

# My 50 years of Cochlear Modeling

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# Abstract

The goal of this presentation is multi-fold: The *primary goal* is to discuss my present understanding of cochlear function. *Secondary goals* are to review my earlier (1970-1995) cochlear modeling work, along with the roles of four close friends: Egbert De Boer, Steve Neely, Paul Fahey and George Zweig.

To understanding of how the cochlea works, one needs an understanding of the experimental data on: **1**) cochlear function (both basilar (BM) and tectorial membranes (TM), **2**) tympanic membrane, **3**) middle ear (ME), **4**) inner and outer hair cells (IHC, OHC), **5**) auditory nerve (AN), and **6**) cochlear amplifier (CA). My views on these topics in the last 50 years have been sharpened, unifying this complex puzzle. A great deal of progress has been made over this time

**Conclusions:** My recent review of neural tuning curve data from 1985, using nonlinear (NL) distortion product generation, has revealed a deeper understanding of cochlear function. *The most surprising result is that the cochlea is more linear than previously assumed. NL behaviour:* “Low-side” suppression is when the suppressor frequency  $f_s$  is at least 1/2 octave lower than the characteristic (“best”) frequency ( $f_{cf}$ ). There is no “low-side” suppression for suppressors below 65 [dB-SPL]Fahey and Allen [1985]. Namely the system acts as if its linear. For suppressors above 65 [dB], the suppression dominates, with a slope of  $\approx 2$  [dB/dB]. The “obvious” explanation is that the neural threshold of excitation to both the inner and outer hair cells have approximately the same threshold. *Namely, the suppression threshold of the OHC, which control the NL suppression, are close to, or even equal to, the IHC threshold.*

If the IHC and OHC thresholds are the same in the tail of the tuning curves, then how can the CA function at threshold levels? This is a highly unexpected result, because low-side suppression, as measured on the basilar membrane, has a 20-30 [dB] higher threshold [Cooper, 1996, Geisler and Nuttall, 1997]. *Is the OHC action restricted to the neighborhood of the neuron’s best frequency (BF)?*

This would require that the neural low-side suppression and loudness recruitment (the reduced loudness of low-intensity sounds in the hearing-impaired ear) are closely related (i.e., must be the same phenomena). The ramifications of this observation seem important as they will impact the diagnosis of cochlear hearing loss, thus the fitting of hearing aids [Allen, 1991, 1990; [See comment by Lyon, page 332](#)],

*In summary:* **Low-side suppression acts like an automatic gain control, elevating the loudness threshold with no audible distortion.**

The PDFs cited here is: <https://auditorymodels.org/index.php?n=Main.Publications>.

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- Secondary goals are to review my earlier (1970-1995) cochlear modeling work, along with the roles of four close friends: Egbert De Boer, Steve Neely, Paul Fahey and George Zweig
- To understand the cochlea, one needs experimental data on the following:
  - The sound pressure level in the ear canal at frequency  $f$
  - The ear canal volume
  - The ear canal admittance
  - The middle ear transfer function
  - The cochlear input and output admittances
  - The cochlear input admittance
  - The cochlear output admittance
  - The best frequency of neural tuning curves
  - The neural tuning curves
- My views on these topics have been sharpened by looking back and unifying this complex puzzle. A great deal of progress has been made in the last 50 years.

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  - $P_{in}(f)$ : sound in the ear canal at frequency  $f$
  - $P_{out}(f)$ : sound in the ear canal at the same frequency
  - $T_{in}(f)$ : total impedance at the ear canal
  - $T_{out}(f)$ : total impedance at the round window
  - $S(f)$ : average power spectrum of neural firing rates
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  - DP: Distortion product
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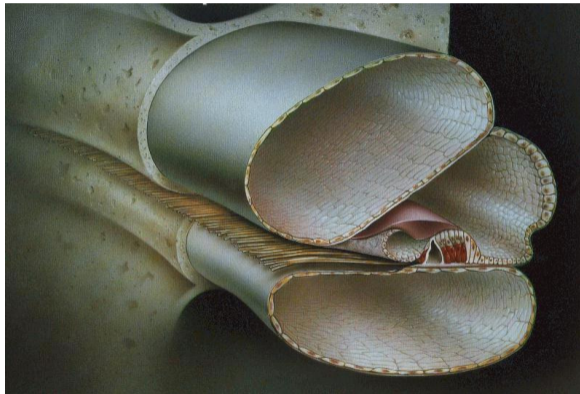
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# The cochlea

