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REVIEW

Bone conduction: An explanation for this phenomenon comprising complex mechanisms

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Summary Bone conduction hearing inevitably involves vibration of the basilar membrane in response to a pressure gradient on either side of the membrane. The propagated wave that symbolizes this vibration of the basilar membrane can be triggered intentionally, when a bone vibrator is placed on the mastoid bone, or inadvertently when testing hearing of one ear by air conduction while disregarding transmission of the sound to the other side. When hearing is tested with a bone vibrator, the pathways leading to the basilar membrane can be divided into two main categories. The first type of pathway short-circuits the middle ear and comprises three distinct mechanisms: cochlear fluid inertia, compression of the cochlear walls, and pressure changes exerted via cerebrospinal fluid. In the second type of pathway, the stimulus reaches the basilar membrane via the middle ear, either directly or via the outer ear. Although it is difficult to precisely determine the contribution of each of these pathways to the basilar membrane, bone conduction remains the clinically most reliable way of directly testing cochlear function.

Introduction

The mechanisms by which an individual is able to perceive sound by bone conduction (BC) have been studied for many decades [1,2]. Such intense interest in these mechanisms can be essentially explained by the growth of otological surgery and the need to inform patients about the chances of success of the proposed operation. Progress in middle ear surgery has therefore been closely associated with increasingly reliable audiometry and rigorous study of BC thresholds that provide essential information on the functional status of the cochlea.

However, the interest in BC is not limited to the distinction between conductive hearing loss and other forms of hearing loss. More recently, the good hearing results obtained in patients with mixed hearing loss after implantation of a vibratory transducer on the round window [3] raised new questions concerning the role of BC in the observed improvement of hearing [4].

Furthermore, the observation of unusually low BC thresholds in subjects with surgically documented dehiscence of the superior semicircular channel [5] has led to new hypotheses concerning the possible mechanisms of BC.

A final common pathway: stimulation of the basilar membrane

Georg von Békésy [6] was the first to raise the question of whether hearing by BC involved stimulation of the cochlea or whether it was mediated by another peripheral organ [7]. To address this essential question, he adopted the following rationale: if a sound stimulates the basilar membrane in

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an identical way whether it is transmitted by air conduction (AC) (thereby passing via the middle ear) or by BC, it should be possible to suppress perception of one (sound perceived by air conduction) by perception of the other (sound perceived by bone conduction) and he demonstrated this effect by asking a normal subject to listen to two signals of equal amplitude and frequency (0.4 kHz) but dephased by 180 degrees with respect to each other.

Using a different process, but with the same objective to elucidate the mechanism of BC, Weaver and Bray [8] completed the hypothesis proposed by von Békésy. It was already known, at that time, that by placing an electrode close to the auditory nerve in the cat, it was possible to record an electrical signal accurately reproducing the shape of the acoustic signal presented to the animal's ear [9]. This potential was therefore called the cochlear microphonic potential. Weaver and Bray therefore confirmed that a sound transmitted by BC was able to evoke the same cochlear microphonic potential as the sound transmitted by AC.

In a psychoacoustic study, Khanna et al. [10] demonstrated that a weak 1 kHz sound transmitted by AC was no longer heard when a sound of the same frequency was simultaneously presented by BC between 40 and 70 dB hearing level (HL).

After this brief historical review, let us now examine what actually happens in the basilar membrane. The basilar membrane is a fibrous structure attached medially to the osseous spiral lamina and laterally to the spiral ligament [11]. Under physiological conditions (transmission of sound by air conduction), movement of the stapes footplate in the oval window induces pressure fluctuations, which are transmitted to the scala vestibuli and scala media and then to the scala tympani via the cochlear partition. Pressure changes in the scala tympani are compensated by a movement of the round window in the opposite direction, without which movement of cochlear fluid would be impossible. The pressure changes induced across the cochlear partition vary as a function of time according to the vibrations of the stimulating sound. The basilar membrane is rigid adjacent to the base of the cochlea and gradually loses its stiffness towards the apex. This rigidity gradient of the basilar membrane is the result of three factors: the width of the membrane, which increases towards the apex; its thickness, which decreases towards the apex; and the general anatomical structure of the membrane. Due to the rigidity gradient of the basilar membrane, the pressure fluctuations induced by a pure tone give rise to a propagated wave, which travels towards the apex, with a waveform presenting a peak followed by a rapid decline at a precise point of the basilar membrane determined by the frequency of the tone. von Békésy [12] was awarded the Nobel Prize in physiology and medicine for his research leading to the discovery of these physiologically important phenomena. In this review on the mechanisms of BC, it must be remembered that propagation of the wave is identical regardless of the site and modality (AC or BC) of stimulation of the cochlea.

The exceptional quality of the research conducted by von Békésy was confirmed half a century later by direct laser Doppler measurements of the movement of the basilar membrane, demonstrating the similarity of the effects of AC and BC [13].

It should also be stressed that differences are observed according to whether the initial conduction is air conduction or bone conduction [14]. When hearing is tested with a bone vibrator (for example Radioear B71) placed on the mastoid, at low frequencies and high amplitudes, the transducer does not just stimulate BC, but also induces vibrotactile excitation, thereby producing multimodal perception [15]. This loss of auditory specificity of BC at low frequencies has important consequences for paediatric audiometry, as children with profound hearing loss may present true behavioural reactions at low frequencies (from 45 dB HL at 250 Hz and 65 dB HL at 500 Hz), while these reactions have a vibrotactile origin [16]. It is important to identify these reactions in young children with hearing loss, as they validate the quality of the conditioning ensured by the examiner and allow more reliable measurement of BC thresholds beyond 1000 Hz.

Bone vibrators can also stimulate the vestibular system and this phenomenon can be observed both in large vestibular aqueduct syndrome and superior semicircular canal dehiscence syndrome [17].

Another difference was observed between AC and BC in a study comparing progression of loudness in the two types of conduction [18]. This study showed that loudness increased more rapidly by BC than by AC, particularly at low frequencies. This could be explained by the multimodal nature of BC perception, allowing loudness to increase more rapidly than by AC despite the similarity of physical loudness levels.

The electrophysiological thresholds measured by AC and BC must also be interpreted cautiously, as suggested by a comparative study conducted on the V wave of brainstem auditory evoked potentials in the same individuals [19]. Three sources of disparity between electrophysiological responses produced by the two types of conduction have been identified [14]: frequency component differences between the listener and the bone vibrator; hearing threshold differences (sound pressure for AC and force for BC); and lower dynamics with the bone vibrator (which presents more nonlinear distortions). Hence the value of using corrections when comparing auditory evoked potentials recorded with the two types of stimulation [20].

A final argument indicating that vibration of the basilar membrane constitutes the main mechanism of hearing by BC is provided by the recording, under certain technical conditions, of distortion products by otoacoustic emissions in response to a pure tone stimulus transmitted by BC, showing comparable results to those obtained with a stimulus transmitted by AC [21].

Pathways to the basilar membrane in bone conduction hearing

If all sounds perceived by BC are mediated by the basilar membrane, how do these sounds reach this membrane?

First of all, it must be stressed that activation of BC mechanisms during audiometry, when the subject's hearing is supposedly tested by AC, can be misleading. When testing a subject by AC using earphones, a sort of filter situated in the middle of the skull base prevents the sound from being transmitted from one cochlea to the other until the intensity of the stimulus exceeds a certain threshold. This