

OVERVIEW AND RECENT ADVANCES IN BONE CONDUCTION PHYSIOLOGY

Stefan Stenfelt, Department of Neuroscience and Locomotion,
Division of Technical Audiology, Linköping University, Linköping, Sweden
Email: stefan.stenfelt@inr.liu.se

.....

During the mid 18th century it was found that sound could be transmitted through solids and in the 19th century it was generally accepted that a person can perceive sound by bone conduction (BC). Since then, the research community has tried to understand its fundamental mechanisms. This report provides an overview of the present state in BC physiology. Five factors contributing to BC hearing are identified: 1) sound radiated into the ear canal, 2) middle ear ossicle inertia, 3) inertia of the cochlear fluids, 4) alteration of the cochlear space, and 5) pressure transmission from the cerebrospinal fluid. Of these, inertia of the cochlear fluid seems most important. The vibration modes in the skull can be divided into three frequency ranges. At the lowest frequencies, approximately below 400 Hz, the skull moves as a whole with rigid body motion. At higher frequencies, up to 1 kHz, the skull motion can be modelled as a mass-spring system whereas at frequencies above 1 kHz, wave propagation dominates the skull vibration response. The wave propagation differs between the thin-boned cranial vault and the thick and dense bone of the skull base. Both vibration measurement of the cochlea and ear canal sound pressure can estimate BC perception changes caused by stimulation alterations for frequencies above 0.8 kHz; below 0.8 kHz measured hearing thresholds differ from skull vibration and ear canal sound pressure data.

1

1. Introduction

Bone conduction (BC) as a means for hearing stimulation has been used for nearly two centuries to distinguish between a sensorineural and a conductive hearing impairment. Although extensive research is reported in the literature, the interpretations are largely dependent on the knowledge of the normal hearing function. And as the knowledge increases in the field of hearing function and in areas as general acoustics and sound transmission in solids, the knowledge in the field of BC physiology increases as well. This report gives an overview of the present state in BC physiology.

Through history, different species of research animals (cats, guinea pigs, etc) as well as human specimens and live subjects have been used for the BC research. There is a potential problem comparing animal BC results with human BC results; one should be careful drawing general conclusions from animal data to the human. For example, animal skulls differ in geometry and composition from the human skull. This results in different vibration modes of the skull that can stimulate the inner ear differently. Further, in the human, the cochleae are positioned in the skull base surrounded by hard dense bone structure, whereas some animals have cochleae protruding out into the air-filled bulla.

One of the fundamental questions of BC sound was whether it was a cochlear stimulation or a stimulation of some other end organ. Another question was whether the BC transmission was linear or not. Several researchers have addressed these questions by cancelling one air conducted (AC) tone with one BC tone [1–3]. These studies are somewhat limited since they only use one single frequency and consequently only produce local basilar membrane stimulation. The concept of canceling a single AC tone with a BC tone was extended to include two tones; one of 0.7 and one of 1.1 kHz that was subjectively cancelled one at the time, simultaneously, and while a disturbing tone was present. These tests were conducted at three stimulation levels: 40, 50, and 60 dB HL. By comparing amplitude and phase settings for three test subjects at cancellation it was found that the deviations from a true linear response was less than 0.7 dB and 8 degrees at any of the test situations or levels used. The conclusion from these tests, together with previous reported cancellation tests, is that BC sound transmission is linear and a cochlear stimulation at frequencies and levels used for normal hearing.

2. Five contributing factors

Some researchers have identified one single main contributor for perceived BC sound [4,5] while others have reported it to be composed of several different contributors [6]. Here, five components are presented as contributing to BC hearing.

2.1 Part I. Outer ear

When the skull is vibrated by BC stimulation, sound is radiated into the ear canal that is subsequently transmitted to the cochlea by the ear drum and middle ear ossicles. With the BC stimulation applied at the mastoid and with the ear canal open, the outer ear part of the BC sound is 5 to 20 dB below other contributing parts and is not considered as a major contributing

part to BC sound [7]. This may change when the stimulation is at another position, e.g. when the stimulation is at the forehead, the outer ear seems to contribute more at frequencies below 1 kHz.

