Bone Conduction and the Middle Ear

Chapter · February 2013

DOI: 10.1007/978-1-4614-6591-1_6

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Chapter 6
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Keywords Audiometry • Bone conduction • Bone conduction hearing aid • Carhart notch • Fluid • Inertia • Middle ear • Occlusion effect • Otosclerosis • Own voice • Skull vibration • Third window • Transcranial attenuation • Wave transmission

6.1 Introduction to the Field of Bone Conduction

There is no general definition of what is meant by bone conducted (BC) sound, but it is often understood as the way vibration of the skull bones can result in a sound percept. However, BC sound usually involves transmission in cartilage and soft tissues, for example, in normal BC audiometry in which the BC transducer is positioned by a static force at the skin-covered mastoid. Even if the BC vibration is transmitted from the transducer to the skull bone, the soft tissue is involved in the transmission. It therefore has been argued sometimes that "body conduction" describes the sound transmission better, or that BC and soft tissue conduction should be separated. It is not clear how to separate the different modes of transmission and how fluid conduction should be included. Here, BC (bone conduction) is used to describe sound energy that is transmitted through the body (in bone or soft tissue) and that it involves the outer, middle, or inner ear to finally produce a perception of sound.

Even before the concept of BC sound was understood, BC sound was used to separate a sensory impairment from a conduction impairment. With the introduction of tuning forks, tests were developed during the nineteenth century to diagnose a hearing impairment as either sensory or conductive, for example, the Weber test

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S. Puria et al. (eds.), *The Middle Ear: Science, Otosurgery, and Technology*, Springer Handbook of Auditory Research 46, DOI 10.1007/978-1-4614-6591-1_6,

or Bing test. After the electric audiometer was introduced in the twentieth century, these tests were superfluous because they gave unreliable results versus a comparison of air-conducted (AC) and BC hearing thresholds (Miltenburg 1994; Behn et al. 2007). The increased usage of BC hearing aids in recent times has also increased the need for understanding the processes underlying perception of BC sound.

6.1.1 Basic Inner Ear Processes with Bone-Conducted Sound

One of the quintessential questions about BC hearing is the end organ for transforming BC vibration in the skull to neural code. The first to show BC vibration leading to a basilar membrane motion in the cochlea was von Békésy when he cancelled the perception of a 400-Hz BC tone with an AC tone of the same frequency in a human subject (von Békésy 1932, 1960). Similar experiments in human subjects were later conducted at several stimulation levels (Khanna et al. 1976) and using multiple tones simultaneously (Stenfelt 2007). It has also been used over a broad frequency range in animal experiments cancelling the cochlear microphonics when stimulating with an AC and BC tone at the same frequency (Lowy 1942; Wever and Lawrence 1954).

More direct measures of basilar membrane motion were performed in human temporal bone specimens in which the relative motion between a position on the basilar membrane and the surrounding bone was measured while shaking the whole specimen (Stenfelt et al. 2003b). This is not conclusive evidence that BC sound has the same end organ as AC sound but the study indicated that the maximum vibration amplitude for a specific position on the basilar membrane appeared at the same frequency regardless if stimulation was provided as AC or BC. Moreover, a modeling approach for understanding basilar membrane response with BC stimulation showed results similar to those in the temporal bone specimen study (Stenfelt and Puria 2010; Kim et al. 2011).

Other evidence for the cochlea and basilar membrane motion as the mechanism for BC sound perception is electrophysiological measures of AC and BC sound. It has been shown that BC electrocochleography (BC-ECoG) correlates well with behavioral hearing thresholds (Kylen et al. 1982). Moreover, BC-evoked brain stem response (BC-ABR) disappears subsequent to masking by an AC source showing that the evoked potentials from the BC stimulation are purely auditory (Collet et al. 1989). However, there is a difference in the latency-intensity function for Jewett wave V between click evoked BC-ABR and AC-ABR (Beattie 1998). This difference can be explained by the difference in spectral content of the stimuli due to the filtering effect of the AC and BC transducers and is not an inherent difference related to AC and BC sound perception in the human (Schwartz et al. 1985). A further indication of the same end organ for AC and BC sound is the ability to produce distortion-product otoacoustic emissions (DPOAE) with AC and BC stimulation (Purcell et al. 1998; Watanabe et al. 2008).

One documented difference between AC and BC sound perception is the ability to perceive BC ultrasonic sound (20–120 kHz); when modulated it can be used for speech detection in profoundly deaf individuals (Lenhardt et al. 1991; Hosoi et al. 1998). The mechanisms for ultrasonic BC perception are not clarified and a number of possible explanations have been provided. One such possibility is the demodulation of the ultrasound due to nonlinearities of BC transmission in the skull itself (Haeff and Knox 1963) or to nonlinear processing in the cochlea, for example, due to processing of the inner hair cells (Nishimura et al. 2011).

6.1.2 Human and Animal Studies

Although animal studies are important for understanding processes involved in hearing, BC data are obtained mainly in humans. One reason for this is that perception of BC sound is strongly dependent on the specific anatomy of the skull and ear. For example, most animal heads differ in composition and geometry compared with the human head. Large interspecies differences also exist. Moreover, the cochlea is positioned in hard dense bone in the skull base in the human whereas it is protruding in the air-filled bulla in some animals (e.g., guinea pigs). Such differences make it difficult to extrapolate findings in animal models to human BC sound perception. In addition, it is far easier to perform psychoacoustic experiments using BC stimulation on humans than it is on animals.

There are only a few studies on animal hearing thresholds when stimulation is by BC. One such study is in dogs, in which brain stem responses indicated that the BC hearing thresholds were similar to those for humans (Munro et al. 1997). However, the measurements were not conducted in a controlled environment, and surrounding noise may have affected the measurement negatively. Tonndorf used primarily cats for his experiments, explaining underlying mechanisms for BC sound perception (Tonndorf 1966). Animals have also been used for artificial middle ear manipulations (stapes or tympanic membrane fixation, mass loading, removal of the ossicular chain) to explore the importance of the middle and outer ear for BC sound perception or BC sensitivity alterations in middle ear disease (Legouix and Tarab 1959; Tonndorf 1966; Irvine et al. 1979).

6.2 Bone Conduction Wave Transmission in the Skull Bone and Soft Tissue

One aspect for understanding BC sound perception in the human skull is how BC sound is transmitted in the skull bone. The vibration response of the human head is complex, involving the thin, sphere-like cranial vault, as well as the more dense bone in the skull base, both types loaded with soft tissue and fluids. Moreover, the thin bone in the cranial vault is not homogeneous but comprises hard shell-like structures with fluid-filled matrix-like bone structures (diploae) in between. Also, the skull consists of many bones connected by sutures. Consequently, such complicated structures, both in terms of geometry and composition, make analytical approaches difficult. Even so, researchers have attempted to formulate analytical or finite element computations to achieve the vibration pattern of the human skull (Advani and Lee 1970; Khalil and Hubbard 1977; Young 2002, 2003). These theoretical approaches were intended primarily for head injury protection and not for the transmission and hearing of BC sound.

An early attempt to analyze the response pattern of the human skull during BC stimulation consisted of approximating the vibration mode to that of a vibrating thin-shell sphere (von Békésy 1932). Another approach to investigate the human skull vibration pattern is modal analyses in which the skull resonance frequencies are extracted. Such a method was used in dry skulls (Franke 1956; Khalil et al. 1979; Stenfelt et al. 2000) and living humans (Håkansson et al. 1994). From these studies it is clear that dry skulls do not represent the true response in living humans. For the dry skulls, the first resonance frequency was in one skull at 1.2 kHz (Stenfelt et al. 2000) whereas in another study it was at 1.4 kHz for a male skull and 1.6 kHz for a female skull (Khalil et al. 1979). In six living human skulls, 14–19 resonance frequencies were identified at frequencies below 7.5 kHz; the average of the lowest two were 0.97 and 1.23 kHz (Håkansson et al. 1994). There were no obvious relations between resonance frequencies and head size; other parameters such as stiffness and thickness of the bone may influence the frequencies of the resonances (Håkansson et al. 1986). However, even if the resonance frequencies are important to determine the mechanical characteristic of the human skull, their effect on BC hearing is minor owing to high damping (Håkansson et al. 1994, 1996; Stenfelt and Goode 2005b).

