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Influence of a Totally Open Oval Window on Bone Conduction in Otosclerosis

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Key Words
Bone conduction · Otosclerosis · Carhart notch · Basilar membrane displacement

Abstract
Objective: The aim of this study was to evaluate changes in bone conduction thresholds before, during and after total stapedectomy. ***Study Design:*** Prospective clinical study. ***Methods:*** In 27 ears of 26 patients undergoing stapedectomy under local anesthesia, bone conduction was measured before surgery, during surgery under open oval window conditions, and after the insertion of a steel wire connective tissue prosthesis. Statistical data analysis was performed on the audiometric results. ***Results:*** Under open oval window conditions, bone conduction hearing was found to be improved between 500 and 2000 Hz, but not at 4000 Hz. After insertion of the prosthesis, an additional improvement was evident at 500 and 1000 Hz, but a loss was seen at 2000 and 4000 Hz. ***Conclusion:*** This is the first investigation reported in which audiometry was performed under open oval window conditions during stapes surgery. Our results demonstrate that at least part of the preoperative bone conduction hearing loss in otosclerosis must be of mechanical, but not of sensorineural origin, as already suspected by Carhart. The fixed footplate suppresses cochlear micromechanics mainly at frequencies between 500 to 2000 Hz. Furthermore, the loss in bone conduction hearing at 2000 and 4000 Hz after insertion of the prosthesis indicates that rather than the surgical procedure of total removal of the footplate, other factors such as the handling of the prosthesis or its mechanical properties after insertion cause high-frequency hearing loss after stapes surgery.

Introduction

The pathologic process of otosclerosis is characterized by an inflammatory lytic phase followed by abnormal bone remodeling, which leads to sclerosis at very specific sites of predilection [Arnold and Friedmann, 1988; Sziklai et al., 2009]. Histologically, the oval window is the most frequently affected area of this process, causing partial or total fixation of the stapes footplate. Blocked sound transmission leads to a conductive hearing loss. However, many patients show a simultaneous loss in bone conduction (BC) hearing, mainly at frequencies between 500 and

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3000 Hz. This loss in BC hearing is worse than age-related hearing loss by itself [Topsakal et al., 2006]. Proteolytic enzymes (hydrolases) from bursting lysosomes in histiocytes as well as TNF-α from otospongiotic microfoci have been suspected of causing sensorineural hearing loss in otosclerosis when released into the perilymph [Bretlau et al., 1982; Causse et al., 1989; Causse and Chevance, 1978; Sziklai et al., 2009]. In rare cases, sensorineural hearing loss is induced by otosclerotic foci that penetrate the cochlear endosteum to grow into the scala tympani or vestibuli [Schuknecht, 1983]. This situation may be an indication for cochlear implantation [Ramsden et al., 2007].

True sensorineural hearing loss, which is caused by diseased cochlear or retrocochlear structures, cannot be influenced by stapes surgery. Therefore, the often dramatic improvement in BC hearing at frequencies below 4000 Hz after successful stapes surgery must be due to changes in the properties of cochlear micromechanics [Arnold et al., 2007; Awengen, 1993]. This means that in otosclerosis, BC thresholds do not always reflect sensorineural cochlear function. In 1949, Carhart already assumed the BC hearing loss in otosclerosis to be at least in part a mechanical suppression of inner ear function due to the fixed stapes footplate [Carhart and Hayes, 1949]. This was demonstrated after successful fenestration surgery, when the postoperative audiograms showed improved BC hearing (on average by 5 dB at 500 Hz, 10 dB at 1000 Hz, 15 dB at 2000 Hz and 5 dB at 4000 Hz).

One explanation for the BC hearing loss might be the limitation of energy transfer with a fixed stapes footplate, leading to a restricted spreading of sound pressure within the cochlear fluids and to a diminished displacement of the basilar membrane (BM). A fixed stapes footplate particularly limits the transmission of low and middle frequencies, while higher frequencies (above 4000 Hz) reach the inner ear nearly without loss of energy [Stenfelt and Goode, 2005]. Therefore, with a fixed footplate, the main energy loss is below 4000 Hz and even often below the notch originally described by Carhart [Carhart, 1960; Perez et al., 2009].

