Original Article

Implications for Bone Conduction Mechanisms from Thresholds of Post Radical Mastoidectomy and Subtotal Petrosectomy Patients

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OBJECTIVES: To assess bone conduction (BC) thresholds following radical mastoidectomy and subtotal petrosectomy, in which the tympanic membrane and the ossicular chain, responsible for osseous BC mechanisms, are surgically removed. The removal of the tympanic membrane and the ossicular chain would reduce the contributions to BC threshold of the following four osseous BC mechanisms: the occlusion effect of the external ear, middle ear ossicular chain inertia, inner ear fluid inertia, and distortion (compression–expansion) of the walls of the inner ear.

MATERIALS and METHODS: BC thresholds were determined in 64 patients who underwent radical mastoidectomy and in 248 patients who underwent subtotal petrosectomy.

RESULTS: BC thresholds were normal (≤15 dB HL, i.e., better) in 19 (30%) radical mastoidectomy patients and in 19 (8%) subtotal petrosectomy patients at each of the frequencies assessed (0.5, 1.0, 2.0, and 4.0 kHz).

CONCLUSION: Normal BC thresholds seen in many patients following mastoidectomy and petrosectomy may be induced by a non-osseous mechanism, and the onset ("threshold") of the classical osseous BC mechanisms may be somewhat higher.

KEYWORDS: Osseous, non-osseous, fluid inertia, ossicle inertia, distortion, radical mastoidectomy, subtotal petrosectomy

INTRODUCTION

Though studied many years, bone conduction (BC) mechanisms are considered complex, not well understood, not completely resolved, and challenging [1-5]. This complexity concerns the relative contribution of each of the four generally accepted osseous BC mechanisms. According to the established views, hearing by BC is elicited when a clinical bone vibrator is applied with a static force of 500 g (5 N) to skin sites overlying the skull bone, such as the mastoid or forehead. The vibrations induced in the underlying bone at the stimulus frequencies are conducted along the skull bone to the temporal bone, leading to vibrations of the bony walls of the outer, middle, and inner ears [1, 2]. Therefore, this is called "bone conduction." Thus, BC threshold is the result of the following four osseous mechanisms of BC induced: (1) outer ear occlusion effect, (2) middle ear ossicular chain inertia, (3) inner ear fluid inertia, and (4) inner ear bone distortion (compression–expansion). Since it is thought that these mechanisms act in parallel (and not in series) [5], the four mechanisms should somehow summate depending on their relative phases [6]. Together, they lead to a pressure difference across the basilar membrane, its displacement and to a traveling wave, as in air conduction (AC) hearing [1-4, 7, 8].

The occlusion effect (mechanism 1) is induced when the BC stimulus on the head leads to vibrations of the wall of the external meatus; therefore, when the meatus is occluded, the air pressures produced in the occluded cavity lead to vibrations of the tympanic membrane and the ossicular chain, as in AC. This mechanism predominates at low frequencies [1]. Ossicular chain inertia (mechanism 2) contributes to BC hearing in parallel with the occlusion effect. The middle ear ossicular chain is loosely coupled to the bony wall of the middle ear by several ligaments and is attached to the tympanic membrane at one end of the chain and to the oval window at the other end of the chain. While at low-frequency stimulation the ossicular chain vibrates together with the surrounding bony wall of the middle ear, at higher frequencies, the vibrations of the ossicular chain can no longer follow the vibrations of the surrounding bony wall of the middle ear due to the inertia of the chain. This induces an inertia-related phase lag between the ossicles and the surrounding bone, i.e., to motion of the stapes footplate in the oval window, leading to inner ear fluid displacements and pressure differences across the basilar membrane, and subsequently its displacement and a traveling wave. This mechanism is considered more effective at low and middle frequencies [9]. In the normal inner ear, the compliance of the round window is approximately 20 times greater than that of the oval window, since the round window is only a simple membrane, without any obstruction. On the other hand, the ossicular chain with its attachments to the oval window and to the tympanic membrane impedes the motion of the oval window. Thus, when the same fluid force is applied from within the inner ear to both windows, the displacement of the round window is approximately 20 times greater than that of the oval window [7]. On the other hand, the compliance of the bony wall of the inner ear to the same applied fluid force is negligible. Therefore, any bulk fluid displacements induced within the inner ear occur with respect to the oval and round windows. Accordingly, in the normal ear, the inertia of the inner ear fluid (mechanism 3) provides an additional inner ear BC mechanism in parallel with the other mechanisms: at low frequencies, the bony wall of the inner ear and the fluid within the inner ear vibrate together at the stimulus frequency. However, at higher frequencies, an inertia-related phase lag between the vibrations of the fluid and that of the inner ear wall is induced. As a result of the higher compliance of the round window, during the phase when the fluid is deflected toward the windows, the basilar membrane is displaced toward the scala tympani. When the phase of the stimulus shifts the fluid away from the windows, the basilar membrane is displaced toward the scala vestibuli. These displacements of the basilar membrane lead to a traveling wave along the membrane. Inner ear fluid inertia is considered the dominant mechanism in BC hearing in the normal ear [1, 2, 9, 10].

