Prediction of the Bone Conduction Gain Curve

After Partial Posterior Stapedectomy:

The Frequency Shift Concept

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Introduction: In this article, we present a method able to reasonably predict the bone conduction (BC) gain curve. It provides the advantage of advising patients who will receive little benefit from surgery.

Materials and Method: A group of 284 cases is studied in an attempt to verify the poststapedectomy predictability of their characteristic gain curve (CGC) to define a pattern, which indicates the outcome of surgery. For that purpose, the postoperative BC curve has been modeled by fitting a linear regression curve (LRC), which I refer to here as “baseline,” into the average audiogram of the 284 cases.

Results: Using the average baseline as the predicted postoperative BC audiogram, in 77% of the cases, the predicted CGC is qualitatively comparable to the measured one.

Discussions: The postoperative baseline can be modeled as a shifting of the average frequency of the preoperative baseline toward higher frequencies. This method is useful to predict the probabilities of having a negative slope in the gain curve after stapes surgery and, therefore, will help in the decision-making process for the indication of surgery and to advise patients on the results they can expect to have. A description of the steps to follow for the application of this method is made available.

Key Words: Stapedectomy—Gain curve—Antolí candela—Bone conduction—Otosclerosis—Carhart notch—Stapes surgery.


There are some publications (1–4) written about the presence of changes in the bone conduction (BC) audiogram after otosclerosis surgery. These changes affect the auditory spectrum differently depending on the preoperative characteristics of the BC audiogram (4).

In this article, we present a method able to predict the BC gain curve, which is positive in 77% of the cases. The possibility of predicting the gain curve is considered important in cases where the slope of the expected gain curve is negative. A negative slope in the gain curve, as it will be described, may discourage the indication for surgery.

MATERIALS AND METHOD

Material

A total of 284 cases have been selected and studied. As in our previous article (4), all surgeries were performed by the first author. The intervention has consisted in a partial posterior stapedectomy with a platinum-Teflon piston over a perichondral graft.

To minimize the influence of middle ear impedance anomalies in the BC audiogram, the sample only includes cases that showed a postoperative closure of the average air-bone gap to 10 dB or less 1 year after surgery (96%).

Two BC audiograms are used for the present study, one obtained preoperatively within a month of surgery “preoperative audiogram” and another obtained 1 year after surgery “postoperative audiogram.” All the audiograms in this article correspond to BC.

Method

The method is presented through the following definitions:

1. Gain curves and characteristic gain curves.
The gain curves (GC) are the result of subtracting frequency by frequency the postoperative audiogram from the preoperative one (4). Gain can be positive (improvement), negative (loss), or zero (no change). The GCs are classified into 5 groups (I to V) according to the frequency with the maximum gain. The frequency with the maximum gain is called dominant frequency (DF). Some GCs have 2 (19%), 3 (6%), and even 4 (3%) DFs. This is due to using discrete 5-dB units to measure the hearing level in clinical audiology. The average gain in each group is called the characteristic gain curve (CGC) (4).

The 5 types of CGC are significantly different ($p < 0.001$) (4). Should we be able to predict them, this would allow us to use the 5 types as a reference for the probabilities of obtaining a descending gain curve after surgery.

2. Average audiogram and average bone conduction.

What we call “average audiogram” is the result of averaging frequency by frequency the thresholds of a group of audiograms (average $y_f = \frac{\sum y_f}{n}$, where “n” is the number of audiograms).

What we name as “average bone conduction” is the result of averaging the thresholds of the 5 studied frequencies (average $y = \frac{y_{0.25} + y_{0.5} + y_1 + y_2 + y_4}{5}$).

3. The baseline.

The preoperative and postoperative curves are modeled by adjusting a linear regression curve (LRC) in the audiogram. An LRC is defined as a technique in which a straight line is fitted to a set of data points. In this particular case, the straight line is fitted to gain values of the preoperative or postoperative audiograms. The preoperative LRC will be called the preoperative baseline and the postoperative LRC the postoperative baseline. The BC audiogram is thus defined by only 2 parameters, the slope and the zero crossing (any straight line is defined by its slope and its zero crossing values as shown below). The relative gain of the 5 frequencies are better studied taking the baseline as the reference value in a given case.

