Does bilateral otosclerosis make pre-operative bone conduction more inaccurate?

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Abstract

Objectives: To assess whether bilateral otosclerosis renders pre-operative bone conduction more inaccurate by increasing the Carhart effect.

Methods: Retrospective review of a database of pre and post-operative audiograms of 745 ears with otosclerosis treated with stapedectomy from 2013 to 2020 in a tertiary centre.

Main outcome measures: Change in bone conduction after stapedectomy for otosclerosis in: unilateral otosclerosis (U1); bilateral otosclerosis undergoing first side surgery (B1); bilateral otosclerosis undergoing second side surgery (B2). The magnitude of change in bone conduction post-operatively within and between each group.

Results: The average difference in pre and post-operative bone conduction was significant within in all groups (T-stat > 2 and P-value <0.05) with the greatest change observed in the U1 group. Analysis of average change in bone conduction between groups did not reach statistical significance (P-value = 0.37). Analysis of change per frequency demonstrated the greatest change in bone conduction post-operatively at 2000 Hz in all groups. The magnitude of change at 2000 Hz was the greatest in the bilateral groups; however, it did not reach statistical significance when compared to the unilateral group (P-value = 0.36).

Conclusions: This is the first study in the literature to assess the accuracy of pre-operative bone conduction in bilateral versus unilateral otosclerosis. There is no evidence that pre-operative bone conduction in bilateral otosclerosis is more inaccurate than in unilateral disease. In order to assess accuracy of pre-operative bone conduction in otosclerosis a reliable method of assessing post-operative bone conduction is required, without assumption of its equivalence to cochlear reserve.

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1. Introduction

The Carhart effect is a depression in bone conduction thresholds due to disruption of the external and/or middle ear components of the air conduction pathway (Gatehouse and Browning, 1982). This effect was initially described by Carhart after observing the improvement in bone conduction thresholds after fenestration of the lateral semi-circular canal in otosclerosis (Carhart, 1950). The effect has subsequently described after ossicular chain reconstruction (Preide, 1970), stapedectomy (Undersen, 1973) and tympanoplasty (Austin, 1978). It occurs because not all sound applied directly to the skull vault reaches the cochlea via the osseous route (Cook et al., 1994). Tondorf described three bone conduction pathways: bone to cochlea; bone to middle ear then to cochlea and bone to external auditory canal then via the middle ear to the cochlea. (Tondorf, 1972) Therefore, to record accurate bone conduction thresholds a normal air conduction mechanism is required.

The Carhart effect is seen across a range of frequencies from 500 Hz to 3000 Hz. The Carhart notch describes the point of maximal depression of bone conduction due to the Carhart effect. This usually occurs at 2000 Hz, the resonant frequency of the ossicular chain, in otosclerosis. In otosclerosis the abnormal bony remodelling causes mechanical fixation of the stapes footplate at the oval window disturbing the self-resonance of the ossicular chain (Wiatr et al., 2019). A Carhart notch at 2000 Hz is therefore an audiological marker of ossicular chain fixation and renders the use of bone conduction thresholds as a proxy for cochlear reserve unreliable (Kashio et al., 2011). Stapedectomy, by releasing the
immobile ossicular chain, normalises the air conduction mechanism and modifies the resonant frequency of the middle ear. This results in normalisation of both air and bone conduction thresholds.

The aetiology of otosclerosis remains uncertain but it is likely a mixture of autosomal dominant inheritance with reduced penetrance, persistent varicella virus infection and auto-immune pathology (Stenfert and Goode, 2005). In 80% of cases there is bilateral histological otosclerosis (Sabbe et al., 2015). Despite this there have been no studies in the published literature assessing the reliability of pre-operative bone conduction in patients with unilateral versus bilateral disease. The objective of this study was to assess the degree of post-operative improvement in bone conduction in patients with unilateral when compared to bilateral disease in order to ascertain whether bilateral disease makes pre-operative bone conduction more inaccurate by increasing the Carhart effect.

