltor™ Sidewinder™ Tactical Communications Headset kit 88044-00000 (product no longer available)	Lightweight bone conduction headphone with boom microphone Durable, tactical headset, with speaker location in front of the ear. Provides best situational awareness and allows operators the choice of when and when not to wear hearing protection while maintaining radio communications. Compatible with both earplugs and muff-style hearing protectors and is compatible with MBITR (AN/PRC-148) • Bone conduction speaker in front of ear • Optimum auditory situational awareness • No interference with eyewear or helmets	Specifications not available	http://www.opticsplanet.com/3m-peltor-sidewinder-kit-30in-straight-cable.html 

Manufacturers and existing models	General properties	Technical parameters	Sources
	Tactical headsets for radio communications		
Atlantic Signal MH180H	Stainless steel frame, on a horizontal plane Helmet and protective eyewear clearance Fully adjustable nylon and Velcro head strap is included Audio transducer(s) located inside the headset housing(s) Can be customized for each individual operator	Specifications not available	http://www.atlanticsignal.com/pages/urban_info_mh180h.html 
Atlantic Signal Gladiator H	The integration of the U.S. Military approved 4th generation combat arms earplugs (a.k.a., CAE) Allows an operator to engage and disengage hearing pro at will while having no impact whatsoever on his ability to RX and TX radio communications Stainless steel frame, on a horizontal plane Adjustable rear stabilizer strap at the rear of the frame Transmitting is accomplished via a waterproof/noise canceling microphone mounted on an articulated boom arm	Specifications not available	http://www.dyplex.com/gladiator-h http://www.atlanticsignal.com/pages/urban_info_gladiatorh.html 

Manufacturers and existing models	General properties	Technical parameters	Sources
Tactical headsets for radio communications			
Atlantic Signal Gladiator V	The world's only tactical bone conduction headset offering the operator the choice from One of 4 differing lengths (S-XL) of vertical, stainless steel, head frame to ensure a secure and comfortable personal fit To attain additional stability, a fully adjustable nylon and Velcro, head strap is included Transmitting is accomplished via a waterproof/noise canceling microphone mounted on an articulated boom arm Each Gladiator V headset comes with the CAE IV mounted to each headset sidepiece housing – ready for field operations Each headset will feature a pair of small/medium and large silicone, flanged earplugs Both the CAE IV stems on headset mountable lanyards, as well as the individual earplug sizes, are available for re-order/replacement	Specifications not available	http://www.dyplex.com/gladiator-v http://www.atlanticsignal.com/pages/urban_info_gladiatorv.html 

Manufacturers and existing models	General properties	Technical parameters	Sources
	Tactical headsets for radio communications		
Atlantic Signal MH180V	Offers the operator a choice from 1 of 4 differing lengths (S-XL) of vertical, stainless steel, head frame to ensure a secure and comfortable personal fit Fully adjustable nylon and Velcro, head strap Allows the operator to position the waterproof, noise canceling boom microphone on the left or right side of the face ensuring an unobstructed cheek weld when using a long weapon Receiving radio communications through the facial bones rather than the ear canal affords the tactical operator the advantage of having no speaker hardware in, on or over either ear - allowing 360° of unobstructed auditory situational awareness Audio transducer(s), located inside the headset housing(s), are positioned in front of the ears An operator can simultaneously use various forms of electronic or inert forms of hearing protection Can be customized for each individual operator including: a choice of single or dual bone conductors for RX, 1 of 4 custom frame lengths, custom cable lengths, multiple body/finger/weapon mount push-to-talk switches, inline quick disconnects, remote radio volume control, breathing apparatus adapter kits and more	Specifications not available	http://www.dyplex.com/mh180v-tactical-headset http://www.atlanticsignal.com/pages/urban_info_mh180v.html 

Manufacturers and existing models	General properties	Technical parameters	Sources
	Tactical headsets for radio communications		
Atlantic Signal MH180S	Specifically designed for snipers Radically reduced, low-profile, side stabilizer bar on the non-microphone side of the headset Offers the sniper clear access for the stock of a long weapon Choose from 1 of 4 different lengths (S-XL) of vertical, stainless steel head frames – ensuring both a secure and comfortable personal fit coupled with the ability to position the waterproof, noise canceling boom microphone on the left or right side of the face To attain additional stability, a fully adjustable nylon and Velcro, combination front/back head strap is included Can simultaneously use various forms of electronic or inert forms of hearing protection Can be customized for each individual operator including: custom cable lengths, multiple body/finger/weapon mount push-to-talk switches, inline quick disconnects, remote radio volume control, breathing apparatus adapter kits and more	Specifications not available	http://www.dyplex.com/mh180s-tactical-sniper-headset http://www.atlanticsignal.com/pages/urban_info_mh180s.html 

Manufacturers and existing models	General properties	Technical parameters	Sources
Tactical headsets for radio communications			
Atlantic Signal MH3	Grants the operator the ability to adjust the headset both vertically and horizontally adjustment of the overall radius of the rear headframe as well as the transducer sidepiece housings - ensuring a custom personal fit A fully adjustable nylon and Velcro head strap is included Custom cable lengths are available along with nearly 20 push-to-talk assemblies, remote switches, remote volume controls and other options to choose from - allowing the individual operator, team, squad, brigade, battalion or regiment to customize their comms system	Specifications not available	http://www.atlanticsignal.com/pages/urban_info_mh3.html 

Manufacturers and existing models	General properties	Technical parameters	Sources
	Tactical headsets for radio communications		
Atlantic Signal and Phonak collaboration	Waterproof/noise canceling boom microphone for TX and both bone conductors and both electronic earpieces for radio RX	Combination of Atlantic Signal bone conduction communication and Phonak hearing protection technologies	http://www.atlanticsignal.com/pages/dominator_info.html
Dominator II suite	The bone conductors and electronic earpieces work independently of one another as well as in concert when operational requirements call for hearing protection. Earpieces are capable of: Radio reception, electronic hearing protection and user control ambient environment amplification When hearing protection is not required, the earpieces can be removed from the ears and stowed out of the way via a magnet assembly on each earpiece cable. Radio RX is maintained without the use of the electronic earpieces via twin bone conductors integrated into the headset. Radio transmissions are received via the facial bones directly in front of each ear and passed via bone conduction to each inner ear canal. The DOMINATOR II is available in both single and dual comm radio models and features a broad mix of mission-specific accessory cables as well as connectors for the most fielded military radio platforms. A wireless, gun mount remote push-to-talk control is also available.	Transducer specifications are unavailable	

Manufacturers and existing models	General properties	Technical parameters	Sources
		Tactical headsets for radio communications	
AUDIO COMMUNICATIONS LTD HDB-2	Bone conduction microphone and conventional earpiece receiver mounted on the headband Uses an acoustic tube and non-intrusive skeleton earpiece from the receiver to the ear Allows the user to monitor incoming messages while having unobstructed hearing	**SPEAKER**: uses a button receiver and an acoustic tube **BONE MICROPHONE**: uses the Percom 17MIT-2000 transducer **Specs for mic w/o interface amplifier** **Impedance**: 2000 Ω **Sensitivity, free air**: .002G for 2mV RMS out at 1 kHz **Frequency response**: 300–12,000 Hz ±10 dB **Noise rejection**: Usable in ambient noise up to 120 dB SPL **Max altitude**: 15000 ft **Max water depth**: 10 ft **Weight (basic device)**: 6.5 g **Weight (in housing)**: 25 g **Connector (in housing)**: IEC No. 5 right angle	http://www.firstaudio.com/headband%20communications.htm#top 
AUDIO COMMUNICATIONS LTD HDB-3	Bone conduction microphone and a waterproof speaker mounted on a short flexible gooseneck, allows the user to adjust the position of the speaker to suit his/her requirements	**Bone microphone**: uses the Percom 17MIT-2000 transducer **Specs for mic w/o interface amplifier** **Impedance**: 2000 Ω **Sensitivity, free air**: 0.002 G for 2 mV RMS out at 1 kHz **Frequency response**: 300–12,000 Hz ± 10 dB **Noise rejection**: Usable in ambient noise up to 120 dB SPL **Max altitude**: 15,000 ft **Max water depth**: 10 ft **Weight (basic device)**: 6.5 g **Weight (in housing)**: 25 gs **Connector (in housing): I**EC No. 5 right angle	http://www.firstaudio.com/headband%20communications.htm 