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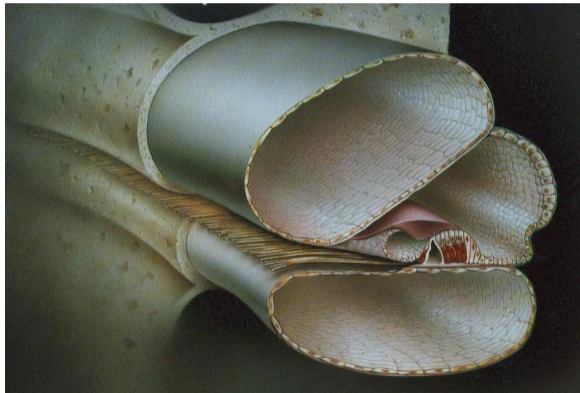


**Figure:** Great picture showing the two cochlear ducts, the Basilar membrane (BM), and the organ of Corti (OoC). The OHC and IHC are buried between the tectorial and basilar membranes.

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# Four experiments

- Four different key experiments are summarized:

- ① The “Allen-Fahey experiment”: Measure the gain of the CA [Allen and Fahey, 1992, AF-92]
- ② The “Second-Filter experiment” [Fahey and Allen, 1985, FA-85]
- ③ The “2d cochlear-map experiment”: Tuning of DPoae responses [Allen and Fahey, 1993, AF-93]  
There is a strange correlation  $\approx 1/2$  oct  $< BF$  (where the tail and tip join)  
This led support to the *resonant-TM 2d filter hypothesis* [Allen and Sen, 1999]
- ④ Kim, Siegel, Molnar (1979): “Kim-Phase population experiment”:  
Phase of a single tone is measured for a large number of tuning curves [Kim et al., 1979, KSM-79]  
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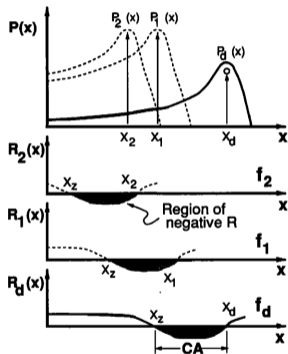
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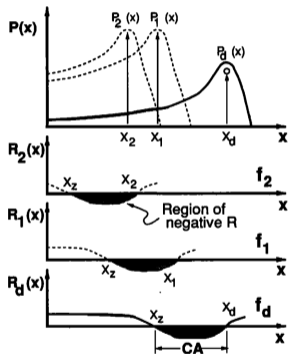
- Two primary frequencies @  $f_2 > f_1 \gg f_d$  create NL DPOAE @  $f_d = f_1 - (f_2 - f_1) = 2f_1 - f_2$



- The two tones "mix" in the region between  $x_2 < x_1$ , but mostly near  $x_2$
- The regions of the CA is assumed to be the three shaded region ( $x_z < x_2(f_2) < x_1(f_1) \ll x_d(f_d)$ )

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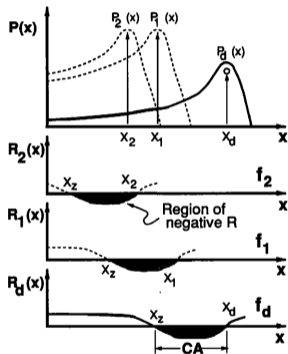
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## Exp-I (AF-92): Measure the gain of the Cochlear Amplifier (CA)

