**Otology**

# Is the Carhart notch a predictive factor of hearing results after stapedectomy?

## *La tacca di Carhart è un fattore predittivo dei risultati uditivi dopo stapedectomia?*

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SUMMARY

The Carhart notch (CN) is a depression in the bone-conduction audiogram of patients with clinical otosclerosis. The middle frequencies from 0.5 to 2 kHz, which correspond to the resonance frequency of the middle ear, can be substantially improved upon following successful stapes surgery. This retrospective audiometric database and chart review in a tertiary referral centre was performed with the aim of assessing whether the presence of a CN could be predictive of results after stapes surgery in otosclerosis, through improvement in bone conduction (BC) thresholds. Nine hundred and thirty-one cases of stapes surgery over a period of 25 years benefitted from audiological assessment before and 4 months after surgery. A CN was considered present when the BC threshold at the notch frequency (0.5, 1 or 2 kHz) exceeded the mean thresholds at higher and lower adjacent frequencies by at least 7.5 dB. BC threshold improvement was better at 2 kHz (+14.1 ± 12.5 dB *vs* +12 ± 13.2 dB) and lower at 4 kHz (+3.6 ± 13.5 dB *vs* +11 ± 14.7 dB) for the CN+ group compared to the CN- group. Moreover, sensorineural hearing loss was more frequent in the CN+ group than in the CN- group. These results indicate that a CN on preoperative audiogram should alert the clinician to lesser postoperative BC improvement at 4 kHz related to a preoperative sensorineural hearing loss or to a higher incidence of postoperative sensorineural hearing loss.

KEY WORDS: otosclerosis, stapedectomy, hearing, Carhart notch, bone conduction

RIASSUNTO

*La tacca di Carhart è una depressione della via ossea nell'audiogramma dei pazienti con otosclerosi clinica. Le frequenze medie da 0,5 a 2 kHz, che corrispondono alla frequenza di risonanza dell'orecchio medio, possono essere efficacemente migliorate mediante un intervento chirurgico di stapedectomia. Sono state eseguite la valutazione di un database audiometrico retrospettivo e la revisione delle cartelle cliniche dei pazienti afferenti in un centro terziario con l'obiettivo di valutare se la presenza di una tacca di Carhart (CN) potesse essere predittiva dei risultati dopo la chirurgia della staffa nell'otosclerosi, attraverso il miglioramento delle soglie di conduzione ossea (BC). Novecentotrentuno pazienti sottoposti a chirurgia della staffa trattati in un periodo di 25 anni sono stati sottoposti a valutazione audiologica prima e 4 mesi dopo l'intervento. Una CN è stata considerata presente quando la soglia BC alla frequenza del notch (0,5, 1 o 2 kHz) ha superato le soglie medie delle frequenze vicine superiori e inferiori di almeno 7,5 dB. Il miglioramento della soglia BC è risultato migliore a 2 kHz (+ 14,1 ± 12,5 dB contro +12 ± 13,2 dB) e inferiore a 4 kHz (+3,6 ± 13,5 dB contro +11 ± 14,7 dB) per il gruppo CN + rispetto al gruppo CN-. Inoltre, la perdita neurosensoriale dell'udito era più frequente nel gruppo CN + rispetto al gruppo CN-. Questi risultati indicano che una CN sull'audiogramma preoperatorio dovrebbe essere predittiva di un minore miglioramento postoperatorio della BC a 4 kHz correlato a una perdita dell'udito neurosensoriale preoperatoria o a una maggiore incidenza di ipoacusia neurosensoriale postoperatoria.*

PAROLE CHIAVE: *otosclerosi, stapedectomia, udito, tacca di Carhart, conduzione ossea*

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## Introduction

Patients with a middle ear pathology have increased air conduction (AC) thresholds. There is often also an accompanying depression of the bone conduction (BC) thresholds. The increase in BC thresholds for otosclerosis, maximal at 2 kHz, is called the "Carhart notch" (CN) [1]. This effect may be explained by BC mechanisms. The inertial component seems to be the most important factor contributing to BC hearing [2]. The ossicular and inner ear fluid inertia are less efficient due to the higher impedance of the fixed stapes footplate in otosclerosis and an increase in BC thresholds is observed. The middle ear inertia is the most effective in the mid frequencies close to the resonance frequency vibration which is 1.5 kHz [3]. In a model simulation of BC excitation of the inner ear, Stenfelt et al. [3] hypothesised that the CN close to 2 kHz could be simulated as a result of increasing the impedance at the oval window seen from inside the inner ear. This explains the predominant presence of CN around 2 kHz in otosclerosis.