Manufacturers and existing models	General properties	Technical parameters	Sources
Tactical headsets for radio communications			
AUDIO COMMUNICATIONS LTD HDB-4	Removable speaker. Has a socket for the speaker connection allowing the user to connect a gooseneck mounted speaker, a bone conduction speaker, or to connect to a number of other accessories such as a set of hearing protectors with inbuilt speakers	**Speaker**: has a connector into which you can plug any of the speaker options **Bone microphone**: uses the Percom 17MIT-2000 transducer **Specs for mic w/o interface amplifier Impedance**: 2000 Ω **Sensitivity, free air**: 0.002 G for 2 mV RMS out at 1 kHz **Frequency response**: 300–12000 Hz ± 10 dB **Noise rejection**: Usable in ambient noise up to 120 dB SPL **Max altitude**: 15,000 ft **Max water depth**: 10 ft **Weight (basic device)**: 6.5 g **Weight (in housing)**: 25 g **Connector (in housing)**: IEC No. 5 right angle	http://www.firstaudio.com/headband%20communications.htm 
AUDIO COMMUNICATIONS LTD HDB-5	Has a one conduction speaker mounted inside the headband	**SPEAKER**: uses the teardrop transducer **BONE MICROPHONE**: uses the Percom 17MIT-2000 transducer **Specs for mic w/o interface amplifier** **Impedance**: 2000 Ω **Sensitivity, free air**: 0.002 G for 2 mV RMS out at 1 kHz **Frequency response**: 300–12,000 Hz ±10 dB **Noise rejection**: Usable in ambient noise up to 120dB SPL **Max altitude**: 15000 ft **Max water depth**: 10 ft **Weight (basic device)**: 6.5 g **Weight (in housing)**: 25 g **Connector (in housing)**: IEC No. 5 right angle	http://www.firstaudio.com/headband%20communications.htm 

Manufacturers and existing models	General properties	Technical parameters	Sources
	Tactical headsets for radio communications		
Earphone Connection Face Mic bone conduction	The word compact has never been more true in describing this microphone. Under the bone conduction speaker, sits the bone conduction microphone. Away from the mouth or throat, this tiny microphone picks up vibrations from the cheekbone delivering clean, crisp audio. Suitable for gas masks or other breathing apparatuses. Combination bone conduction speaker and microphone Lightweight and durable Adjustable head and neck strap Hands-free wireless finger PTT transmitter and large button receiver kit with various mounting options 29 NRR ComplyTM Ear Tip sound protection.	Specifications not available	http://earphoneconnect.com/product_industries_filter.asp?Prod_IndustryID=229andIndustryID=9 

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Manufacturers and existing models	General properties	Technical parameters	Sources
	Tactical headsets for radio communications		
Earphone Connection CRANE Bone Conduction boom microphone	CRANE bone conduction speakers with noise cancellation boom microphone Headband and neck band are adjustable Speakers pickup vibration from the temples Comfortable for all day use Noise cancellation microphone blocks out background sound Plunger PTT available with Velcro clip and finger PTT	Specifications not available	http://www.earphoneconnect.com/product_industries_filter.asp?Prod_IndustryID=165andIndustryID=9 

Manufacturers and existing models	General properties	Technical parameters	Sources
	Tactical headsets for radio communications		
Elno Defense and Security BCH300	BCH300 is an innovative headset using bone conduction for both earphone and microphone. Ears free, maintains audible spatial awareness Less susceptible to background noise NBC mask compatible Whisper speech capabilities under stealth conditions Waterproof Usable with most helmets and balaclavas	Transducer specifications not available Foldable earphones Adjustable neckband and strap Bone conduction earphones (right and left) Bone conduction microphone Adjustable to any head size **Weight:** 130 g (excl. PTT and connector) Waterproof (80 cm of water: 30 min) **Distortion:** –5% **Power supply:** 2,7 V to 6 V	http://www.elno.fr/en/defence-security/headsets-helmets/infantryman.html 
HANHO Electronics Co. (HANICS) HIB-909V-B	Receiving through facial bones. Unobstructed hearing for complete situational awareness. Heavy duty robust design. MIL-STD-810F (Optional). Optional IP67 waterproof version. Application for SWAT, riot police, sniper, military etc. **Optional Accessories** Optional Remote Push-to-Talk styles give hands-free operation to users driving, carrying weapons or tools, or any applications when their hands are full Allows the EOD operator to ensure PTT without having to reach the radio itself Big button designed for use with chem-bio or EOD suits and gloves Positive stroke and "click" when activated gives the operator added confidence that the transmission is being sent	**SPEAKER** **Impedance:** DC 8.5 ± 10%Ω **Sensitivity:** 100 dB at 1 kHz **Input Power:** Rate : 0.5 W, Max: 1 W **MICROPHONE** **Type:** Optional dynamic or condenser **Direction:** Optional unidirectional or noise cancellation	http://www.hanho.com/products/hib_909v_b/?ckattempt=1 

Manufacturers and existing models	General properties	Technical parameters	Sources
	Tactical headsets for radio communications		
Huari Communication and Technology HRE-3345	Durability and reliability and high sensitive for discreet communication Designed with bone vibration microphone and suitable for very noisy environment A very good quality bone-conduction microphone/earphone with robust PTT unit Excellent audio reproduction and robust construction Finger PTT available Soft silicon rubber earbud provide comfort and secure to your ears A variety of plug and PTT for your choice and available for all kinds of 2-way radio brands	Specifications not available	http://www.huaripower.com/Products/products-59361753381.html 
Huari Communication and Technology HRE-5673	Gas mask headset Sound collector: vibration sensor 30 dB noise reduction Speaker: Bone conduction vibrating sensor Working voltage: 3.7 VDC	Specifications not available	http://www.huaripower.com/Products/products-89381756481.html 
INVISIO INVISIO® X6	Customized to your exact ear shape! Features Custom Protect™ Design for Hear Pro Combat noise protection 25NRR/29SNR Rating IP68 Rating 2m (Submersibility) for 2 h in salt water	Invisio X5 and X6 have the same types of receiver and microphones **RECEIVER** Type dual balanced armature receiver **Maximum Peak Output:** 118 dB **Frequency Range:** 0–20 kHz **THD:** less than 1% up to 100 dB	http://invisio.com/products/headsets/invisio-x6.aspx 

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Manufacturers and existing models	General properties	Technical parameters	Sources
		Tactical headsets for radio communications	
INVISIO® X5	Universal fit with Soft Spring™ and foam tips Enhanced digital hearing Combat noise protection 29NRR/32SNR rating IP68 rating (2m Submersibility)	**Communication microphone:** Type Vibration Sensitive Transducer **Noise level:** –99.5 dBA (re. 1V) **Frequency response:** 0–6 kHz **Hear-thru microphone** Type electret microphone **Noise Level:** –9.1 dBA (re. 1V) **Frequency response:** 0–20 kHz **IP rating:** IP 68 (2 m for 2 h)	http://invisio.com/products/headsets/invisio-x5.aspx 