- Basic idea: move the acoustic source from the ear canal onto the BM, by using DPOAEs
- Record from a neuron having BF frequency  $f_{bf}$
- Fixed the DP frequency  $f_d = f_1 - (f_2 - f_1)$  equal to  $f_{bf}$
- Fixed the DP pressure @ neurons threshold
- Vary the source location at  $X_2(f_2)$  along the BM @  $X_2(f_2) < X_d(f_d)$ .
- Move source through the region of negative resistance (region of CA gain)
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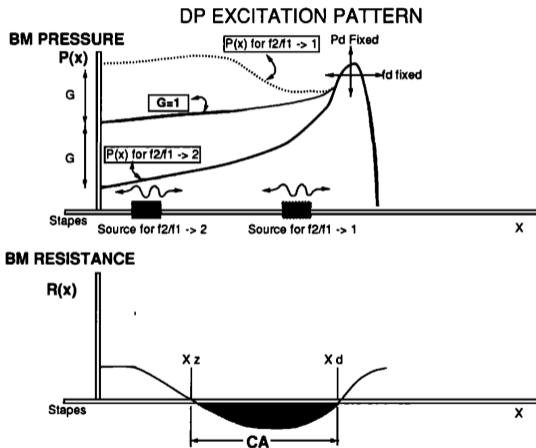
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# Measuring the gain of the CA via a BM DPOAE-SOURCE

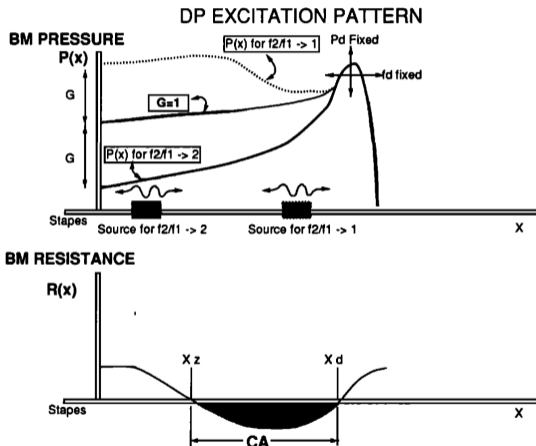
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Experimental data:

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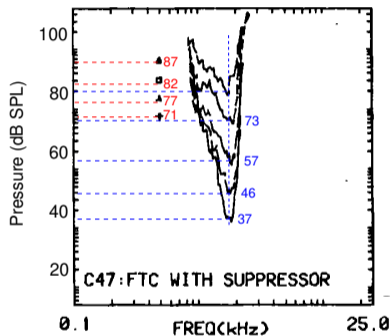
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## Example of Low-side suppression (FA-85)

- $BF = 1.8 \text{ kHz}$ ,  $f_2 = 500 \text{ [Hz]}$ ,  $f_1 = (1800+500)/2 = 650 \text{ [Hz]}$