Skull bone transmission of BC sound has been suggested to produce nonlinear distortion (Khanna et al. 1976; Arlinger et al. 1978). In a study to investigate nonlinearities of BC sound in the living human skull, transcranial BC transmission was measured in subjects with skin-penetrating fixtures ensuring rigid connection to the skull bone (Håkansson et al. 1996): they report skull bone transmission of BC sound to be linear up to at least 77 dB HL at frequencies between 0.1 and 10 kHz. In an investigation of skull vibration in cadaver heads, no indications of nonlinear distortion caused by the skull bone were detected at levels corresponding to 80–100 dB HL (Stenfelt and Goode 2005b). Investigations of the human mechanical point impedance have also suggested skull bone transmission to be linear at hearing frequencies and levels (Flottorp and Solberg 1976; Khalil et al. 1979; Håkansson et al. 1986).

6.2.1 Vibration Transmission to the Cochlea

The earlier investigations on BC sound transmission in the human skull focused on the vibration pattern of the cranial vault, either as whole head vibrations (von Békésy 1932; Ogura et al. 1979; Hoyer and Dörheide 1983) or as transcranial transmission measurements (Håkansson et al. 1994). This is not the same as the vibration pattern of the cochlea, and more recent investigations have studied the three-dimensional cochlear vibration during BC stimulation at the skull surface in a damped dry skull (Stenfelt et al. 2000) and in cadaver heads (Stenfelt and Goode 2005b), or as one-dimensional cochlear vibration in cadaver heads (Eeg-Olofsson et al. 2008, 2011) or living humans (Eeg-Olofsson et al. 2013). These studies indicated that the vibration pattern for the human skull can be categorized into four regions (for frequencies below 10 kHz, see Fig. 6.1). At the lowest frequencies, below the resonance frequency of the mechanical point impedance (150–400 Hz; Stenfelt and Goode 2005b), the skull moves as a rigid body (Fig. 6.1a) and above this resonance frequency and up to approximately 1 kHz where the first free resonance of the skull appears (Håkansson et al. 1994), the motion can be described as a mass-spring system wherein large parts of the skull move in phase and in the direction of the stimulation (Fig. 6.1b). This also means that at these frequencies, bilateral stimulation is primarily added in-phase or out-of-phase depending on the stimulation direction (Deas et al. 2010; Eeg-Olofsson et al. 2011).

At frequencies above 1 kHz, the wavelength of the BC sound is short enough to facilitate wave transmission in the skull bone. Between 1 and 2 kHz, the skull transitions from a mass-spring system to a system dominated by wave transmission, and at frequencies above 2 kHz, wave transmission dominates the skull vibration pattern of the skull (Fig. 6.1c). At these high frequencies, the vibration response at the cochlea is more or less independent of the stimulation direction; the response vibration is in all three space dimensions without any dominating direction (Stenfelt and Goode 2005b). The types of vibration in the cranial vault have been suggested to occur as plate waves constituting both longitudinal and transverse components (Tonndorf and Jahn 1981). More recently, the vibration in the cranial vault was separated from the skull base, enabling separate analysis of the two. At frequencies above 2 kHz, the phase velocity at the skull base was almost constant at 400 m/s whereas it increased with frequency at the cranial vault (250 m/s at 2 kHz to 300 m/s at 10 kHz). This suggests that the sound transmission at the thicker skull base is dominated by longitudinal wave motion whereas a mixture of modes including bending wave motion is present in the thinner cranial vault (Stenfelt and Goode 2005b) (Fig. 6.1c). Others who have investigated the group and phase velocity of BC sound in the human head have reported it to be between 260 and 540 m/s (von Békésy 1948; Zwislocki 1953; Franke 1956; Tonndorf and Jahn 1981).

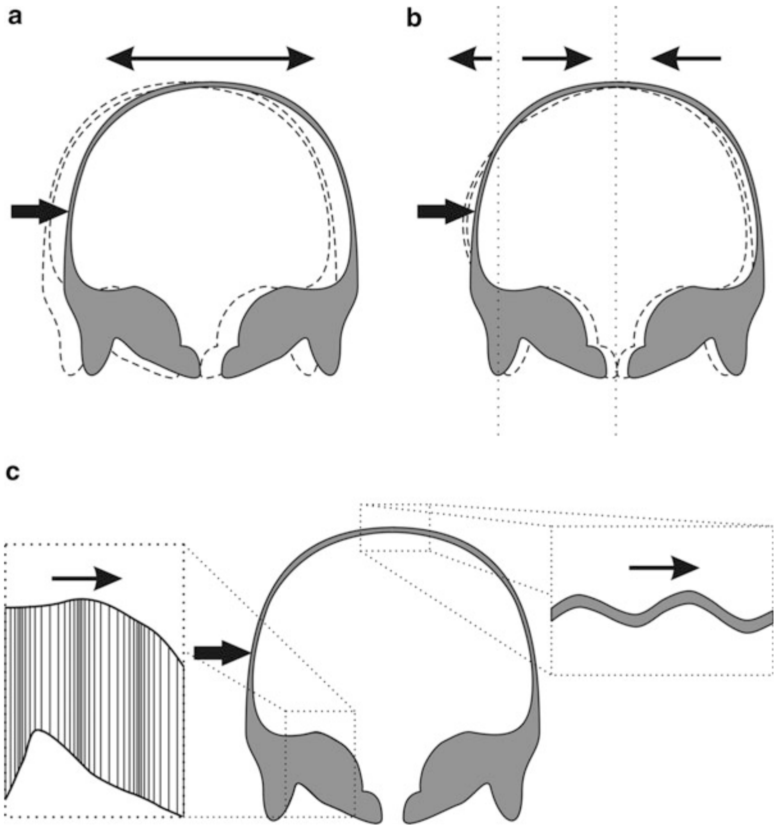

Fig. 6.1 Two-dimensional illustration of the vibration modes of the human skull at frequencies between 0.1 and 10 kHz. The *thick arrows* indicate the stimulation position and the *thin arrows* indicate the response directions. The rigid body response at the lowest frequencies is illustrated in (**a**) while the response at frequencies between approximately 0.3–1.0 kHz that is similar to a mass-spring system is shown in (**b**) where three sections of the skull move sequentially in opposite directions. In (**c**) the vibration responses for frequencies above 2 kHz is illustrated differently for the skull base and the cranial vault: at the skull base longitudinal wave propagation dominates the response while a mixture of vibration modes including bending waves is present at the cranial vault (From Stenfelt 2011)

6.2.2 Influence of Skin and Soft Tissue

The most frequently used mode of BC stimulation is by a transducer pressed on the skin-covered bone at the mastoid or forehead. This means that the skin and soft tissue are interposed between the transducer and the skull bone, affecting BC sound transmission. This is often suggested to interact negatively on BC sound transmission, wherein thicker soft tissue between transducer and bone results in greater attenuation. Except at the very low frequencies, below 250 Hz, the mechanical parameters of the skin and soft tissue are the primary mechanical load (mechanical point impedance) for a transducer on the skin-covered skull. At frequencies below 3 kHz the impedance is stiffness controlled whereas at the higher frequencies, the mass of the skin and soft tissues determine the impedance (Flottorp and Solberg 1976; Håkansson et al. 1986). However, the transmission depends on the interaction between the mechanical parameters of the transducer and the skin and soft tissues. For example, the acceleration transmission is attenuated (Håkansson et al. 1985a) whereas the force transmission is affected only at the higher frequencies (Carlsson et al. 1995; Stenfelt and Håkansson 1999); the effect seen at the electrical input to the transducer is usually between the two (Håkansson et al. 1984; Stenfelt and Håkansson 1999). Moreover, when investigating attenuation of the soft tissue, no relation to the thickness of the soft tissue was found (Mylanus et al. 1994).

Because the mechanical parameters of the skin and soft tissue in the transmission path affect the BC sound transmission, all manipulations that affect the mechanical parameters also affect the transmission. One such parameter is the compression of the skin. It has been shown that increased static force influences BC hearing sensitivity at 1 kHz and below; an increase from about 1.5 N to 6–10 N can improve sensitivity of up to 10 dB (Nilo 1968; Khanna et al. 1976). However, recently it was shown that hearing thresholds improved only 1.5 dB when the static force increased from 2.4 to 5.4 N (Toll et al. 2011); such a difference is of small clinical significance. Another parameter is the size of the vibration interface. A larger size of the vibration interface improves the BC hearing sensitivity primarily at the higher frequencies (above 1 kHz); however, there is an interaction between size and static force of the transducer (Nilo 1968; Khanna et al. 1976).