Definite criteria for the detection of a CN are unclear and previous studies were conducted with different definitions [4-8]. Hence, the reported CN prevalence in otosclerosis varies considerably among authors, ranging from 31% to 80%. We propose a new definition of CN in order to standardise the reporting of audiometry results in future studies.

In 1950, Carhart [1] was the first to observe that BC thresholds were improved following successful fenestration surgery for otosclerosis: this BC improvement is called "overclosure" [9]. Although the initial diagnosis of sensorineural hearing loss (SNHL) is usually made on the basis of abnormal BC hearing thresholds, this apparent BC loss is not a true indicator of the inner ear function, since it could improve following successful surgery; it reflects the successful reestablishment of the former impedance of the oval window by surgery [10]. Thus, the term overclosure, while widely used, remains confusing. We prefer to use BC improvement.

Bone lesions in otosclerosis were reported to affect intracochlear structures and also cause SNHL [11]. In some cases the audiogram is unusual and may be attributed to sensorineural impairment: this could be the case if the BC curve shows a notch which is duplicated on the air conduction (AC) curve; this AC-notch is usually called a "cookie bite" [12]. Indeed, the question of BC improvement is particularly pertinent in patients with mixed hearing loss to determine the influence of preexisting SNHL. We aimed to determine whether different types of AC curve impacted BC threshold improvement.

Audiological predictive factors of successful surgery are well known [13], but few authors have focused on preoperative tools predicting BC threshold improvement [5,12]. The main goal of our study was to determine whether preoperative audiological assessment as the presence of a CN were predictive factors for postoperative hearing results such as BC threshold improvement.

## Materials and methods

### *Patients*

All patients treated for otosclerosis were included in this retrospective consecutive case-series study. Patients were operated on by the same senior surgeon over a period of 25 years in our tertiary referral centre. The surgical procedure consisted of a stapedotomy with interposition of either a perichondrium or a vein graft, and placement of a Causse-type Teflon stapes 0.4 mm diameter prosthesis [14], the loop of which was anchored to the long process of the incus.

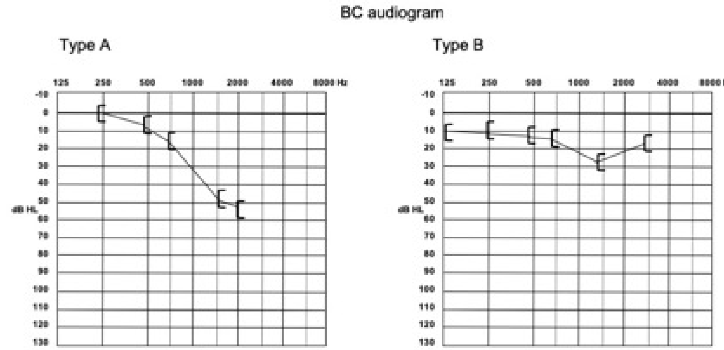
### *Audiological assessment*

Assessment of hearing status was performed before and after surgery (at 4 months and at 1 year). The audiological assessment included the preoperative and postoperative AC and BC thresholds. We used a 4-frequency pure-tone average (PTA) for AC and BC thresholds (0.5, 1, 2 and 4 kHz). The thresholds at 3 kHz were not available in the database at its implemention and were replaced in all cases with those at 4 kHz.

Only AC and BC results that were obtained at the same time postoperatively were used for calculation of the postoperative air-bone gap (ABG). Audiometry was assessed according to the American Academy of Otolaryngology Head and Neck Surgery guidelines [9], except for thresholds at 3 kHz which were substituted in all cases with those at 4 kHz. This was necessary because 3 kHz measurements were not performed at the beginning of this study.