Figure 1 shows the method and nomenclature used for that purpose. In the illustration, the average preoperative and postoperative audiograms and corresponding baselines are presented as examples of the method used.

The parameters “a” (slope gain) and “b” (gain at zero crossing) of the preoperative and postoperative baselines are obtained as follows:

$$y = ax + b$$
$$a = \frac{\sum(f_n - \bar{f})(y_f - \bar{y})}{\sum(f_n - \bar{f})^2}$$
$$b = \bar{y} - af$$

$$\bar{f} = \frac{1}{5} \sum_{1}^{5} f_n = 1.55 \text{ KHz}$$

$$\bar{y} = \frac{1}{5} \sum_{1}^{5} y_n$$

In a logarithmic scale, as is conventionally used to represent the horizontal scale in audiograms, the baselines have a curved shape that matches the shape of audiograms (Fig. 1, A–C, and Fig. 2A).

![Figure 1](image-url)
4. Corrected postoperative baseline.

Surgery affects the 2 parameters that define the baselines (a and b). To eliminate the effect of changes induced in the parameter (b), the postoperative baseline is corrected, so it has the same zero crossing (b) as the preoperative one. This new baseline will be called the “corrected postoperative baseline” (Fig. 2, A and B).

5. The intersection.

This is the point in frequency were the “corrected postoperative baseline” intersects the “average preoperative BC.” In our data, this happens at frequency 2.536 KHz (Fig. 2B). The intersection provides a good measure of the influence of the surgical approach used. It is an expression of how surgery affects the middle ear and oval window transfer function.

6. The measured and predicted gain curves.

The method used to evaluate the results is presented in Figures 1 to 4.

The result of subtracting frequency by frequency the postoperative audiogram from the preoperative audiogram will be called “measured gain curve” (Fig. 2C, measured gain). The result of subtracting frequency by frequency the average corrected postoperative baseline from the preoperative audiogram will be called the “predicted gain curve” (Fig. 2 C, predicted gain). Should both be similar, we would have a simple model of the postoperative BC audiogram defined by only 2 parameters and a linear function of frequency.

The process to obtain the predicted gain will yield only 1 DF per gain curve. This is due to the continuous and nondiscrete increments (5 dB unit) of the computed data.

7. The frequency shift.

The difference between the intersection point where the preoperative baseline crosses the average preoperative BC level and the intersection point where the corrected postoperative baseline crosses the average preoperative BC level is called the frequency shift (Fig. 2B). The frequency shift further reflects how surgery affects the middle ear and oval window transfer function.

The same process is illustrated for each individual CGC type in Figure 3, A and B. Notice that all the data have been normalized to have the preoperative average BC at level zero in the plots.

As expected, both average preoperative and postoperative baselines have different characteristics across the CGC types because of the differences in their average audiograms (Fig. 3B). The intersection is also different going from 1.05 for Type I CGC to 4.32 KHz for Type V CGC (Fig. 3B).

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The slope change with surgery is obtained, taking the difference between the preoperative and the postoperative baseline slopes and is presented in Figure 3C. Positive differences imply a greater slope in the preoperative baseline than in the postoperative baseline. These are cases with a greater recovery of the high frequencies than the low frequencies in the BC audiogram after surgery.
The differences between the postoperative and preoperative baselines have been subdivided into 2 components: a frequency-dependent component (Fig. 4, gain a), and a uniform, frequency independent gain (Fig. 4, gain b). In the BC curves, there is a third component, the notches. Notches will be analyzed in a future article.

In Figure 4, gain (a), which is due to the baseline slope change, is obtained by computing the difference between the preoperative and corrected postoperative baseline. Gain (b) (Fig. 4) is obtained subtracting the zero crossing of the postoperative baseline from that of the preoperative baseline. The results are presented for each of the 5 CGC types.

