GENERATION OF DISTORTION PRODUCTS IN A MODEL OF COCHLEAR MECHANICS

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Considerable evidence implicates outer hair cells (OHC) as being responsible for the generation of distortion products (DP) in cochlear mechanics. Forces exerted on the basilar membrane by OHCs must saturate at high levels and, thereby, become a major source of nonlinearity. Realistic growth of distortion products requires that the saturation of OHC forces (with increasing level) be gradual. The apparent band-pass filtering of the distortion product otoacoustic emission (DPOAE) observed in ear canal sound pressure can be explained as the combination of two effects. (1) The DPOAE becomes smaller as the primary frequencies are separated because the basilar membrane vibration becomes smaller at the place where the two tones interact. (2) The DPOAE becomes smaller as the primary frequencies are brought closer together because reflected energy from the DP place partially cancels the retrograde signal. This explanation does not require the presence of any "second filter" in the mechanics of the cochlear partition. With a nonlinear, active model of cochlear mechanics, we have explored whether a simulated hearing loss at the DP frequency can influence the apparent band-pass filtering of DPs, which are generated primarily at the f_2 place. Results of this simulation are compared with DP measurements from a subject with low-frequency hearing loss.

1 Introduction

Distortion product otoacoustic emissions (DPOAE) are generated within the cochlea when two tones interact at some place on the basilar membrane (BM). Distortion products (DP) are a consequence of nonlinear forces exerted on the BM by outer hair cells (OHC). These OHCs forces have the beneficial effect of extending the dynamic range of hearing because they provide greater gain at low levels than at high levels[1]. DPOAEs are a by-product of the OHC influence on cochlear mechanics. The most prominent DPOAE is observed at the frequency $f_d=2f_1-f_2$.

The DPOAE measured with f_1 swept and f_2 held constant is observed to have maximum amplitude when f_d is 0.25 to 0.75 octave below f_2. When DP amplitude is plotted as a function of DP frequency, it has a band-pass appearance because it decreases when f_d becomes either greater or smaller than the optimum f_d. It has been suggested that this so-called "DP filter" is due to resonant tuning of the tectorial membrane[2,3] or other, similar "second filter" mechanism in the micromechanics of the organ of Corti[4]. The model results presented in this paper require an alternative explanation.

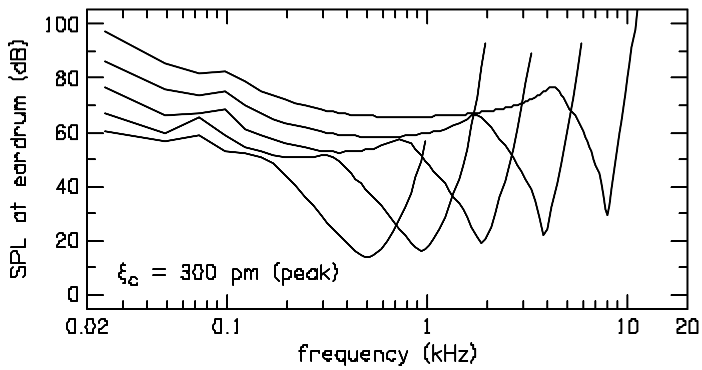

Figure 1: Isodisplacement tuning curves. The curves indicate the stimulus pressure at the eardrum required to produce a 300 pm displacement (1 pm = 10^{-12} m) in the shearing between tectorial membrane and reticular lamina at 5 places along cochlear partition, 6.8, 11.8, 16.7, 21.0, and 24.7 mm from the base. The frequency-place map resembles a human cochlea. These tuning curves were inferred from the response of the model to a very low level click, because the model is nearly linear at low levels.

2 Methods

DPOAEs were generated in a nonlinear, active model of cochlear mechanics. The major differences between the present model and the model described previously by Neely and Stover[4] are (1) the model parameters were adjusted to obtain the isodisplacement tuning curves shown in Fig 1 and (2) the saturating nonlinearity in the OHC mechano-electric transduction was modified to produce more gradual saturation.