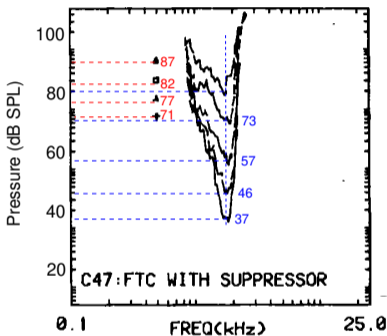


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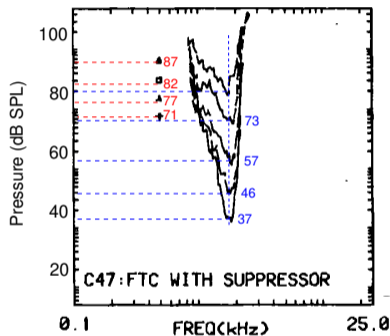
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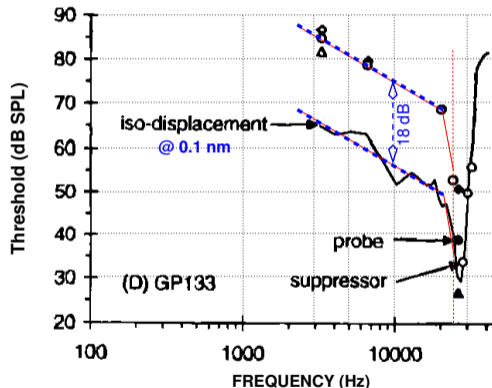
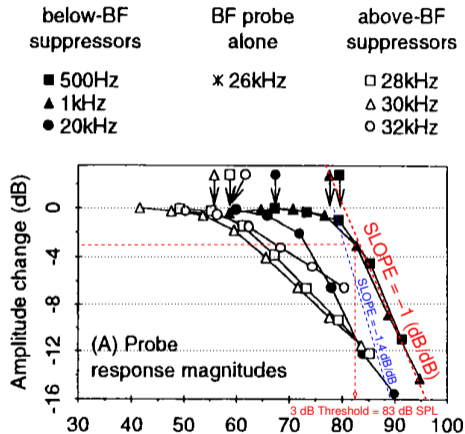
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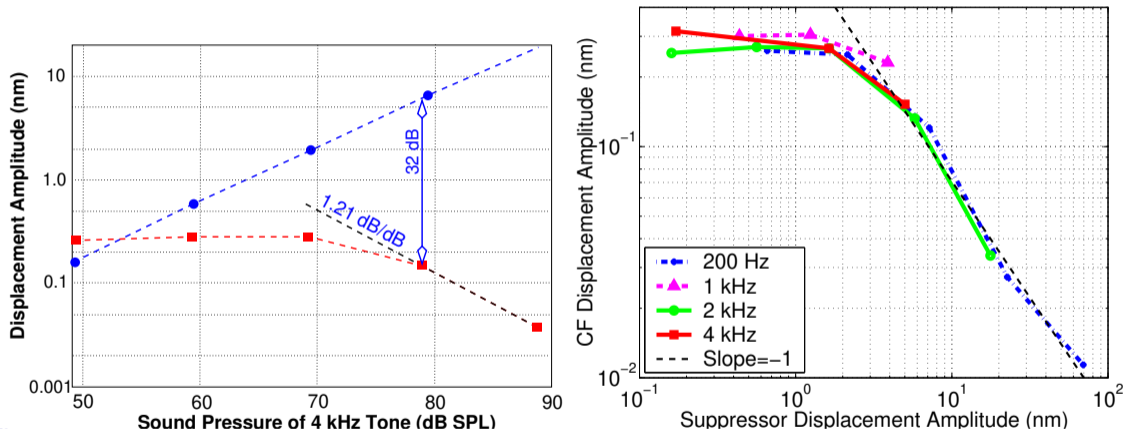
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# Low-side suppression on the BM [Cooper, 1996]



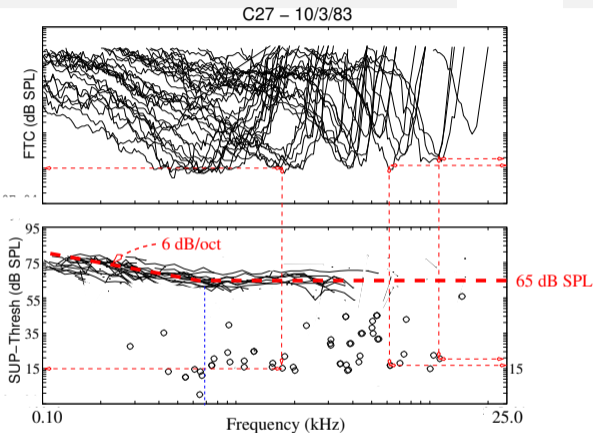
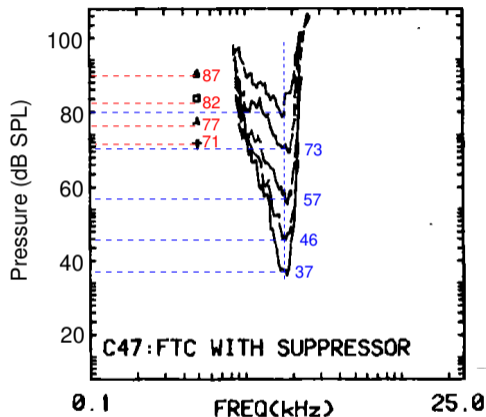
**Figure:** LEFT: BM Suppression of a 26 [kHz] probe by Low-side suppressors @ 0.5, 1, 20 [kHz] RIGHT: BM Suppression as a function of frequency The BM low-side suppression is very different from the neural data of AF-93: 1) The detection and suppression threshold are 18 [dB] apart, and 2) it depends on frequency [Cooper, 1996]

