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Abstract

Bone conduction (BC) is the way sound energy is transmitted by the skull bones to the cochlea causing a sound perception. Even if the BC sound transmission involve several pathways including sound pressure induced in the ear-canal, inertial forces acting on the middle-ear ossicles and cochlear fluids, alteration of the cochlear space, and pressure transmission through the 3rd window of the cochlea, the BC sound ultimately produces a wave motion on the basilar membrane similar to that of air conducted sound. The efficiency of the BC stimulation is largely dependent on the skull bone where the skull acts as a rigid body at low frequencies and incorporates different types of wave transmission at higher frequencies. The interaural stimulation difference is determined by the difference between contralateral and ipsilateral BC sound transmission: the transcranial BC sound transmission. To benefit from binaural processing the transcranial transmission should be low while the same should be high when using BC hearing aids for unilateral deaf subjects. By appropriate positioning of the stimulation, high or low transcranial transmission can be achieved.

Introduction

The conventional way of auditory stimulation is by an airborne sound that is transmitted through the ear-canal, where it induces mechanical vibrations in the eardrum that is transmitted via the middle-ear ossicles and becomes a sound pressure in the cochlea (scala vestibuli). This sound pressure acts on the basilar membrane producing a traveling wave that excites the sensory cells in the organ of Corti causing an auditory sensation. Bone conduction hearing is when the sound is transmitted through the skull bone, cartilage, skin and soft tissue, and fluids in the body ultimately resulting in a sound pressure in the cochlear scalae. This type of sound transmission is sometimes divided between body conduction and bone conduction, where the latter is only sounds transmitted in the skull bone. Here, for simplicity, both body and bone conduction will be referred to as bone conduction and abbreviated BC.

Clinical measurements using bone conduction

Understanding the processes of BC sound was early driven by its use for differential diagnosis between conductive and sensorineural hearing loss. In the 19th century, the usage of the tuning fork provided tests as Weber test and Rinne test [1]. After the introduction of the audiometer and the BC transducer (e.g. Radioear B71) during the 20th century, most diagnosis of conductive hearing losses is by comparison of air conduction (AC) and BC hearing thresholds (termed the air-bone gap). Although BC hearing thresholds are affected by an outer or middle-ear lesion, the alteration is small compared to the change in AC thresholds and the air-bone gap is often used to quantify the conductive loss.

It is sometimes desirable to use BC stimulation with other types of auditory measures such as speech recognition, otoacoustic emissions, or electro-physiology based tests such as brainstem response audiometry [2-4]. Even if it is possible, the results are most often not directly comparable with those obtained using AC stimulation. This difference is mostly related to the difference in frequency response between earphones and the BC transducer, differences in hearing thresholds (sound pressure for AC stimulation and force for BC stimulation) and the general poorer dynamic range of a BC transducer (greater amount of non-linear distortion). Moreover, testing setups for AC may be incompatible with BC excitation. An example of the latter is otoacoustic emissions [3], where normally the emissions are measured by a high-quality low-noise microphone tightly fitted in the ear-canal giving a considerable occlusion effect thereby affecting the result at frequencies below 2 kHz (see later section)[5].

The most commonly used BC transducer for audiometry is the Radioear B71 which has well known characteristics and is used in the international standard for hearing thresholds [6]. The drawback of this device is poor dynamic and frequency range: the great amount of non-linear distortion and housing resonances limits its practical use to the frequency range 0.25 to 4 kHz and levels below 60-70 dB HL. These limitations have often been addressed and recently another BC transducer was proposed enabling high frequency BC testing [7]. Other designs of BC transducers providing greater dynamic range [8] and measurement of the transducer-skull interface [9] have also been suggested to improve BC audiometry.

Basilar membrane stimulation

One important issue related to perception of BC sound is the sensory input to the neural system. Since BC vibration causes motion of the whole skull and, most probably, also other parts of the human body, the vibration perception is not necessarily only auditory. At lower frequencies and at higher stimulation levels, BC sound causes vibro-tactile excitation and the perception is multimodal [10]. Moreover, BC vibration stimulation can excite the vestibular system, which is especially noticeable in large-vestibular aqueduct syndrome and semi-circular canal dehiscence [11]. In a study on loudness growth comparing AC and BC sound it was shown that the loudness of BC sound increased more compared with loudness of AC sound, especially at the low frequencies [12]. This may be explained by multimodal excitation when stimulation is by BC resulting in a greater growth of loudness compared to AC sound for equal increase in sound intensity.