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Manufacturers and existing models	General properties	Technical parameters	Sources
		Tactical headsets for radio communications	
INVISIO® M3S	Most popular selling INVISIO H2O Model Dive in with TEA H2O PTT's or OSK's Works under re-breather IP68 Rating (2m Submersibility)	**Receiver** Type balanced armature receiver **Maximum Peak Output:** 118 dB **Nominal Impedance:** 450 Ω (at 1 kHz) **DC Resistance:** DC Blocked **Sensitivity:** 25 dB (re. 1 Pa/V at 1 kHz) **Frequency Range:** 200–6 kHz **THD:** less than 1% **Communication microphone:** Type Vibration Sensitive Transducer **Nom. Output Impedance:** 200 Ω (at 1 kHz with 5 V) **Sensitivity:** -32 dB (re. 1 V/(m/s2) at 1 kHz) **Equivalent Noise Level:** -105 dBA **Frequency Response:** 200–6 kHz **Power Supply Operating Voltage:** 1.5–10.0 V (DC) **Current Consump.:** 1 mA min	http://invisio.com/products/headsets/invisio-m3s.aspx 

Manufacturers and existing models	General properties	Technical parameters	Sources
	Tactical headsets for radio communications		
INVISIO® M3h	Left or right ear, MIL-STD 810F Provides certified hear pro rating of 29NRR/32SNR 3 different foam tip sizes available IP67 Rating (1m Submersible)	Invisio M3h, M3 and M4h have the same types receiver and microphone Receiver Type balanced armature receiver Maximum peak output 118 dB Nominal impedance 730 Ω (at 1 kHz) DC Resistance DC Blocked Sensitivity 30 dB (re. 1 Pa/V at 1 kHz) Frequency Range 200–6 kHz	http://invisio.com/products/headsets/invisio-m3h.aspx 
INVISIO® M3	Most popular selling INVISIO model Universal design with Soft Spring Works with Analog or Digital Radios IP64 Rating (Can get wet)	THD less than 1% Communication Microphone Type Vibration Sensitive Transducer Nom. Output Impedance 200 Ω (at 1 kHz with 5 V) Sensitivity -28 dB (re. 1 V/(m/s2) at 1 kHz) Equivalent Noise Level –87 dBA (re. 1 V) Frequency Response 200–6 kHz Power Supply	http://invisio.com/products/headsets/invisio-m3.aspx 
INVISIO® M4h	Custom earmold for superior comfort Custom Protect™ Hear Pro provides 25NRR/29SNR Great for extended use IP64 rating (Can get wet)	Operating Voltage 1.5–15.0 V (DC) Current Consump. 1 mA min	http://invisio.com/products/headsets/invisio-m4h.aspx 

Manufacturers and existing models	General properties	Technical parameters	Sources
		Tactical headsets for radio communications	
Shenzhen Qili Industrial Co., Ltd PeaceEar-FI, PeaceEar-PI, PeachEar-MI	Have both bone conduction receivers and bone conduction microphone All PeaceEar-xI models have the same headset, but have different PTT box for different radios. PeaceEar-FI for firefighter, PeaceEar-PI for Police and PeachEar-MI for military personnel. Adjustable headband and good contact	**Bone conduction receiver** Sensitivity (1 kHz) 0.14 V rms (0.1 mW) 77 ±3 dB(dB re 1.0 dyne) Normal impedance 20 Ω ± 20% at 1 kHz DC resistance 10 Ω ± 20% Normal power (1 kHz) 0.774 V rms (30 mW) 91.5 ± 3dB (dB re 1.0 dyne) THD <5% Maximum power(1 kHz) 1.183 V rms (70 mW) 95.2 ± 3 dB (dB re 1.0 dyne) THD <10% at 1 kHz **Bone conduction microphone** Bias 1.5 V Sensitivity (re 1 V/1 g acceleration 1 kHz –39dB (re 1.0/g) Output impedance (1 kHz) 5200 Ω ± 30 0 Ω (depending on frequency response) Maximum current drain 50 uA	http://www.qdc.com/Product/Default.html PeaceEar-MI 
Shenzhen Qili Industrial Co., Ltd PeaceEar-FII, PeaceEar-PII, PeachEar-MII	Semi bone conduction headset with bone conduction vibrator and boom microphone All PeaceEar-xII models have the same headset; the only difference is the interface PTT box for different radios. PeaceEar-FII for firefighter, PeaceEar-PII for Police and PeachEar-MII for military personnel. Adjustable headband and good skin contact	**Boom microphone** Specifications not available **Bone conduction receiver** Sensitivity (1 kHz) 0.14 V rms (0.1 mW) 77 ± 3dB (dB re 1.0 dyne) Normal impedance 20 Ω ± 20% at 1 kHz DC resistance 10 Ω ± 20% Normal power (1 kHz) 0.774 V rms (30 mW) 91.5 ± 3 dB (dB re 1.0 dyne) THD <5% Maximum power(1 kHz) 1.183 V rms (70 mW) 95.2 ± 3 dB(dB re 1.0 dyne) THD <10% at 1 kHz	http://www.qdc.com/Product/Default.html PeaceEar-MII 

Manufacturers and existing models	General properties	Technical parameters	Sources
	Tactical headsets for radio communications		
Tactical Command Industries (TCI) Inc. Tactical Assault Bone Conduction Headset (TABC II™)	Lightweight, progressive headset This system provides exceptional audio performance Binaural bone conduction transducers with Dynamic Audio Resonance System (DARS) and a TCI Tactical Press-to-Talk system. System features a behind-the head fit that is comfortable, tactical helmet compatible and stable during vigorous activities. Compatible with an array of conventional and specialized helmets, as well as many combinations of public safety and military communication radios	Specifications not available	http://www.tacticalcommandstore.com/files/TABC%20II-2012.pdf http://www.tacticalcommandstore.com/tci_tactical_assault_bone_conduction_headset.aspx 
Tactical Command Industries (TCI) Inc. * TABC II Tactical Assault Dual-Comm Bone Conduction Headset (TABC-2 DC)	Split audio feature so incoming audio from each radio remains separated in the headset One radio is monitored using the left side of the headset and the second radio is monitored using the right side of the headset Dual-Button PTT enables central control of 2 radios from a convenient location on your assault kit Color-coded PTT buttons ensure the proper radio is transmitted when communication is critical Compatible with an array of conventional and specialized helmets, as well as many combinations of public safety and military communication radios	Specifications not available	http://www.tacticalcommandstore.com/files/TABC%20II%20Dual-2012.pdf http://www.tacticalcommandstore.com/tci_tactical_assault_dual-comm_bone_conduction_headset.aspx 

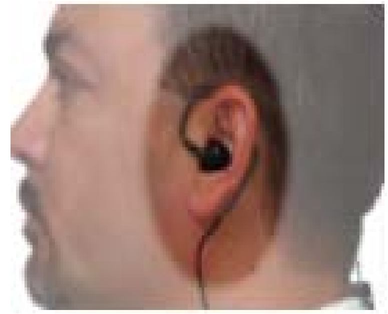
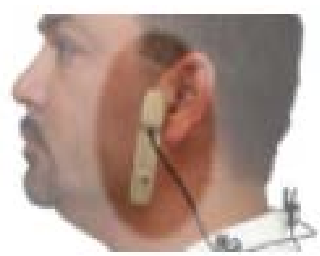
Manufacturers and existing models	General properties	Technical parameters	Sources
	Tactical headsets for radio communications		
Tactical Command Industries (TCI) Inc.	Dual-Comm/Dual-Channel/Dual PTT button system	Specifications not available	http://www.tacticalcommandstore.com/tabc-iii-tactical-assault-dual-comm-bone-conduction-headset-tabc-3-dc.aspx
* TABC III Tactical Assault Dual-Comm Bone Conduction Headset (TABC-3 DC)	Offers state of the art electronics, Binaural Dynamic Audio Resonance System "DARS" (our proprietary sound reproduction system that provides pristine audio fidelity directly to the Cochlea through bone conduction) Comfortable fit with MICH, ACH and other commonly used ballistic helmets Kits include a Dual-Comm capable TABC III Headset, TCI U-Series Dual-Comm Tactical PTT for your specific radio models and TCI Headset Storage Bag		
Tactical Command Industries (TCI) Inc.	Lightweight, progressive headset offering state of the art bone conduction technology	Specifications not available	http://www.safariland.com/products/comms-and-hearing-protection/headsets/bone-conduction-headsets/
Tactical Assault Bone Conduction Headset (TABC III™)	Bone conduction transducers are positioned in front of the operator's ears Provides exceptional audio performance, binaural bone conduction transducers with DARS and a TCI Tactical PTT system Behind-the head fit that is comfortable, tactical helmet compatible and stable during vigorous activities		