# Low-side suppression on the BM [Geisler and Nuttall, 1997]



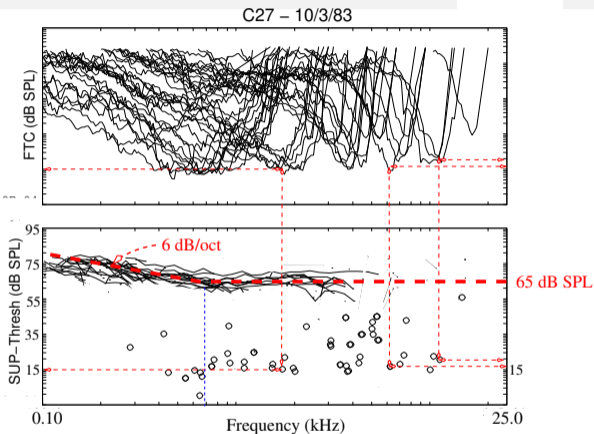
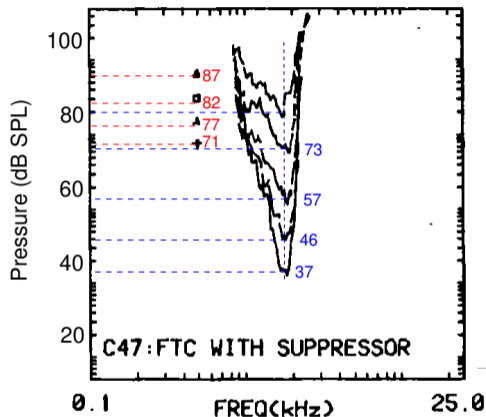
**Figure:** LEFT: Data similar to that of [Cooper, 1996] showing low-side suppression on the BM. The suppressed tone frequency is 17[kHz]. There is no suppression at 69 dB and 6 [dB] for the 4 [kHz] tone is increased from by 10 dB from 69 to 79 [dB-SPL] compared to 0 [dB/dB] as seen neurally in AF-85. In this case the low-side suppression threshold difference at 0.1 [nm] is 32 [dB]. RIGHT: The BM low-side suppression is very different from the neural data of AF-93: 1) The detection and suppression threshold are 18 [dB] apart, and 2) it depends on frequency [Geisler and Nuttall, 1997].

# There is no low-side suppression below 65 [dB-SPL]



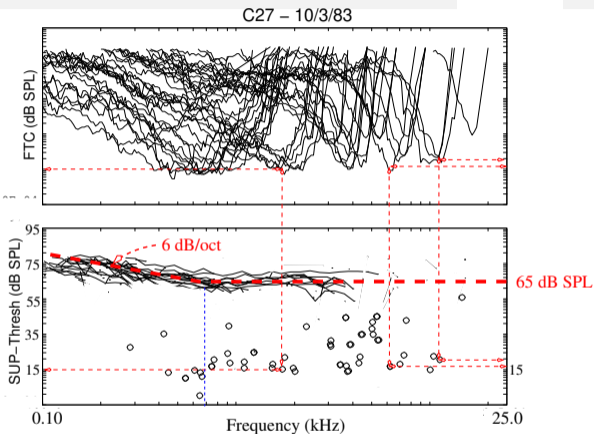
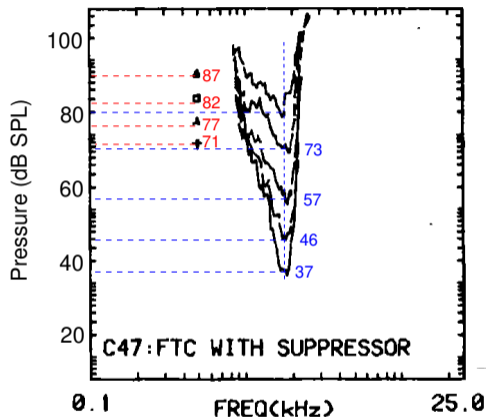
- The bold-red dashed line is the locus of Low-side suppression thresholds (@65 [dB-SPL])
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# Block model of Cochlear function