The mechano-electric transduction stage of the OHCs in the model was made to be nonlinear by the introduction of a dimensionless multiplier g which was a function of the displacement hair bundle (HB) at the top of the OHC. The HB displacement is equal to the shear displacement x_c between the tectorial membrane and reticular lamina.

$$g = \left[1 + \left(\frac{x_c}{d_o}\right)^2 + \left(\frac{x_c}{d_o}\right)^4\right]^{-\frac{1}{4}}$$

The form of this saturating nonlinearity, is similar, but more gradual, than the nonlinear function described by Yates[5]. For the model results in this paper, the value of the parameter d_o was 10 nm.

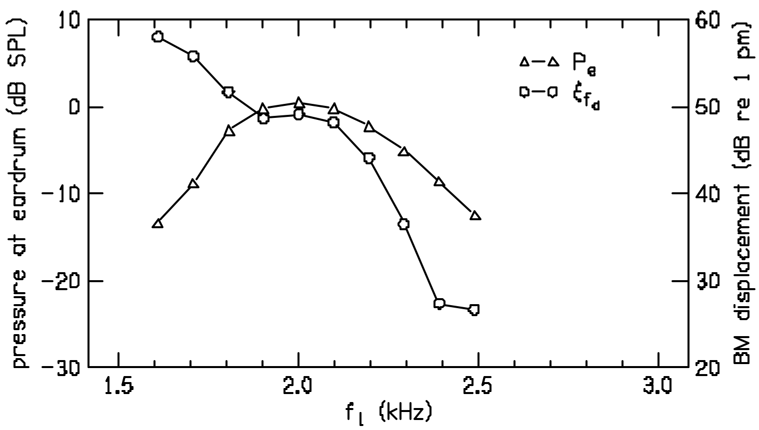

Figure 2: Simulated DPOAE and BM displacement with f_d constant. The f_2 frequency was chosen to keep the DP frequency, $f_d=2f_1-f_2$, constant at 1550 Hz. The primary tone levels were 60 and 55 dB SPL. The triangles indicate the amplitude of the DP in the pressure at the eardrum as a function of the f_1 frequency. This simulated DPOAE was separated from the total pressure at the eardrum by Fourier analysis. The circles show the amplitude of the DP component of BM displacement at the DP place, 18.1 mm from the base of the cochlea. Note that as f_1 approaches f_d below 1.9 kHz, the DPOAE decreases, whereas, the BM displacement continues to increase.

3 Results

3.1 DP generated with f_d held constant

In order to compare the frequency dependence of the DPOAE amplitude with BM displacement at the characteristic place for the DP frequency, it is convenient to vary the frequency of the primary tones in a manner that keeps the DP frequency (and thereby also the DP place) constant. Figure 2 shows results of DP generation as a function of the f_1 frequency. The f_2 frequency was adjusted to keep $f_d=2f_1-f_2$ constant at 1550 Hz. The level of the f_1 tone at the eardrum was 60 dB SPL and the level of the f_2 tone was 55 dB SPL. A band-pass characteristic is observed in the amplitude of the pressure at the eardrum, but not in BM displacement at the DP place. Unlike the pressure at the eardrum, the BM displacement continues to increase as f_1 approaches f_d.

The observation that the frequency dependence of the simulated DPOAE differs from that of the BM displacement suggests that the DPOAE represents the combination of signals from multiple sources. Apparently, the DP generation is distributed over multiple points on the BM. Evidence to support this interpretation is provided in upper panel of Fig. 3 where the f_1, f_2, and f_d components of BM displacement are plotted as a function of place along the BM