Considering the fact that coupling is the key to energy transmission in sound transfer, the size of the contact surface of the stapes prosthesis should have a major impact on the post-surgical improvement of BC hearing. In postoperative audiograms of otosclerosis patients, this effect is seen mainly at frequencies from 250 to 3000 Hz [Arnold et al., 2007; Awengen, 1993; Persson et al., 1997].

Considering the results of clinical observations that show how the prosthesis diameter can improve otosclerotic BC hearing loss, one question is still of interest: how and to what extent does an open oval window during surgery already influence cochlear micromechanics (i.e. BC)?

Patients and Methods

Study Protocol

Total stapedectomy under local anesthesia was performed on 27 ears of 26 patients (16 females, 10 males, age 25–74 years) suffering from various degrees of mixed hearing loss on both sides, caused by otosclerotic stapes fixation.

All patients had to fulfill the following criteria: otoscopically normal ear drums, no previous inflammatory middle ear diseases or ear surgery, an average air-bone gap of 20 dB or more, missing ipsilateral and contralateral acoustic reflexes on both sides, and normal mastoid pneumatization on both sides (Schüller X-ray).

All patients underwent the regular preoperative diagnostic audiometric tests using Aurical audiometers (Madsen/GN Otometrics, Taastrup, Denmark) calibrated to EN ISO 389 in a soundproof chamber. Air conduction was tested with Sennheiser HDA 200 headphones (Sennheiser GmbH & Co. KG, Wedemark-Wennebostel, Germany) at the frequencies 500, 1000, 1500, 2000, 3000, 4000 and 8000 Hz. BC was tested with the Radioear B71 bone vibrator (Radioear Corp., New Eagle, Pa., USA) at the frequencies 500, 1000, 2000, 3000 and 4000 Hz.

For intraoperative BC measurements after removal of the stapes footplate, a special custom-made audiometer, calibrated to EN ISO 389 with a JKG 96 bone vibrator (CB-Elmec, Königslutter, Germany) and certified for audiological measurements (Physikalische Technische Bundesanstalt, Germany), was used. This audiometer features a remote control allowing quick access to the test frequencies of 500, 1000, 2000 and 4000 Hz while the transducer is placed at the mastoid during surgery under sterile conditions. Masking of the contralateral ear during intraoperative testing was performed with noise equivalent to standard masking noise of the Aurical audiometer used for pre- and postoperative measurements. Test time was between 3 and 5 min.

The study was planned and performed according to the declaration of Helsinki, and all patients gave written consent for the intraoperative measurements.

In order to avoid any bias, control BC measurements were performed preoperatively in 10 patients with the Aurical audiometer using a Radioear B71 bone vibrator, as well as with the custom-made audiometer, using a JKG 96 bone vibrator. No difference between these two testing devices was found.

The BC thresholds of the preoperative audiograms were compared with the intra- and postoperative thresholds and statistical evaluation was performed for each frequency. Furthermore, the pure-tone averages (PTA) of the frequencies 500, 1000 and 2000 Hz, as well as of the frequencies 500, 1000, 2000 and 4000 Hz, were calculated for all 3 BC measurements. Statistical analysis was performed using GraphPad Prism 5 software (GraphPad Software, La Jolla, Calif., USA). All data passed the normality tests (Kolmogorov-Smirnov, D'Agostino-Pearson, Shapiro-Wilson). Repeated-measures one-way ANOVA followed by Bonferroni's