It is well established that BC sound perception is primarily caused by basilar membrane vibration. Firstly, BC pure tones can be cancelled by AC tones [13-15] indicating that the two ways of stimulation excites the same sensory cells for auditory perception. Secondly, direct measurement of basilar membrane motion show similar excitation pattern independent if stimulation is by AC or BC [16]. Thirdly, electro-physiology measures such as brainstem audiometry gives similar results for AC and BC stimulation when differences in stimulation spectrum is corrected for [17] and, fourthly, distortion-product otoacoustic emissions can be generated by one AC and on BC tone [3]. Even if a BC sound influences the whole cochlea and not only at a local point as AC sound, the inherent response of the basilar membrane is always a wave motion beginning at the base traveling towards the apex [18]. Therefore, the assumed important parameter for BC induced wave motion on the basilar membrane is the pressure difference between scala vestibuli and scala tympani.

Pathways for bone conducted sound

Since it became generally accepted that humans can perceive BC sound, theories of how a BC vibration in the skull bone become a basilar membrane vibration have been presented. Early theories identified one or two pathways that resulted in BC sound. Today it is generally accepted that BC sound transmission involve multiple pathways and there is no obvious way to distinguish between them. One often used categorization is the anatomical division where BC sound affecting the outer, middle, and inner-ear is referred to as the outer-ear component, the middle-ear component, and the inner-ear component, respectively [19]. However, this categorization does not divide between different physical processes that are involved in the transformation from a skull bone vibration to a pressure difference between scala vestibuli and scala tympani and subsequent basilar membrane wave motion. Tonndorf, who investigated different mechanisms contributing to BC sound perception in the cat, identified seven components believed to be important for BC sound [20]. In a previous paper, five components were presented as the most important for BC sound perception in the normal and impaired ear [21]. Below is a short summary of these five components (Fig 1).

Sound pressure in the ear-canal and the occlusion effect

When the skull is excited with BC sound, the ear-canal will deform due to the vibrations and airborne sound is produced in the ear-canal. This sound is transmitted to the eardrum and further transmitted through the middle-ear ossicles and produces a sound pressure in the scala vestibuli causing a basilar membrane traveling wave. Consequently, this BC sound pathway is similar to an AC sound transmission and should be considered as a skull vibration produced AC sound. This means that this pathway is affected by the status of the outer and middle-ear and the transmission is altered by it. For the normal open ear, the contribution of the ear-canal pathway of BC sound is some 10 dB below other contributors at frequencies below 2 kHz and less important at higher frequencies [22]. The outermost part of the ear-canal comprises cartilage and soft tissue and is referred to as the cartilage part of the ear-canal while the innermost part is surrounded by skull bone known as the bony ear-canal. If the BC transducer is positioned close to the ear-canal, for example on the mastoid, the soft tissue is efficient in transmitting the sound to the ear-canal at low frequencies while the bony part is the primary source for the BC induced ear-canal sound pressure at higher frequencies [22].

The outer-ear pathway of BC sound can be dominating at lower frequencies if the open part of the ear-canal is closed, often termed the occlusion effect. The effect of occluding the ear-canal depend on the type and position of the occluding device, but can give up to 40 dB increased sensitivity to BC sound at low frequencies [5]. The origin of the occlusion effect is the change in radiation impedance at the ear-canal opening. With the ear-canal open and at low frequencies, the radiation impedance is low and a large part of the sound energy induced in the ear-canal by the BC skull vibration leaks out of the ear-canal. However, if the canal is occluded, the sound energy is trapped and transmitted to the eardrum. This phenomenon was described by Tonndorf [20] and later modeled in [5]. As predicted by Békésy [23], the model showed that if the occlusion is deep enough, the occlusion effect is insignificant [5]. Also, if circumaural devices are used, the enclosed volume is primarily determining the occlusion effect where greater volume results in less occlusion effect. It should be noted that the occlusion effect measured as change of ear-canal sound pressure is usually 5-10 dB greater than the occlusion effect as measured by alteration of BC hearing thresholds at frequencies below 1 – 2 kHz [5].