When the ear canal is closed (e.g. by a finger or an ear plug) the BC sound in the ear canal is enhanced at the low frequencies; this is termed the occlusion effect. The exact frequency range and amount of elevation caused by the occlusion depends on the type and location of the occlusion device. However, the occlusion effect is determined by the acoustics of the ear canal and the resulting ear canal sound pressure alteration caused by the occlusion device can be estimated with good accuracy if the position and type of device is known. An estimate of the occlusion effect with ear plugs at two different depths and with one ear muff is shown in Fig 1.

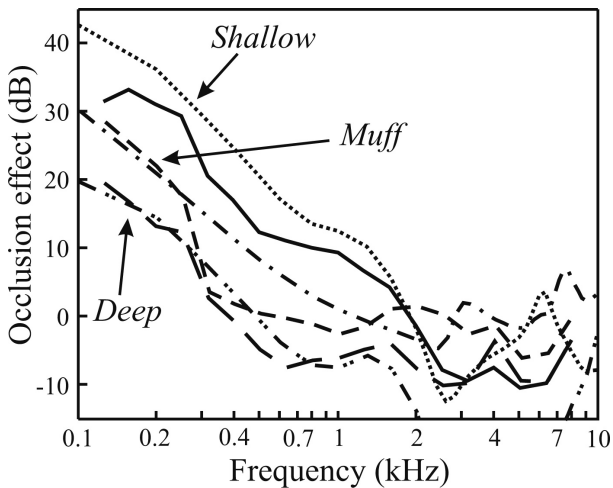


Fig. 1 The graph presents the measured ear canal sound pressure occlusion effect together with model prediction for ear plugs shallow and deeply inserted and with an ear muff of about 30 cm³. Solid line: measured shallow inserted ear plug, dotted line: model estimated ditto, long-dashed line: measured deeply inserted earplug, dash-double dotted line: model estimated ditto, dashed line: measured ear muff, dash-dotted line: model estimated ditto.

3

2.2 Part II. Middle ear ossicle inertia

The three middle ear ossicles are suspended by several ligaments, the TM and two muscle tendons. This becomes a mechanical mass-spring system that, due to inertial forces on the masses, constitutes different vibration than the surrounding bone during BC stimulation. This difference motion between the stapedius footplate and the cochlear promontory provides a stimulation input to the cochlea [8]. The importance of the ossicle inertia

component can be estimated by comparing the stapes footplate motion at threshold stimulation by AC and BC; this was done in [9] and some of those results are presented in Fig 2.

Ossicle motion at thresholds, BC re AC stimulation

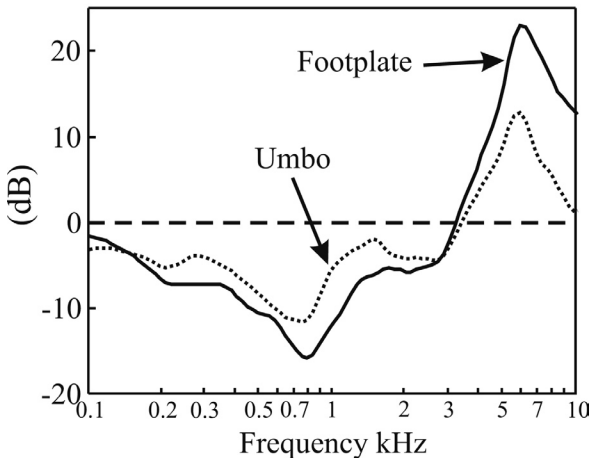


Fig. 2 Stapes footplate (solid line) and malleus umbo (dotted line) motion at BC threshold stimulation compared with the motion at AC threshold stimulation.

The vibration of the umbo and footplate at threshold vibration is 5 to 15 dB lower with BC stimulation compared with AC stimulation at frequencies between 0.2 and 1.5 kHz. This result indicates that middle ear inertia is not an important contribution to BC perception at these frequencies. At frequencies above 4 kHz, the comparison is not valid since the stimulation is probably no longer through the oval window. However, the similarity between the ossicle threshold motion between 1.5 and 3.5 kHz indicates that the inertial effects of the ossicles can contribute to BC sound perception within this frequency range. Also, lesions and manipulations of the ossicles provides results indicative of possible importance of ossicle inertia at the mid-frequency range [10].