2. Methods

Retrospective review of a database of 796 stapedectomy surgeries performed by the senior author between 2013 and 2020 was conducted. Fifty-one patients were excluded due to incomplete data. The study group consisted of 745 patients (248 men and 497 women) with an average age of 45 years. Patients were divided into three groups: unilateral otosclerosis with no clinical or audiological indicators of contralateral disease at time of surgery (U1 = 264 ears); bilateral otosclerosis undergoing first side surgery (B1 = 235 ears) and bilateral otosclerosis undergoing second side surgery (B2 = 246).

Stapedectomy was performed under local anaesthesia with complete posterior crurotomy using a KTP laser. Ossicular reconstruction was achieved using a SMART 360 nitinol fluoroplastic piston (Gyrus ACM, Inc.; Southborough, Mass.).

Audiometric testing using headphones was performed by certified clinical audiologists. Pure tone octave-wide audiometry with adequate masking was used to test bone conduction. Pre-operative audiometric testing was carried out between 1 and 12 weeks prior to stapedectomy and post-operative testing at 6 weeks post-surgery. Bone conduction was tested at 500 Hz, 1000 Hz, 2000 Hz, 3000 Hz and 4000 Hz. In accordance with the guidelines of the Committee on Hearing and Equilibrium from the American Academy of Otolaryngology-Head and Neck Surgery (Committee on Hearing and, 1995), 3000 Hz was used in the calculation of average bone conduction. Average bone conduction was calculated using the average of thresholds at 500 Hz, 1000 Hz, 2000 Hz, 3000 Hz.

Statistical analysis was performed using Microsoft Excel 2016 Data Analysis. The null hypothesis used for statistical calculation was no difference between pre and post-operative bone conduction within or between groups.

3. Results

3.1. Change in average bone conduction pre and post-stapedectomy

The average change in bone conduction was greatest in the U1 group at 4.4 dB followed by B2 (3.9 dB) and B1 (3.6 dB) (See Table 1). The range was equal in both bilateral otosclerosis groups (45) and narrower in the U1 group (40). (See Graph 1).

All groups showed a positive linear correlation between pre and post-operative bone conduction (See Graph 2). Correlation analysis showed the correlation between pre and post-operative bone conduction to be strongest in the B2 group (Adjusted $R^2 = 0.67$) when compared to the B1 (Adjusted $R^2 = 0.59$) or U1 (Adjusted $R^2 = 0.62$) groups (See Table 2).

The difference between the average pre and post-operative bone conduction was calculated using the paired T-test. The T-stat was greatest in the U1 group (T-stat = 10.36) indicating greater evidence against the null hypothesis (no difference between pre and post-operative bone conduction) than in the B1 (T-stat = 8.05) or B2 (T-stat = 8.65) groups. P-values were <0.05 in all groups (See Table 3).

The one-way ANOVA test was used to compare the average difference in pre and post-operative bone conduction between groups. The difference was not statistically significant (P-value = 0.37).

3.2. Change in bone conduction pre and post-stapedectomy per frequency

The difference between pre and post-operative bone conduction was assessed for all frequencies tested (500 Hz, 1000 Hz, 2000 Hz, 3000 Hz and 4000 Hz). The greatest change in bone conduction was seen at 2000 Hz in all groups (See Graph 3). The highest magnitude change at 2000 Hz was in the B2 group of 6.1 dB followed by 5.2 dB in the B1 group and 4.7 dB in the U1 group.

A paired T-test was used to assess variance from the null hypothesis (no change between pre and post-operative BC) for each frequency (See Table 4). T-stat values were significant (T-stat >2) in all groups at 500 Hz, 1000 Hz, 2000 Hz and 3000 Hz, with maximal magnitude at 2000 Hz, and insignificant (T-stat <2) at 4000 Hz. B1 and B2 groups showed maximum variance from the null hypothesis at 2000 Hz however in the U1 group maximum variance was seen at 1000 Hz.

Analysis of P-values showed no statistical difference between average difference in pre and post-operative bone conduction between groups when subdivided for bone conduction frequency tested (See Table 5).