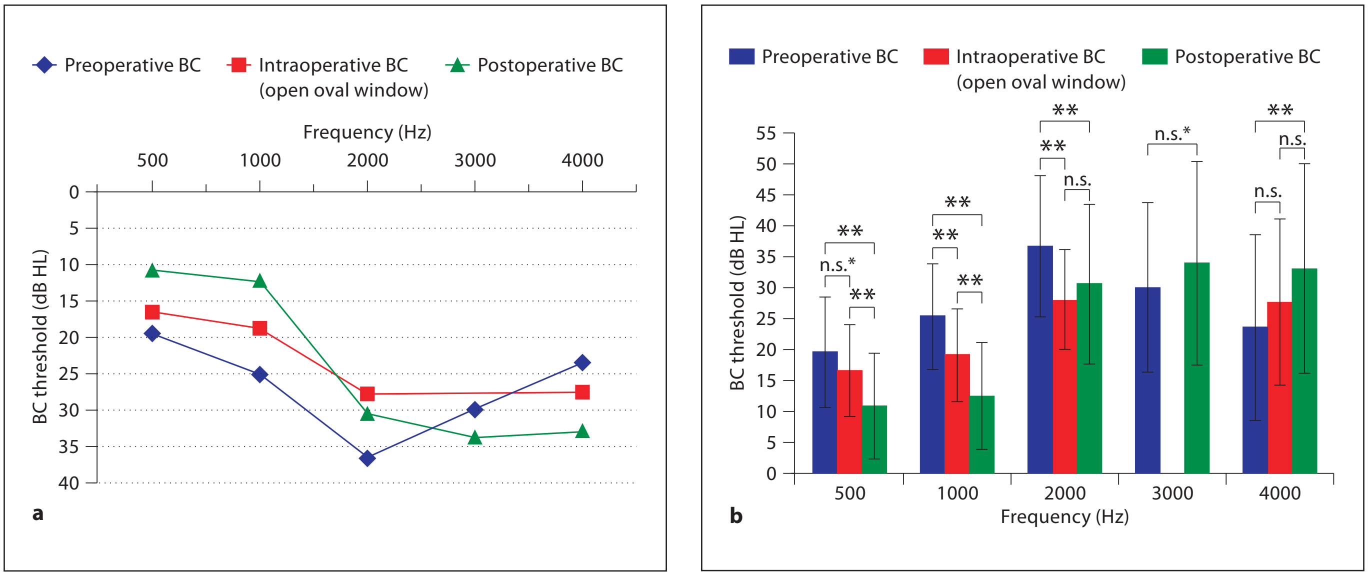

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Fig. 1. a Average frequency values from all 27 ears: the improvement in intraoperative BC thresholds (squares) at 500–2000 Hz is evident. **b** The histogram depicts the standard deviation and the results of the statistical comparison of the single frequency measurement means. ** = Significant ($p < 0.05$); n.s. = not significant; n.s.* = significance just missed.

multiple comparison post hoc test was performed, except for the data at 3000 Hz, where the paired t test was used, as intraoperative data were not measured at this frequency. We assumed the results to be significant at a level of $p < 0.05$.

Surgical Procedure

After peri- and endaural injection of local anesthesia containing adrenaline, and following intravenous administration of 250 mg prednisolone for inner ear protection, surgery was performed via an endaural approach. The tympanomeatal flap was lifted and the oval window exposed. After confirmation of a fixed stapes, the suprastructure was removed. Gelfoam soaked with diluted adrenaline was placed into the oval window niche to avoid any later blood contamination to the perilymph. Meanwhile, a Schuknecht connective tissue, steel wire prosthesis of custom length was manufactured according to the distance between the incus and the footplate as well as the size of the footplate. After removal of the gelfoam, the footplate was fractured with a needle and the posterior and anterior parts of the footplate were totally removed. Under the condition of the totally open oval window, BC thresholds were tested. Following this measurement, the prosthesis was placed into the oval window and fixed to the long process of the incus. The oval window was sealed with fibrin glue.

After replacing the tympanomeatal flap, a dressing was placed into the external meatus; the dressing was removed 2 weeks later. Air and BC were measured again 4 weeks postoperatively. The surgical procedures were done by W.A. and J.K.

Results

The frequencies 500, 1000, 2000 and 4000 Hz were tested intraoperatively with the special BC audiometer.

Comparing the pre-, intra- and postoperative averaged frequency values at 500, 1000, 2000 and 4000 Hz from all 27 ears, an improvement in BC hearing below 2000 Hz is evident (fig. 1a).