2.3 Part III. Inertia of the cochlear fluids

As with the middle ear ossicles, inertial effects cause a relative motion between the cochlear fluids and the cochlear promontory bone. This type of motion relies on several compliant fluid in and outlets in the cochlea: the oval and round windows are two such fluid pathways, and others that can be of importance are the cochlear and vestibular aqueducts, nerve fibers,

veins, and microchannels entering the cochlea. Since many BC threshold alterations with middle ear lesions corroborate the theory of fluid inertia it is believed to be the most important BC contributor for frequencies below 4 kHz [10].

2.4 Part IV. Alteration of the cochlear space

One of the first theories presented for BC perception was alteration of the cochlear space, often termed compression response. Since the cochlear fluids can be considered incompressible, any alteration of the cochlear space would force fluid to move and most probably cause a stimulation of the basilar membrane. First, alteration of the cochlear space requires wave propagation in the skull bone which begins at around 1 kHz [11]. Second, according to the theory a compression response would benefit from reduced fluid flow at the oval window (otosclerosis), and would be reduced by an opening at the vestibular side (fenestration operation or semicircular canal dehiscence). This is opposite to clinical findings for frequencies below 4 kHz. Compression may well be important at higher frequencies.

2.5 Part V. Pressure transmission from the CSF

A recent identified contributor to perception of BC sound is pressure set up in the cerebrospinal fluid surrounding the brain that is transmitted to the cochlea producing a traveling wave on the basilar membrane [12]. Although this mode does provide cochlear stimulation, it fails to explain several experimental findings, including BC threshold losses with certain lesions of the middle ear ossicles, lateralization of a BC tone, and transcranial attenuation. It is therefore unlikely that this contribution is significant for BC perception in the hearing frequency range.

3. BC transmission and skull vibration

When a BC stimulation is applied to the skull, the resulting skull motion depends on the position, direction, and frequency of the stimulation. The frequency response of the skull can roughly be divided into three response modes: (1) pure rigid body motion, (2) mechanical mass-spring system, and (3) wave propagation. The pure rigid body motion is at the lowest frequencies (up to 250 to 400 Hz). At these low frequencies the skull motion is solely determined by its geometry together with three translational and three rotational components. This vibration mode can be identified by investigation of the mechanical point impedance; it is the frequency range below the first impedance resonance where the impedance shows a mass-like behavior.

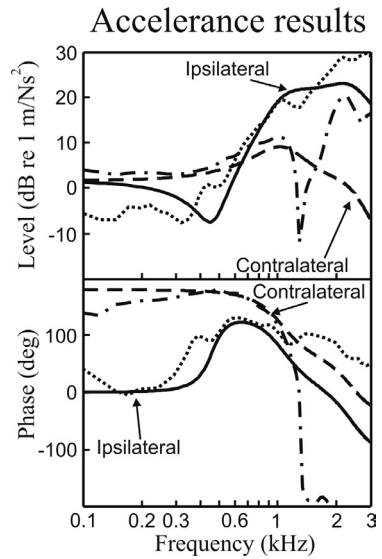
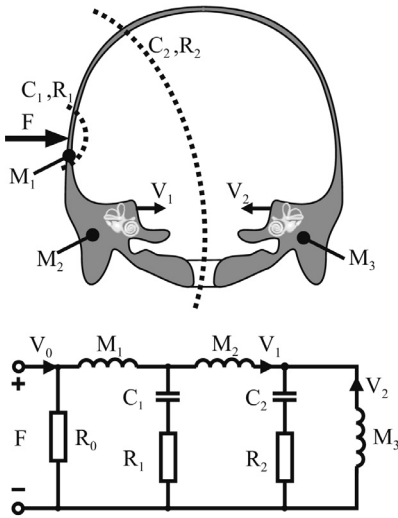


Fig. 3 The left part shows the anatomical structure and related lumped element model for estimation of the cochlear vibration during mastoid stimulation. The right part presents the level and phase of the accelerance transmission between the mastoid and cochlea. Solid line: modelled accelerance of the ipsilateral cochlea, dashed line: measured ditto, dotted line: modelled accelerance of the contralateral cochlea, dash-dotted line: measured ditto.

