Are basilar-membrane traveling waves necessary for long OAE delays?

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QUESTION

Are BM traveling waves necessary for long OAE delays?

MOTIVATION

How is energy propagated through the mammalian cochlea? If BM traveling waves are absent, would delays be smaller?
Comparative Approach

Systematic examination in wide range of ears where anatomy & physiology vary significantly

HUMANS

CHICKENS

GECKOS (two species)

FROGS
[Frog has two papillae]
COMPARING ACROSS SPECIES

SIMILARITIES: hair cells, tectorial membrane, ossicular/typanmonic middle ear

DIFFERENCES: tuned/flexible membrane, somatic motility, different sizes, fewer HCs

HEARING ACUITY:
- low thresholds (at least 20 dB SPL)
- tuned responses
- poor high frequency hearing
**How long is long?**

**Middle ear delays:** \(\sim 0.05-0.1 \text{ ms}\)
(possibly shorter in non-mammals)

**Inner ear:** \(\sim 1500 \text{ m/s (speed of sound in water)}\)
\(\sim 0.001-0.03 \text{ m (range of inner ear dimensions)}\)
\[\Rightarrow 0.001-0.02 \text{ ms}\]

**ballpark:** \(\sim 0.1 \text{ ms (excluding traveling waves)}\)
METHODS

- Stimulus frequency otoacoustic emissions (SFOAEs) (suppression paradigm)

- Phase response (frequency gradients) in steady-state used to determine delays

- ‘Low-Level’ stimuli used: $L_p=40$ dB SPL, $L_s=55$ dB SPL
SFOAEs  
Lp=40 dB SPL, Ls=55 dB, fs=fp+40 Hz
**SUMMARY**

*Long* delays (>1 ms) observed in all species

(being significantly largest in human)

**QUESTION:** Are BM traveling waves necessary for *long* OAE delays?

**ANSWER:** NO, *long* delays (~1 ms or longer >> 0.1 ms) arise in species lacking a tuned/flexible BM
Extending Further

Not due to differences between mammals and non-mammals nor size

[cat and guinea pig data from Shera and Guinan, 2003]
Extending Further

⇒ So where does the additional delay come from?

TUNING
Tuned Responses Take Time

\[ x(t) = A(\infty) \left[ 1 - e^{-t/\tau} \right] \]

Second Order System
(resonant frequency \( \omega_0 \))

\[ \Rightarrow \text{External driving force at frequency } \omega \]

\[ \tau = \frac{Q}{\omega_0} \]
Q and Phase Gradients Co-vary

Second Order System
(resonant frequency $\omega_o$)

\[ Q = \frac{\omega_o}{(2\pi \times \text{BANDWIDTH})} \]

\[ N = \frac{\omega_o \times \text{Phase Gradient}}{2\pi} \]

(at $\omega_o$)

\[ Q \propto N \]

(Shera, Oxenham and Guinan, 2007)
Plot Delay in Dimension-less Form as $N$

$L_p=40 \text{ dB SPL}, \; L_s=55 \text{ dB}, \; f_s=f_p+40 \text{ Hz}$

$N_{SFOAE} = \text{phase gradient} \times f_p$
Comparison of $N$ (SFOAE) to $Q$-value (ANF)
SUMMARY (II)

Similar frequency dependence between N and Q
[ for human, chicken and gecko]

Sharper tuning in human would account for differences
[ N-values relative to other species]

Additional delay not associated with tuning in frog
⇒ Due to unique anatomy (‘tectorial curtain’)?

Connection between tuning and traveling waves?
CONCLUSIONS

What has the comparative approach revealed?

BM traveling waves not needed for long OAE delays

Similarity in frequency dependence between OAE phase gradients and Q-values suggest tuning can account for delays in most species
Supported by NIH grants T3200038, DC0023821 (DMF) and DC03687 (CAS)
QUESTION 1

SFOAEs: Nonlinear suppression paradigm

**Step 1.**
Present Probe Alone
(export is present)

FFT reveals magnitude and phase **AT Probe Freq.**

**Step 2.**
Present both Probe & Suppressor tones
(export not present)

FFT reveals magnitude and phase **AT Probe freq.**

**Step 3.**
Subtract phasors

SFOAE revealed!!
Phase can reveal time delays
Input (stimulus we present)

- vary frequency of stimulus
- stimulus phase is ALWAYS 0 at t = 0

Output (response we measure)

- delaying = 7 ms

Phase Gradient

reference time we pick to measure phase (steady-state)

slope is 0.002 cycles/Hz,
or 2 ms → delay revealed!!

- f1 (1000 Hz) phase = 0 cycles (ϕ_A)
- f2 > f1 (1050 Hz) phase = 0.1 cycles (ϕ_B)
- f3 > f2 (1100 Hz) phase = 0.2 cycles (ϕ_C)
Nsfoae with cats and pigs

Lp=40 dB SPL

Emission Frequency [Hz]

[cat and guinea pig data from Shera and Guinan, 2003]