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The characteristics of the preoperative and postoperative baselines are different for each CGC type (Fig. 3). You may observe that the (a) gain (slope gain) can be negative more frequently in the lower types of CGC. This implies a greater gain in the lower frequencies than in the higher frequencies in the postoperative audiogram.

8. Normalized histograms and gain curves.

Histograms have been chosen to compare all the data of measured and predicted gain curves. Using a 5 dB bin width, the difference between the measured data obtained with a 5 dB unit and the predicted data that is continuous, is minimized.

To eliminate the effect of the baseline gain (b), the histograms and CGC presented in Figure 8 have been corrected by subtracting from each value the average of the corresponding gain curve (Average $y = (y_1+y_2+y_3+y_4+y_5)/5$). By doing it, we avoid the spread of the data over the horizontal scale that would make its visual inspection and analysis more difficult.

RESULTS

A notch at 0.5 KHz is present in 43% of the cases in the postoperative BC audiograms, and its implications will be studied in a future article.

Slope changes after stapedectomy have a wide range of values going from 5.9 dB/Oct. to 13.9 dB/Oct. The changes are a function of the CGC type (Fig. 3C), and they justify part of the postoperative gain (gain a, Fig. 4), especially in the higher frequency CGCs (Types III, IV, and V). The differences in the higher frequency CGCs increase progressively, whereas the lower frequency CGCs (Types I and II) do not show significant differences.
The second component of gain because of the change in the zero crossing of the baseline also shows a wide range of values going from $Y_{18.3}$ to 22.3 dB HL. They do not have a clear relationship with the CGC types with the exception of Type V which has the highest percentage of loss (Fig. 4, gain b, Type V). The average of all cases is 2.4 dB HL. These results show that, although some BC audiograms have a very large (b) gain, and others a very small one (or even loss) independently of the CGC type, in the average, the flat gain is very small. These facts suggest a different mechanic cause for the flat gain; being a reversal of a preoperative flat loss, the cause could be related to an interruption of the ossicular chain. This suggests the possibility of the incudo-malleolar and/or the incudo-estapedial joints becoming incompetent when the stapes is fixed for long periods. This implies a decrease in the load of the ossicular chain for the inner ear impedance.

The sum of both gain types (a and b) shows an average gain of 5.56 dB HL, ranging from $Y_{12}$ to 25 dB HL. In 79% of the cases, the average gain is positive, that is, there is an improvement of the BC. In 84% of the cases, the DF of the predicted and measured gain curves coincide in the same frequency (Fig. 5A). The cases where the DF is not coincident have, for the most part, DFs that are immediately higher or lower than the predicted ones. The exception being Type I CGCs because they have more than 50% of the measured cases of Types III (6 cases) and IV (5 cases) as shown in Figure 5, A and B.

Some $y$ values are plotted by the data points to show that the differences between the predicted and measured DFs, in the noncoincident cases, are actually small.

The coincident 84% of the cases have very similar CGCs, showing that the corrected baseline can be used as a reference of postoperative gain. All the data are presented, forming histograms with the measured and predicted gain curves in Figures 6 and 7. See Method, Definition 8, “Normalized histograms and gain curves.”

The similarity of the histograms in the predicted and measured CGCs is very obvious for those cases (84% of them) with coincident DFs (Figs. 6 and 7). In Types I and II, the amplitude of gain is much smaller than in Types III, IV, and V; therefore, the histograms show that the DFs are not as conspicuous in the histograms as they seem in the CGCs. The predicted and measured CGCs and histogram are almost identical, confirming that the corrected postoperative baseline represents well the postoperative BC audiogram.

**PREDICTABILITY OF THE GAIN CURVE**

The incidence of each CGC type in the 284 studied cases and their percentage is presented in Figure 8A.

Obviously, the postoperative baseline is not known before surgery, and the results of 84.2% of coincident CGCs presented in Figure 5 are not realistic from the standpoint of predictability. This process has been used to develop and validate a method. In actuality, to estimate the (a) gain characteristics of the postoperative BC, the average baseline of all postoperative BCs has to be used. By doing it, the coincidence of predicted and measured CGCs is 77%.