6.2.3 Influence of Stimulation Position

Generally speaking, the closer the stimulation is to the cochlea, the better the sensitivity of BC sound. As a consequence, mastoid placement is preferred over forehead placement of the transducer due to 11 dB improved sensitivity (Richter and Brinkmann 1981). It has been suggested that the forehead is less sensitive to variation in the stimulation position (von Békésy 1960) but the forehead has been shown to be sensitive to small changes in stimulation position with up to a 25 dB difference between adjacent positions (Khanna et al. 1976). There are also no differences in test–retest results or intersubject variability between the mastoid and forehead (Studebaker 1962; Dirks 1964).

Also, when the stimulation position is at the mastoid and adjacent bone structures, a stimulation position closer to the cochlea compared with a position farther away results in greater response, either as cochlear vibration (Stenfelt and Goode 2005b; Eeg-Olofsson et al. 2008) or as improved hearing thresholds (Eeg-Olofsson et al. 2013; Stenfelt 2012b). The reason for the improved sensitivity at the

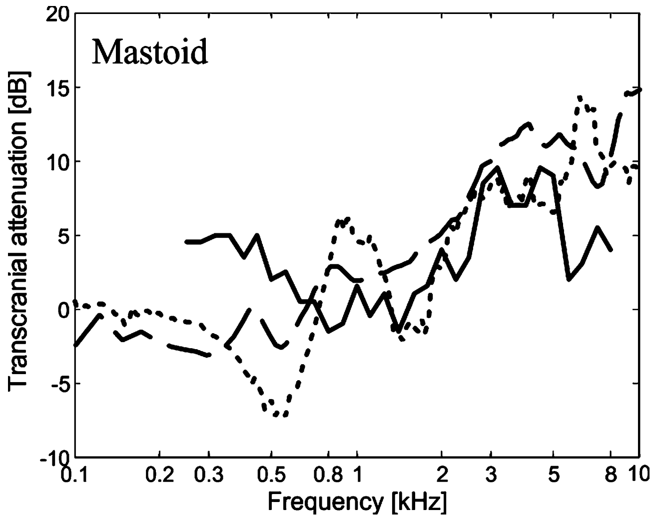

Fig. 6.2 Transcranial attenuation measured in three ways: (1) by hearing thresholds in unilaterally deaf subjects (*solid line*), (2) by one-dimensional vibration response of the cochlea (*dotted line*), and (3) by three-dimensional vibration response of the cochlea (*dashed line*) (From Stenfelt 2012b)

mastoid may be that the sound transmission from the skull surface to the petrous bone encapsulating the cochlea is more efficient when stimulation is positioned directly in line with this bone structure (Eeg-Olofsson et al. 2008). However, it could also be a result of not involving any of the skull bone sutures (Eeg-Olofsson et al. 2008).

Another issue often debated is the amount of BC transcranial attenuation in the human head, that is, how much less the stimulation is at the contralateral cochlea than at the ipsilateral cochlea. When measured as differences in hearing thresholds with ipsilateral and contralateral BC stimulation, it is between 0 and 15 dB, with large individual variability (Hurley and Berger 1970; Snyder 1973; Nolan and Lyon 1981; Reinfeldt et al. 2007a; Stenfelt 2012b). It has also been estimated from cochlear vibration with ipsilateral and contralateral stimulation; it shows almost no attenuation up to 1 kHz, where it increases and becomes close to 20 dB at 10 kHz (Stenfelt and Goode 2005b; Eeg-Olofsson et al. 2011, 2013). A comparison of threshold-based and cochlear vibration-based transcranial attenuation is shown in Fig. 6.2. Similar results were obtained when the transcranial attenuation was assessed by ear canal sound pressures caused by the BC sound (Reinfeldt et al. 2007a). The transcranial attenuations obtained using thresholds are, on average, similar to average vibration measurements at the cochlea at frequencies between 0.8 and 6 kHz (Reinfeldt et al. 2007a; Stenfelt 2012b); at frequencies below 0.8 kHz and above 6 kHz, there are discrepancies in the results from the different methods (Fig. 6.2).

6.3 Perception of Bone-Conducted Sound: Influences from the Outer, Middle, and Inner Ear

Several theories of how skull vibrations ultimately result in a hearing perception have been proposed. Early theories often suggested one or two pathways to dominate the BC perception (Allen and Fernandez 1960; Brinkman et al. 1965) whereas more recent literature suggests multiple pathways that contribute to BC sound perception (Tonndorf 1966; Stenfelt and Goode 2005a; Stenfelt 2011). However, there is no obvious way to distinguish between them because they are interconnected. One often used categorization is the anatomical division inspired by early investigators (von Békésy 1960). This categorization does not differentiate between the different physical mechanisms involved in the transformation from skull vibration to sound pressure differences between the scala vestibuli and scala tympani setting up a traveling wave on the basilar membrane. Recent literature has presented five components as being important for BC sound perception in normal and impaired ears, as indicated in Fig. 6.3 (Stenfelt and Goode 2005a; Stenfelt 2011); these are presented here divided according to ear anatomy.

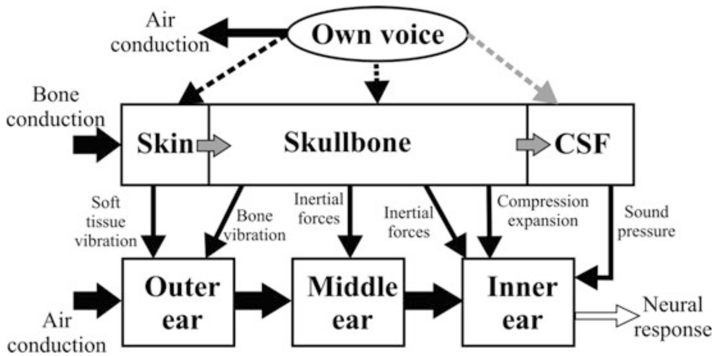

Fig. 6.3 A model of the multiple pathways for hearing BC sounds. A BC vibration onto the compressed skin of the skull bone causes vibrations of the skull and also produces a sound pressure in the skull interior. The vibration of the skin and bone produces a sound pressure in the ear canal while inertial forces cause relative vibration between the ossicles and the surrounding bone. The sound is transmitted to the inner ear from the outer and middle ear, but also directly through inertial forces acting in the cochlear fluids, through compression and expansion of the cochlear space, and, to some extent, through sound pressure transmission from the skull interior. The own sound production is transmitted to the inner ear by both airborne sound and BC (From Stenfelt 2011)

6.3.1 Outer Ear

The human ear canal is approximately 30–35 mm deep with two sharp bends; roughly half is surrounded by cartilage and half by bone. During BC stimulation a sound pressure is produced in the ear canal, primarily due to motions of the bony and cartilaginous ear canal walls. This sound pressure is then transmitted via the eardrum and ossicular chain to the cochlea in a way similar to AC sound. This also means that this pathway is affected by the status of the middle ear. Because the ear canal is easily accessible, several manipulations of the ear canal have been made and results reported. However, many of these involve occluding the ear canal and thereby changing the sound pressure in the ear canal; the occlusion effect is discussed in Sect. 6.6. It has been suggested that the cartilage part rather than the bony part of the ear canal contributes to the low-frequency sound; at higher frequencies the bony part become dominant (Naunton 1963; Stenfelt et al. 2003a).

One way to elucidate the importance of the ear canal sound pressure for BC perception is to compare ear canal sound pressure during AC and BC stimulation for the same sensation. To achieve the result for the normal ear, such comparison should be made for an open ear canal. This was tested, and greater sound pressure with AC stimulation than with BC stimulation at frequencies above 0.5 kHz was found, indicating that ear canal sound pressure is not the most important pathway for BC perception at frequencies above 0.5 kHz (Huizing 1960). A similar approach was to examine the umbo motion in relation to the ear canal sound pressure when stimulation was by AC and BC (Stenfelt et al. 2003a). That study indicated that the ear canal sound pressure was about 10 dB below other contributors to BC perception when the ear canal was open; when the ear canal was occluded the outer ear dominated the BC perception between 0.4 and 1.2 kHz. Another indication that the ear canal sound pressure is not the dominant contributor for BC sound is the fact that large perforations of the eardrum have only small effects on the BC sound perception in cats (Brinkman et al. 1965).