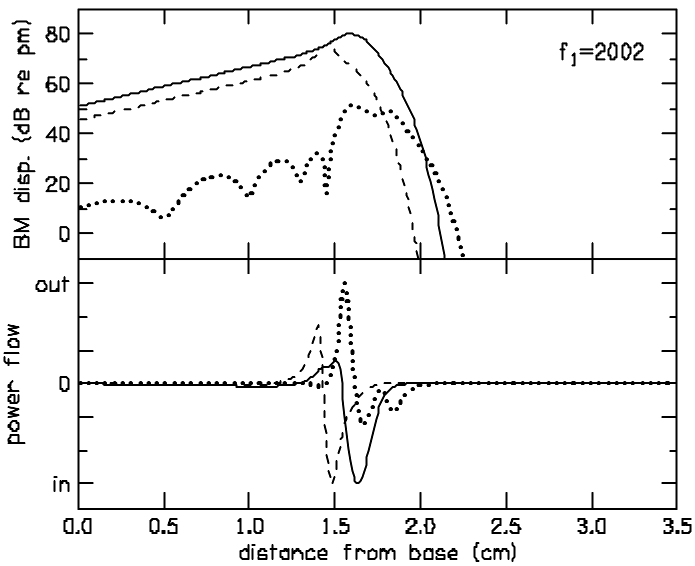

Figure 3: BM displacement and power flow as a function of place. The primary frequency components for these model results were f_1=2002 and f_2=2490. The solid, dashed, and dotted lines represent the f_1, f_2, and f_d frequency components, respectively, obtained by Fourier analysis. The upper panel shows BM displacement in dB re 1 pm. Each power flow curve in the lower panel was normalized so that its maximum value (positive or negative) is at full scale. Positive values of power flow for the primary frequencies indicate places along the cochlear partition where signal energy is generated due to OHC forces. The positive peak in the power flow for f_d indicates the place where the DP is generated. Negative power flow values indicate places where that frequency component is absorbed by the cochlear partition.

for one particular choice of primary frequencies. The notches observed in the f_d component suggest "standing waves" due to interference between the DP generated at the f_2 place and the reflected signal from the DP place. The power flow plot (in the lower panel of Fig. 3) shows the site of DP generation between the f_1 and f_2 places.

3.2 DP generated with f_2 held constant

Although, the DP is generated near the f_2 place, the DPOAE is apparently also influenced by the region of the cochlea apical to the f_2 place. This question was further investigated by altering OHC forces in the cochlear model at all points apical to the f_2 place. DP were

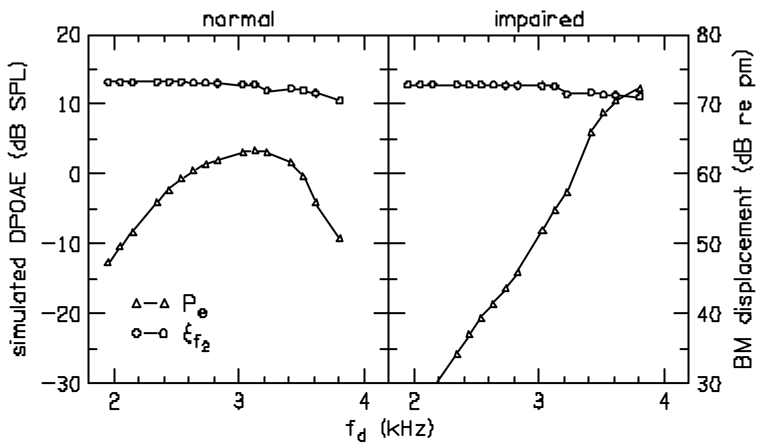

Figure 4: Simulated DPOAE and BM displacement with f_2 constant. The left panel shows results from the normal model condition. The right panel shows results the impaired model condition in which OHC forces are eliminated from all points apical of the f_2 place. The triangles show the amplitude of the DP component of the pressure at the eardrum, i.e. the simulated DPOAE. The circles show the amplitude of BM displacement at the f_2 place. The primary tone levels were 55 and 60 dB SPL. Note that the impaired DPOAE does not have the band-pass characteristic observed in the normal DPOAE.

generated with a paradigm that kept the f_2 frequency constant in order to monitor the effect of the simulated cochlear impairment on BM vibration at the f_2 place.