At 500 Hz, the pre- to intraoperative improvement was 3 dB and the intra- to postoperative improvement 6 dB, resulting in a total of 9 dB BC threshold improvement.

At 1 kHz, the pre- to intraoperative improvement was 6 dB and the intra- to postoperative improvement was 7 dB, resulting in a total of 13 dB.

The results are different for 2000 Hz: while pre- to intraoperative thresholds showed an amelioration of 9 dB, a loss of 3 dB was seen from intra- to postoperative thresholds. The total improvement in BC was 6 dB.

At 4000 Hz, a loss in BC hearing from pre- to intraoperative thresholds of 4 dB and from intra- to postoperative thresholds of 5 dB was noticed, leading to a total loss of 9 dB.

Statistical analysis for each frequency is shown in figure 1b. Standard deviations are rather large, expressing the range in preoperative BC hearing thresholds of our patients. It becomes even larger at higher frequencies where the test-retest variability of high-frequency BC measurements comes into play [Laukli and Fjermedal, 1990]. The difference in measurement means was found to be statistically significant for the frequencies 500, 1000, 2000 and 4000 Hz (one-way ANOVA $p < 0.001$). Bonferroni's post hoc test revealed that the difference in pre- and intraoperative measurement means at 500 Hz just misses significance [$p > 0.05$, 95% confidence interval (CI): –0.8595 to 6.785]. No significant difference was found for the intra- to postoperative measurement means at 2000 Hz and for the pre- to intraoperative as well as the intra- to postoperative measurement means at 4000 Hz. The pre- to postoperative BC hearing loss at 4000 Hz was statistically significant ($p < 0.001$, 95% CI: –15.316 to –3.572). At 3000 Hz, the paired t test found that the pre- to postoperative BC hearing loss just misses significance ($p = 0.0523$, 95% CI: –7.82 to 0.042).

PTA were calculated from the collected data and statistically analyzed. The pre- to intraoperative (open oval window) improvement was significant for PTA from 500 to 2000 Hz ($p < 0.001$, 95% CI: 2.929–8.923). Significance was also found for PTA from 500 to 4000 Hz ($p < 0.05$, 95% CI: 0.3957–6.456). Comparison of pre- and postoperative BC PTA showed a significant improvement in PTA from 500 to 2000 Hz ($p < 0.001$, 95% CI: 6.202–12.20) and from 500 to 4000 Hz ($p < 0.01$, 95% CI: 1.507–7.567).

Comparison of intra- and postoperative BC PTA showed a significant improvement in PTA from 500 to 2000 Hz ($p < 0.05$, 95% CI: 0.2756–6.270). No significance was found for PTA from 500 to 4000 Hz ($p = 0.44$, 95% CI: –1.919 to 4.141).

Discussion

Our results demonstrate that after total removal of the fixed stapes footplate, the condition of a totally open oval window has an influence on BC threshold and therefore on cochlear micromechanics.

Statistical analyses of the pre-, intra- and postoperative audiometric tests clearly showed that the preoperative suppression of BC was continuously ameliorated at frequencies below 2000 Hz. This improvement of BC is mainly due to the presence of an open oval window.

At 4000 Hz, a total BC hearing loss of 9 dB was measured; 4 dB of the total 9-dB loss were due to the removal of the stapes footplate, whereas 5 dB were observed after the insertion and crimping of the prosthesis.

The pathologic situation of a fixed stapes footplate restricts normal spreading of sound energy and appropriate movement of the BM. Under these conditions, sound transfer to the BM is mechanically reduced, resulting in 'pseudo-sensorineural hearing loss'. The improvement in BC hearing after opening of the oval window at 500 Hz (3 dB), at 1000 Hz (6 dB) and at 2000 Hz (9 dB) shows the extent of the so-called 'cochlear reserve' of Carhart. The loss in BC hearing at 2000 Hz (3 dB) and at 4000 Hz (5 dB) after insertion and fixation of the prosthesis could be due to the variability of BC audiometry at higher frequencies [Lightfoot and Hughes, 1993] or induced by a traumatic damage of cochlear neuronal elements due to manipulation [Fisch, 1982]. Another reason may be the impedance of the reconstructed ossicular chain. However, ossicle inertia is reported to influence BC hearing for low and middle frequencies. Therefore, the reestablished ossicle inertia can explain the additional increase in BC threshold at 500 Hz (6 dB) and at 1000 Hz (7 dB) after reconstruction of the ossicular chain by insertion of the prosthesis [Stenfelt and Goode, 2005].