Inertia of the middle-ear ossicles

From a mechanical point of view, the middle-ear ossicles are suspended in the middle-ear space by the eardrum, ligaments, and tendons. Most important for BC sound is the eardrum and the annular ligament positioning the stapes footplate in the oval window: these two acts as mechanical springs attached to the free masses (ossicles). When the skull bone surrounding the middle ear cavity vibrates due to BC excitation, the spring-effect causes the ossicles to vibrate in-phase with the skull at low frequencies. At higher frequencies the ossicles become vibrationally decoupled from the surrounding bone resulting in a relative motion between the stapes footplate and the otic capsule. This behavior was experimentally verified in [24] where the ossicles vibrated with the surrounding bone at low frequencies and showed large relative motion above the middle-ear ossicle resonance frequency of 1.5 kHz. This finding was later verified in [25] showing that the difference in middle-ear ossicle resonance frequency between BC and AC (e.g.[26]) sound was caused by differences in vibration modes of the ossicles.

It has been speculated that the middle-ear ossicle inertia is important for BC sound perception at frequencies around the resonance frequency and below, i.e. approximately 2 kHz and below. Supporting this theory is, for example, the worsening in BC thresholds around 2 kHz following immobilization of the ossicles due to otosclerosis of the stapes (also known as the Carhart's notch) [27] and incresead BC sensitivity below 2 kHz with artificial mass-loading of the ossicles (lowering the resonance frequency) [28]. When comparing ossicle vibration at hearing threshold with AC and BC stimulation, it was found that the ossicle inertia can be important for BC perception in the normal ear at and slightly above the resonance frequency (2-3 kHz)[29].

Inertia of cochlear fluids and fluid pressure transmission

The fluid in the cochlea is also subject to inertial forces when the bone surrounding the cochlea vibrates. The result of these forces is a pressure gradient across the basilar membrane that would form a traveling wave. Since the fluid can be considered incompressible, a fluid flow in the cochlea would require compliant inlet and outlet of the fluid on both sides of the basilar membrane. The two obvious examples are the oval window on the scala vestibuli side and the round window on the scala tympani side. However, there are several other structures that can act as compliant pathways of the cochlea. These structures are collectively known as the third window [30]. This means that, as long as there is a pressure gradient over the basilar membrane, there will also be fluid flow acting on the basilar membrane initiating a traveling wave.

The pathways other than the oval and round windows that enable pressure and fluid transmission to and from the cochlea include the vestibular and cochlear aqueducts, nerve fibers, veins, and micro-channels entering the cochlea [31]. It has for example been noticed that an improved fluid connection between the vestibular space and the cranial space, known as a semi-circular canal dehiscence, improves the low-frequency BC sensitivity [11]. Similar results are found when the dehiscence is made artificially into the middle-ear space [32]. The concept of the third window offers two different interpretations of BC stimulation pathways. One is the inertial effects of the cochlear fluid resulting in a fluid displacement mentioned above. The other interpretation is sound pressure transmission from the cranial space to the cochlea [33]. It has been shown that static pressure can be transmitted from the cranial space to the cochlea [34]; the same is also possible for dynamic pressure [33]. This type of transmission has primarily been attributed to a patent cochlear aqueduct but the vestibular aqueduct and other channels may well enable such mechanism. Although the sound pressure transmission from the skull interior to the cochlea has been suggested as an important BC contributor, clinical results as transcranial transmission and pathological findings in semicircular canal dehiscence and large vestibular aqueduct syndrome suggest that this contributor to BC sound perception is not the most important one.