The results using each case’s baseline for the prediction is presented in Figure 8, B and D. The results using the average baseline for the computation in the same cases are presented in Figure 8, C and E.
Notice how the slope of the predicted CGC of Type V in Figure 8E makes the curve descend to cross the measured CGC between 1 and 2 KHz. This is due to the relative weight of each CGC type when the average baseline is used to compute the predicted gain curve. The opposite is seen in Type III where the predicted CGC ascends to cross the measured Type II between 2 and 4 KHz.

We highlight this because it explains why the predictability of those 2 CGC types is lower than Type IV. For the same reason, Types I and II are less similar, and the probabilities of guessing the correct CGC type is lower.

FIG. 5. Coincidence of measured and predicted CGC types using the individual postoperative baseline for the prediction. A, Histograms corresponding to the incidence of the gain curves presented in B. The white columns correspond to the cases where there is coincidence between the measured and predicted CGC types. The figures by the columns are the y values of the columns. B, Four-dimensional X/Y plot of the measured and predicted CGC types. Predicted Ip to Vp. Measured Im to Vm. The figures on the upper left of the coincident CGC plots are the correlation coefficient of the averages presented in the corresponding plot. We used the correlation coefficient as an estimate of similarity to help the visual inspection of the plots. The figures by some of the data points (black data points) are their y values.

In partial posterior stapedectomy, I estimate to remove from one-third to two-thirds of the footplate in all cases. It is impossible to remove precisely one-half of the footplate, owing to its small size and the fact that the otosclerotic focus alters its limits. The size of the footplate cannot be assessed with precision. In stapedotomy, where the opening into the vestibule is done more precisely, the percentage of the footplate removed depends on the size of the footplate in each case. Unfortunately, the size of the footplate has a very wide range (8), from 2.7 to 4.9 mm², and a calibrated circular opening of 1 mm of diameter would remove from 16% to 29% of the footplate area.

It is generally accepted that in stapedotomy, the gain curve shows a greater recovery for high frequencies than other techniques that require a greater removal of footplate area (5–7). Therefore we have to assume that they have a greater frequency shift than posterior half stapedectomy or complete footplate removal.

The average postoperative baseline can be derived from the frequency shift as illustrated in Figure 9A. The formula allows obtaining the 5 new frequencies for the

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Computation of the baseline on the bases of the new average frequency (Fig. 9B).

1. Process to obtain the predicted CGCs:
   - Average the postoperative BC audiogram of a sufficiently large sample of cases (100), and compute its baseline (slope and zero crossing).
   - Compute the LRC for the average preoperative audiogram in the same cases.
   - Obtain the coefficient (Coef. in Fig. 9A).
   - Calculate the predicted frequencies as described in Figure 9B.
   - Compute the predicted baseline using the shifted frequencies (Fig. 9C, Predicted $f_n$) and the corresponding thresholds of the measured preoperative audiogram of the case you are studying (CH 946291 in Fig. 9).
   - The predicted gain curve is obtained by subtracting, frequency by frequency (0.25–4 KHz), the thresholds of the preoperative BC audiogram and the corresponding threshold of the predicted postoperative baseline for the same frequencies (Fig. 9D).
   - Steps (a) to (d) must only be followed once to obtain the coefficient of your method for stapes surgery (Fig. 9A).

The frequency shift reflects the average change in the ossicular chain and oval window transfer function induced by the surgical technique.

2. Theoretical implications
   - The described frequency shift is arbitrarily named as such, and it is the consequence of a manipulation of the data. We do not believe that it is factual nor does it imply a true change in the location of the maximum stimulation of the sensory elements of the cochlear partition. It is interesting though to notice that operated patients refer to a sensation of “metallic hearing, like higher frequency and less warmth than the opposite ear.” This is a frequent description in the immediate postoperative period. The “metallic hearing” sensation improves with time, but it never gets to be completely “normal.” Speech discrimination in noisy atmospheres is also referred to as better in the nonoperated ear.

