A Phon Loudness Model Quantifying Middle Ear & Cochlear Sound Compression: Towards Assessing Acoustic Reflex Protection from Intense Sound

Julius L. Goldstein, PhD, Hearing Emulations (hearem.com), St. Louis, MO

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'a 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.]

Preview of Figures

1 Standard PHON Contours: ISO 226:2003.

2 Phon data: Lydolf and Moller (1997).

3 MEM data: Rabinowitz (1977).

4 (MECALP) Phon model with middle-ear and cochlear-amplifier sound compression.

5 MECALP model of phon data.

6 Evidence for two cochlear responses.

7 Agreement of MEM models and MEM data.

8 MEM variability among normal subjects.

9 MECALP models of MEM compression at extreme sound levels.

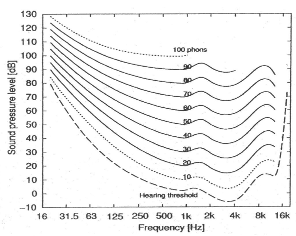

Fig. 1 STANDARD PHON CONTOURS: ISO 226:2003. Idealized smoothing of phon data above 60 phons has removed evidence for middle ear compression. From Suzuki & Takeshima (2004).

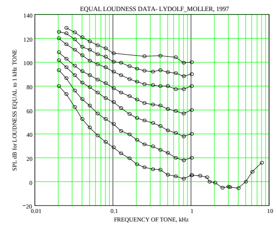

Fig. 2 Lydolf & Moller's (1997) normative phon data, cited by Suzuki & Takeshima (2004). Data are third octave means for normal hearing subjects. 27 subjects listened in a free field at frequencies 50 –1000 Hz, and 14 subjects listened in a pressure field at 20 -100 Hz. These data are a major component of the ISO standard. (Conference report provided by Prof. Moller.)

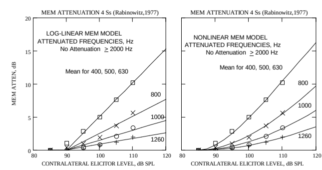

Fig. 3 MEM data, i.e. Middle-Ear-Muscle attenuation, (Rabinowitz, 1977, Fig. 11) are fitted in the present study with two different algorithms, log-linear and nonlinear MEM growth models, each with a common threshold at different frequencies. Rabinowitz's study employed a contralateral 2-4 kHz noise-band elicitor, which is not subject to MEM attenuation. The elicitors in the phon experiment are the target tones, which are subject to MEM attenuation. The two experiments differ with open versus closed loop configurations, and with monaural versus binaural elicitors. (Dissertation provided by Dr. Rabinowitz.)

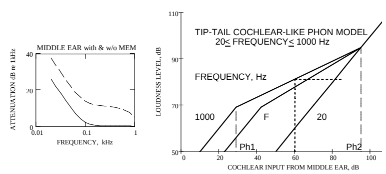

Fig. 4 (MECALP) Model used to quantify normal sound compression by the **M**iddle **E**ar and **C**ochlear **A**mplifier in equal **L**oudness data in **P**hon units. The Tip-Tail cochlear phon model is based on earlier modeling research (Goldstein, 2009) in which tuned cochlear responses are represented as linear at low and high sound levels joined with ideal power-law compression at intermediate levels (Ph1-Ph2).

Cochlear compression is represented with a loudness model (Goldstein, 2009) whose parameters were fitted with MSE estimation to Lydolf & Moller's data at 20, 40 and 60 phons. A 2nd-order 90 Hz high-pass middle ear fits the phon data better than 1st or 3rd orders. 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. Phon data in excess of predicted equal loudness levels at 80, 90 and 100 phons are attributed to middle ear sound compression by the acoustic reflex. Estimates of middle ear compression were obtained using each of the MEM growth algorithms suggested by Rabinowitz's MEM data, with parameters chosen to provide MSE fits to phon data.