It has been estimated that only a small fraction of the fluid of the cochlea (less than one-millionth) is necessary to be displaced to give a hearing sensation of 80 to 100 dB HL [21]. This indicates that the fluid inertia would be an efficient way to excite the cochlea. Moreover, in cases of immobilization of the stapes, e.g. otosclerosis of the stapes, the AC hearing thresholds deteriorate significantly while the BC thresholds are only slightly affected in the 2 kHz range. Since transmission through the middle ear is severely reduced in such case, the BC sound is transmitted directly to the cochlea. Moreover, the skull is believed to constitute near rigid body motion (wavelength longer than the size of the skull) at lower frequencies, compression and expansion of the cochlear walls cannot explain the BC sound perception. Consequently, for lower frequencies, fluid inertia is likely the most important pathway for BC sound in the normal ear but probably less important at higher frequencies.

Alteration of the cochlear space

When a transversal wave propagates in the skull bone, the skull bone compresses and expands with the wave. This means that the structure deforms. When such wave affects the cochlea, the deformations alter the cochlear space, causing a fluid motion that gives a sound pressure. This pathway was termed inner-ear compression by Békésy [19] and distortional component by Tonndorf [20] and has often been central when explaining BC sound perception. The theory for the compressional response is that the cochlea is unsymmetrical regarding scala tympani and scala vestibuli: scala vestibuli space is about 50% greater than scala tympani and the impedance of the oval window is greater (stiffer) than the impedance of the round window (more compliant) [20]. Consequently, when the cochlea is compressed, excess fluid is forced from the scala vestibuli side to the scala tympani side and the round window. The opposite happens when the cochlea expands, i.e. fluid flows from scala tympani towards scala vestibuli thereby exciting the basilar membrane.

The cochlea is coiled and its dimension can be thought of like a sphere with approximately 10 mm diameter. If the limit for effective compression response is set to a wavelength that is less than ten times the size of cochlea, the lowest frequency where the compressional response would be an effective excitation of the cochlea would be 4 kHz. This is in line with other estimations of its importance in the normal ear of the human [21].

BC sound transmission in the skull

The human cranial bone comprises dense cortical bone with fluid-filled spondaic bone in-between, loaded on one side with skin and subcutaneous tissue and fluid (cerebrospinal fluid) and brain tissue on the other. Also, the bone in the skull base, where the inner-ear is situated, differs from the cranial bone with thicker and denser bone structure. To complicate things even more, the skull is not a single bone structure but consists of several parts fused with sutures. Due to its complexity, modeling efforts have so far only provided limited insight to the BC sound transmission in the skull.

Most earlier experimental studies of BC sound transmission focused on the motion of the skull surface [19, 35, 36] while more recent studies have measured the response at the cochlea, either in all three space dimensions [37, 38] or in one dimension [39, 40]. Even if these studies provide insight to the vibration characteristics of the skull bone and differences in transmission efficiency between stimulation positions and the cochlea, it is not clear how to relate a vibration of the cochlea to a hearing sensation. However, the hypothesis is that, in relative terms, a greater vibration response of the cochlea at a specific frequency leads to a greater BC sound perception. It was shown in the Stenfelt and Goode study [38] that with BC stimulation at the skull surface, the cochlea vibrates in all space dimensions without any dominant direction.

In normal BC hearing testing, the BC transducer is placed on the compressed skin that transmits the BC vibration to the skull bone. The effect of the skin, in terms of dynamic force transmission, is small at low frequencies but will attenuate the BC sound at frequencies above approximately 2 kHz [41]. Moreover, the transmission through the skin improves with the area of the skin-transducer interface and static pressure between transducer and skull [14]. If the vibration transducer is coupled directly to the skull bone, as with the Bone Anchored Hearing Aid [42] coupling system, the attenuation caused by the skin is avoided. For hearing testing, the attenuation of BC sound through the skin can often be overcome by an increase of the output from the audiometer. For BC hearing aids, where the output is limited, the skin-attenuation is of greater importance. Since the attenuation depend on both the BC hearing aid design and the skin and skull impedance, a specific number for this skin attenuation cannot be given. But, a general 5 to 15 dB of sensitivity improvement at frequencies above 1 kHz can be expected when the BC transducer is attached directly to the skull (as with the Bone Anchored Hearing Aid) instead of the compressed skin.

A general finding is that the closer the stimulation position is to the cochlea, the greater the BC sound stimulation of the cochlea. This is frequency dependent and the greatest improvement is seen at the highest frequencies [38, 40]. In a study investigating the squamosal suture's influence on BC sound transmission, an average attenuation of about 2 dB was found for frequencies above 2 kHz [40]. However, it could not be concluded if the attenuation was a pure effect of the suture, of moving the stimulation position closer to the cochlea, or a combination of both.