The appearance of frequencies other than the tone test would require the middle ear to have a nonlinear transfer function. Should these frequencies actually be generated, the added stimulation would be located farther into the lower end of the cochlear partition.
Both air and bone conduction are a combination of "sensory neural hearing level" and "transmission hearing level." It is impossible to determine the amount of sensory-neural component in a BC audiogram. Thus, the postoperative audiogram could have, at least for some frequencies, lower thresholds than the sensory-neural ones because of a higher than normal transmission gain. This would result in over stimulation of the sensory elements.

The area of the "active" replacement membrane could be very small, altering its relative size in relation to the tympanic membrane that is thought to account for most of the middle ear sound amplification.

The flat (b) gain could be due, as previously stated, to the incompetence of the joints in the ossicular chain in enduring stapes fixation. Should this be the case, it would explain why the maximum admittance in the tympanogram does not clearly reflect the fixation of the stapes in otosclerosis.

CONCLUSION

Surgical treatment of otosclerosis modifies the inner ear input impedance. It also modifies the ossicular chain, especially the incudo-stapedial and the stapedio-vestibular joints, and eliminates the effect of the stapedial muscle. The consequence is a gain in both the air and bone conduction audiograms. This gain affects the various frequencies differently.

In BC, the gain can be subdivided into 3 components: the gain due to the slope change, the uniform zero crossing gain (Fig. 4), and the notches. The reversal of notches, such as Carhart’s and others with surgery, do not explain by themselves the (a) slope change (4).

The slope changes are a function of the CGC type of the BC gain (Fig. 3, A and B). CGC Types I and II show high probabilities of negative slope gain (Fig. 3C).

Predicting the CGC type is possible in 77% of the cases with this method. Predictability is higher for Types III, IV, and V CGCs (Fig. 8F), which have the highest incidence of positive slope gain.

The zero crossing gain cannot be predicted with the proposed method.

All these conclusions have to be considered under the perspective, given by the fact that the changes we see, in the lower frequencies, are in the limit of being measurable with the 5-dB unit used in clinical audiology. It is not surprising that even using each case’s own baseline as the predicted postoperative BC audiogram, only 84% of the cases predict their CGC type correctly.

The importance of being able to predict the type of gain lies in deciding whether surgery is indicated or not in cases.
FIG. 8. Incidence of CGC Types I to V. A, Measured CGC types and their percentage over the 397 DFs obtained in the 284 cases. B, Predicted 284 cases using their own postoperative baseline (only 1 DF per case) and distribution by CGC type of the 239 cases (own baseline, 84%) that coincide with the measured CGC types. C, Same as in B but using the average postoperative baseline to predict the CGC type (220 coincident cases, 77.4%). D, X/Y plots of measured and predicted CGC, with own postoperative baseline. E, X/Y plots of measured and predicted CGC, with the average postoperative baseline. F, Probabilities of correct prediction and random coincidence as a function of CGC type. I to V = CGC types. The figures by the data points are their \( y \) values.

FIG. 9. Average frequency shift. Method to obtain the predicted postoperative baseline and the corresponding expected CGC. A, Formula to obtain the coefficient for the frequency shift (Fig. 2). B, Derived 5 frequencies because of the average frequency shift (stimulus frequency times coefficient). C, Example of a Type IV CGC showing the preoperative audiogram, the corresponding frequency shifted audiogram and its computed baseline. The average frequency is shifted by 0.976 KHz (coefficient = 1.63) in posterior half stapedectomy. D, Predicted (preoperative audiogram – corresponding frequency shifted baseline) and measured (preoperative BC audiogram – postoperative BC audiogram) gains. Sfn, stimulus frequency of n; Pfn, predicted frequency of n; fpr, preoperative average frequency; fps, postoperative average frequency; Coef, coefficient; stimulus, frequency of the stimulus pure tone; predicted, shifted frequencies; GC, gain curve.

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with a predicted Type I or II CGC, which have high probabilities of a negative slope gain. Here, we consider that cases of predicted Type I or II CGC, associated with a small air bone gap and significant BC losses, will benefit more from a hearing aid than surgery.

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