### *Carhart notch definition*

Choosing relevant factors for a precise definition of a CN was necessary (Fig. 1). First, we identified a CN at various frequencies from 0.5 to 2 kHz. To avoid underestimation, we determined that the minimum differences between the CN frequency and the adjacent frequencies was 7.5 dB and not 10 dB as reported in other studies [4], otherwise some audiograms (e.g. type B in Figure 1) were not defined as including a CN pattern. Finally, to avoid overestimation, the CN frequency had to be higher than the adjacent frequencies, or other audiograms (e.g. type A in Figure 1) were considered as including a CN pattern [6-8]. Indeed, a CN was defined by BC threshold at the notch frequency (0.5, 1 or 2 kHz) ≥ 7.5 dB above the mean of thresholds at higher and lower adjacent frequencies. Another criterion was that the




| | Type A | Type B |
|---|---|---|
| Minimum depression of 10 dB in comparaison of thresholds at any frequency from 0.5 to 4 kHz (Yasan [6], Perez [5], Shishegar[7], Ahmad [8]) | No CN | No CN ? |
| BC thresholds at 2 kHz exceeded the mean of thresholds at 1 and 4 kHz by at least 10 dB (Kashio [4]) ***BC thresholds 2kHz – mean BC threholds (1+ 4 kHz) > 10 dB*** | CN ? | No CN ? |
| Our definition BC thresholds at the notch frequency exceeded the mean thresholds at the adjacent frequencies by at least 7.5 dB (with CN frequency higher than adjacent frequencies) ***BC thresholds (CN) – mean BC thresholds at adjacent frequencies > 7.5 dB*** | No CN | CN |

**Figure 1.** CN considered present or not on various type of BC curves according to previous CN definitions and according to our definition (example of right ear).

CN frequency threshold had to be higher than the adjacent frequency thresholds.

*Hearing outcomes*

BC threshold improvement was measured by the preoperative minus the postoperative pure-tone BC average following successful surgery. Various AC curve types were described to determine whether preoperative AC thresholds impact postoperative BC thresholds (Fig. 2): 1) a flat AC curve; 2) a downward AC curve (defined by high frequency AC hearing loss > 2 kHz); 3) an AC-notch or "cookie bite" (defined by a notch in the AC threshold along with the CN at 2 kHz). The success rate in stapes surgery was defined in two ways. Firstly, an AC PTA < 30 dB as primary criterion alone. Secondly, combined criteria of this primary assessment with 2 additional criteria: absence of postoperative sensorineural hearing loss (SNHL defined by a 4 kHz BC threshold postoperative increase > 10 dB) and a postoperative ABG < 10 dB.

*Statistical analyses*

We used SPSS software (*V13.0; SPSS Inc., Chicago, IL, USA*). Quantitative data were expressed as mean and standard deviation. We used the Chi-square and Fisher's exact test for the analysis. Univariate analysis was used to identify a CN as a possible predictive factor for hearing outcome. A P value < 0.05 was considered significant.

## Results

*Population studied*

This retrospective study was conducted on 1,029 patients who underwent 1,250 stapes surgeries for otosclerosis in our tertiary referral centre. Seven hundred and ninety-nine patients (931 surgical cases) were followed at 4 months after surgery and 355 patients (415 surgical cases) at 1 year.

*Preoperative data: Carhart notch description*

A CN was observed in 495 (53.1%) of the 931 surgical cases in the preoperative audiogram according to our defi-