The next response mode, where the skull behaves as a mass-spring system, is at frequencies below the first skull resonance, which is approximately at 1 kHz [11]. In this frequency range, the motion of the skull can be approximated by three masses with springs in-between (see Fig 3). At higher frequencies, above the first skull resonance, the BC sound is transmitted by wave propagation. This wave propagation depends on type and size of the bone. At the cranial vault, where the skull bone is thin, the wave transmission is a mixture of bending, longitudinal, and transverse wave propagation. These waves are dispersive and the phase velocity increases from just above 200 m/s at 2 kHz to between 300 and 350 m/s at 10 kHz. In the skull base, where the cochleae are positioned, the bone is thicker and denser and the wave transmission is primarily by longitudinal wave propagation producing a constant wave speed of approximately 400 m/s. The different transmission modes and frequency ranges are depicted in Fig 4.

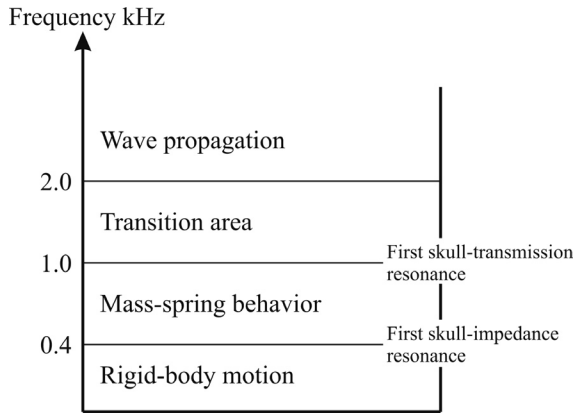


Fig. 4 Overview of the frequency ranges of the human heads' vibration modes.

The transcranial transmission, i.e. the sound transmitted from the mastoid to the contralateral cochlea compared with that transmitted to the ipsilateral cochlea was measured by three different methods; (1) mechanical vibration of the cochleae obtained in cadaver heads [11], (2) ear canal sound pressure, and (3) hearing thresholds obtained in live humans. The results are presented in Fig. 5 where the three methods show similar results at frequencies above 0.8 kHz; almost monotonically decreasing transmission of -2 dB at 0.8 kHz to -15 dB at 8 kHz. At lower frequencies, the vibration and ear canal sound pressure data are similar whereas the threshold data are almost 7 dB lower at 0.5 kHz. This indicates that both vibration and ear canal sound pressure can be used to estimate changes in BC perception at frequencies at and above 1 kHz.

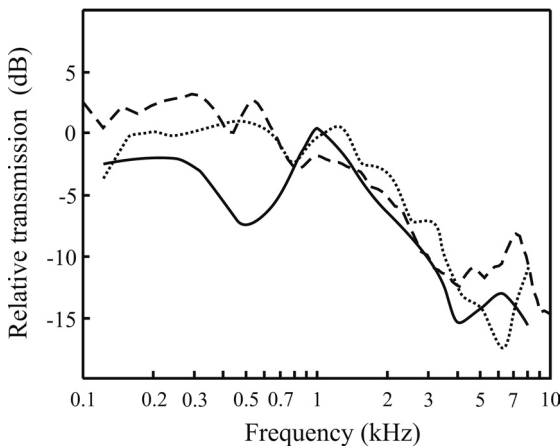


Fig. 5 The transcranial transmission with the stimulation at the mastoid estimated by three methods. Solid line: hearing thresholds, dotted line: ear canal sound pressure, dashed line: vibration of the cochlear promontory.