Manufacturers and existing models	General properties	Technical parameters	Sources
		Tactical headsets for radio communications	
Temco Communications	Clear transmission in loud noise	**Bone vibrator speaker** **Type**: Magnetic	http://www.kogon.de/mediapool/30/307911/data/10KOGON_HG21_.pdf
HG21 CN-L	High output bone vibration speaker Light duty professional gear Both ears are free	**Impedance**: 8 Ω ± 30% at 1 kHz **Frequency Range**: 300 Hz ~ 3 kHz **Output Level**: 96 dB ±4.5 dB at 1 kHz (0dB = 1 μN/mW) **Nominal Input**: 0.1W **Maximum Input**: 1 W **MICROPHONE** **Type**: Electret **Output Impedance**: Less than 2.2 kΩ Directivity: Close talking **Frequency Range**: 200 Hz~8 kHz **Current Consumption**: Max 0.5 mA **Output Level**: –47 dB ± 4.5 dB at 1 kHz, L=50 cm (0 dB = 1 V/Pa) **Weight**: 55 g (1.93 oz) w/o cable	

Manufacturers and existing models	General properties	Technical parameters	Sources
	Tactical headsets for radio communications		
Temco Communications HG17 (DM1 radio interface)	Bone vibration microphone on top of head Clear reception in high noise environment Open ears Allows using of head protection equipment such as hard hat or helmet Bone vibration speaker “BoneKnocker” Waterproof IP67	**Bone vibration speaker** **Type**: Electromagnetic **Frequency Range**: 300 Hz ~3 kHz **Impedance**: 36 Ω ± 30% at 1 kHz DC RESISTANCE 236 Ω ± 24 Ω **Output Level**: 100 dB ±5 dB at 1 kHz (0 dB = 1 μN /1 mW) **Nominal Input**: 0.1 W **Maximum Input**: 1 W **Microphone** **Type**: Electret microphone **Output Impedance**: Rated condition 5 V 2.2 kΩ **Frequency Range**: 200 Hz ~ 3 kHz **Output Level**: –21 dB ± 4.5 dB at 1 kHz, (0 dB = 1 V/0.1 G) **Current Consumption**: Less than 1.2 mA (5 V 2.2 kΩ) **Weight**: 130 g (4.18 oz) w/o cable	http://www.rtcom.pl/product/Temco-HG17-zestaw-taktyczny-naglowny/?id=81 

Manufacturers and existing models	General properties	Technical parameters	Sources
	Tactical headsets for radio communications		
Temco Communications	Great for use with all breathing apparatus's, including SRS-5 with SCBA	**Bone vibration speaker**	http://www.temcom.net/tactical-communications.html
FM3 - Facemask Tactical Headset (Replaced FM2)	Interfaces directly with most public safety and military gas masks BC speaker and microphone allows the operator to receive and transmit clearly while wearing a SCBA and chem-bio suit	**Type**: Electromagnetic **Frequency Range**: 300 Hz~ 3 kHz **Impedance**: 10 Ω ±30% at 1 kHz **Frequency Range**: 300 Hz ~ 3 kHz **Impedance**: 10 Ω ±30% at 1 kHz **Output Level**: 98 dB ± 5 dB at 1 kHz (0 dB = 1 μN/1mW) **Nominal Input**: 0.1W **Maximum Input**: 0.5W **Microphone** **Type**: vibration sound conversion microphone (VSCM) **Output Impedance**: Rated condition = 5 V 2.2 kΩ **Frequency Range**: 200 Hz ~ 3 kHz **Output Level**: –15 dB ±4.5 dB at 1kHz, (0 dB = 1 V/0.1 G) **Current Consumption**: Less than 1.1 mA (5 V 2.2 kΩ) **Weight**: 80 g w/ cable **Waterproof**: IP68	

Manufacturers and existing models	General properties	Technical parameters	Sources
		Tactical headsets for radio communications	
Temco Communications	Gives operator the freedom to retain natural hearing or to wear hearing protection	**Bone vibration speaker**	http://www.temcom.net/tactical-communications.html
HG30CN- T (BC Tactical Headset radio interface DM19)	Noise canceling boom microphone designed to reduce ambient noise	**Type**: Electromagnetic **Frequency Range**: 300 Hz ~ 3 kHz	
HG30CP-X1	Secure communication headset	**Impedance**: 36 Ω ± 30% at 1 kHz	
HG30(full duplex interface-DM3)		**Output Level**: 100 dB ± 4.5 dB at 1 kHz (0 dB = 1μN /1mW) **Nominal Input**: 0.1 W **Maximum Input**: 1 W	
		Microphone **Type**: Electret **Output Impedance**: <2.2 KΩ **Frequency Range**: 100 Hz ~ 10 kHz **Output Level**: –46 dB ± 5 dB at 1 kHz, L=1 cm from center of Lip (0 dB= 1 V/Pa) **Current Consumption**: MAX 0.5 mA **Weight**: 160 g (5.2 oz) w/o cable	

Manufacturers and existing models	General properties	Technical parameters	Sources
	Tactical headsets for radio communications		
Temco Communications EM20 EM7B-05 - BC Ear-microphone EM20 newer model	Enables the user to transmit and receive audio from the earpiece Allows user to transmit in high noise environments Provides ability to communicate in low profile applications .	**Receiver** **Type:** Electromagnetic **Frequency Range**: 100 Hz ~ 5 kHz **Impedance**: 400 Ω ± 80 Ω at 1 kHz **DC resistance** 236 Ω ± 24 Ω **Output Level**: 104 dB ± 4.5 dB at 1 kHz (0 dB = 20 µPa) Input 0.5 mW **Nominal Input**: 0.5 mW **Maximum Input**: 2 mW **Microphone** **Type**: Electret VSCM microphone **Output Impedance**: Rated condition 5 V 2.2 kΩ **Frequency Range**: 200 Hz ~ 3 kHz **Output Level**: –13 dB ± 4.5 dB at 1 kHz, (0 dB = 1 V/0.5 G) **Current Consumption**: <1.2 mA (5 V 2.2 kΩ) **Weight**: 7.5 g w/o cable and PTT	http://www.temcom.net/tactical-communications.html 
Temco Communications SK1-T (Band Aid Tactical Headset)	Low profile Waterproofed Designed to be worn in front or behind the ear Held in place with medical adhesive tape Can be used for chem-bio, tactical, or surveillance as well as other applications	Note: In proof of concept phase. Specifications not available.	http://www.temcom.net/tactical-communications.html 