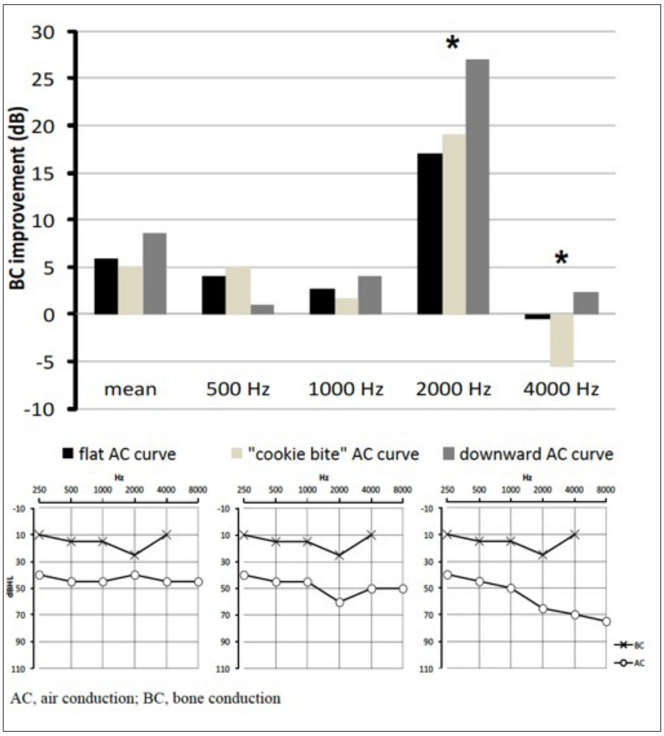



**Figure 2.** BC improvement for cases with a 2 kHz CN preoperatively depending on the AC curve type (a flat AC curve; a "cookie-bite" AC curve defined by "CN duplication" on an AC curve 4 months after surgery (*: $p < 0.05$, Anova).

nition. Notches were distributed according to the peak frequency as follows: 273 (29.2%) surgical cases at 2 kHz, 44 (4.7%) at 1 kHz and 178 (19.1%) at 0.5 kHz. The CN dip means (corresponding to the difference of mean adjacent thresholds minus CN threshold) were: 13 ± 4.7 dB for 2 kHz CN, 11.3 ± 4.4 dB for 1 kHz CN, and 11.5 ± 4.7 dB for 0.5 kHz CN.

*Postoperative data: BC threshold improvement*

Table 1 is a list of BC threshold improvement using primary successful surgery criteria from 931 cases and 415 cases respectively, 4 months and 1 year after stapes surgery. The mean BC threshold improvement for cases with successful surgery at 4 months of follow-up was: +5.4 dB at 0.5 kHz, +3.8 dB at 1 kHz, +13.8 dB at 2 kHz and +8.5 dB at 4 kHz. The mean BC threshold improvement decreased in cases of failed hearing restoration but remained in positive values. The results were stable at 1 year after surgery.

*Preoperative audiological predictive factors affecting audiological results*

Improvement of BC thresholds 4 months after surgery were significantly different if a CN was observed on preoperative audiogram (495 cases with CN: CN+ group) or not (436 cases without CN: CN- group). BC thresholds improvement for the CN+ group were better at 0.5 and 2 kHz (+7.1 ± 11 dB *vs* +3.8 ± 10.3 dB, p = 0.00015, Anova; +14.1 ± 12.5 dB *vs* +12 ± 13.2 dB, p = 0.017, Anova) and lower at 4 kHz (+3.6 ± 13.5 dB *vs* +11 ± 14.7 dB, p = 0.00019, Anova) compared to the CN- group (Fig. 3). We measured the likelihood of a > 10 dB BC thresholds improvement and found it to be greater in the CN+ group at 0.5 kHz (odds ratio = 2; 95% CI = 1.5-2.7; p = 0.029) and at 2 kHz (odds ratio = 1.6; 95% CI = 1.3-2.1; p = 0.035). The likelihood of a > 10 dB BC thresholds improvement was lower at 4 kHz (odds ratio = 0.4; 95% CI = 0.3-0.5; p = 0.022).

Figure 3 shows that if a CN was observed at 2 kHz in the preoperative audiogram there is no BC threshold improvement (negative overclosure) at 4 kHz if the AC thresholds presented a corresponding notch. The likelihood of a > 10 dB BC threshold improvement was significantly lower (odds ratio = 0.08; 95% CI = 0.01-0.6; p = 0.016). On the other hand, in the event of a "downward" AC curve, BC threshold improvement at 2 kHz was significantly better (p = 0.0001, Anova). The likelihood of a > 10 dB BC threshold improvement was significantly higher (odds ratio = 3.6; 95% CI = 1.1-10.1; p = 0.0013).

The univariate analysis did not allow any significant relationship to be determined between the presence of a preoperative CN and successful surgery, considering the primary

**Table I.** BC threshold improvement according to surgical results after stapes surgery.

| | | | BC threshold improvement (dB) | | | |
|---|---|---|---|---|---|---|
| Follow-up | | n (%) | 500 Hz | 1000 Hz | 2000 Hz | 4000 Hz |
| 4 months | Total | 931 | 5.6 | 2.6 | 13.2 | 7.1 |
| | Successful surgery (AC PTA < 30dB) | 609 (65%) | 5.4 | 3.8 | 13.8 | 8.5 |
| | Failed hearing restoration | 322 (35%) | 6 | 0.4 | 12 | 4.3 |
| 1 year | Total | 415 | 5.1 | 2.3 | 13 | 6.5 |
| | Successful surgery | 263 (63%) | 4.8 | 3.5 | 14.2 | 9.2 |
| | Failed hearing restoration | 152 (37%) | 5.5 | 0.2 | 11.1 | 1.8 |