Figure 4 shows results of DP generation as a function of the $f_d=2f_1-f_2$ frequency. The f_1 frequency was adjusted to keep f_2 constant at 4004 Hz. The level of the f_1 tone at the eardrum was 60 dB SPL and the level of the f_2 tone was 55 dB SPL. The left panel shows the normal state of the model; the same nonlinear, active model used to generate the results shown in Figs. 1-3. A band-pass characteristic is observed in the amplitude of the pressure at the eardrum, the simulated DPOAE. BM displacement at the f_2 place (11.3 mm from the base) is almost constant, but shows some evidence of suppression as f_1 approaches f_2.

The right panel of Fig. 4 shows an impaired cochlear model. Low-frequency hearing loss was simulated in the model by eliminating OHC forces at all points apical of the f_2 place (12 to 35 mm from the base). BM displacement at the f_2 is essentially unaffected by this alteration to the model. In contrast, however, the simulated DPOAE loses its band-pass characteristic. The amplitude of the DPOAE in the impaired model condition continues to increase as f_1 approaches f_2.

Measurements of the DPOAE in ears with normal hearing threshold at f_2 and elevated threshold at lower frequencies do not have the same band-pass appearance observed in normal

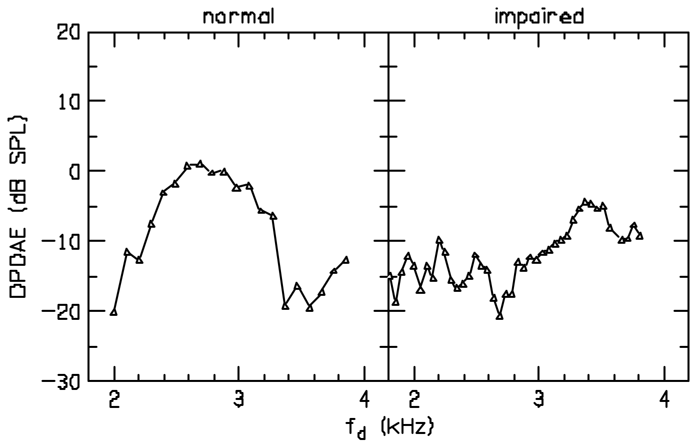

Figure 5: DPOAE measurements from normal and impaired ears. The right panel shows DPOAE amplitudes as function of f_d (with f_2 held constant) in an ear with normal hearing thresholds. The primary tone levels were 50 and 60 dB SPL. The left panel shows the results of similar measurements in an ear with low-frequency hearing loss showing the loss of the band-pass filter shape that is observed in the normal ear. The primary tone levels were 70 and 60 dB SPL.

ears. Examples of DPOAE frequency response from a normal hearing subject and a subject with low-frequency hearing loss are show in Fig. 5. The DP filter shape in the impaired ear appears to be more high-pass than band-pass. The change from band-pass to high-pass is similar to the trend observed in the model.

Inevitable differences in tuning-curve shape and growth of BM displacement between the model and the subjects' ears may account observed between Figs. 4 and 5. The impaired subject had normal hearing at 4 kHz (f_2) and moderate hearing loss at 3 and 2 kHz (within the range of f_d), but the extent and severity of the cochlear damage is not know and probably less extensive than the simulated impairment.

4 Conclusions

The model results support the interpretation that the apparent band-pass characteristic of the DP frequency response is due to two separate mechanisms. (1) As the primary tones come closer together, the DPOAE is reduced by out-of-phase contributions coming from either near the f_2 place or reflected from the DP place. (2) As primary tones are separated further apart, the DPOAE is reduced because the amplitude of basilar membrane (BM) vibration at the place where the primary tones interact becomes smaller. This observation was first reported by

Matthews and Molnar[6] who showed that the band-pass tuning of DPOAEs does not require a second-tuning in cochlear micromechanics. This type of "interference filter" should also work for higher-order distortion products; however, this result has not yet been demonstrated. Although, the model used in this paper does possess a second tuning as a part of the OHC feedback system, the "spectral zero" is about an octave below the characteristic frequency (as can be seen in Fig. 1) and, therefore, cannot be responsible for the band-pass tuning of the DPOAE.

Acknowledgments

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