The vibration modes of the skull have been reported in several studies (e.g.[19, 38]) and for the frequency range 0.1 to 10 kHz four different types of vibration modes appears (Fig 2). At the very low frequencies, below the resonance frequency of the skull mechanical point impedance (150 to 400 Hz), the skull behavior can be approximated with rigid body motion (Fig 2a) [38]. Above this region and up to about 1 kHz, where the first global skull resonance appear [35], the skull vibration can be described as a mass-spring system where large parts of the skull move in-phase (e.g. the petrous part of the temporal bone hosting the cochlea, Fig 2b). Above 1 kHz, wave transmission appears in the cranial bone and between 1 and 2 kHz, the skull transitions from a mass-spring like behavior to be dominated by wave transmission. The wave transmission types differ between the cranial vault and the skull base (Fig 2c) where the wave speed in the skull base seems constant at approximately 400 m/s while the wave speed in the cranial vault is frequency dependent with around 250 m/s at 2 kHz increasing to 300 m/s at 10 kHz [38].

Transcranial transmission

The BC stimulation at one mastoid is transmitted to both cochleae and for testing BC thresholds the non-test ear requires masking to ensure the response from the test ear. For simplicity, in audiometry the BC sound transmission to the contralateral cochlea is often assumed equal to that of the ipsilateral cochlea (transcranial transmission equals 0 dB). However, there can, at certain frequencies, be substantial interaural differences of up to 40 dB where the sound is either greatest at the ipsilateral or the contralateral cochlea [43]. When BC sound transmission is estimated from vibration measurements at the cochlea, the transcranial transmission is close to 0 dB for frequencies up to 1 kHz, where it starts to decrease and becomes -15 to -20 dB at 10 kHz [38, 39].

We measured the transcranial transmission in 30 unilateral deaf subjects using both the normal mastoid stimulation position for BC audiometry and the typical BAHA implant position some 55 mm behind the ear canal opening in the parietal bone. Bone conducted hearing thresholds were obtained at 31 1/6th octave frequencies between 250 Hz and 8 kHz. From these data it could be concluded that there is a general trend of greater interaural differences at the higher frequencies (Fig 3). However, the individual spread was great and no general trends in the specific configuration of the transcranial transmission were found. It was also seen that a normal audiometric positioning of the BC transducers gave greater interaural differences than a positioning at the usual BAHA implant site. According to Eeg-Olofsson et al, the transcranial transmission is almost independent of position of the contralateral stimulation transducer [39]. When transcranial transmission (or the opposite, transcranial attenuation) is measured as the difference in sensitivity between a contralateral and ipsilateral stimulation at symmetrical positions, it is the ipsilateral transmission that dominates the interaural difference.

From the perspective of BC hearing aids, a low transcranial transmission (i.e. the stimulation of the ipsilateral cochlea is substantially greater than the contralateral cochlea) is beneficial when bilateral application is used since more binaural information can be extracted from the two stimulation positions (less cross-over transmission, see below). However, from the perspective of using BC hearing aids for unilateral deaf subjects, a high transcranial transmission is beneficial as more BC sound energy is transmitted from the deaf side to the healthy cochlea.

Binaural bone conduction hearing

Binaural auditory processing are functions that are superior by the use of two ears rather than one including the ability to localize sound sources in three dimensions and identify speech in a noisy environment. The general understanding is that the human uses interaural temporal differences at frequencies below 1 kHz and interaural level differences at the higher frequencies for efficient binaural processing. Both the temporal and level differences can be negatively affected by the BC transcranial transmission reducing the information separation between the cochleae. The low temporal differences between the cochleae at low frequencies with BC sound shown in Stenfelt and Goode [38] impedes the low-frequency binaural processing. At the high frequencies the transcranial transmission may limit the level separation normally given by the head-shadow; this could also impede binaural processing. So how efficient is bilateral application of BC sound in terms of binaural hearing, for example with BC hearing aids?