4. Discussion

It was hypothesised that in bilateral otosclerosis pre-operative bone conduction would be more inaccurate than in unilateral disease due to bilateral disturbance of the bone conduction pathway.

| Table 1 | Descriptive statistics for average change from pre to post-operative BC in each group. |
|---------|-------------------------------------|
|         | B1          | B2          | U1          |
| Average | 3.554878    | 3.888298    | 4.412879    |
| Max     | 21.25       | 20          | 25          |
| Min     | -23.75      | -25         | -15         |
| Range   | 45          | 45          | 40          |
| SD      | 6.889473    | 6.823635    | 6.948068    |
| Median  | 3.125       | 3.75        | 3.75        |
| Observations | 246 | 235 | 264 |

Graph 1. Average change in pre and post-operative BC change presented as average spread with range.
Graphs 2. a, b, c: Correlation between average pre and post-operative bone conduction in decibels (dB).
utilising the middle ear. In this study the bilateral otosclerosis group was subdivided into bilateral otosclerosis undergoing first side surgery (B1) and bilateral otosclerosis undergoing second side surgery (B2). This was to determine whether change in bone conduction in the subject ear would be affected by co-existing (B1) or surgery (B2). This was to determine whether change in bone conduction would show the most inaccurate bone conduction, due to contralateral otosclerosis, followed by B2 group with a contralateral post-stapedectomy ear and that the most accurate pre-operative bone conduction would be seen in unilateral disease (U1). Accuracy of bone conduction was made using analysis of the difference between pre and post-operative bone conduction thresholds based on the assumption that post-operative bone conduction thresholds represent cochlear reserve after successful stapedectomy.

Contrary to the hypothesis the largest difference in average bone conduction was seen in the unilateral group (U1) followed by the B2 group and the smallest magnitude change was seen in the B1 group. This was supported by analysis with the paired T-test showing greater magnitude of variance from the null hypothesis (no difference between pre and post-operative bone conduction) in the unilateral group than in the bilateral groups. With the proviso that T-stat value > 2 indicates significance of evidence against the null hypothesis these results support the presence of the Carhart effect within each group. However analysis of the average difference between pre and post-operative bone conduction between groups did not reach statistical significance and therefore no definitive conclusion can be drawn regarding the accuracy of the average pre-operative bone conduction in unilateral versus bilateral disease.

In all groups the paired T-test showed significant variance from the null hypothesis (T-stat > 2) at 500 Hz, 1000 Hz, 2000 Hz and 3000 Hz indicating significant change in bone conduction pre to post-operatively at these frequencies and therefore the Carhart effect. Change at 4000 Hz was not significant in any group. For this reason, 4000 Hz was not used in calculation of the average bone conduction thresholds in this study. The greatest change in bone conduction per frequency was seen at 2000 Hz in all groups. This is explained by the Carhart notch, with the maximal depression of bone conduction at the resonant frequency of the ossicular chain. The largest magnitude change at 2000 Hz was seen in the B2 group, followed by the B1 group, and the smallest change in the U1 group.

Of interest was that the average decibel change in the U1 group at 2000 Hz (4.7 dB) was almost equivalent at 1000 Hz (4.6 dB). This pattern was not seen in the bilateral groups. Paired T-test analysis confirmed the highest magnitude of variance at 2000 Hz in the bilateral groups and at 1000 Hz in the U1 group. However again analysis of change between groups at both 2000 Hz and 1000 Hz did not reach statistical significance.

This study has shown no significant difference in either the average or the per frequency pre to post-operative bone conduction change between the three groups studied and therefore between unilateral and bilateral disease. It has demonstrated the Carhart effect, with significant improvement in bone conduction post-operatively at frequencies between 500 Hz and 3000 Hz, but not at 4000 Hz, in all groups. It has also demonstrated the Carhart notch in each group at 1000–2000 Hz with maximum average change seen at 2000 Hz. However, in view of the lack of significant variance between groups it must be concluded that there is no difference in bone conduction change post-operatively in unilateral or bilateral otosclerosis.

