Effects of Stimulus Level and Hearing Status on OAE Latencies

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Acknowledgments

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Outline

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II. Frequency Tuning
III. OAE Generation
IV. OAE Latency
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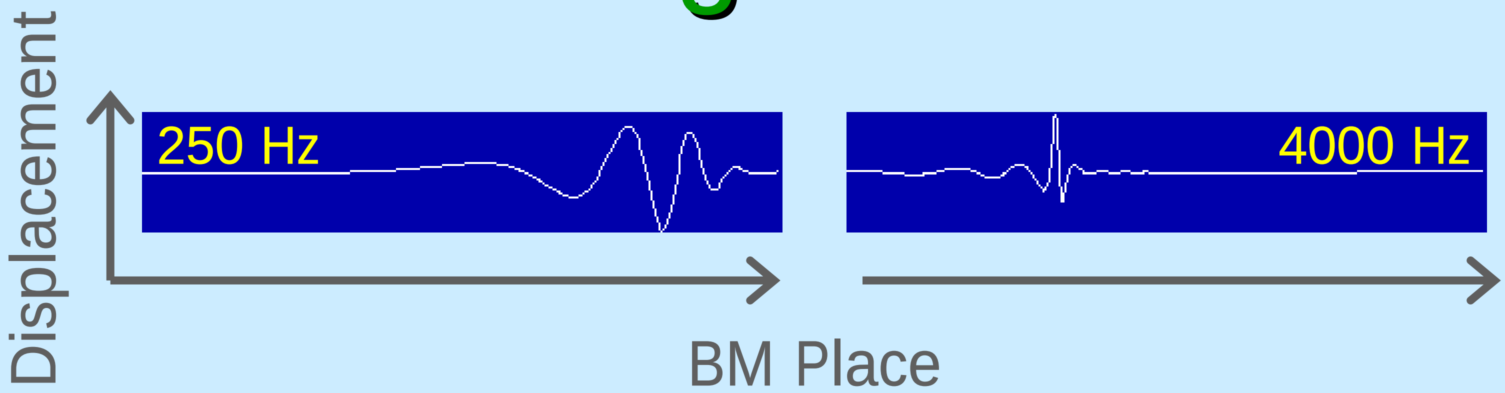
   – Relation to Generation Mechanisms
V. Experiment by Konrad-Martin & Keefe
VI. Future Directions

I. Traveling Wave Motion



- Each place is tuned (responds best) to a particular frequency
- Tuning actively sharpened at low stimulus levels by the cochlear amplifier (OHC motility?)
- Sharper tuning allows better frequency separation

Drawing found at
http://www.bcm.edu/oto/research/cochlea/ by
Stephen Neely, Communication Engineering
Laboratory, Boys Town National Research Hospital

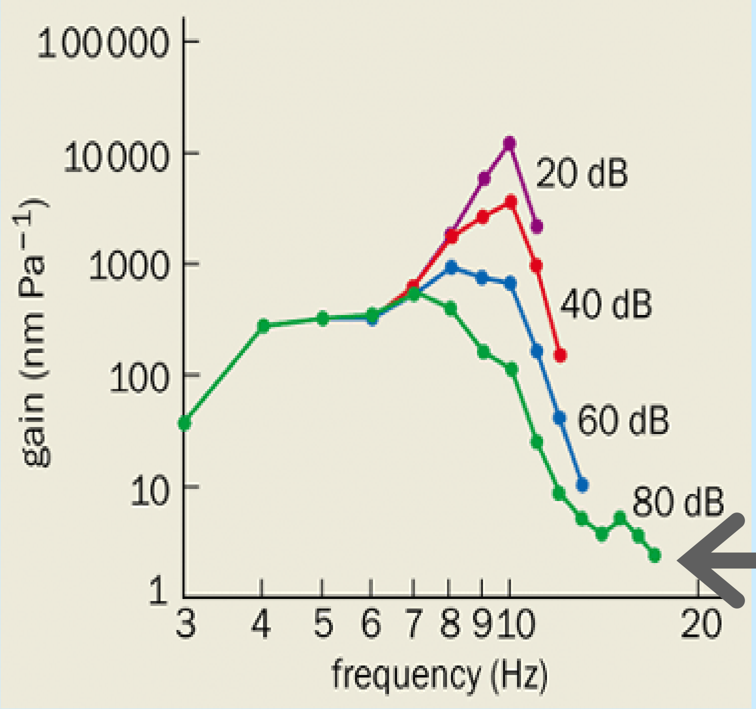
I. Traveling Wave Motion

- Stimulus frequencies are distributed according to BM place, with each characteristic frequency place determined by BM mass and stiffness
  - Stiff base (high frequencies vibrate best)
  - More compliant apex (low frequencies vibrate best)
- For each frequency, the BM responds with a traveling wave
  - Each bit of BM responds with a time delay
  - Short delay near base, delay increases at more apical positions
- For each traveling wave, the velocity decreases as the wave reaches its peak