It should be noted that the following discussion is limited to two rather similarly functioning cochleae; binaural auditory processing is not possible for unilateral profound deaf subjects. The research into BC binaural hearing is sparse and has mainly been directed to binaural benefit in patients with bilateral fitted BAHAs [44, 45]. Those studies have shown that there are benefits in terms of better spatial perception (sound localization) and release of masking for bilateral BAHA users compared with monaural application. Also, studies in normal hearing subjects have indicated similar results: there are binaural benefit with bilateral BC stimulation but the binaural processing is not as good as when then the stimulation is purely by AC [46, 47]. One way to quantify the binaural processing ability with BC stimulation have been to measure binaural masking level differences (BMLD) using low-frequency sinusoids in narrow band masking noise [44, 45]. Beside the binaural masking release the stationary sinusoids from the two sources adds constructively or destructively depending on the signals' phases, and the results are influenced by the summation of two signals as well as of binaural effects: these cannot be separated [39]. Consequently, the BMLD-test using stationary sinusoids are not suited for testing of binaural processing with BC stimulation.

Own voice

Most people are familiar with the influence from BC on their own voice: when listening to a recording of one's own voice, people are often struck by the difference between the recording and the way they normally perceive their own voice. The difference is that while the recording only picks up the airborne sound, we hear ourselves through both AC and BC sound (see Fig 1). The importance of the two pathways of our own voice, AC and BC, have been estimated by Békésy [48] to be approximately equal; it was later estimated that the AC component is most important at low and high frequencies while the BC component dominated the own voice between 0.7 to 1.2 kHz [49]. A recent thorough investigation showed large differences in the AC and BC components for 10 speech sounds [50]. It was concluded that the differences originated in the sound production itself, sounds that are produced similarly and belong to the same speech sound groups, had similar relation between AC and BC contribution of one's own voice. Even if later studies confirmed Békésy's result of approximately equal proportion of AC and BC sound for own voice perception, they also showed frequency dependency between the pathways as a function of the sound produced [49, 50].

It has been argued, for example by Bárány [51], that own-made sounds such as vocalization, chewing, etc, are less in animals with three middle-ear ossicles than in animals with only one bone. Due to the three-bone structure, the effective mass, and consequently the inertial force, are less than in a single bone structure. As a result, the influence from the middle-ear ossicles inertia is lower. Also, the stapedius muscle is elicited during vocalization [52]. Such contraction affects the low-frequency sound transmission through the middle-ear. It would also impede inertial force effects on the middle-ear ossicles. However, to what extent the stapedius muscle contraction affects the perception of BC sound and the own voice is currently not clear.

BC in relation to hearing protection

People who are exposed to high level sounds should protect the ears with hearing protection devices. In the extreme environments the noise can exceed 150 dB SPL and conventional hearing protection devices are no longer sufficient. Even if earplugs and earmuffs attenuate the AC pathway of sound to the cochlea, sound is reaching the cochlea by BC transmission. The head and body in a sound field is affected by the sound field and BC sound is induced and transmitted to the cochlea. This sound field induced BC sound limits the possible attenuation by conventional earmuffs and earplugs. According to Reinfeldt et al, the BC transmission is 50 – 60 dB below the AC sensitivity at frequencies below 1 kHz, 40 – 50 dB at 2 kHz and 50 – 60 dB below the AC sensitivity at the higher frequencies [53]. Consequently, to achieve more than 60 dB attenuation the BC sound transmission needs to be attenuated as well. This can be accomplished by helmets or body covers.

Implications for BC hearing aid usage

Recent understanding of BC sound and sound transmission in the skull have indicated that the gain in sensitivity by stimulating close to the cochlea can overcome drawbacks of transcutaneous signal transmission for implantable BC hearing aids [54]. Also, for bilateral application of BC sound a position close to the cochlea result in greater interaural separation and would be beneficial for binaural processing abilities [38, 39]. However, when BC hearing aids are used with patients suffering from unilateral deafness, a positioning close to the cochlea does not improve the transcranial transmission, but does not decrease it either. It should be noted here that bilateral application of BC hearing aids does not only enable (reduced) binaural hearing, it also gives hearing from the non-hearing side (in a monaural fitting) and thereby removes the head-shadow effect; the primary reason for giving a BC hearing aid in unilateral deafness [55]. Consequently, giving a 2nd BC hearing aid to a bilateral conductive impaired patient provides greater benefit than giving a BC hearing aid to a unilateral deaf patient since no binaural processing is possible for the latter.