An additional BC mechanism, acting in parallel with the others, is distortion (alternate compression–expansion at the stimulus frequency) of the wall of the inner ear (mechanism 4). This produces volume displacements of the two windows, inward and outward (at the stimulus frequency). During the compression phase, the fluid is shifted toward the windows, and since the displacements of the round window are greater than those of the oval window due to the greater compliance of the round window, a pressure difference is induced across the basilar membrane, leading to its displacement and a traveling wave. With the expansion of the inner ear wall, the basilar membrane is displaced toward the scala vestibule [2, 10].

Several modes of ear surgery, such as radical mastoidectomy [11] and subtotal petrosectomy [12], may have an adverse impact on these osseous BC mechanisms.

MATERIALS AND METHODS

Radical Mastoidectomy, Subtotal Petrosectomy, and Audiological Evaluation

The study was conducted on two groups of patients who underwent surgery in two different institutions. The first group included 64 consecutive patients who underwent radical mastoidectomy in the Department of Otolaryngology, Head, and Neck Surgery in our tertiary referral center. The mean age of the patients was 34 (3-83) years. The study included 28 female and 36 male patients. Radical mastoidectomy was performed in 41 right ears and in 23 left ears. The major etiology for radical mastoidectomy was chronic otitis media, with and without cholesteatoma. In radical mastoidectomy, the tympanic membrane, the ossicular chain, the posterior wall of the external auditory canal, and the mastoid air cells were surgically drilled out, leaving an enlarged cavity open to the external canal.

The second group included 248 consecutive patients who underwent subtotal petrosectomy in the Department of Otology and Skull Base Surgery of a quaternary referral center hospital and had residual hearing of some degree following surgery. The mean age of the patients was 51 years. The study included 112 female and 136 male patients. The right ear was operated in 132, and the left in 116. The major etiology for surgery was chronic recurrent otitis media, with cholesteatoma in most cases. In subtotal petrosectomy, the tympanic membrane, the ossicular chain, the posterior wall of the external meatus, and the mastoid air cells were surgically removed, with blind sac closure of the external meatus. The resulting cavity was filled with fat tissue from the patient.

The study was conducted in accordance with the ethical standards of the respective committees and with the Declaration of Helsinki. Informed consent was obtained from all patients for surgery and clinical–audiological follow-up. As part of the routine, periodic follow-up, each of the patients in the two groups underwent repeated examination of their ears with cleaning of the cavity and comprehensive audiological evaluations, with emphasis on the thresholds to BC stimulation. In younger patients (e.g., a 3-year-old with congenital cholesteatoma), the thresholds considered here were those when they were older, and a reliable audiogram could be obtained. The stimulating bone vibrator was applied to the post-auricular area, over the cortical bone, posterior to the surgical area. To assess the possible effects of the state of the stapes on BC thresholds, the surgical records were reviewed, and the post-surgical state of the stapes (with or without stapes superstructure) was compared with their post-surgical BC thresholds.