The relative motion between the lower jaw and the skull has been suggested as a major contributor to the ear canal sound pressure during BC stimulation (von Békésy 1932). However, several studies show no or a small effect of the lower jaw on the ear canal sound pressure during BC stimulation (Allen and Fernandez 1960; Howell and Williams 1989; Stenfelt et al. 2003a).

6.3.2 Middle Ear

The middle ear can contribute to BC sound perception primarily by two components: ossicular inertia and sound pressure in the middle ear cavity. The latter is deemed insignificant because middle ear sound pressure measured in sealed human temporal bones did not indicate any significant sound pressure level during BC stimulation (Stenfelt et al. 2002). The ossicular inertia effect relies on the mass

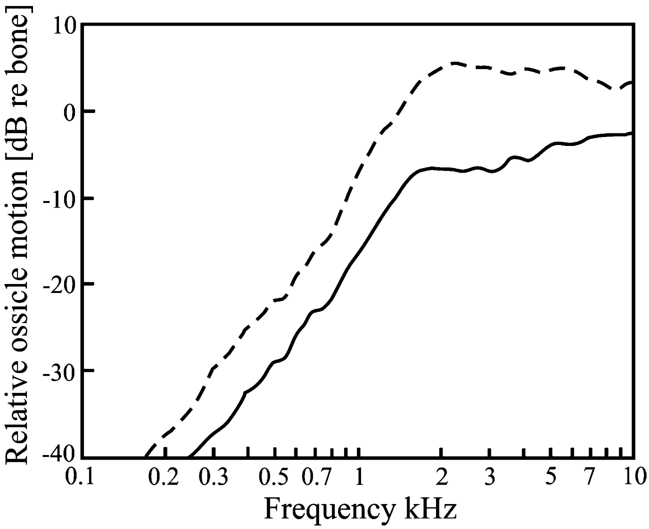

Fig. 6.4 The relative motion between the stapes footplate and the promontory bone (*solid line*) and the malleus umbo and the promontory bone (*dashed line*) in temporal bone specimens when stimulation is in line with the ossicles. The results are averages from 26 ears (Data from Stenfelt et al. 2002)

of the ossicles suspended by ligaments and tendons in the middle ear cavity producing inertial forces when the skull bone vibrates during BC stimulation. This effect is low at low frequencies, at which the stiffness of the suspensory ligaments forces the ossicles to move in phase with the surrounding bone whereas the ossicles become mechanically decoupled from the skull bone at higher frequencies, resulting in a large relative motion between ossicles and skull bone. This behavior is shown in Fig. 6.4 for temporal bone specimens where the relative motion between ossicles and skull bone increases at 40 dB/decade at frequencies below the resonance frequency above which the relative motion flattens out; it stays between 5 and 10 dB re bone motion for the umbo and −5 to 0 dB re bone motion for the stapes (Stenfelt et al. 2002; Homma et al. 2009). The resonance frequency was found to be 1.5–1.7 kHz in the aforementioned studies.

The influence of the middle ear ossicles on BC has been studied extensively; experimental and pathological findings are described in Sect. 6.5. When comparing ossicle motion at AC and BC hearing threshold levels, the vibration of the ossicles is approximately 10 dB below other contributors for BC sound at frequencies below the resonance frequency (1.5–1.7 kHz) (Stenfelt 2006). That analysis also indicated that the ossicles may contribute to BC perception at the resonance frequency and up to approximately 3 kHz. Another experimental and computational modeling study of middle ear ossicle vibration also suggested a contribution at the ossicle resonance frequency of about 1.7 kHz due to a “pivoting” mode that is dominantly excited by BC stimulation (Homma et al. 2009).

6.3.3 Cochlea

In audiology, BC thresholds are compared with AC thresholds to diagnose a conductive impairment. This is based on the notion that BC thresholds are minimally affected by the impairment (situated in the outer or middle ear) while the AC thresholds are affected more significantly. This means that even if the middle or outer ears are involved in the BC sound perception, there is very little effect on the BC sensitivity. Consequently, the BC stimulation of the cochlea can be seen as the dominating part for BC sound perception. However, the processes in the cochlea that result in the perception of sound are to date still debated. The major theories are described in sections "Compression," "Inertia," "Third-Window Theory," "Dynamic Pressure Transmission" and "Pathological Third Window of the Inner Ear."

6.3.3.1 Compression

Due to the wave motion in the skull bone, the bone itself compresses and expands. Such deformation forces displacement of the inner ear fluids and creates a sound pressure in the cochlea. This mode of BC was first termed "inner ear compression" (von Békésy 1932) and later renamed as the "distortional component" (Tonndorf 1966). A better name is "cochlear space alteration" because it is based on the idea that fluid is incompressible during the expansion and compression phase of the cochlear space. During the compression phase the space is reduced and the excess fluid displaced at the compliant oval and round windows. The round window is more compliant (lower impedance) than the oval window and can displace more volume, forcing fluid from the scala vestibuli toward the scala tympani, thus exciting the basilar membrane in the process. Further, the greater volume in the scala vestibuli than in the scala tympani, combined with the higher impedance of the oval window, also forces excess fluid in the direction of the scala tympani adding to the process. During expansion of the cochlear space the process is the opposite.

The significance of this mode of BC perception is disputed and there are clinical findings with obstruction of the cochlear windows and reopening them (fenestration), indicating it not to be important at lower frequencies. Moreover, the cochlea is coiled and its dimensions in the bone can be approximated with that of a sphere with a diameter of 10 mm. If the limit for effective compression response is set to a wavelength that is less than 10 times the size of the cochlea, the lowest frequency for an effective compressive response of the cochlea would be 4 kHz. This is in line with other estimations of the importance of the compression response in the human (Stenfelt and Goode 2005a). Also, based on finite element simulations, the compression component of the bone encapsulating the cochlea is some 25 dB below the rigid body motion of the same up to around 5 kHz (Hudde 2005).

6.3.3.2 Inertia

Similar to the middle ear ossicles, inertial forces also act on the cochlear fluid during vibration of the cochlea. The result of such forces is a sound pressure gradient across the basilar membrane. Consequently, the greater this pressure gradient is, the more efficient is the fluid inertia as a contributor for BC sound. If the fluid is considered incompressible, the fluid flow would require a compliant inlet and a compliant outlet, one on each side of the basilar membrane. In the healthy ear the oval and round windows accomplish this. However, BC sound is relatively unaffected by closing, for example, the oval window in otosclerosis. This can still be explained as an inertial response in the cochlea due to other compliant pathways, known collectively as the "third window" (see section "Third-Window Theory") (Ranke et al. 1952). This means that as long as there is a pressure gradient between the two scalae, there will be fluid flow acting on the basilar membrane resulting in a traveling wave.

Another way to explain the contribution of fluid inertia was suggested by Kim et al. (2011), who stimulated basilar membrane response to BC excitation in a 3D tapered box model of the cochlea. In their model, they decomposed the volume velocities at the oval and round windows into antisymmetric (slow wave) and symmetric (fast wave) volume velocities similar to Peterson and Bogert (1950) for AC. Kim et al. found that the basilar membrane vibration correlated to the antisymmetric volume velocities of the round and oval windows with no dependence on stimulation direction. They therefore argue that manipulations of the middle ear and fixation of the oval and/or the round windows directly influence the antisymmetric volume velocity input to the cochlea (i.e., the difference in volume displacement between the oval and the round window). The caveat is that the model simulations are made in a simplified geometry of the cochlea and the results need experimental validation.

It should be realized that only a small fluid flow is required to produce a hearing sensation based on inertial fluid flow in the cochlea. An estimation of the flow with BC stimulation at 80–100 dB HL yields a displacement that is less than one-millionth of the total fluid volume in the cochlea (Stenfelt and Goode 2005a). It should be pointed out that even if the compressibility of both the fluid and the cochlear bone is small, it is nonzero (Shera and Zweig 1992), and part of the displacement may be attributed to the small compliance of these entities. Because the BC response is nearly unaffected at low frequencies with removal of outer and middle ear components (immobility or removal of middle ear ossicles; Sect. 6.5), the response is directly due to the cochlea. Also, at low frequencies compression is unlikely to be a major contributor (Hudde 2005; Stenfelt and Goode 2005a), indicating that fluid inertia is likely the most important contributor to BC perception at frequencies below 4–5 kHz (Stenfelt and Goode 2005a; Taschke and Hudde 2006; Kim et al. 2011). However, it may be less important at higher frequencies.