BM motion has been shown to be similar whether the stimulation is BC or air conduction [Stenfelt et al., 2003]. In a normal cochlea with mobile windows, fluid inertia is the most important factor to BC [Stenfelt and Goode, 2005]. Within a cochlea with a totally fixed stapes, BM displacement during BC stimulation is reduced compared to the physiologic situation. By removing the fixed footplate, more energy becomes available for increased BM displacement, corresponding to a better BC threshold. Sohmer et al. [2004a, b] investigated the mechanisms responsible for cochlear activation at low sound intensities. The semicircular canal was fenestrated in fat sand rats, and a hole was drilled over the scala vestibuli of the first turn of the guinea pig cochlea. Such 'third windows', which expose the inner ear fluids to air, provide a sound pathway out of the cochlea that is of lower impedance than the one through the round window. Fenestration would be expected to decrease the pressure differences across the cochlear partition, causing a reduction in the amplitude of the classical base to apex input traveling wave, and should therefore lead to better BC hearing. Indeed, during these experiments, BC thresholds improved following fenestration. Thus, the cochlea becomes more sensitive to BC in the presence of a third window.

Such a third window is present in superior semicircular canal dehiscence, which can affect vestibular [Minor, 2000] and hearing function, leading clinically to a conductive hearing loss [Merchant and Rosowski, 2008]. Experimental and clinical studies on superior semicircular canal dehiscence and its effect on hearing mechanisms suggest that the conductive hearing loss is induced by the dual mechanism of worsening of air conduction hearing thresholds and improvement of BC hearing thresholds. The improved BC hearing thresholds are thought to be caused by a decrease in cochlear impedance resulting in an increased BM displacement [Merchant and Rosowski, 2008; Merchant et al., 2007; Rosowski et al., 2004].

In our present work, we studied a cochlea with only one mobile window (round window membrane), and likewise found that when creating a second window during stapedectomy, the preoperatively reduced BC hearing improved at frequencies below 4000 Hz.

At 4000 Hz and above, we could not find any improvement of BC after opening of the oval window. This is in accordance with the relevance of cochlear wall compression at higher frequencies [Stenfelt and Goode, 2005].

After successful insertion of the mobile prosthesis, an additional BC hearing improvement was observed below 2000 Hz but not at or above 2000 Hz. This observed pattern of hearing change may have been caused by the known variability of BC audiometry at higher frequencies [Lightfoot and Hughes, 1993], or by a vulnerability of higher frequencies to surgical trauma to the inner ear caused by prosthesis handling or crimping. If the latter argument is valid, then our investigations may additionally show that the insertion of the prosthesis and/or the procedure of crimping, and not the opening and removal of the footplate, could be the reason for high-frequency sensorineural hearing loss during stapes surgery. This interpretation is supported by the audiological results when comparing the self-crimping Nitinol piston with the manually crimped Fisch piston [Bretlau et al., 2008].

Conclusion

Under the condition of a totally open oval window during stapedectomy, the preoperatively measured depression of BC threshold significantly improves between the frequencies of 500 and 2000 Hz, indicating an increase in BM displacement by reduced impedance. After insertion of a steel wire, connective tissue prosthesis (Schuknecht), a further elevation of BC threshold can only be observed below 2000 Hz. At and above 2000 Hz, there is a slight loss of BC hearing after insertion and crimping of the prosthesis. This supports the notion that rather than the removal of the footplate, the manipulation of the prosthesis is the most delicate procedure during stapes surgery.

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