Manufacturers and existing models	General properties	Technical parameters	Sources
		Tactical headsets for radio communications	
Temco Communications Dual-bone conduction headset HG 70	Latest product Waterproof IP67 Bone conduction headset Bone vibration microphone VSCM (vibration sound conversion microphone) High output bone conduction speaker 2 types of interfaces: Inline PTT type, which connects directly with the radio, and indirect type, which connects with the radio via DM or BM interface. Anti-noise DSP VOX DM series (used with PTT or VOX mode) DSP programmed with algorithm which only respond to human voice. BM type interface with a large size waterproof PTT button is usable in PTT or smart PTT (lock/release) mode. Single push while in Smart PTT mode holds the transmit mode another push bringing back to the wait/receive mode.	**BONE VIBRATION** **Speaker type:** Electromagnetic **Impedance:** 36 Ω ± 30% at 1 kHz **Frequency range:** 300 Hz~3 kHz **Output level:** 100 dB ± 5 dB at 1 dB = 1 μN /1 mW) **Nominal input:** 0.1 W **Maximum input:** 1 W **Microphone type:** Electret vibration sound conversion microphone **Output impedance rated condition:** 5 V 2.2 kΩ **Frequency range:** 200 Hz ~ 3 kHz **Output level:** –21 dB ± 4.5 dB at 1 kHz (0 dB = 1 V/0.1 G) **Current consumption:** <1.2 mA (5 V 2.2 kΩ) **Nominal input:** 0.1 W **Maximum input:** 1 W **Weight:** 130 g (4.18 oz) w/o cable	http://www.temco-j.co.jp/catalog/cat_HG70_en.pdf 

Manufacturers and existing models	General properties	Technical parameters	Sources
	Tactical headsets for radio communications		
Threat4 SNIPER	**Tactical Bone Conduction (Temple Transducer) Headset** Submersible (IP68) Dual bone conduction transducers Compatible with gas masks No audio bleed on receive (others can't hear your radio receive) Compatible with ballistic helmets Available in right or left shooter boom Can be worn with ear plugs Noise cancelling boom mic Flexible metal rear headband	Specifications not available	http://www.threat4.com/product_info.php?products_id=353#.V9MDlDbr3DA 
Threat4 SNIPER-WPTT	**Tactical Bone Conduction (Temple Transducer) Headset with Body and Wireless PTT** Full size Body PTT and Wireless PTT Includes a wireless PTT (WPTT-1) Unmatched 3 year warranty	Specifications not available	http://www.threat4.com/product_info.php?products_id=371#.V9MICDbr3DA 
Threat4 SNIPER-SPTT	**Tactical Bone Conduction (Temple Transducer) Headset with Standard and Finger PTT** Includes a wired finger PTT (FPTT-1) Unmatched 3 year warranty	Specifications not available	http://www.threat4.com/product_info.php?cPath=29_44andproducts_id=370#.WG067n1O7dI 

Manufacturers and existing models	General properties	Technical parameters	Sources
Tactical headsets for radio communications			
IntriCon	Flexible boom arm	**Microphone:** Electret condenser	http://www.intricon.com/products/professional-communication/headsets/lv-23/
LV-23	High-quality easy-maintenance headband	**Polar Pattern:** Bidirectional (noise cancelling)	http://www.intricon.com/assets/documents/uploads/LV23.pdf 
	Great acoustic performance		
	Included sweat drip ring	**Frequency Response:** 200 Hz–6 kHz	
	Utilizing bone conduction technology	**Loudspeaker: Frequency Range:** 350 Hz to 4 kHz	
	Allows user to hear incoming messages while donning earplugs	**Output:** 102 dB ref 1 µN at 1 mW	
	Low profile headset	**Others: Water Resistance:** Splash Proof (optional 1 m immersion proof)	
		Accessories: Windscreen	

Manufacturers and existing models	General properties	Technical parameters	Sources
Commercial bone conduction headsets for phone and entertainment			
Aftershokz Trekz Titanium Mini and Trekz Titanium	Lightweight, flexible titanium wraparound headband Wireless Bluetooth® 4.1, multipoint pairing LeakSlayer™ technology reduces natural sound leakage Repel sweat, dust and moisture Six h of continuous music + calls on a single charge EQ presets boost bass and reduce vibration on the go Dual noise canceling microphones exclude ambient noise Voice guide users through power, pair, play and talk	**Speaker type:** bone conduction transducers **Frequency response:** 20 Hz ~ 20 kHz sensitivity: 100 ± 3 dB **Microphone:** -40 dB ± 3 dB **Bluetooth version:** v4.1 **Compatible profiles**: A2DP, AVRCP, HSP, HFP **Wireless range:** 33 ft (10 m) **Battery:** rechargeable lithium ion **Continuous play:** 6 h **Standby time:** 10 days **Charge in:** 1.5 h **Weight:** 1.27 oz . (36 g)	http://aftershokz.com/collections/all/products/trekz-titanium-mini 
Aftershokz Bluez 2S	Same features as above except plastic headband, bluetooth V3.1 and somewhat heavier	**Speaker type:** bone conduction transducers **Frequency response:** 20 Hz~20 kHz **Sensitivity:** 100 ± 3 dB **Microphone:** –40 dB ± 3 dB **Bluetooth version:** v3.0 **Compatible profiles:** A2DP, AVRCP, HSP, HFP **Wireless range:** 33 ft (10 m) **Battery:** rechargeable lithium ion **Continuous play:** 6 h **Standby time:** 10 days **Charge in:** 2 h **Weight:** 1.45 oz (41 g)	http://aftershokz.com/collections/wireless/products/bluez-2s 

Manufacturers and existing models	General properties	Technical parameters	Sources
Commercial bone conduction headsets for phone and entertainment			
Aftershokz Gamez	Same feature as Bluez 2S Compatible for gaming on PC, Mac and mobile devices	Same features as Bluez 2S	http://aftershokz.com/collections/wireless/products/gamez 
Aftershokz Sportz 3	OpenFit™ design ensures maximum situational awareness and comfort Premium audio experience Enjoy 12 h of continuous music on a single charge Sweat and moisture resistant Hassle-free 2-year warranty	**Speaker type:** bone conduction transducers **Frequency response:** 20 Hz ~ 20 kHz **Sensitivity:** 100 ± 3 dB **Compatible profiles:** A2DP, AVRCP, HSP, HFP **Battery:** rechargeable lithium ion **Continuous play:** 12 h **Standby time:** 10 days **Charge in:** 2 h **Weight:** 1.60 oz (41 g) **Cable length:** 51 inches (130 cm)	https://aftershokz.com/collections/all/products/sportz-3 

Manufacturers and existing models	General properties	Technical parameters	Sources
	Commercial bone conduction headsets for phone and entertainment		
Aftershokz Sportz M3	Same features as Sportz 3 Plus dual noise canceling microphones exclude surrounding noise for phone conversations	**Speaker type:** bone conduction transducers **Frequency response:** 20 Hz~20 kHz **Sensitivity:** 100 ± 3 dB **Microphone:** –40 dB ± 3 dB **Compatible profiles:** A2DP, AVRCP, HSP, HFP Battery: rechargeable lithium ion Continuous play: 12 h **Standby time:** 10 days **Charge in:** 2 h **Weight:** 1.60 oz. (41g) Cable length: 51 in (130cm)	http://aftershokz.com/products/sportz-m3 
HANHO Electronics Co. (HANICS) HIB-707BM	Bone conduction headset with boom microphone Offers high-clarity and discrete 2-way radio communications while offering the additional comfort necessary for extended wear. Appropriate for continuous use in various situations like the hospital, retail market, recreation and public place.	Speaker: Bone conduction Speaker –140 dB (BandK Artificial mastoid 4903) Microphone: Condenser type Noise cancellation microphone (optional) Bluetooth version: v3.0+EDR with microphone PTT switch: waterproof type (Optional) Cable length : 1.2 ~ 1.5 m	http://www.hanho.com/products/hib-707bm/ 