*AC PTA: air conduction threshold pure tone average.*

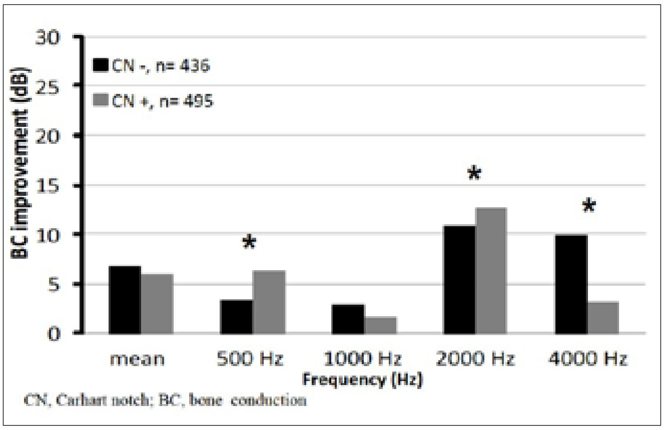



**Figure 3.** BC improvement according to the presence of a CN, 4 months after surgery (*: $p < 0.05$, Anova).

criterion alone or the 3 associated criteria (Tab. II). However, SNHL if considered separately, was more frequent in the CN+ group than in the CN- group at 4 months (odds ratio = 3.1; 95% CI = 1.7-5.7; p = 0.00016) and at 1 year of follow up (odds rati = 2.6; 95% CI = 1.3-5.4; p = 0.0013).

## Discussion

In our study, a CN was observed according to our definition in 53.1% of the 931 preoperative audiograms, mainly at 2 kHz. Definite criteria for the detection of a CN were not yet clearly established, and the authors of previous studies used different definitions. The definition that we propose describes CN at various frequencies (0.5, 1 and 2 kHz), whereas some authors suggested defining CN only at 2 kHz. In addition, as shown in Figure 1, some definitions used previously to define the presence of a CN were inadequate, leading to over- or underestimation. The definition we propose helps to describe with accuracy if a CN is present or not, but it does not account for notches with broader spectrum.

CN was renamed "the Carhart effect" by Gatehouse [15] since increases in bone conduction thresholds are reported from 0.5 to 4 kHz. This increase of BC thresholds are not an indicator of the inner ear function since BC thresholds were demonstrated to improve after surgery [1]. The Carhart effect is due to the lack of excitation mainly from the inertial component of the ossicles close to a resonance frequency of 1.5 kHz, and to a lesser extent from the inertia of the cochlear fluid for lower frequencies [3]. Indeed, the presence of a CN in a patient with conductive hearing loss cannot be used for the specific diagnosis of otosclerosis [4] because the CN can also be due to other disorders of the middle ear that reduce the movement of ossicles, such as otitis media with effusion, tympanosclerosis, or ossicular malformations [4,6-8]. The mean BC improvement in our series was +5.4 dB at 0.5 kHz, +3.8 dB at 1 kHz, +13.8 dB at 2 kHz, and +8.5 dB at 4 kHz. The authors of previous studies confirmed the finding of largest BC improvement at 2 kHz [5,15-17]. The values of BC improvement in our study correlated with those of Gatehouse [15] who also assessed the magnitude of the Carhart effect in his series from precise criteria of successful surgery (ABG < 10 dB, mean BC thresholds not worsened by > 5 dB, AC improved by > 10 dB). BC improvement varies considerably according to the author, but Gatehouse demonstrated that discrepancies were markedly reduced when the appropriate selection criteria were used. Thus BC improvement can be underestimated with other methods such as comparing BC thresholds of patients with BC in an age-matched healthy population, or including only patients whose BC improved [15]. Gatehouse also demonstrated that BC values before and after surgery underes-