In another study, the ipsilateral vibration transmission was measured where the distance between the stimulation position and the ear canal opening increased by 10 mm for each new stimulation position. By comparing the decreased cochlear stimulation for each new stimulation position with the attenuation obtained when the stimulation position was moved over the sutura squamosa, the influence of the suture on BC transmission could be estimated. For frequencies below approximately 1.5 kHz, no significant difference was found while at frequencies above 1.5 kHz about 2 dB extra damping was caused by the suture. Hence, an extra high frequency loss of about 2 dB is found when the stimulation is behind this suture compared with in front of the same suture.

4. BC influence on hearing protectors

A hearing protection device (HPD) usually attenuates the sound field in (ear plugs) or just outside (ear muffs) the ear canal. In extremely noisy environments a combination of ear plugs and ear muffs can be used to obtain greater attenuation. The sound field is transmitted to the ear by three different routes: (1) the normal AC route, (2) by sound induced in the skull bone (BC), and (3) sound induced in the hard and soft tissues of the body that is transmitted to the cochlea by the skeleton and surrounding tissues (termed body conduction). For simplicity, the two latter are not separated but treated as a single entity termed BC.

8 The HPDs aims at reducing the AC transmission. However, due to the placement in or outside the ear canal, they cause an occlusion effect improving the BC sensitivity at low frequencies. The AC transmission from a sound field is 50 to 60 dB better than the BC transmission for frequencies up to 1 kHz, 40 to 50 dB greater around 2 kHz, improving to 50 to 60 dB at 4 kHz, to decrease again to 40 to 50 dB at 8 kHz. Hence, the maximal attenuation achievable with HPDs is 50 to 60 dB at low frequencies and 40 to 60 dB at higher frequencies; above these levels the BC transmission dominates and increasing the attenuation of the HPD does not increase the attenuation for the sound reaching the cochlea. However, due to the occlusion effect from the HPD, the achieved attenuation is often much lower than the theoretical limit. For example, at low frequencies an ear plug may produce up to 40 dB occlusion effect and with a theoretical limit for the BC sensitivity of 60 dB the resulting attenuation may be reduced to merely 20 dB.

References

1. von Békésy G., Zur Theorie des Hörens bei der Schallaufnahme durch Knochenleitung. *Ann Physik* **13** (1932) pp. 111–136
2. Wever E.G. and Lawrence M., *Physiological Acoustics* (Princeton University Press, Princeton 1954) pp. 240
3. Khanna S.M., Tonndorf J. and Queller J., Mechanical parameters of hearing by bone conduction. *J. Acoust. Soc. Am.* **60** (1976) pp. 139–154
4. Allen G. and Fernandez C., The mechanism of bone conduction. *Ann Otol. Rhinol. Laryngol.* **69** (1960) pp. 5–28
5. Brinkman W., Marres E. and Tolk J., The mechanism of bone conduction. *Acta Otolaryngol.* **59** (1965) pp. 109–115
6. Tonndorf J., Bone conduction: studies in experimental animals. *Acta Otolaryngol. Suppl.* **213** (1966) pp. 1–132
7. Stenfelt S., Wild T., Hato N. and Goode R.L., Factors contributing to bone conduction: the outer ear. *J. Acoust. Soc. Am.* **113** (2003) pp. 902–913
8. Stenfelt S., Hato N. and Goode R.L., Factors contributing to bone conduction: the middle ear. *J. Acoust. Soc. Am.* **111** (2002) pp. 947–959
9. Stenfelt S., Middle ear ossicles motion at hearing thresholds with air conduction and bone conduction stimulation. *J. Acoust. Soc. Am.* **119** (2006) pp. 2848–2858
10. Stenfelt S. and Goode R.L., Bone conducted sound: Physiological and clinical aspects. *Otol. Neurotol.* **26** (2005) pp. 1245–1261
11. Stenfelt S. and Goode R.L., Transmission properties of bone conducted sound: Measurements in cadaver heads. *J. Acoust. Soc. Am.* **118** (2005) pp. 2373–2391
12. Freeman S., Sichel J.Y. and Sohmer H., Bone conduction experiments in animals: evidence for a non-osseous mechanism. *Hear. Res.* **146** (2000) pp. 72–80