Manufacturers and existing models	General properties	Technical parameters	Sources
Commercial bone conduction headsets for phone and entertainment			
Damson Audio	Wireless, light weight incisor diffusion technology bone conduction headphones	Bone conduction transducer specifications not available	http://us.damsonaudio.com/collections/headbones/products/damson-headbones
Damson Headbones- Bluetooth Bone Conduction Headphones	A call button allows easily answer calls or make voice calling like Siri or google voice Flexi-fit arms allow to mold the headbones to fit head and ear shape Gaming compatible Sport/Hearing enhancement Unique dual driver operation: Use bone conduction to hear everything around you or 3.5 mm headphones to block out external sound Driver type: Incisor diffusion Technology – bone conduction driver Driver type 2: 3.5 mm line out for standard headphones or earbuds (pair supplied)	**Bluetooth:** Version 3 **Bluetooth range:** Up to 10 m (line of sight) APT-X: For high quality audio playback and low latency video support Water resistant: Rated to IPX5 (heavy rain or heavy sweating **Battery type:** built in Lithium Ion rechargeable via micro USB (cable supplied) **Battery size:** 320 mAh **Playback time:** Up to 8 h through bone conduction or over 20 h with 3.5 mm headphones **Standby time:** Up to 300 h (12 days) **Built in microphone:** for hands free calls Voice dial support: Double tap for Siri, Google Voice or Cortana voice support Support 2 simultaneous connections Auto switch for call answering **Frequency response:** 70 Hz – 20,000 Hz **Cables:** Micro USB for charging **Protective case:** Glasses style case for protective storage **Weight:** 80 g **Warranty:** 1 year	

Manufacturers and existing models	General properties	Technical parameters	Sources
Commercial bone conduction headsets for phone and entertainment			
iHeadBones 501 Series Bluetooth (wireless)	Includes: Lightweight Bluetooth headset with stereo speakers Microphone and an adjustable sizing strap USB power adapter cube Micro USB charging cable Accessory bag	**Speaker type:** bone conduction metal can transducers **Bluetooth version:** v3.0+EDR with microphone **Bluetooth IC:** ISSC 1681S with noise and echo reduction, 4 dBm transmit and –91 dBm sensitivity **Compatible profiles:** HFP, HSP, AVRCP, A2DP **Frequency response:** 20 Hz ~ 20 kHz **Wireless range:** 33 ft (10 m) **FCC ID:** 2ACP8-NICE2 **Battery:** rechargeable lithium ion **Continuous play:** up to 6 h **Standby time:** up to 10 days **Charge in:** 2 h **Weight:** 1.7 oz (43 g) **Warranty:** 1 year	http://iheadbones.com/shop.html 

Manufacturers and existing models	General properties	Technical parameters	Sources
	Commercial bone conduction headsets for phone and entertainment		
iHeadBones 201 Series Wired, magnet free (non-magnetized)	Includes: Adjustable and foldable lightweight headset iHeadbones stereo speakers Rechargeable amplifier Mini USB charging cable 3 different length audio cables Wire clip 3 Velcro® strips Accessory bag	**Speaker type:** Ceramic piezo acoustic device (without magnets) **Amplifier Type:** Class D NJU 8764 Frequency response: 20 Hz ~ 12 kHz Sensitivity: 100 ± 3 dB **Battery:** rechargeable lithium ion **Continuous play:** up to 12 h **Standby time:** up to 10 days **Charge in:** 2 h **Headset weight:** 1.7 oz (43 g) **Warranty:** 1 year	http://iheadbones.com/shop.html 
GameChanger Products LLC Audio Bone 1.0	Completely waterproof (except the jack) IPx7 waterproof rating Available in several stunning colors Uses a standard stereo headphone jack Stylish design	**Normal Input:** 30 mW **Maximum Input:** 100 mW **Impedance:** 8 Ω ± 15% **Sound Pressure Sensitivity:** 88 dB/mW (dB 1.0 dyne) **Frequency Response:** 50–12,000 Hz **Cord Length:** 120 cm / 4 ft **Plug Stereo:** 3.5 mm **Weight:** 35 g/1.3 oz	http://www.audioboneheadphones.com/product/audio-bone-1-0/ http://www.audioboneheadphones.com/how-it-works/ 

Manufacturers and existing models	General properties	Technical parameters	Sources
	Commercial bone conduction headsets for phone and entertainment		
GameChanger Products LLC Audio bone adjustable	Has adjustable, rotating phones Comes with ear clips Not water proof Headphones are foldable Comes with its own carrying pouch	**Normal Input:** 30 mW **Maximum Input:** 70 mW **Impedance:** 8 Ω ± 15% **Sound Pressure Sensitivity:** 80 dB/mW (dB 1.0 dyne) **Frequency Response:** 50~-4,000 Hz **Cord Length:** 120 cm / 4 ft **Plug Stereo:** 3.5 mm **Weight:** 60 g / 2 oz	http://www.audioboneheadphones.com/product/audio-bone-adjustable/ http://www.audioboneheadphones.com/how-it-works/ 
Goldendance Audiobone Fit Model number: GD-HS-601	Fits naturally and less pressure to your head Very light Water-resistant Unique curved line will fit to your head 80cm extension cord included for adjustment of the cord length case by case Designed for comfort Can wear headphone over glasses with comfort	**Type:** Dynamic **Driver unit:** 17 mm **Sensitivity**: 88 dB **Frequency Response** : 20 Hz–10,000 Hz **Max input power** : 100 mW **Impedance :** 8 Ω **Weight :** 31g（with cord） **Plug :** Φ3.5 mm stereo Mini-plug **Cord length :** 1.2 m 0.4 m＋extension 0.8 m）	http://www.goldendance.co.jp/English/product/p_ab29.html 

Manufacturers and existing models	General properties	Technical parameters	Sources
Commercial bone conduction headsets for phone and entertainment			
Goldendance PC Bone In (model number:GD-SK-SB2)	Built in bone conduction oscillator and USB microphone Offering smaller level of sound leakage Earphone is smaller than the old model, fits well in small ears Special urethane ear cushion offers good fit No air hole in earphone Comes with a soft pouch for carrying convenience.	**Type** : Dynamic **Driver unit :** 12 mm **Sensitivity :** 62 ± 3 dB **Frequency :** 20 Hz ～ 10,000 Hz **Max. input :** 100 mW **Impedance :** 8 Ω **Weight :** 15 g (with cord) **Plug :** φ3.5 stereo **Cord length :** 1.05 m (0.35 m + extension 0.7 m)/Y cord **USB CORD SPECIFICATION:** **Jack :** φ3.5 mm stereo **Cord length :** 0.7 m **Plug :** USB	http://www.goldendance.co.jp/English/product/p_ab26.html 
Goldendance SmartBone In (model number: GD-SM-SB2)	Earphone is smaller than the old model, fits well in small ears Smaller level of sound leakage Special urethane ear cushion offers good fit Water and sweat proof Microphone cord length can be adjusted as the cord can be taken up	**Type :** Dynamic **Driver unit :** 12 mm **Sensitivity** : 62 ± 3 dB **Frequency** : 20 Hz～10,000 Hz **Max. input :** 100 mW **Impedance** : 8 Ω **Weight :** 15 g (with cord) **Plug :** φ3.5 stereo **Cord length :** 0.35 m/Y cord **SMARTPHONE CORD SPECIFICATION:** **Jack :** φ3.5 mm stereo **Plug :** φ3.5 mm 4 pole **Cord length :** 0.75 m	http://www.goldendance.co.jp/English/product/p_ab27.html 

Manufacturers and existing models	General properties	Technical parameters	Sources
Commercial bone conduction headsets for phone and entertainment			
Goldendance SoundBone2 (model number:GD-SB2)	Smaller level of sound leakage compared to the conventional earphones and headphones Suitable for use in a train and other public places Earphone is smaller than the old model, fits well in small ears. Water and sweat proof Special urethane ear cushion offers good fit	**Type** : Dynamic **Sensitivity :** 62 ± 3 dB **Driver unit** : 12 mm **Frequency:** 20 Hz〜10,000 Hz **Max. input** : 100 mW **Impedance** : 8 Ω **Weight :** 15 g (with cord) **Plug :** φ3.5 stereo **Cord length :** 1.05 m (0.35 m + extension 0.7 m)/Y cord	http://www.goldendance.co.jp/English/product/p_ab28.html 
Goldendance A-Hum	Optimum for receiving the operational instruction and the danger signal Not troublesome of wearing the conventional headset Easily attaches to the edge of a conventional helmet Optimum under noisy field. Can connect Motorola GL-2000	**Type**: Magnet **Impedance**: 8 Ω **Frequency range**: 300 Hz – 3,500 Hz **Rated input**: 0.5 W **Max input**: 1.0 W **Output**: is different per transceiver (see link) Note: Bone conduction speaker GDS-701, has been used for A-hum	http://www.goldendance.co.jp/English/product/p_ab32.html http://www.goldendance.co.jp/English/oem/01.html 