**Table II.** Hearing results at 4 months and 1 year after surgery according to the presence of a CN (Chi 2 Pearson).

| | | CN- | | CN + | | |
|---|---|---|---|---|---|---|
| | | n | % | n | % | *p* |
| 4 months after surgery | Total, n | 436 | | 495 | | |
| | PTA AC< 30 dB:1 criterion | 276 | 63.3% | 333 | 67.3% | 0.204 |
| | 3 criteria | 246 | 56.4% | 290 | 58.6% | 0.505 |
| | ABG < 10 | 376 | 76.0% | 316 | 72.0% | 0.225 |
| | SNHL | 14 | 3.2% | 46 | 9.3% | 0.00016 |
| 1 year after surgery | Total, n | 201 | | 214 | | |
| | PTA AC < 30 dB :1 criterion | 121 | 60.0% | 142 | 66.4% | 0.193 |
| | 3 criteria | 111 | 55.2% | 118 | 55.1% | 0.986 |
| | ABG < 10 | 135 | 67.2% | 164 | 76.6% | 0.032 |
| | SNHL | 11 | 5.4% | 28 | 13.1% | 0.013 |

*CN-: absence of Carhart notch; CN+: presence of a Carhart notch; PTA AC: air conduction threshold pure tone average; ABG: air bone gap; SNHL: sensorineural hearing loss.*

timated the Carhart effect for low frequencies compared to theoretical considerations, with an experimental model in which pressure changes were applied to the external canal to simulate the Carhart effect. Indeed, our results could be underestimated for low frequencies.

We found that a CN observed at 2 kHz with a corresponding AC-notch in the preoperative audiogram was correlated to lesser BC thresholds improvement at 4 kHz (negative overclosure). Therefore, an AC-notch on preoperative audiogram is a warning sign for the lack of postoperative BC improvement related to a preoperative SNHL or to a higher incidence of postoperative SNHL. The assessment of whether SNHL was preoperative or postoperative is difficult to know as postoperative BC thresholds were the result of a combination of improvement by adequate impedance change and loss by surgical trauma. Cook et al. [18] described a method allowing changes in BC to be predicted according to air conduction at any frequency by a linear regression. In Cook's model, changes in BC other than those expected could be attributed to other causes than the Carhart effect, and help assess the degree of SNHL in the presence of conductive hearing loss. Our findings using our new definitions have never been described.

We did not find any relationship between the presence of a CN and successful surgery rate, according to our criteria. However, postoperative SNHL tended to be more frequent when a CN was present.

These results must be balanced by the fact that our study was monocentric and retrospective. In addition, only audiological data were considered: patient characteristics, imaging features, or intraoperative data were not assessed. It has been demonstrated that a larger diameter piston (0.6 *vs* 0.4 mm) allows a higher AC gain [19,20]. In our study, only type of 0.4 mm diameter prosthesis was used. Hearing results may differ according to the radiological otosclerosis classification [21]. Marx et al. [21] reported according to CT-scan analyses that AC and BC thresholds were increased in cases of extensive otosclerosis: BC thresholds were significantly higher when the disease involved the pericochlea, the cochlear endosteum, or the round window. Furthermore, they found that SNHL was at higher risk of aggravation in case of extensive otosclerosis. Most authors have confirmed that CT-scan is a sensitive diagnostic method and a useful tool for differential diagnosis of otosclerosis [21,22]. However, diagnosis relies on clinical observation and imaging is not always mentioned in national guidelines [23]. Our consecutive case series of 931 stapes surgery should be large enough to cover all CT-scan grades with a distribution similar to that of Veillon [24]. This classification was based on more than 2,000 CT scans of otosclerosis according to the size and topography of foci with the following distribution: type Ia 14%, Ib 8%, II 52%, III 10% and IV 12% [25]. Age was not considered in our study since functional results do not vary according to age group [26]. Likewise, there was no difference in initial or late postoperative hearing outcome, depending on vein or tragal perichondrium interposition [27].

## Conclusions

CN or more appropriately the Carhart effect was observed at a wide range of frequencies, predominantly at 2 kHz. It is illustrated by the improvement in BC thresholds, which is predominant at 2 kHz, but that is not an indicator of successful surgery. We identified preoperative audiological factors influencing BC improvement: 4 kHz BC improvement was significantly lower in case of preoperative CN or in presence of an AC–notch at 2 kHz. These findings should alert the clinician to mixed hearing loss with preoperative SNHL or to an incidence of postoperative SNHL.

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