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Figure Legends

Fig 1: A model of the 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.

Fig 2: Illustration of the vibration modes of the human skull for frequencies between 0.1 and 10 kHz. For simplicity, the vibrations are shown as one-dimensional motions while the real human skull show vibration responses in all space dimensions. 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 mass-spring system response at frequencies between approximately 0.3 to 1.0 kHz is shown in (b) where thee sections of the skull moves 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.

Fig 3: Transcranial transmission of BC sound measured as the ipsilateral sensitivity related to the contralateral sensitivity when stimulation is on the mastoid (normal BC audiometry position). A positive number indicate better transmission from the contralateral side. The dots indicate individual results (a larger dot indicates several individuals with equal result). The thick solid line (in the middle) is the median of all subjects and the thinner solid lines are the median plus or minus one standard deviation.

Figures

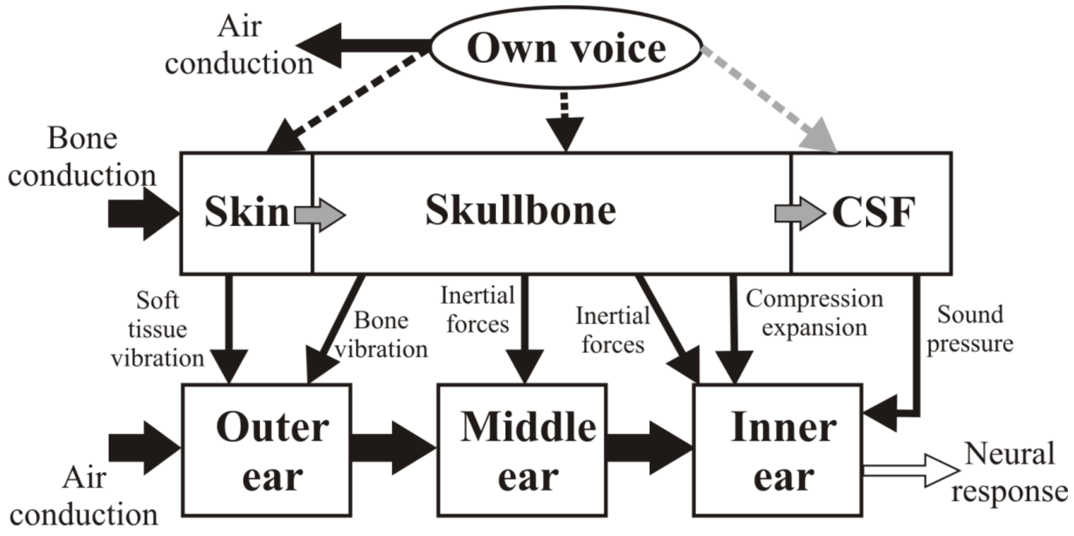


Figure 1

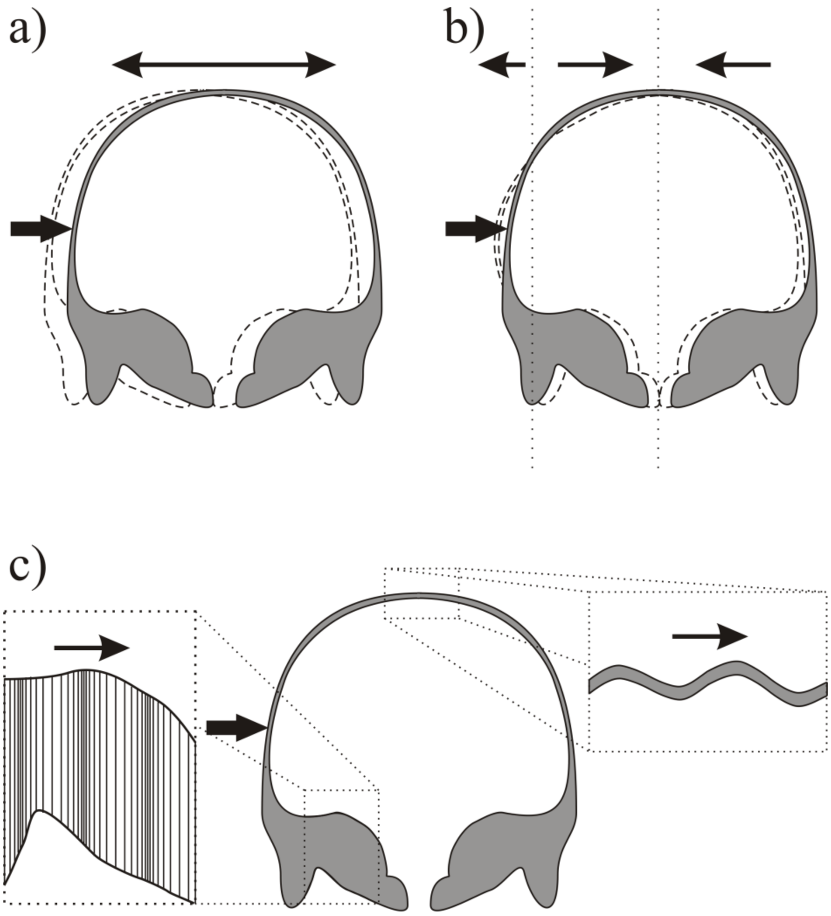
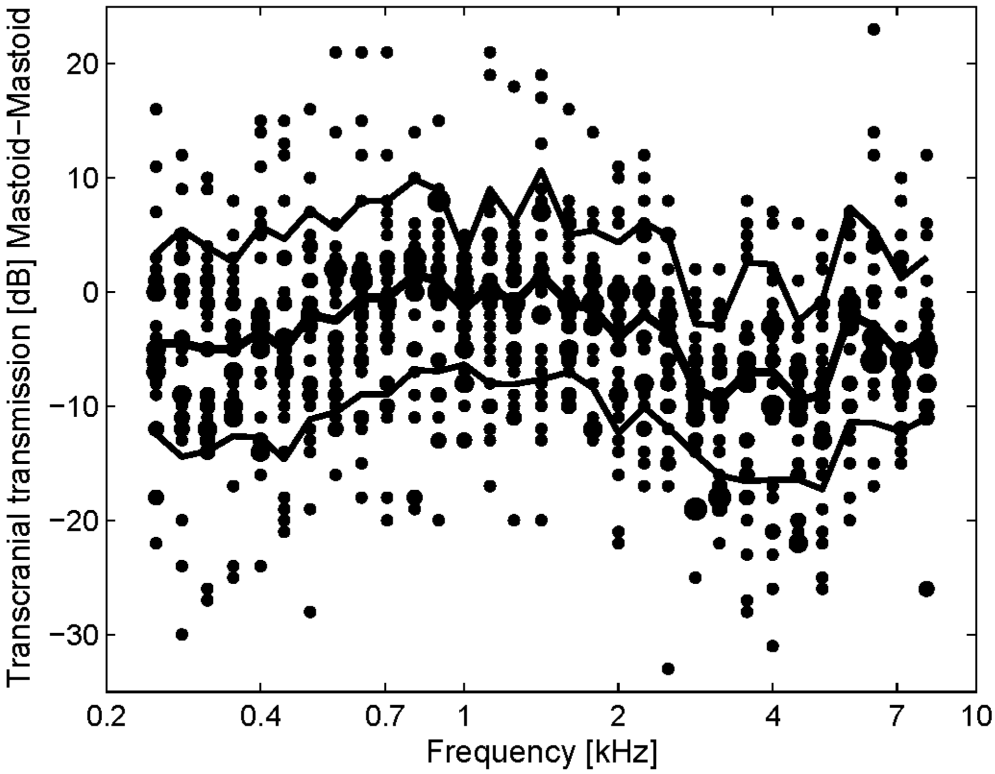


Figure 2



Transcranial transmission [dB] Mastoid−Mastoid
20
10
0
−10
−20
−30
0.2
0.4
0.7
1
2
4
7
10
Frequency [kHz]

Figure 3