Manufacturers and existing models	General properties	Technical parameters	Sources
Commercial bone conduction headsets for phone and entertainment			
Goldendance Listening Bone (model number:GD-RH)	Special noise canceling microphone allowing smooth telecommunications Both ears are not covered allowing you to hear surrounding sound Suitable for noisy environments	**MICROPHONE** **Type**: Electrets **Impedance** : Low impedance **Characteristic** : Noise cancelling **Frequency :** 150 Hz～10 kHz **Sensitivity Reduction S/N Ratio:** Within —3 dB at 1.5 V More than 58 dB **Electricity Consumption :** MAX <0.5mA **BONE CONDUCTION SPEAKER** **Type :** Magnetic **Impedance :** 18 Ω ± 30% at1 kHz **Frequency :** 300 Hz～ 3.5 kHz **Output Level** : 102 dB ± 5 dB at 1 kHz (0 dB = 1 μN/mW) **Normal Input :** 0.1W **MAX Input :** 0.3 W <0.5 mA	http://www.goldendance.co.jp/English/product/p_ab06.html 
Goldendance Double Bone(model number:GD-WH)	Unbelievable clear sound allowing smooth telecommunications even noisy environments Double Bone does not cover the ears and you can use earplugs to protect your ears from the loud noise Originally developed headsets which uses bone conduction system for both receiving and transmitting (patented)	**BONE CONDUCTION SPEAKER** **Type :** Magnetic **Impedance :** 8 Ω ± 30% at1 kHz **Frequency :** 300 Hz～ 3.5 kHz **Output Level :** 102 dB ± 5 dB at Hz(0 dB = 1 μN/mW) **Normal Input :** 0.1 W **MAX Output** : 0.3 W	http://www.goldendance.co.jp/English/product/p_ab07.html 

Manufacturers and existing models	General properties	Technical parameters	Sources
Bone conduction for hearing aids			
Audifon hearing systems	AutoFit, NAL, BC Fit (Bone conduction)	**Dimension in mm w/o Clip**: 60 length × 19 wide × 71 height	http://www.audifon.com/2114.html
apollon	4-Band audio-processor	**Weight:** 31 g w/o batteries 76.5 g with batteries	http://www.audifon.com/fileadmin/pdf/professionals/en/datasheet/apollon_en.pdf
	2 Batteries size AA	**Current drain w/o signal:** 5.1 mA +/- 10% at 3 V	
	4-position switch (O-T-MT-M)	**Telecoil Sensitivity (IEC 60118-1):** 109 dB typ.	
	Optical and acoustical low battery warning	**Impedance of audio inputs** >20 k Ω	
	DAI-Input	**Sensitivity of DAI, Line-In: -** 54 dBV	
	Volume control		
	Audio-Input (3,5 mm jack socket)		
Audifon hearing systems	High power bone conducted spectacle, suitable for mild to severe hearing losses	**Battery life:**508 h at a 610 mAh battery capacity	http://www.audifon.com/2111.html
contact star evo 1	2 channel digital amplifier with programing options over 4 pin programing socket	**Current drain:** 1,2 mA ±10% (1.35 V)	http://www.audifon.com/fileadmin/pdf/professionals/en/datasheet/contact_star_evo_1_en.pdf
	O-T-M switch	**Equivalent input noise level:** 24 dB(A) SPL	
	Low battery warning	**Sensitivity of telephone coil**: typ. 95 dB (at 10 mA/m, 1 kHz) programmable	
	Program switching indication	**Total harmonic distortion:** 500 Hz <3%, **(pi=70dBSPL ref. test gain)** 800 Hz <0.6%, 1000 Hz <1.0%, 1600 Hz <0.3%	
	Passive noise cancelation		
	Battery size 675		

Manufacturers and existing models	General properties	Technical parameters	Sources
		Bone conduction for hearing aids	
Audifon hearing systems AN evo 1	Battery size 675 2 channel digital amplifier with programing options over 4 pin programing socket Low cut trimmer (N - H) O-T-M switch	**Total harmonic distortion:** 500Hz <1%, **(pi=70 dB SPL ref. test gain)** 800 Hz <0.5%, 1000 Hz <0.5%, 1600 Hz <0,2% **Sensitivity of telephone coil:** typ. 90 dB (at 10 mA/m, 1 kHz) programmable **Equivalent input noise level:** 26 dB(A) SPL **Current drain:** 1.2 mA +/- 10% (1.35 V) **Battery life**:475 h at a 570 mAh battery capacity	http://www.audifon.com/2112.html 
Audifon hearing systems contact mini	Battery size 13 2-channel digital amplifier with programming options On/off switch via the battery door Volume setting via trimmer Acoustic low battery warning Alternative size of conductor plate	**Harmonic distortions:** 500 Hz <1% **(pi=70 dB SPL reference - test gain)** 800 Hz <1%, 1000 Hz <0.6%, 1600 Hz <0.5% **Equivalent input noise level:** 22 dB SPL **Power consumption:** 1.25 mA ±10% (at 1.35 V) **Battery life time:** approx. 232 h at 290 mAh battery capacity	http://www.audifon.com/2113.html http://www.audifon.com/fileadmin/pdf/professionals/en/datasheet/contact_mini_en.pdf 

Manufacturers and existing models	General properties	Technical parameters	Sources
	Bone conduction for hearing aids		
Cochlear Baha BP100 Sound Processor	Fully programmable, premium head worn sound processor 12 channel sound analysis 3 user-defined programs Wide-band dynamic range compression Automatic adaptive multi-band directional system Automatic noise management Active feedback cancellation Acoustic shock protection Dedicated fitting rationales for mixed loss, conductive loss, and SSD Dedicated listening programs for music and noisy environments Direct audio input with Europlug connector	**Weight:** 14g **Size**: 30 × 21 × 12 mm **Battery Voltage:** 1.1–1.5 V **Battery type**:13 **Current Consumption**: 1.6 mA (in silence) 1.9 mA (at 60 dB SPL, 1600 Hz) **Frequency range**: 250–7000 Hz (ANSI 3.22) **Peak OFL at 90 dB SPL:**126 dB **Peak OFL at 60 dB SPL:**104 dB **Acousto-mechanical gain at 60 dB SPL, 1600 Hz**: 34 dB **Harmonic distortion:** Below 3% above 600 Hz **Equivalent input noise level (EINL):** 28 dB **Electrical input equivalent to an acoustic input of 70 dB SPL**:1 mVRMS, 1600 Hz **Input impedance:**> 10 kΩ **Processing delay**:3 ms	http://la.cochlearamericas.com/sites/default/files/e81528%20Baha%20BP100.pdf **http://www.cochlear.com/wps/wcm/connect/in/home/discover/baha-bone-conduction-implants/about-baha/sound-processors/sound-processors 

