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Compression estimates using behavioral and otoacoustic emission measures

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Abstract

Cochlear compression in normal-hearing listeners was estimated at octave frequencies from 250 to 4000 Hz using a forward-masking paradigm. Temporal masking curves (TMCs) for a 10-dB SL signal were obtained with two maskers – one equal in frequency to the signal and another an octave below the signal. The ratio of the slope of the off-frequency function to that of the mid-level portion of the on-frequency function was computed as an estimate of the amount of compression at each frequency. Compression was less frequency selective at low frequencies, so an average of the off-frequency slopes at high frequencies (1000, 2000, and 4000 Hz) was used in computing the ratio for each signal frequency. Results indicated strong compression (~0.15–0.30) at all frequencies using the averaged off-frequency slopes, indicating little difference in compression across frequencies. Distortion product otoacoustic emission (DPOAE) input–output (I–O) functions were obtained for each subject at 1000, 2000, and 4000 Hz. The slopes of the DPOAE I–O functions and the psychophysical growth rates were similar to one another, reinforcing the assumption that the forward-masking procedure is providing an estimate of cochlear compression, at least at frequencies from 1000 to 4000 Hz.

Keywords: Compression; Distortion product otoacoustic emissions; Forward masking

1. Introduction

It is well established that the mammalian cochlea is nonlinear, due to normally functioning outer hair cells (OHCs; Ruggero and Rich, 1991b; Sellick et al., 1982). One manifestation of this nonlinearity is a compressive growth of response, which can be measured directly at the basilar membrane (BM; e.g., Robles et al., 1986; Ruggero et al., 1997) or estimated indirectly via psychophysical masking experiments (e.g., Oxenham and Plack, 1997; Nelson et al., 2001).

An important question of current interest is whether the magnitude of compression is independent of place (or overall frequency) within the cochlea, or whether it is weaker in the apical (low-frequency) region than in the basal (high-frequency) region. The results to date are somewhat equivocal. Physiological evidence suggests that compression may be weaker in the apical region of the cochlea. Measurements of response growth of the BM and Reissner's membrane obtained by Cooper and Rhode (1995), Rhode and Cooper (1996) and Zinn et al. (2000) suggest minimal compression in the apical region of the cochlea, although cochlear damage was mentioned as a possible explanation for some of these findings. Furthermore, Cooper and Yates (1994) found

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Abbreviations: BM, basilar membrane; CF, characteristic frequency; DPOAE, distortion product otoacoustic emission; f_s, signal frequency; f_m, masker frequency; GOM, growth-of-masking; I–O, input–output; OHC, outer hair cell; SL, sensation level; SD, standard deviation; TDT, Tucker–Davis technologies; TMC, temporal masking curve; 2IFC, 2 interval forced choice

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that BM input–output (I–O) functions derived from auditory-nerve rate-level functions support a reduction in compression in the apical region of the cochlea. Because the cochlea was not likely to have been damaged by the surgery required to record from the auditory nerve, these results suggest that the apical region may be less compressive than the basal region.

The results from psychophysical studies, however, have been mixed with regard to whether or not the low-frequency region of the cochlea is less compressive than the high-frequency region. These studies have typically employed one of two approaches to estimate BM compression, either growth-of-masking (GOM) functions (Oxenham and Plack, 1997) or temporal masking curves (TMCs; Nelson et al., 2001). Both approaches use nonsimultaneous masking and rely upon the following key assumptions: the signal is detected at a place equal or nearly equal to the signal frequency; threshold depends upon a fixed signal-to-masker ratio in terms of an internal response; and the response to a masker much lower in frequency than the signal will be linear at the signal frequency place. Compression is typically estimated by computing the ratio of the slope of an off-frequency function (masker about an octave lower in frequency than the signal) to that of an on-frequency function (masker and signal equal in frequency). This ratio provides an estimate of the (compressive) growth of response. The inverse of that growth rate is referred to as the compression ratio.

Hicks and Bacon (1999a,b) obtained GOM functions in forward masking for a wide range of signal frequencies and found that the estimated growth of response varied from about 0.80 at 375 Hz to 0.40 at 1500 and 3000 Hz. Plack and Oxenham (2000) obtained similar results using the pulsation-threshold technique. Their growth rates ranged from about 0.75 at 250 Hz to about 0.35 at 1000 Hz and above. Thus, the results from both studies suggest that the low-frequency region is less compressive than the high-frequency region.

More recently, Lopez-Poveda et al. (2003) used TMCs to estimate the growth of BM response from 500 to 8000 Hz. This technique involves keeping the signal constant at a low sensation level (SL) and varying the time delay between the offset of the forward masker and the onset of the signal. The resulting TMCs display masker level as a function of this time delay. A particularly important finding by Lopez-Poveda et al. (2003) was that at low signal frequencies the response to a masker much lower in frequency than the signal might not be linear at the signal frequency place, suggesting that compression may be less frequency selective in the low-frequency region. This represents a violation of the third assumption listed above, and results in an underestimation of compression at low frequencies. When Lopez-Poveda et al. used an off-frequency function from a single high-frequency region to estimate compression at all signal frequencies, they found that compression was independent of frequency. Plack and Drga (2003) measured TMCs for signal frequencies of 250 and 4000 Hz, and reported results that were similar to those of Lopez-Poveda and his colleagues, as did Nelson and Schroder (2004) for signal frequencies from 250 to 8000 Hz. Thus these more recent studies are inconsistent with the earlier psychophysical studies and the physiological studies reviewed above. It is worth noting, however, that the I–O functions derived from auditory-nerve data also rely upon the response to an off-frequency stimulus being linear, and thus it is possible that Cooper and Yates (1994) underestimated BM compression at low frequencies.

The primary goal of the present study was to estimate the growth of response of the BM from 250 to 4000 Hz using the TMC procedure. Data collection began prior to the publications by Lopez-Poveda et al. (2003); Plack and Drga (2003) and Nelson and Schroder (2004). The present results support those recent studies. A secondary goal was to compare the growth rates obtained from TMCs with those from distortion product otoacoustic emission (DPOAE) I–O functions in the same group of subjects. The results of those comparisons support the notion that TMCs provide an estimate of the compressive response of the BM.

2. Experiment 1

2.1. Methods

2.1.1. Subjects

Four normal-hearing listeners with ages ranging from 19 to 34 years participated. All had absolute thresholds no greater than 10 dB HL at octave frequencies between 250 and 8000 Hz (ANSI, 1996). With the exception of S4 (the first author), subjects were paid for their participation. All subjects were inexperienced with these listening tasks and were given at least 4 h of practice before data collection began. This experiment was approved by the Institutional Review Board at Arizona State University.

2.1.2. Apparatus and stimuli

The sinusoidal signals and maskers were digitally generated and produced at a 50-kHz sampling rate. The signal and masker were produced via separate channels of a digital-to-analog converter [Tucker-Davis Technologies (TDT) DD1]. The output of each was low-pass filtered at 8 kHz (TDT FT6-2), attenuated (TDT PA4), and then added together (TDT SM3). The summed waveform was digitally shaped to flatten the frequency response of the headphones as measured with a flat-plate coupler. The shaped waveform was sent to one earpiece of a pair of headphones (Sennheiser HD 250 linear II) via a headphone buffer (TDT HB6). Signal frequencies were 250,