The initial question however was regarding accuracy of pre-operative bone conduction, specifically in regard to using bone conduction as a proxy for cochlear reserve. We are limited in the investigation of this problem by the necessity to assume that post-operative bone conduction is ‘normalised’ bone conduction and can therefore reliably be used to predict cochlear function. It is widely accepted that fixation of the stapes footplate in otosclerosis, although manifesting mainly as a conductive hearing loss, also has a deleterious effect on the bone conduction pathway which is partially reliant on middle ear transmission. (Tondorf, 1972) Bone conduction has been shown in many studies to improve after

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**Table 2**
Regression statistics for correlation between pre and post-operative BC in each group.

|     | B1        | B2        | U1        |
|-----|-----------|-----------|-----------|
| Adjusted R Square | 0.589908  | 0.672892  | 0.622253  |
| Standard Error    | 6.626737  | 6.68321   | 6.647312  |
| Observations      | 246       | 235       | 264       |

**Table 3**
Paired T-test and P-values for average pre and post-operative bone conduction in each group.

|     | B1         | B2         | U1         |
|-----|------------|------------|------------|
| T-stat | 8.047326  | 8.649301   | 10.36119   |
| P-value | 3.70E-14  | 8.54E-16   | 2.63E-21   |
| Observations | 246       | 235       | 264       |

**Table 4**
T-stat values per frequency (bone conduction) per group.

|     | B1         | B2         | U1         |
|-----|------------|------------|------------|
| 500 Hz | 4.98       | 4.51       | 3.67       |
| 1000 Hz | 6.15       | 6.98       | 7.68       |
| 2000 Hz | 8.16       | 10.17      | 5.70       |
| 3000 Hz | 4.76       | 4.61       | 5.76       |
| 4000 Hz | –1.33      | –1.81      | –0.79      |

**Table 5**
P-value analysis of difference between groups at each frequency (bone conduction).

|     | P-Value    |
|-----|------------|
| 500 Hz | 0.607196   |
| 1000 Hz | 0.450953   |
| 2000 Hz | 0.355204   |
| 3000 Hz | 0.724098   |
| 4000 Hz | 0.759687   |
successful stapes surgery with published figures for average improvement ranging from 4.5 dB to 15.6 dB (Mokhtarinejad et al., 2013; Awengen, 1993; Vijayendra and Parikh, 2011; García-Iza et al., 2016).

However, whether post-operative improvement in bone conduction in otosclerosis can be reliably equated to normalisation of bone conduction thresholds and therefore an accurate proxy measure of cochlear reserve is less clear. In otosclerosis the availability of bone conduction thresholds prior to the onset of disease, if it is even possible to accurately determine this point, is unusual and was not available in any cases examined in this study. Even if this information was available, the claim of ‘normalisation’ of bone conduction is difficult if not impossible to prove, due to difficulties in quantifying the effect of presbycusis on bone conduction thresholds over time. In addition to this, while the assessment of the contralateral ear in most otological conditions can offer insight into baseline functioning, the bilateral nature of disease in 80% of patients with otosclerosis, constitutes yet another confounding factor (Sabbe et al., 2015).

To determine whether pre-operative bone conduction is more or less accurate in bilateral than unilateral disease, we must be assured that post-operative bone conduction is itself accurate. Several authors have attempted to estimate cochlear reserve in otosclerosis pre-operatively using bone conduction speech audiometry, speech discrimination testing, aided pure-tone audiometry, various methods of mitigating the Carhart notch and assessment of the patient’s cardiovascular co-morbidities (Caussé et al., 1973; Caussé and Caussé, 1981; Abdelghaffar et al., 2010). Yet there is no widely accepted method assessing cochlear reserve in otosclerosis pre or post-operatively.

To our knowledge this is the first study in the literature comparing the accuracy of pre-operative bone conduction in unilateral and bilateral disease. In order to further examine any increased inaccuracy in bilateral disease more work is required to develop an accepted method to accurately measure cochlear reserve in otosclerosis, thus eliminating reliance on post-operative bone conduction as a proxy measure of cochlear reserve and the difference between pre and post-operative bone conduction thresholds as a measure of accuracy.

5. Conclusion

Additional studies that examine how to accurately assess cochlear reserve in otosclerosis are required. Only with a reliable method of doing so can the question of whether pre-operative bone conduction is more inaccurate in bilateral disease be answered. This study has shown that, with the assumption that post-operative bone conduction represents normalised thresholds and an accurate measure of cochlear reserve, there is no evidence that pre-operative bone conduction is more inaccurate in bilateral than in unilateral otosclerosis.

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