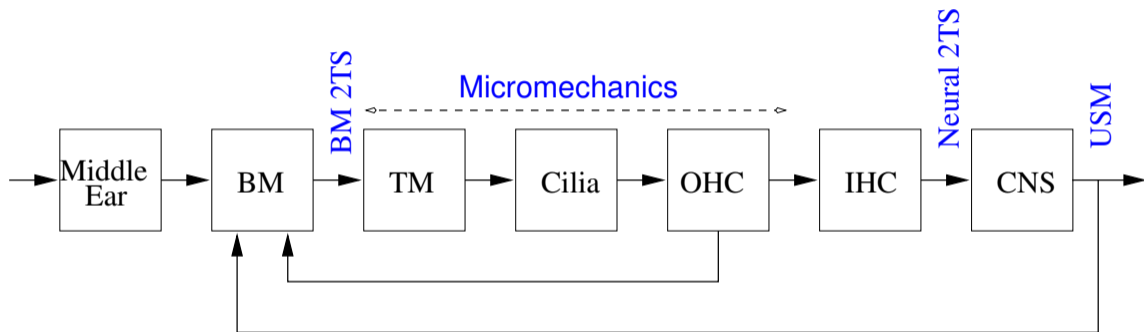


Figure: Sound enters via the middle ear, travels down the BM and TM, excites the cilia of the OHC, IHC → AN

If the two thresholds differ, that difference must be due to the TM



## Exp-III (AF-93): Slopes of cat neural tuning curves [dB/oct]

- Above CF  $f > f_{CF}$  and below CF  $f < f_{CF}$  the BF, as a function of the BF Allen [1983]
- The 2d cochlear map function is defined where tail and tip meet below BF [Allen and Fahey, 1993]

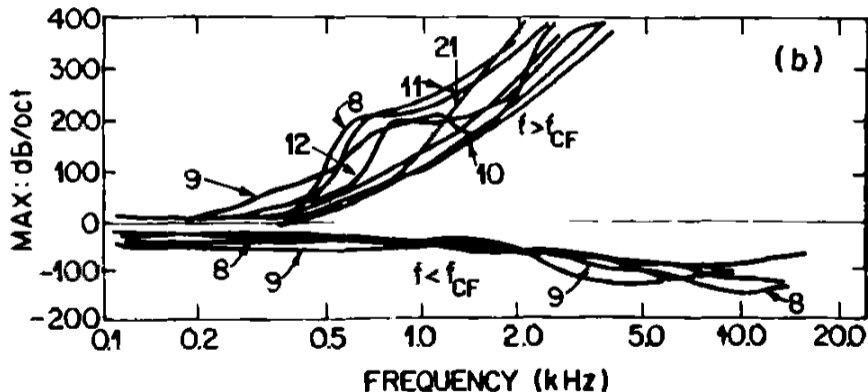


Figure: Neural tuning curve slopes above and below BF (Cat)

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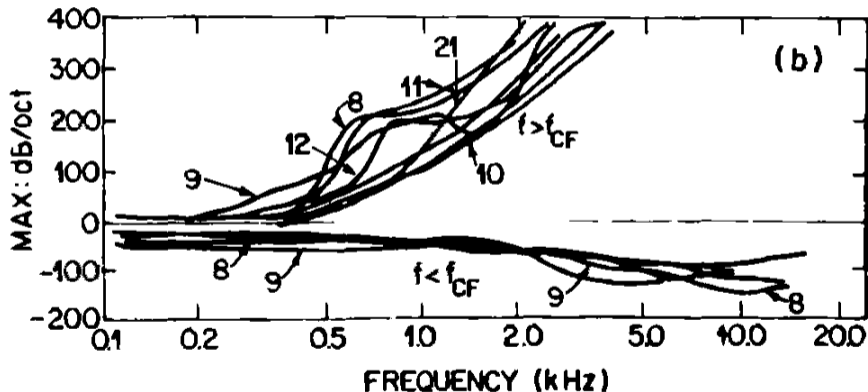


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## Exp-IV (KSM-79): Single-tone neural population study [Kim et al., 1979]

- Note the  $\pi$  phase shift just below 2 [kHz]. The arrow represents the tone frequency.

