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A Phon Loudness Model Quantifying Middle Ear & Cochlear Sound Compression:

Towards Assessing Acoustic Reflex Protection from Intense Sound

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ABSTRACT

The acoustic reflex is an automatic gain control (AGC) system providing one of the defenses against intense sound. Not only can the acoustic reflex be stressed and damaged by excessive sound, but because it requires time for neural feedback, this AGC sound compression can be too slow to cope with sudden intensity increases, such as blasts. Moreover, while the reflex is triggered by the full range of audio frequencies, compression of middle ear transmission is restricted to frequencies below 2000 Hz. Another possible defense is cochlear nonlinear sound compression, which responds with effectively no delay, but cochlear hair cell gains are fully compressed by about 95 phons, so that for sound levels above 95 phons it provides no protective function. However, the cochlea compression mechanism teaches how bandpass nonlinearity filters with instantaneous gain compression can be designed to compress sound at all levels and still provide useful sound quality.

A phon loudness model including both compression mechanisms was developed to account for equal loudness sound pressure levels measured by Lydolf and Moller (1997) at third octave frequencies below 1 kHz. Their data at each frequency exhibit clear departures above 60 phons from uniform level versus phon gradients. This phenomenon is neglected in the current international standard for phon levels versus frequency, as a result of fitting phon data to uniform power laws (ISO 226:2003, Suzuki and Takeshima, 2004). The consistency of Lydolf and Moller's data with middle ear sound compression above 60 phons is supported by Rabinowitz's (1977) direct measurements of middle ear compression using a novel method based on aural combination tone phase (Rabinowitz & Goldstein, 1973).

Cochlear compression in the new phon model is represented with a loudness model (Goldstein, 2009) whose parameters are fit to Lydolf and Moller's data at 20, 40 and 60 phons. The fitted model represents the cochlea with frequency-dependent uniform compression between 29 to 95 phons, and with linearity below and above this range. The cochlear model predicts sound levels required for loudness above 60 phons. Lydolf and Moller's measured levels in excess of the predicted levels at 80, 90 and 100 phons are attributed to middle ear sound compression by the acoustic reflex. A correct estimate of middle ear compression requires knowledge of this compression at 1000 Hz, which is provided by Rabinowitz's measurements. It is not directly available from the phon data, because this frequency serves as the phon loudness reference. Middle ear compression at lower frequencies quantified by the complete model from the phon data is consistent with Rabinowitz's (1977) measurements and extensions to low frequencies with his proposed reflex model based on Zwislocki's (1962) acoustic model of middle ear physiology.

The complete phon model serves as a tool for improving understanding of the function and limitations of physiological mechanisms involved in protection against intense sounds. This knowledge would contribute to improved technologies and interventions for blast protection and treatment of injury. [Research originated in NIH grants to JLG, 1972-2004.]