6.3.3.3 Third-Window Theory

As presented in the previous section, the major compliant pathways of the inner ear are the oval and round windows. But besides these there are several other compliant pathways that may serve as compliant inlets and outlets for fluid motion. These include the cochlear and vestibular aqueducts (Gopen et al. 1997), as well as nerve fibers, blood vessels, and microchannels entering the cochlea (Kucuk et al. 1991). Also, the compliance of the fluid itself and the bone encapsulating the cochlea yields a general compliance for fluid displacement. These structures provide a combined compliant pathway collectively known as the third window (Ranke et al. 1952). Such a compliant pathway facilitates two possible excitation modes for BC sound. One is the displacing of fluid due to inertial forces of the fluid, described in section "Inertia." The other is by providing a channel for sound pressure transmission from the cranial space to the cochlea, described in section "Dynamic Pressure Transmission."

For AC transmission in the normal cochlea, the volume displacements at the oval and round windows are equal but with opposite phases (Kringlebotn 1995; Voss et al. 1996; Stenfelt et al. 2004). However, this was not found when stimulation is by BC, where the volume displacement between the two windows may differ by up to 10 dB (Stenfelt et al. 2004); this was also found in a model of inertial BC in the cochlea (Kim et al. 2011). This indicates that fluid in the cochlea is displaced at places other than the oval and round windows during BC stimulation, or that the cochlear space is deforming and being "squeezed." However, the difference of volume displacement at the oval and round window is seen at low as well as high frequencies. Because cochlear space alteration is not believed to be present at lower frequencies owing to the nature of wave transmission in the skull bone at these frequencies, the third window effect is considered as important for BC sound. In experiments in cats, it was found that the third window effect was important for BC but not for AC stimulation (Tonndorf 1966). However, in diseased cochleae with round window atresia, AC thresholds are elevated but not absent (Linder et al. 2003). This suggests that the third window may also be important in for AC stimulation in pathological ears.

6.3.3.4 Dynamic Pressure Transmission

It has recently been shown that a sound percept can be evoked in the cochlea with stimulation on the body without involving the skull bone, for example, by applying a vibration stimulus to the eye (Perez et al. 2011). This type of soft tissue transmission is hypothesized to rely on sound pressure transmission from the cerebrospinal fluid through compliant pathways to the cochlea (Sohmer et al. 2000). However, it is not clarified how this sound pressure transmission occurs. Also, several clinical findings such as BC sensitivity change due to a semicircular canal dehiscence indicate that this mode is not the most important for BC sound perception (see section "Pathological Third Window of the Inner Ear"). Also, similarities between cochlear vibration pattern and BC perception suggest that that the vibration of the cochlea itself is responsible for BC sound perception (Stenfelt 2012b).

6.3.3.5 Pathological Third Window of the Inner Ear

As described in section "Third-Window Theory," the third window provides compliant inlets and outlets of the cochlea. The impedance of these pathways depend on their diameter and length; they are normally long and thin (relative to the oval and round window), resulting in a high impedance not affecting normal AC stimulation (Gopen et al. 1997). However, when they become wider (pathological) their impedance decreases and they affect both AC and BC sensitivity when situated on the scala vestibule side. Two such pathologies are semicircular dehiscence and large vestibular aqueduct syndrome (Merchant and Rosowski 2008).

Both types of pathologies have, from the AC and BC sound perspective, similar explanations. In semicircular dehiscence, AC hearing sensitivity is decreased at frequencies below 2 kHz while BC sensitivity is improved in the same frequency region (Mikulec et al. 2004; Merchant and Rosowski 2008). Large vestibular aqueduct syndrome also shows low-frequency pathological differences between AC and BC thresholds (known as air–bone gaps) (Merchant et al. 2007; Sato et al. 2007). The explanation for the low-frequency air–bone gaps is the reduced impedance for fluid flow at the scala vestibuli side: for the AC sound, part of the sound energy is rerouted to the enlarged canal or dehiscence instead of the round window, reducing the stimulation of the basilar membrane, whereas for BC sound the reduced impedance parallels the oval window, facilitating larger fluid flow between the scalae and increased basilar membrane stimulation (Songer and Rosowski 2007, 2010).

6.4 Bone Conduction Audiometry

BC hearing thresholds are together with AC thresholds the fundamental measure of a person's hearing ability. The configuration of the absolute thresholds as well as the difference between AC and BC thresholds guide the clinician categorizing a hearing impairment as sensorineural, conductive, or mixed. This relies on the notion that BC thresholds are minimally affected by the outer and middle ear status, while the AC thresholds are highly influenced. The maximum possible difference between AC and BC thresholds depends on the specific test method and equipment; at a certain level the AC stimulation induces a BC vibration in the skull that is audible. For a sound field, this level is between 40 and 60 dB (Reinfeldt et al. 2007b).

Throughout history, different transducers have been used for BC testing but today the Radioear B71 is most frequently used. This transducer is limited in useable frequency (approximately 250–4,000 Hz) and dynamic range, and there have been suggestions for other designs to overcome some of the current limitations (Håkansson 2003; Popelka et al. 2010a). Test–retest variability is another problem associated with BC threshold testing; however, with careful positioning of the transducer, the standard deviation of test–retest is in the 3–5 dB range (Laukli and Fjermedal 1990); this variability does not improve with smaller step size (Jervall and Arlinger 1986). Besides conventional pure tone threshold estimations, BC stimulation can be used in brain stem response audiometry (Collet et al. 1989; Beattie 1998), auditory steady-state response audiometry (Ishida et al. 2011), otoacoustic emissions (Kandzia et al. 2011), and speech testing (Beattie and Smiarowski 1981).

6.4.1 *Factors Affecting Bone Conduction Threshold Estimations*

Variables that have a particular influence on the reliability of BC testing are the specific type of BC transducer, the static force, presence or absence of contralateral masking (see Sect. 6.4.2), and location of the transducer (Dirks 1964). Adding to the list of uncertainties are the functional state of the middle ear (see Sect. 6.5), the position of the lower jaw, and the large amount of distortion produced at low frequencies (Salomon and Elberling 1988). Most of these variability problems can be avoided by carefully following standardized testing procedures (ISO:8253-1 2010).

As stated in Sect. 6.2.3, the forehead has an overall lower sensitivity than the mastoid with a difference of approximately 11 dB at the normal test frequencies (Richter and Brinkmann 1981). This sensitivity difference is important because nonlinear distortion affects the maximum level available from the BC transducer at low frequencies: hence the maximum hearing loss testable is less at the forehead than at the mastoid. Another problem is vibrotactile sensitivity: At the mastoid the vibrotactile thresholds for BC testing are 43 and 55 dB HL at 250 and 500 Hz, respectively (Brinkmann and Richter 1983). That is another limit for the maximum testable hearing loss at low frequencies.

A problem with BC testing at the higher frequencies, at 3–4 kHz, is that the vibration of the transducer couples to the air causing airborne sound at the same level as the BC stimulation (Shipton et al. 1980; Frank and Crandell 1986). It is therefore sometimes advised that BC threshold testing should be done with ear plugs. The caveat is the occlusion effect at low frequencies caused by the ear plug giving erroneous BC threshold data (see Sect. 6.6).

6.4.2 *Masking*

To ensure BC testing of a specific ear, the nontest ear requires masking. The level and frequency of the masking noise is important. Inadequate masking allows the nontest ear to participate while excessive masking falsely makes the BC threshold worse. Optimum masking is produced by narrow band noise centered at the test frequency. The optimal level is difficult to predict beforehand. One issue is the attenuation of the BC sound to the contralateral side. It is assumed to be, on average, 0–15 dB (see Fig. 6.2), but the large variability may cause the BC stimulation at the opposite ear to be 20 dB higher than at the test ear at certain frequencies (Stenfelt 2012b). The masking is usually provided by circumaural or insert earphones that causes an occlusion effect at low frequencies that can amount to 20 dB (Elpern and Naunton 1963). Consequently, the BC stimulation at the nontest ear may be 40 dB greater than at the test ear.

Because the exact masking level is difficult to predict according to the foregoing, an adaptive masking procedure is often used (Studebaker 1964). This is also known as the plateau technique, wherein the unmasked threshold is elevated by increasing masking level in the nontest ear. Above a certain level, a further increase of the masking noise in the nontest ear causes no further threshold elevation in the test ear. The threshold at this plateau is considered as the true masked threshold of the test ear.

