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Cochlear compression in listeners with moderate sensorineural hearing loss

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Abstract

Psychophysical estimates of basilar membrane (BM) responses suggest that normal-hearing (NH) listeners exhibit constant compression for tones at the characteristic frequency (CF) across the CF range from 250 to 8000 Hz. The frequency region over which compression occurs is broadest for low CFs. This study investigates the extent that these results differ for three hearing-impaired (HI) listeners with sensorineural hearing loss. Temporal masking curves (TMCs) were measured over a wide range of probe (500–8000 Hz) and masker frequencies (0.5–1.2 times the probe frequency). From these, estimated BM response functions were derived and compared with corresponding functions for NH listeners. Compressive responses for tones both *at* and *below* CF occur for the three HI ears across the CF range tested. The maximum amount of compression was uncorrelated with absolute threshold. It was close to normal for two of the three HI ears, but was either slightly (at CFs $\leqslant$ 1000 Hz) or considerably (at CFs $\geqslant$ 4000 Hz) reduced for the third ear. Results are interpreted in terms of the relative damage to inner and outer hair cells affecting each of the HI ears. Alternative interpretations for the results are also discussed, some of which cast doubts on the assumptions of the TMC-based method and other behavioral methods for estimating human BM compression.

Keywords: Basilar membrane; Cochlear compression; Recovery from forward masking; Hearing loss; Inner hair cell; Outer hair cell

1. Introduction

The mammalian basilar membrane (BM) responds compressively to sound level in a frequency-selective manner (Rhode, 1971; Robles and Ruggero, 2001). Low-level sounds elicit a narrowly tuned response that grows nonlinearly with level to become more broadly tuned at high levels (Ruggero et al., 1997; Rhode and Recio, 2000). The degree of compression is less for frequencies well below the characteristic frequency (CF) of the recording site (for a review see Robles and Ruggero, 2001). This response pattern is vulnerable to acoustic trauma, cochlear injury or death (for a review see Ruggero et al., 1996 and Robles and Ruggero, 2001). Direct measurements of BM motion on acoustically or chemically traumatized cochleae show reduced sensitivity near CF and broadly tuned responses that grow more linearly with level than do the responses of healthy BMs. This study investigates how *human* BM compression, as estimated by behavioral methods,

Abbreviations: BM, basilar membrane; CF, characteristic frequency; HI, hearing impaired; IHC, inner hair cell; NH, normal hearing; OHC, outer hair cell; TMC, temporal masking curve; RP, receptor potential; SL, sensation level; SD, standard deviation; SPL, sound pressure level

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change as a result of moderate sensorineural hearing loss.

Estimates of human BM compression may be inferred from masked thresholds (for reviews see Oxenham and Bacon, 2004; Bacon and Oxenham, 2004). Forward-masking techniques are preferred because they avoid the suppressive effects that can contribute to simultaneous masking. Nelson et al. (2001) proposed one such technique in which BM responses are derived from temporal masking curves (TMCs). A TMC is a plot of the level of a forward masker required to mask a fixed low-level probe as a function of the time interval between the masker and the probe. As the time interval increases, the masker level required increases. However, the rate of increase varies across masker frequencies. For masker frequencies well below the probe frequency, it appears to be constant (at least for high-frequency probes, see Lopez-Poveda et al., 2003; Nelson and Schroder, 2004; Plack and Drga, 2003). On the other hand, for masker frequencies close or equal to the probe frequency, the rate of increase changes as the delay between the masker and the probe increases. In fact, these TMCs show two or three segments with clearly different slopes. Nelson et al. (2001) reasoned that the steeper segments reflect BM compression. Their reasoning requires a number of assumptions. First, it assumes that during the task the listener is always attending to the place on the BM tuned to the probe frequency. Second, it assumes that the internal effect of the masker decays with time in the same way for *all stimulation frequencies* at a given CF. Third, it assumes that the BM is the only source of frequency-specific compression before the effect of the masker interacts with the effect of the probe. If these assumptions hold, BM response functions may be inferred from TMCs by plotting the levels for a masker frequency that elicits a linear BM response (hereafter referred to as the "linear reference TMC") against the levels for any other masker, paired according to time interval.

Lopez-Poveda et al. (2003) used this technique to estimate BM compression in normal-hearing (NH) listeners over a range of CFs from 500 to 8000 Hz, and at a number of stimulation frequencies relative to each CF. They concluded that the degree of cochlear compression for frequencies at CF is approximately constant over the range of CFs they studied. Their compression estimates for tones at CF correspond to BM input/output functions with slopes of 0.2–0.3 dB/dB. They also concluded that the response of the BM is compressive to a wider range of stimulation frequencies (relative to CF) in the apical region of the cochlea. In the basal region, however, the estimated compression was restricted to stimulation frequencies close to CF. Additional studies (Nelson and Schroder, 2004; Oxenham and Dau, 2004; Plack and Drga, 2003; Williams and Bacon, 2005) have confirmed these results with the same or other methods and extended them to other CFs.

The present work extends the study of Lopez-Poveda et al. (2003) to hearing-impaired (HI) listeners. Identical stimuli and methods are used to here to allow a direct comparison between the present results and those previously reported for NH listeners. The aim is to characterize the consequences of this type of hearing impairment with regard to BM compression. A recent study (Plack et al., 2004) on the CF region of 4000 Hz suggests that NH listeners and listeners with mild-to-moderate sensorineural hearing loss may show similar degrees of BM compression. They differ, however, in that compression extends over a narrower range of sound levels in the HI listeners. One aim of the present study was to determine whether this result can be generalized to a wider range of CFs (500–8000 Hz). Furthermore, given that the compression pattern seems to be clearly different at low CFs, another aim was to determine whether at low CFs the compression for tones well below CF changes for HI listeners.

2. Material and methods

2.1. Stimuli

TMCs were measured for probe frequencies (f_p) of 500, 1000, 2000, 4000, and 8000 Hz, and for masker frequencies (f_m) of 0.5, 0.6, 0.7, 0.9, 1.0, 1.05, 1.1, and $1.2 \times f_p$, although some masker frequencies were not tested for all listeners. For any given masker-probe pair (f_m,f_p), masked thresholds were measured for masker-probe intervals ranging from 10 to 100 ms in steps of 10 ms. The time interval was defined as the duration of the silence period between the masker offset and the probe onset. The sinusoidal maskers were gated with 5-ms raised-cosine onset and offset ramps and had a total duration of 110 ms. The sinusoidal probes had a total duration of 10 ms and were gated with 5-ms raised-cosine ramps (no steady-state portion). The level of the probe was kept constant at approximately 14 dB sensation level (SL) for two of the listeners (DHA and ESR), but 10 dB SL for the third listener (ETA).

Because data were collected over a long period of time, different equipment was employed for different listeners. For two of the listeners (DHA and ESR), stimuli were generated digitally on a Silicon Graphics™ O2 workstation at a sampling rate of 32 kHz, with 16-bit resolution. For the third listener (ETA), however, stimuli were generated with a Tucker Davis Technologies™ psychoacoustics workstation (System III) at a sampling rate of 48.8 kHz and 24-bit resolution. All stimuli were played monaurally via the workstations' headphone connections through the same pair of circumaural Sennheiser HD-580 headphones. Listeners sat in a double-walled sound-attenuating room. The sound pressure