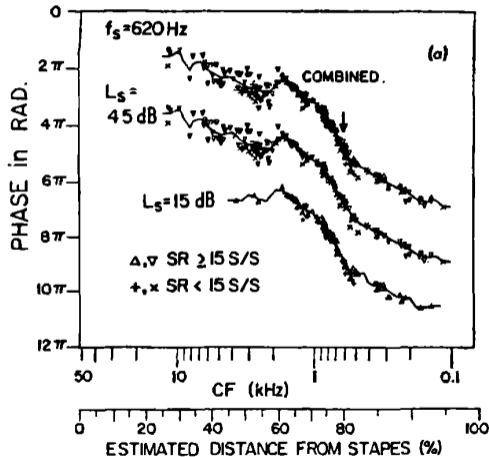


Figure: Population study: phase results [Allen, 1980]

# Nonlinear BM “migration” model

- Model tuning curves as a function of input level: 0, 20, 60, 80 [dB-SPL]  
LEFT: BM response with TM 2d-filter model.  
RIGHT: NL model as a function of level

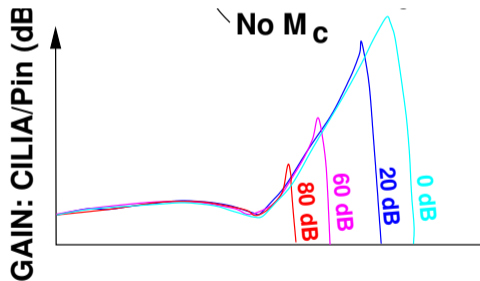
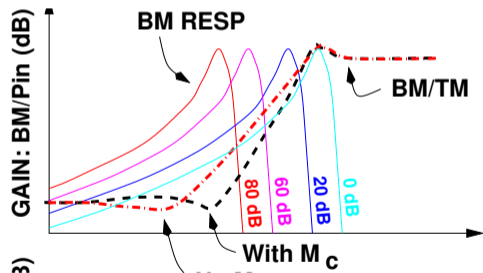


Figure: “Second filter” on TM at 2d cochlear map frequency.

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- BM Impedance as a function of input level: Note basal drop in stiffness with level
- The model assumes the OHC change the BM stiffness 2x with increasing input level

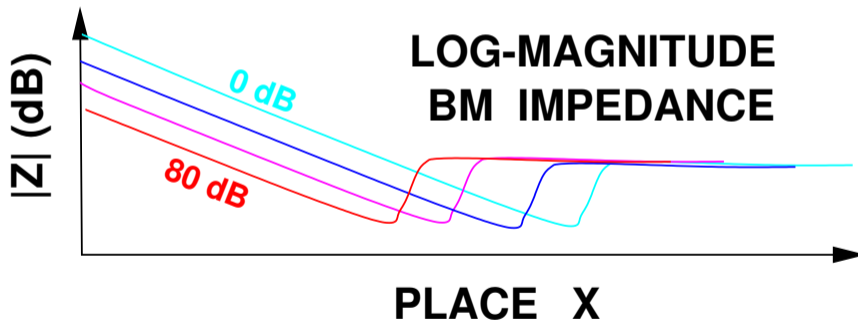


Figure: OHC stiffness decreases with increasing SPL [Dallos et al]