6.5 Bone Conduction Thresholds Influenced by the Status of the Middle Ear

The role of the middle ear in BC was explained in Sect. 6.3.2. To reveal the importance of the middle ear ossicles in BC, different types of artificial lesions have been made in living humans, for example, mass loading of the eardrum and ossicles or the addition of a static pressure in the ear canal, and also by manipulation of the ossicles in research animals. Moreover, the alteration of the BC sensitivity in pathological middle ears adds to the understanding of the middle ear ossicles' role in perception of BC sound.

6.5.1 *Experimental Conditions*

Because the middle ear ossicles are not accessible in the normal ear, most investigations have used mass loading of the eardrum to increase the mass of the ossicular system (Bárány 1938; Legouix and Tarab 1959; Huizing 1960; Stenfelt et al. 2002) or by increasing the static pressure in the ear canal and thereby increasing the stiffness of the ossicular chain (Bárány 1938; Huizing 1960; Aazh et al. 2005; Homma et al. 2010). Most studies agree that adding mass improves BC thresholds at frequencies below 2 kHz; direct measurement of the ossicle vibration shows that adding a mass to either malleus umbo or stapes footplate decreases the resonance frequency for the ossicular vibration with BC stimulation and thereby improves sensitivity below the normal resonance frequency at approximately 1.5 kHz (Stenfelt et al. 2002). The lowering of the resonance frequency is an effect of the increased mass while the stiffness is the same; this result in greater velocity at low frequencies owing to the increased inertial force caused by the greater mass. The evidence that increased static pressure decreases BC sensitivity is not equally conclusive; there are studies that show decreased threshold sensitivity (Huizing 1960; Humes 1979; Nolan et al. 1985) but also show improved sensitivity (Aazh et al. 2005). A caveat is that achieving the static pressure in humans also creates an occlusion effect known to improve low-frequency sensitivity of BC sound (see Sect. 6.6). The static pressure does increase the stiffness and by that the resonance frequency of the ossicles with BC stimulation, leading to decreased vibration velocity of the ossicles below the new resonance frequency (Homma et al. 2010); however, its effect on BC sensitivity for the normal human ear is not clear.

In a thorough study of the vibration response of the middle ear ossicles during BC stimulation in temporal bone specimens, the effects of several manipulations were studied (Stenfelt et al. 2002). Gluing the stapes or the malleus to the surrounding bone reduced the ossicle vibration, more so for gluing the stapes than for gluing the malleus; almost no effect was seen at frequencies above 3 kHz for gluing the malleus on the stapes vibration. This is attributed to the ossicular joints, primarily the incudo–stapedial joint but the incudo–malleolar joint may also contribute. It was also shown that severing the incudo–stapedial joint affected the vibration of the stapes only at 1.5–2 kHz, where it decreased by approximately 10 dB; this is the frequency region of the middle ear ossicle resonance where the inertia of the ossicles may contribute to the perceived BC sound (see Sect. 6.3.2). Another interesting finding was that when the cochlea was drained of the fluids, the low-frequency response of the ossicles decreased while it increased at around 2 kHz; yet another indication of a middle ear ossicle inertia contribution at this frequency.

6.5.2 Pathological Conditions

There are indications that the status of the middle ear affects BC thresholds more when the stimulation is at the mastoid than at the forehead. Approximately 5 dB worse BC thresholds at frequencies between 0.5 and 4 kHz are obtained with the stimulation at mastoid compared with at the forehead for several different middle ear lesions (Studebaker 1962; Dirks and Malmquist 1969; Goodhill et al. 1970). This may suggest that the middle ear is more influential for BC perception when stimulation is in line with the ossicles than when directed perpendicularly.

However, there is only a minor vibration response difference for the ossicles when stimulation is in line with the ossicles than when perpendicular (Stenfelt et al. 2002). It is also argued that the difference for BC sensitivity at mastoid and forehead does not hold for all middle ear impairments (Dirks and Malmquist 1969).

6.5.2.1 Otosclerosis of Stapes and/or Malleus

One well accepted change in the BC sensitivity with middle ear lesions is the so-called Carhart notch that manifests itself in otosclerosis of the stapes and oval window. The depressed BC threshold in otosclerosis is approximately 20 dB at 2 kHz, with lesser losses at frequencies below and above this frequency (Carhart 1950, 1971). The depressed BC sensitivity has been explained as a lack of contribution from the resonating middle ear ossicles (Tonndorf 1966). However, it may also be caused by the impedance change seen for the fluid flow in the cochlea.

It has been suggested that the Carhart notch may be used to diagnose a stapedial otosclerosis based on the depressed BC threshold at and around 2 kHz when the same depression is not seen in the AC thresholds. However, there are a few caveats in doing so. One is that not just conductive lesions affect otosclerotic ears. When comparing nonoperated ears with proven otosclerosis with a control group, it was shown that the otosclerotic ears had greater BC deterioration than the normal ear even after correction for the Carhart effect, indicating additional cochlear impairment due to the otosclerosis (Browning and Gatehouse 1984). Such an effect obscures the Carhart notch, making the diagnosis uncertain. Another caveat is that the Carhart notch is not specific to otosclerosis or congenital absence of the oval window. To a lesser degree it also exists in cases of otitis media with effusion, tympanosclerosis, and congenital ossicular anomalies (Ysan2007). However, it is only when the incudo–stapedial joint has become part of the ossicular fixation that a fixed malleus produces BC thresholds comparable to those seen in otosclerosis of the stapes (Goodhill 1966).

6.5.2.2 Fluid in the Middle Ear Cavity

There are several reports indicating that fluid in the middle ear, for example, associated with serous or adhesive otitis media, temporally worsen the BC thresholds, and after incision of the eardrum and insertion of a ventilation tube, the BC thresholds recover (Palva and Ojala 1955; Huizing 1960; Milner et al. 1983). As pointed out in section "Otosclerosis of Stapes and/or Malleus," the alteration of the BC thresholds in patients with chronic ear diseases such as chronic suppurative otitis media, cholesteatoma, and adhesive otitis media show BC thresholds similar to those of patients with otosclerosis (Lindstrom et al. 2001). After tympanoplasty and ossicular reconstruction, the BC thresholds improved between 4 and 10 dB at frequencies between 0.25 and 4 kHz. Also, children suffering from otitis media with effusion showed BC threshold depression similar to that found in otosclerosis (Carhart notch) (Ahmad and Pahor 2002; Shishegar et al. 2009). However, a study of children with suppurative otitis media without cholesteatoma reported no alteration of the BC thresholds (Kaplan et al. 1996).

6.5.2.3 Ossicular Discontinuity

The literature on the effect of ossicular discontinuity on BC thresholds is less conclusive than for other middle ear pathologies. However, most studies report no or insignificant alteration of the BC threshold as a result of ossicular discontinuity (Møller 2000). In a group of patients with chronic otitis media who underwent tympanomastoidectemy without ossicular reconstruction, no change in the BC thresholds was seen. However, in a group who underwent ossicular reconstruction, the gain in BC thresholds were on average 2.3–3.9 dB at frequencies between 0.5 and 4 kHz, with the greatest improvement at 2 kHz (Lee et al. 2008). Another study indicated no significant difference in BC thresholds in a group of patients after ossiculoplasty subsequent to traumatic ossicular dislocation (Yetiser et al. 2008). However, in patients with radical mastoidectomy removing the major part of the ossicular chain, the greatest reduction was around 2 kHz, where the ossicles normally resonate (Dirks and Malmquist 1969). This finding is in line with artificial manipulations of the ossicles in which severing the incudo–stapedial joint did reduce vibration of the stapes at 2 kHz (Stenfelt et al. 2002).

6.5.2.4 Oval-Window and Round-Window Occlusion

The most common reason for oval-window and/or round-window occlusion is otosclerosis, but there exist cases with congenital absence of one or both inner ear windows (House 1959). Early on, the common treatment for otosclerosis was a fenestration of the vestibule. With this treatment the BC thresholds almost returned to normal (Walsh 1962). The improvement of the BC thresholds was, as a pure tone average (PTA) for the frequencies 0.5, 1, and 2 kHz, on the order of 6.5–12 dB, reflecting the depression of the Carhart notch (Miyamoto and House 1978; Brooks 1985). It was reported that a patient with congenital absence of the oval window due to malformation showed BC thresholds close to normal (Everberg 1968), but most report that congenital absence of the oval window shows BC results similar to that in otosclerosis of the stapes (Yi et al. 2003).