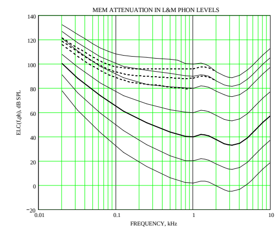

Fig. 5 MECALP model of Lydolf and Moller's phon data. The solid curves closely reproduce the phon data, retaining the large spacing between the 60 and 80 phon contours at low frequencies. The dashed curves show the 80–100 phon contours reduced by MEM compression. Both MEM growth algorithms yield similar MEM estimates at these phon levels. (See Fig. 9.) The 100 phon contour indicates that equally loud sound levels at 20, 100, and 3,000 Hz are about 130, 110, and 90 dB SPL, resp.

Notes:

1. The MECALP parameters, including MEM, were all calculated from the phon data. Smoothing was provided by replacing the 40 phon data with the similar but smoother ISO 40-phon contour, while retaining the original model parameters. The main effect is removal of depressions in the phon contours between 630-1000 Hz.
2. Extension of the phon contours above 1 kHz, assumes equally spaced contours between 1 – 10 kHz, for 20-80 phons.
3. The hearing threshold curve is approximated as an equal loudness contour, requiring it to be equally spaced at all frequencies below the 20 phon contour. Threshold data below 40 Hz rising above the equally spaced model contour was treated quantitatively as a stimulus increment required to overcome an intermodulation disturbance between external and internal signals.

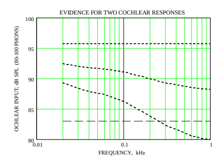

Fig. 6 Evidence for two distinct cochlear responses. The model cochlear inputs at phon levels 80, 90, and 100 shown above are the MEM attenuated phon contours from Fig. 5 minus quiescent middle ear attenuation. The acoustic reflex is triggered by cochlear inputs exceeding 83 dB. It is known that the acoustic reflex is insensitive to mild hearing losses, while loudness levels are sensitive (Gelfand et al, 1990). This behavior is consistent with two distinct cochlear outputs, possibly corresponding to afferent types I and II (Weisz et al, 2009; Mukerji et al, 2010).

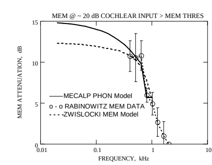

Fig. 7 Agreement of MEM models and data. Statistics are shown for 3 of 4 consistent subjects in Rabinowitz's (1977, Fig. 12) MEM measurements with a 110 dB SPL elicitor, which is ~20 dB above the subjects' MEM thresholds. The dashed line is calculated for the MEM model proposed by Rabinowitz based on Zwislocki's (1962) middle ear model. The solid line is a calculation of MEM attenuation for the MECALP model with a *cochlear input at 17 dB* above MEM threshold. Calculation based on the cochlear input approximately compensates for the difference between the open and closed loop MEM elicitors, but not necessarily for their one ear versus two ear presentations . (See Fig. 3.)

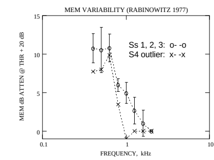

Fig. 8 MEM variability at 20 dB above MEM threshold (from Rabinowitz 1977, Fig. 12). One of 4 normal Ss had significantly less MEM attenuation above 630 Hz than the others, with no attenuation at 1-2 kHz. This behavior may be correlated with susceptibility to injury from intense sound. If so, MEM measurement can be used to profile individuals.

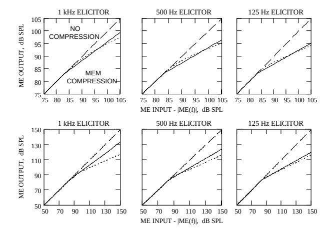

Fig. 9 MEM Compression at normal and extreme sound levels re quiescent middle-ear attenuation, based on MECALP modeling of Lydolf & Moller's data. At extreme SPLs the nonlinear MEM Model (**....**) predicts greater sound compression than the log-linear model (—). The Zwislocki physiological MEM model is more consistent with the nonlinear MEM algorithm. Experiments with animal models could resolve this.

CONCLUSION: Psychophysical measurement of equal loudness levels for simple tones provides information on sound compression by the acoustic reflex, which is quantifiable with an idealized model of the auditory periphery.

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