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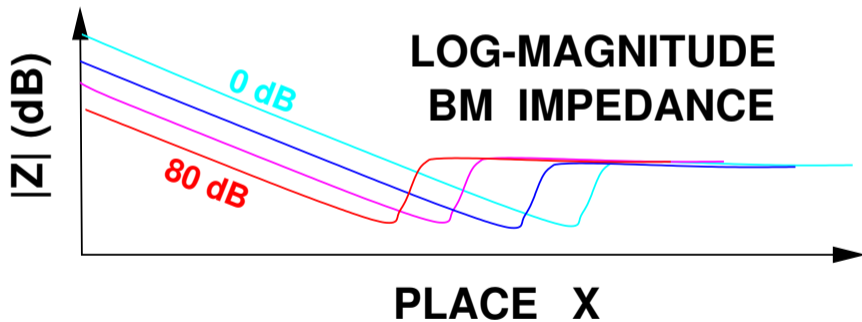


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# Nonlinear BM “migration” model

- Big picture of NL cochlear model

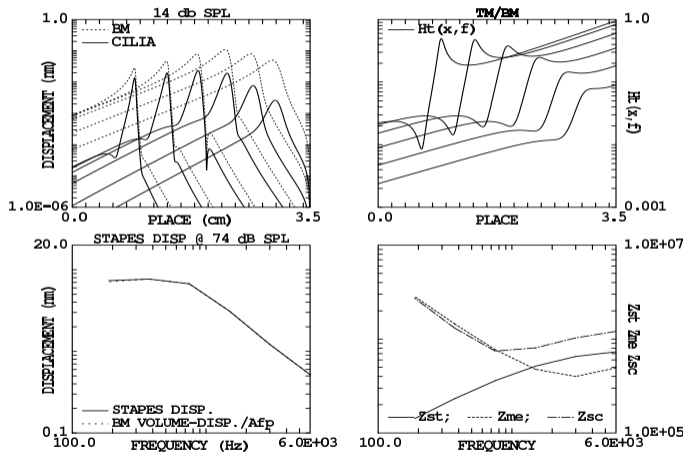


Figure: Migration figure.

# Model output Sen and Allen [2006]

- Input signal is a pure tone from 14-124 [dB-SPL]

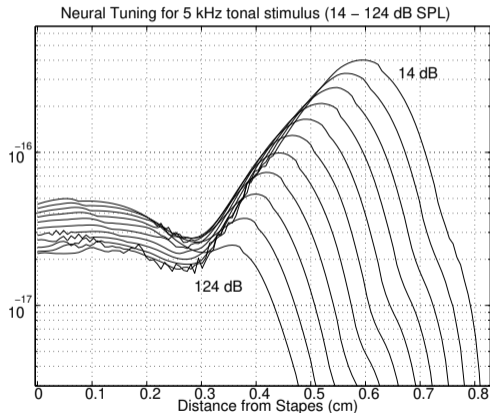


Figure: Results of the Sen-Allen time-domain model for a single input tone with varying level.



# Cartoon of Low-side suppression Allen [2001]

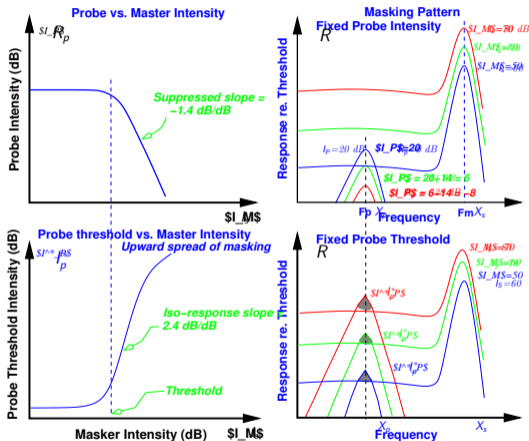


Figure: Cartoon shown a cartoon-model showing low-side suppression. Excitation is equal to suppression threshold.

# My 50 years of Conclusions

- Present view of cochlear tuning (BM vs Neural are very different → Second filter)
- The use of DPOAEs is key to our understanding of the cochlea
- The cochlea is much more linear in its filtering properties than we previously assumed
- Low-side suppression opens the door to an improved understanding of Cochlear function
- There is NO (i.e., zero) Suppression below 65 dB-SPL
- Above 65 dB-SPL, the suppression  $\approx 2$  [dB/dB]
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