Today, more common treatments in otosclerosis are stapedectomy or stapedotomy. With total footplate stapedectomy, the BC thresholds generally improve by more than 5 dB at frequencies between 0.5 and 2 kHz (Awengen 1993). Stapedectomy (total or partial) gives significantly larger improvement in BC thresholds (in otosclerotic ears) of 10–12 dB at 1 and 2 kHz compared with stapedotomy, giving 3–6 dB improvement at the same frequencies (Persson et al. 1997). Another study reports mean BC threshold improvement of 8 dB at 2 kHz after a piston was inserted in a series of otosclerotic ears (Tange et al. 2000).

There have also been studies investigating the BC improvement with relation to diameter of the piston in stapedotomy. One such study reported the improvement of the BC thresholds at 1 and 2 kHz after stapedotomy to increase with increased diameter of the stapedotomy piston (Teig and Lindeman 2000) whereas another study pointed in another direction, indicating that the increase of BC thresholds is greater for a 0.4-mm piston compared with a 0.6-mm piston, PTA (0.5, 1k, 2k, 4k) 4.5 and 2 dB, respectively (Shabana et al. 1999). A meta-analysis of the literature indicated no difference between 0.4- and 0.6-mm pistons on BC sensitivity (Laske et al. 2011).

An occlusion of the round window affects the BC thresholds more than occlusion of the oval window. In a case of otosclerosis primarily of the round window, the audiogram showed BC thresholds that decreased by approximately 16 dB per octave (Groen and Hoogland 1958). The BC improvement after surgery was 4 dB per octave, with a gain of 5 dB at 250 Hz and 20 dB at 8 kHz. In other cases with absence of the round window, the BC thresholds are reported as approximately 20 dB worse than normal (Martin et al. 2002; Linder et al. 2003).

6.5.3 Influence from the Stapedius Muscle

The effect of the stapedius muscle on AC transmission in humans have been reported to increase with decreased frequency at frequencies below 2 kHz, reaching 40 dB attenuation (Morgan and Dirks 1975). There are no similar reports on the effect of the stapedius muscle on BC transmission in the human. A study on the effect of the stapedius muscle on BC transmission in the cat suggests it to be similar to the effect of AC: The BC attenuation was approximately 10 dB at frequencies below 1.5 kHz (Irvine 1976). The effect may be similar to that of static pressure in the ear canal increasing the stiffness of the ossicular chain. If so, the effect of the stapedius muscle on BC transmission in humans is expected to be similar to that obtained in cats.

6.6 The Occlusion Effect

The occlusion effect is the low-frequency BC sound increase subsequent to an occlusion of the ear canal. One common manifestation of the occlusion effect is the low-frequency emphasis of one’s own voice while speaking with the ears occluded (see Sect. 6.7). Because the ear canal is easily accessible and the occlusion effect is important in several areas for BC sound, the occlusion effect has been investigated thoroughly, either as the perceptual change (alteration of hearing thresholds) (Klodd and Egerton 1977; Small and Stapells 2003), a change of the ear canal sound pressure (Howell et al. 1988; Stenfelt et al. 2003a), or both (Huizing 1960; Berger 1983; Stenfelt and Reinfeldt 2007). Several explanations for the occlusion

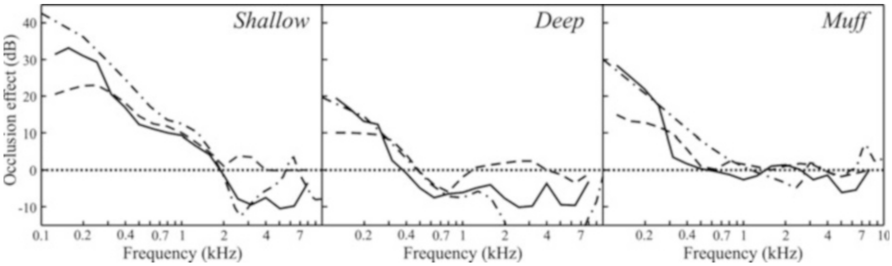

Fig. 6.5 The occlusion effect obtained as ear canal sound pressure changes (*solid line*), threshold differences (*dashed line*), and estimated according to an acoustic model (*dashed-dotted line*). Three conditions are displayed: (1) shallow occlusion (7 mm down the ear canal), (2) deep occlusion (22 mm down the ear canal), and (3) earmuff with 30 cm^3 internal volume (From Stenfelt and Reinfeldt 2007)

effect have been proposed: Huizing measured the ear-canal sound pressure and related threshold changes and explained the occlusion effect by the impedance change of the ear canal caused by the ear canal length and terminations, changing resonances and anti-resonances (Huizing 1960). Tonndorf presented a simple mass-spring model of the ear canal to explain the occlusion effect; the occlusion changes the filter parameters rerouting low-frequency BC sound to the cochlea (Tonndorf 1972). In an acoustic modeling effort, the ear canal sound pressure change with the occlusion effect could be well predicted by a transmission line model of the ear canal in which the length of the ear canal and radiation impedance were altered due to the occlusion device (Stenfelt and Reinfeldt 2007).

Figure 6.5 shows the occlusion effect measured as the changes of ear canal sound pressure, BC threshold change, and according to a model (Stenfelt and Reinfeldt 2007) for three different conditions: (1) shallow occlusion (7 mm down the ear canal), (2) deep occlusion (22 mm down the ear canal), and (3) earmuff with 30 cm^3 internal volume. The model verified that different positions in the ear canal gave different occlusion effects (Stenfelt and Reinfeldt 2007). It corroborated the assumption that deep occlusion causes no or negligible occlusion effect (von Békésy 1941). Also, large enough air volume inside ear phones or earmuffs removes the occlusion effect (Elpern and Naunton 1963; Khanna et al. 1976; Stenfelt and Reinfeldt 2007; Reinfeldt et al. 2010).

With BC stimulation at the mastoid, the perceived occlusion effect is often 10 dB lower than the change in ear canal sound pressure (Huizing 1960; Berger 1983; Stenfelt and Reinfeldt 2007). This is explained by the significance of the ear canal sound pressure for BC sound perception; the ear canal component is believed to be about 10 dB below other contributing parts for BC perception (see Sect. 6.3.1). However, when the stimulation is at the forehead the perceived occlusion effect is greater than when stimulation is at the mastoid (Klodd and Egerton 1977; Dean and Martin 2000; Stenfelt and Reinfeldt 2007). This may indicate that the contribution of pathways to BC sound depends on the stimulation position or the direction of the stimulation. It should be noted that not all studies show differences between mastoid- and forehead-stimulated occlusion effect (Goldstein and Hayes 1971).

The occlusion effect is most pronounced at the lowest frequencies, meaning that low-frequency hearing sensitivity is increased for BC sound. However, the sensitivity for other body sounds is also increased. When these body sounds are enhanced (breathing, heartbeat, and swallowing) they can mask the BC sound at the lowest frequencies (125 and 250 Hz). The masking due to this enhancement of body sound is as much as 5 dB (Berger and Kerivan 1983). This means that if hearing thresholds are used for estimating the occlusion effect, the occlusion effect at the lowest frequencies may be underestimated.

6.7 Own Voice Perception

One example in which the influence of BC sound is familiar to most people is in the act of hearing one's own voice. When listening to a recording of one's own voice people are often struck by the difference between the sound of the recording and the way that they normally perceive their voice. The reason for this difference is that a person hears his or her own voice through two routes, airborne (AC transmission) and via the skull bones (BC transmission), whereas the recording contains only the airborne sound.