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Manufacturers and existing models	General properties	Technical parameters	Sources
		Bone conduction for hearing aids	
Cochlear Baha 5	Small, easy to hide Hear Your Best – Automatically made for iPhone® True Wireless Freedom Baha 5 smart app, quick and easy change program, volume, treble and bass, save settings for certain locations, find sound processor if misplace Baha 5 Power and Baha 5 SuperPower Sound Processors for higher level of hearing loss Data logging	**Weight:** 9.8g **Size**: 26 × 19 × 12 mm **Battery Voltage**: 1.1–1.5 V **Battery type:** 312 (PR41 Zinc-Air) **Current Consumption:** 1.4 mA (in silence) 1.9 mA (at 60 dB SPL, 1600 Hz) **Frequency range**: 250–7000 Hz (ANSI 3.22) **Peak OFL at 90 dB SPL:** 117 dB **Peak OFL at 60 dB SPL:** 105 dB Acousto-mechanical gain at 60 dB SPL, 1600 Hz: 35 dB **Harmonic distortion:** Below 3% above 600 Hz **Equivalent input noise level (EINL):** <26 dB SPL **Input impedance:** > 10 kΩ **Processing delay**: 4.5 ms **Input impedance:** > 10 kΩ **Processing delay**: 4.5 ms	http://www.cochlear.com/wps/wcm/connect/uk/home/discover/baha-bone-conduction-implants/baha-5-sound-processor  

Manufacturers and existing models	General properties	Technical parameters	Sources
	Bone conduction for hearing aids		
Medtronic Sophono magnetic bone anchored hearing system (BAHS) Alpha 2 MPO (replaced Alpha1)	Includes a titanium encases magnetic implant, the attract magnetic spacer with variable strength to ensure comfort and secure fit and an external alpha 2 MPO sound processor Smallest implant on the market (2.6 mm high) The implant secure to bone with 5 screws making it less likely to break, come loose or fall out during an impact MRI compatible up to 3 Tesla and the smallest transcutaneous MRI shadow (5 cm). 3 choices for attachment: Abutments(post/screws), magnets or headband Low profile implant follows the curve of the bone, making it a safe bone conduction implant Can be implanted completely flat against the skull, hidden under your hair The implant lies completely under skin and has low risk of skin issues, less likely to have severe complications after trauma – far safer for a more active lifestyle The processor is a completely programmable, digital hearing system including 8 channels, 16 frequency bands, and 4 programs Dual-directional microphone system amplifies the sound in front of you while reducing background noise; Automatic feedback suppression Direct audio input for FM, personal music players, and mobile phones	Feature details alpha 2 MPO processor data logging programs/memories 4 Two microphones in an isolated compartment with omni and directional modalities Direct audio input Standard Europlug Auto noise reduction Auto feedback suppression Samarium cobalt magnets sealed in titanium **Frequency Range:** 125– 8000 Hz **Dimensions:** 39 mm L × 16 mm W × 2.6 mm H × 10 mmD **Weight:** 3.5 g **Processor:** 16-band, 8-channel WDRC **Power Supply:** Type 13 zinc air battery **Battery Life:** Up to 320 h **Peak Output:** Force level 3 115 dB at 90 dB SPL re 1 µN **Output:** Force: level 3 105 dB at 60 dB SPL re 1 µN **Colors:** Anthracite, brown, champagne, silver Audible warning tones	http://www.sophono.com/professionals/bone-conduction-hearing-device-product-details 

Manufacturers and existing models	General properties	Technical parameters	Sources
Bone conduction for hearing aids			
Oticon Medical AB Ponto Plus	15 sound processing channels Automatic multiband adaptive directionality Wind noise reduction Inium feedback shield Speech guard Tri-state noise reduction Battery management system 10-channel frequency response shaping Up to 4 programs Volume control Wireless capabilities Soft band fitting mode Single-sided deafness fitting mode Feedback manager Low battery warning	**Battery voltage:** 1.1–1.5 V **Current consumption, in silence:** 1.20 mA **Current consumption, typical:** 1.45 mA **Average battery lifetime:** Typically 80–140 h **Frequency range:** 125 Hz–8 kHz **Frequency range (DIN45.605):** 200 Hz–9.5 kHz **Peak OFL at 90 dB SPL input (skull sim.):** 124 dB rel. 1 µN **Peak OFL at 60 dB SPL input (skull sim.):** 107 dB rel. 1 µN **Peak OFL at 50 dB SPL input (skull sim.):** 97 dB rel. 1 µN **Total harmonic distortion (THD60):** <3% above 600 Hz **Equivalent input noise:** 26 dB SPL **Processing delay:** 6 ms **Battery size:** 13 **Weight:** 14 g without battery **Physical dimensions (LxWxH):** 34 × 21 × 11 mm **IRIL GSM/DECT:** 41/ 43 dB SPL	http://www.oticonmedical.com/~asset/cache.ashx?id=34233andtype=14andformat=web http://www.oticonmedical.com/Medical/OurProducts/Sound%20Processors/ponto-plus.aspx#.U7DKsLHzJjs http://www.oticonmedical.com/Medical/OurProducts/The%20Ponto%20System/what-is-ponto.aspx#.U7DK67HzJjs 

Manufacturers and existing models	General properties	Technical parameters	Sources
		Bone conduction for hearing aids	
Oticon Medical AB Ponto Plus Power	15 sound processing channels Wind noise reduction Automatic multiband adaptive directionality Inium feedback shield Speech guard Tri-state noise reduction Battery management system Up to 4 programs 10-channel frequency response shaping Volume control Wireless capabilities Soft band fitting mode Single-sided deafness fitting mode Feedback manager Low battery warning	**Battery voltage:** 1.1–1.5 V **Current consumption, in silence:** 1.25 mA **Current consumption, typical:** 2.10 mA **Average battery lifetime:** Typically 80–160 h **Frequency range:** 125 Hz–8 kHz **Frequency range (DIN45.605):** 260 Hz–9.6 kHz **Peak OFL at 90 dB SPL input (skull sim.):** 128 dB rel. 1 µN **Peak OFL at 60 dB SPL input (skull sim.)**: 116 dB rel. 1 µN **Peak OFL at 50 dB SPL input (skull sim.):** 106 dB rel. 1 µN **Total harmonic distortion (THD60):** <3% above 600 Hz **Equivalent input noise:** 26 dB SPL **Processing delay:** 6 ms **Battery size:** 675 **Weight:** 17 g without battery **Physical dimensions (LxWxH):** 34 × 21× 14 mm **IRIL GSM/DECT:** 30/53 dB SPL	http://www.oticonmedical.com/~asset/cache.ashx?id=34233andtype=14andformat=web http://www.oticonmedical.com/Medical/OurProducts/The%20Ponto%20System/what-is-ponto.aspx#.U7DK67HzJjs 

Notes: * Product is no longer shown on webpage. **The link is not accessible (12/31/2016)

List of Symbols, Abbreviations, and Acronyms

3-D	three-dimensional
ABR	auditory brainstem response
AC	air conduction
AM	amplitude modulation
AR	augmented reality
ARL	US Army Research Laboratory
BC	bone conduction
BCU	bone-conducted ultrasound
BCUHA	bone conduction ultrasonic hearing aid
BM	basilar membrane
BMD	bone mineral density
BRTF	bone related transfer function
CAT	callsign acquisition test
CC	cartilage conduction
CER	conduction equivalency ratio
CHL	conductive hearing loss
CID	Central Institute for the Deaf
CRM	coordinate response measure
CSF	cerebrospinal fluid
CU	categorical units
DLF	difference limens for frequency
DPOAE	distortion product otoacoustic emission
DRT	Diagnostic Rhyme Test
DSB-SC	double side band suppressed carrier
DSB-TC	double-side band transmitted carrier

ECSP	ear canal sound pressure
ELC	equal-loudness contour
FE	finite element
HL	hearing level
HRTF	head-related transfer function
IID	interaural intensity difference
ILD	interaural level difference
ITD	interaural time difference
MRT	Modified Rhyme Test
S^3	Synchronized Sentence Set
SD	standard deviation
SL	sensation level
SNR	speech-to-noise ratio
SOAE	spontaneous otoacoustic emission
SPL	sound pressure level
TTD	transcranial time delay

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