RESULTS

In 64 post-radical mastoidectomy ears, BC thresholds in 19 (30%) were normal, ≤15 dB HL, i.e., better, at each of the frequencies assessed: 0.5, 1.0, 2.0, and 4.0 kHz. Considering only the pure tone average (PTA) BC thresholds (PTA=0.5, 1.0, and 2.0 kHz, i.e., without 4.0 kHz), there were 24 (38%) with normal BC thresholds (average 6 dB HL). The mean PTA AC threshold in the 19 ears with normal BC thresh-

olds was 43 dB HL. In 21 (31%), BC thresholds were <25-30 dB HL. In several, BC thresholds actually improved following surgery.

The audiological assessment of the 248 post-subtotal petrosectomy patients revealed severely elevated mean PTA postoperative AC thresholds (to 115 dB HL). There were no postoperative changes in BC threshold in 97 (39%), and BC thresholds actually improved by approximately 10 dB after surgery in 34 (14%) patients. Following this initial audiological evaluation, the actual number of patients with normal (≤15 dB, i.e., better) BC thresholds after surgery was determined as part of the present study, and normal BC thresholds were found in 19 (8%).

Furthermore, no correspondence was found between the presence or absence of stapes superstructure in post-radical mastoidectomy patients and BC threshold; there were patients with stapes superstructure, and patients without, who nevertheless had normal BC thresholds. In addition, in all petrosectomy patients, only the footplate was consistently left in place, and there were patients in whom the BC thresholds were normal (≤15 dB HL), threshold remained the same, in others even improved, and in others deteriorated.

DISCUSSION

As a result of the removal of the tympanic membrane and the middle ear ossicular chain in both radical mastoidectomy and subtotal petrosectomy, the occlusion effect of the external ear (mechanism 1) and ossicular chain inertia of the middle ear (mechanism 2) would no longer contribute to BC threshold. Furthermore, removing the ossicular chain together with its attachment to the tympanic membrane (also removed), the impedance acting on the oval window would be greatly reduced so that the compliance of the oval window would increase. Therefore, with respect to both inner ear BC mechanisms of fluid inertia (mechanism 3) and distortion (mechanism 4), the displacements of the oval window would then be greater and more similar to those of the round window. This would lead to smaller pressure differences across the basilar membrane, with a reduction of the magnitude of the resulting traveling wave (mechanisms 3 and 4).

In other words, the effectiveness of each of the four "established view" osseous mechanisms eliciting BC threshold would be either entirely absent (occlusion effect and ossicle inertia) or greatly reduced (fluid inertia and inner ear wall distortion) in patients who had undergone radical mastoidectomy and subtotal petrosectomy. Similar results of normal BC thresholds in many patients following radical mastoidectomy have been reported [11].

Therefore, we now have evidence that in spite of mastoidectomy and petrosectomy, which should have interfered with each of the four "established view" osseous BC mechanisms based on bone vibrations and lead to BC threshold elevations, BC thresholds can be normal, remain unchanged, or even improve after surgery.

Phase Relationships and Site of Action of Osseous BC Mechanisms in the Normal Ear

With respect to the outer ear occlusion effect (mechanism 1) and middle ear ossicle inertia (mechanism 2), the pressure difference across the basilar membrane, inducing its displacement, is a result of the vibrations of the tympanic membrane (occlusion effect) or of the stapes footplate (ossicle inertia), which act inward to the inner ear, as in AC. On the other hand, the forces eliciting the inner ear BC mechanisms 3 (fluid inertia) and 4 (inner ear wall distortion) result from fluid displacements induced within the inner ear, and they "act" from within the inner ear, outward via the two windows. Therefore, it is possible that during BC stimulation, the forces acting on the basilar membrane in the inner ear at threshold may not be in phase with each other and may even partially cancel each other.