There have been attempts at estimating the two components of one's own voice. One attempt was done by attaching tubes filled with cotton to the ears, removing the AC component without causing an occlusion effect (not affecting the BC component) (von Békésy 1949). The decrease in loudness of vocalization subsequent to attaching the tubes was about 6 dB, and this was assumed to be equivalent to the AC component of the subject's own voice; this indicated that the AC and BC components of one's own voice were similar in magnitude (von Békésy 1949). Another estimate used masked thresholds by one's own voice, in which the AC and BC components were manipulated. The estimation was performed for a voiced (/z/) and an unvoiced (/s/) sound: The results showed the BC components to be greater at frequencies between 0.7 and 1.2 kHz whereas the AC component dominated outside this frequency region (Pörschmann 2000). A third investigation of the two components were conducted with a large earmuff removing the AC component without adding the occlusion while measuring the ear canal sound pressures from the AC and BC components of the subject's own voice (Reinfeldt et al. 2010). That study used ten different utterances: four vowels and six consonants. It was found that the relative contribution of AC and BC for one's own voice perception depends on the utterance, but similar utterances gave approximately similar relative contributions. For example, /m/ and /n/ gave similar relative contributions but differed from, for example, /k/ and /t/, that were similar to each other. At frequencies below 2 kHz, there were different regions for the different utterances where the AC and BC components dominated. However, at frequencies above 2 kHz the AC component dominated the subject's own voice regardless of utterance (Reinfeldt et al. 2010).

Besides better understanding of one's own voice as provided by the aforementioned studies, the knowledge about the two components during vocalization is important for designing and fitting hearing aids because the perception of one's own voice is affected by a hearing aid (Killion et al. 1988; Carle et al. 2002; Stenfelt 2012a). Also, BC transmission of one's own voice is important for designing BC microphones that record the BC component of a subject's own voice (Ono 1977; Zheng et al. 2003).

6.8 Bone Conduction Hearing Aids

One area in which BC hearing is of importance is the use of BC hearing aids. The primary use of BC hearing aids is in patients needing amplification but in whom normal AC hearing aids are contraindicated. The typical BC hearing aid wearer has a large conductive hearing loss but BC hearing aids are also used in patients with draining ears or eczema in the ear canal and have recently been introduced as an alternative for contralateral routing of signal (CROS) hearing aids.

6.8.1 Conventional Bone Conduction Hearing Aids

The concept of BC hearing is old, as are BC hearing aids (Berger 1976; Mudry and Tjellström 2011). The general function of a BC hearing aid is the same as an AC hearing aid: A microphone picks up the sound and a sound processor shapes the sound according to a fitting rule for the hearing loss. The difference is that instead of a normal receiver as in the case of the AC hearing aid, the signal is supplied to a transducer vibrating the skull by pressing on the skin-covered mastoid. The typical BC hearing aid is either positioned by a headband or incorporated into spectacles for improved cosmetics (Banga et al. 2011). The requirement of a static force to facilitate sound transfer as well as positioning of the device causes discomfort when used for long periods of time, and the sound quality of these devices is often poor (Snik et al. 1995). These shortcomings have led to the development of the bone-anchored hearing aid (BAHA). Recently, a conventional BC hearing aid was introduced that uses implanted magnets in the mastoid to retain the transducer and achieve the necessary static force to transmit the BC sound (Siegert 2011).

6.8.2 Bone-Anchored Hearing Aids

The BAHA is attached to the skull using a skin-penetrating titanium implant (Håkansson et al. 1985b). Such a design avoids problems associated with the static pressure in the conventional BC hearing aid, and the direct coupling to the skull bone offered by the implant removes the high-frequency attenuation of the skin. As with conventional BC hearing aids, the degree of conductive loss is not important for BAHA users; it is the sensorineural hearing loss that is the limit. When used within the suggested limits of the different devices, the BAHA system is considered beneficial and is a well-accepted rehabilitation (Snik et al. 2005).

Because a BC sound is transmitted to the contralateral side with low attenuation (Stenfelt 2012b), the BAHA is usually fitted only unilaterally even though the hearing problem is bilateral. One reason is the unclear binaural effect with bilateral bone conduction (Stenfelt 2005). However, a systematic review of the literature of patients fitted bilaterally with BAHAs shows a clear benefit with bilateral fitting compared with unilateral fittings (Colquitt et al. 2011). It should be noted that due to the cross transmission with BC stimulation, the binaural effect is less for BC sound than for AC sound bilaterally stimulated at the ears (Stenfelt and Zeitooni 2013).

Another patient group fitted with the BAHA is one with unilateral profound deafness. In this case, the low attenuation of cross transmission for BC sound is used to transmit sound from the deaf side, picked up by the BAHA and transmitted to the skull bone at the deaf side, reaching the healthy cochlea by means of BC sound transmission (Stenfelt 2005). A review of the literature shows benefit, both subjective and objective, with this rehabilitation (Stewart et al. 2011). It should be noted that using BC hearing aids for treatment of unilateral deafness, or any other type of CROS hearing system, does not provide any binaural hearing but solely improves hearing sensitivity from the deaf side that is deteriorated by the head shadow.

A drawback of the current BAHA system is the skin penetration itself; such a solution requires special care and good hygiene. In a few percent of BAHA users, the skin problems become severe and, if untreated, can result is loss of the implant. Consequently, other alternatives to the BAHA are considered and two such alternatives are presented in Sects. 6.8.3 and 6.8.4.

6.8.3 Teeth-Applied Bone Conduction Hearing Aids

The teeth as a sensitive site for BC stimulation have been reported in the literature (Sabatino and Stromsta 1969; Dahlin et al. 1973; Stenfelt and Håkansson 1999). The teeth provide a more or less direct attachment to the skull bone (in the upper jaw). However, there is compliance in the teeth–bone interface reducing the high-frequency BC sound transmission (Stenfelt and Håkansson 1999). The teeth have been suggested as a site for attaching a BC hearing aid but the unfriendly environment in the oral cavity has hindered several attempts. Recently, a system was presented for unilaterally deaf patients in which the sound is picked up at the ear canal of the deaf side with a microphone and wirelessly transmitted to a removable bone transducer attached to the teeth in the oral cavity (Popelka et al. 2010b). This is yet another system using BC sound transmission for patients with unilateral deafness. One benefit compared to the BAHA system is that it avoids skin penetration and by that, surgery. But the use of the oral cavity for an active system is not yet proven in the marketplace.

6.8.4 Implanted Bone Conduction Hearing Aids

Another way to avoid skin penetration is to implant the BC hearing aid. Such systems are termed BCI: bone conduction implants (Håkansson et al. 2008, 2010). The idea of such a system is to have a microphone and sound processing unit on the outside and transmit the signal wirelessly to a receiver and transducer implanted in the mastoid of the skull, similar to that of cochlear implants or active middle ear implants. However, even if the skin penetration is avoided, surgery is still required. The concept of implanting the transducer facilitates a new transducer solution that may provide more effective stimulations modes (Adamson et al. 2010). Also, implanting the system enables a closer position of the transducer to the cochlea. A closer position provides greater BC sensitivity and separation between the cochleae beneficial for binaural hearing (Stenfelt and Goode 2005b; Eeg-Olofsson et al. 2008; Håkansson et al. 2010).

6.9 Summary

The research to understand the underlying processes of BC sound was intense in the mid-1900s. However, after Tonndorf's 1966 publication, the number of BC publications was meager for a period of time. With the advent of the BC hearing aids based on implantable techniques, there has been a significant increase in BC-related research. At the end of the twentieth century and beginning of the twenty-first century, BC research is once again flourishing. There are several reasons for this increase. The development of BC hearing aids requires new data to optimize behavior of these devices, but equally important are advances in measuring techniques (e.g., the laser Doppler vibrometer for contactless vibration measurements) and modeling and computational methods. Also, understanding the mechanisms for BC sound relies to a large extent on the understanding of normal AC hearing and the mechanical and physiological processes in the outer, middle, and inner ear. There remains a need to integrate knowledge of AC mechanisms and BC mechanisms into a common framework.

Most pathology in the outer and middle ear that severely affects the AC sound transmission affects the BC sensitivity only to a minor extent. Thus even if the changed BC sensitivity in a middle ear lesion is helpful for understanding underlying BC physiology, its clinical relevance is minor. Also, the use of BC thresholds for differential diagnosis of the specific middle ear lesion is risky; the Carhart notch is not always identifiable in cases of otosclerotic ears, and other lesions show BC depression similar to the Carhart notch. There are several pitfalls when conducting BC testing. The most common are occlusion of the ear canal, airborne sound radiation from the transducers, and unmasked or over-masked nontest ear.

With more than a century of research in the field of BC hearing, the importance of the contributors for BC sound is not clarified and there is no consensus on the issues. However, the literature suggests that the inner ear fluid inertia is the most important mechanism for speech frequencies. But several other contributors are generally within 10 dB of the most important one.

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