Studies Leading to BC Mechanisms

How can these established views regarding BC mechanisms be reconciled with the clinical findings of normal BC thresholds in many post-radical mastoidectomy and petrosectomy patients? The actual experimental studies from which the mechanisms of BC had been derived were conducted mainly on cats [6, 7], cadaver heads, and temporal bone preparations [1]. In experiments in cats [6, 7], the cochlear microphonic potentials of the ear in response to bone vibrator stimulation that elicited responses with criterion magnitudes on the order of several microvolt were assessed. Therefore, this intensity level was by definition not threshold, but still on the linear portion of the cochlear microphonic intensity function. The analysis of the BC mechanisms involved experimental manipulations of relevant parts of the ear, followed by the determination of how much the stimulus intensity had to be elevated to again reach the original criterion magnitude of the cochlear microphonic potentials. Therefore, these studies involved supra-threshold stimulation. Stenfelt et al. [1] conducted studies on cadaver heads or temporal bone preparations, and therefore high-intensity BC stimulation had to be used. The effects of manipulations on vibrations of parts of the ear were assessed by laser Doppler vibrometry [1]. The resulting conclusions with respect to the BC mechanisms determined in cats [6, 7] and cadavers [1, 2, 9, 10] elicited in response to higher-intensity stimulation were also assumed to be effective in normal hearing human subjects at threshold. However, conclusions derived from vibration studies in cadavers and temporal bone preparations and in cats using high-intensity stimulation may not accurately reflect the vibrations in normal, live human ears at BC threshold level.

Normal Post-Surgical BC Thresholds and Possible Explanations

It is possible that the reduction of the contributions of one or more of the osseous BC mechanisms following surgery may have altered the phase relationships between them; therefore, there is less mutual cancellation, and BC threshold may be normal, as suggested by Stenfelt [10]. It is also possible, or perhaps even more likely, that since each of the four suggested osseous BC mechanisms would be adversely affected by radical mastoidectomy and subtotal petrosectomy, while nevertheless BC thresholds were normal in many patients who had undergone such surgery, the effective mechanism eliciting BC threshold may not be one of the four. It is possible that an alternative non-osseous mechanism, not taken into account in the "established views" (all of which involve actual vibrations of the bone), is effective at actual threshold, and the intensity of the onset ("threshold") of the osseous BC mechanisms is somewhat higher. The specific nature of such an alternative non-osseous mechanism that may be effective at threshold intensities, is not clear at this time. However, it may involve third window fluid [5, 13-15] or soft tissue conduction pathways that are initiated by the delivery of the vibratory stimuli to the skin. The vibrations induced can be conducted via soft tissues of the body and may

activate the hair cells directly [16-18]. For example, it has been shown that bone vibrator stimulation delivered to soft tissues (on the eye—Watanabe et al. [19] and on the dura following craniotomy-Stump et al. [20]) elicits oto-acoustic emissions so that the vibrations somehow reach and excite the outer hair cells. Therefore, there is a need for further evaluation and discussion of the mechanisms leading to threshold in the normal ear in response to BC stimulation.

CONCLUSION

Though radical mastoidectomy and subtotal petrosectomy patients with normal BC thresholds responded to the auditory stimulation delivered by the bone vibrator, their threshold response may not have been elicited by actual osseous BC mechanisms, but rather by an alternative non-osseous mechanism that may have been effective at actual threshold. The osseous BC mechanisms may begin to elicit responses only at higher stimulus intensities.

Ethics Committee Approval: The study was conducted in accordance with the ethical standards of the respective committees and with the Declaration of Helsinki.

Informed Consent: Written informed consent was obtained from patients who participated in this study.

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