I. Traveling Wave Motion

- Traveling wave slows down near the characteristic frequency place, with greater wave velocity decreases associated with sharper tuning of the resonant peak
  - At low levels (Zweig, 1991; Zweig & Shera, 1995)
  - For a BM modeled as a set of minimum phase filters (Zweig, 1976; de Boer, 1997)

II. Frequency Tuning

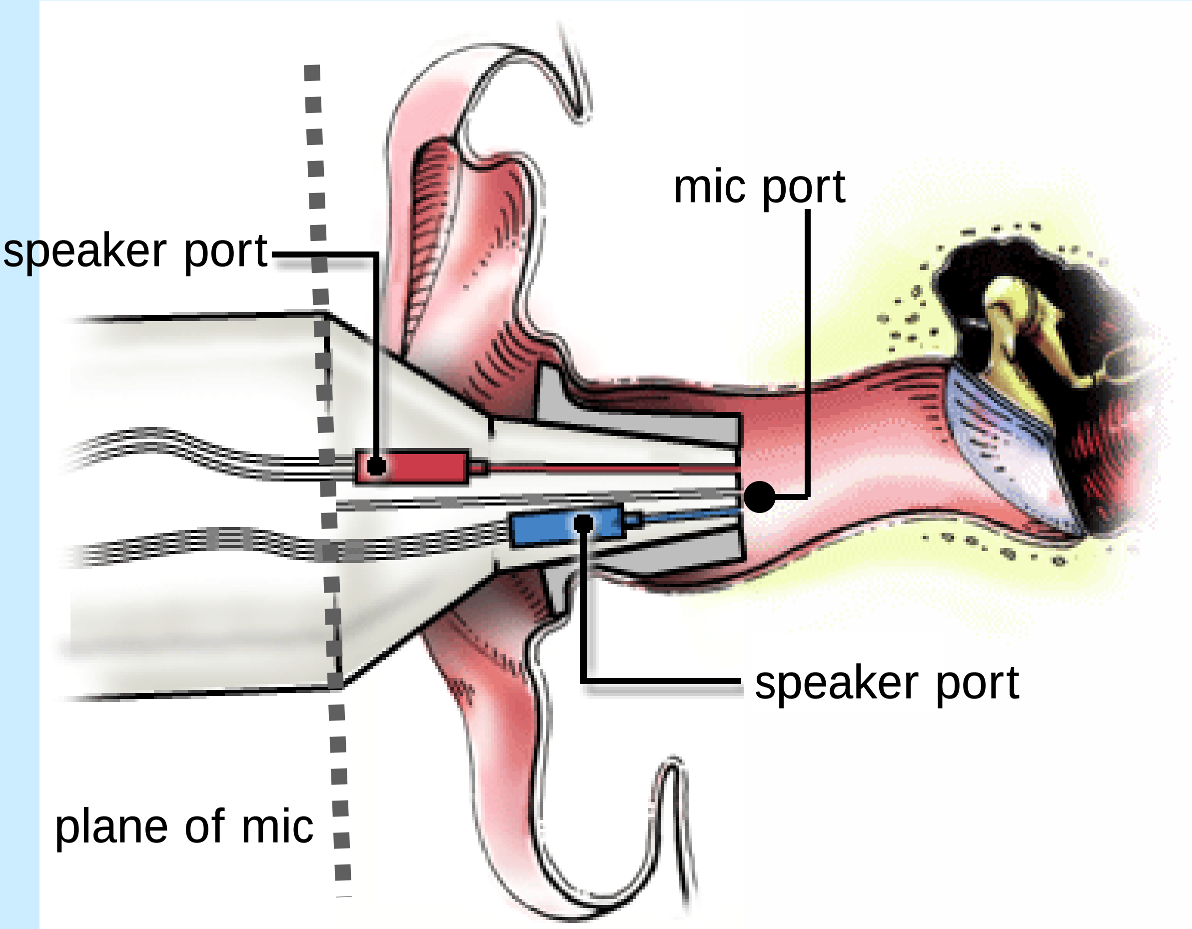


- Important for speech perception
- Established at basilar membrane
- Enhanced at low stimulus levels
- Diminished by hearing loss

High stimulus levels are required to elicit responses in impaired ears, amplified or not

Image provided by Luis Robles and Mario A. Ruggero, Northwestern University. As published in Mechanics of the Mammalian Cochlea, *Physiol. Rev.* 81: 1305-1352, 2001.

III. OAE Generation



Drawing adapted from S. Blatrix from "promenade around the cochlea" EDU website www.cochlea.org by Rémy Pujol et al., INSERM and University Montpellier

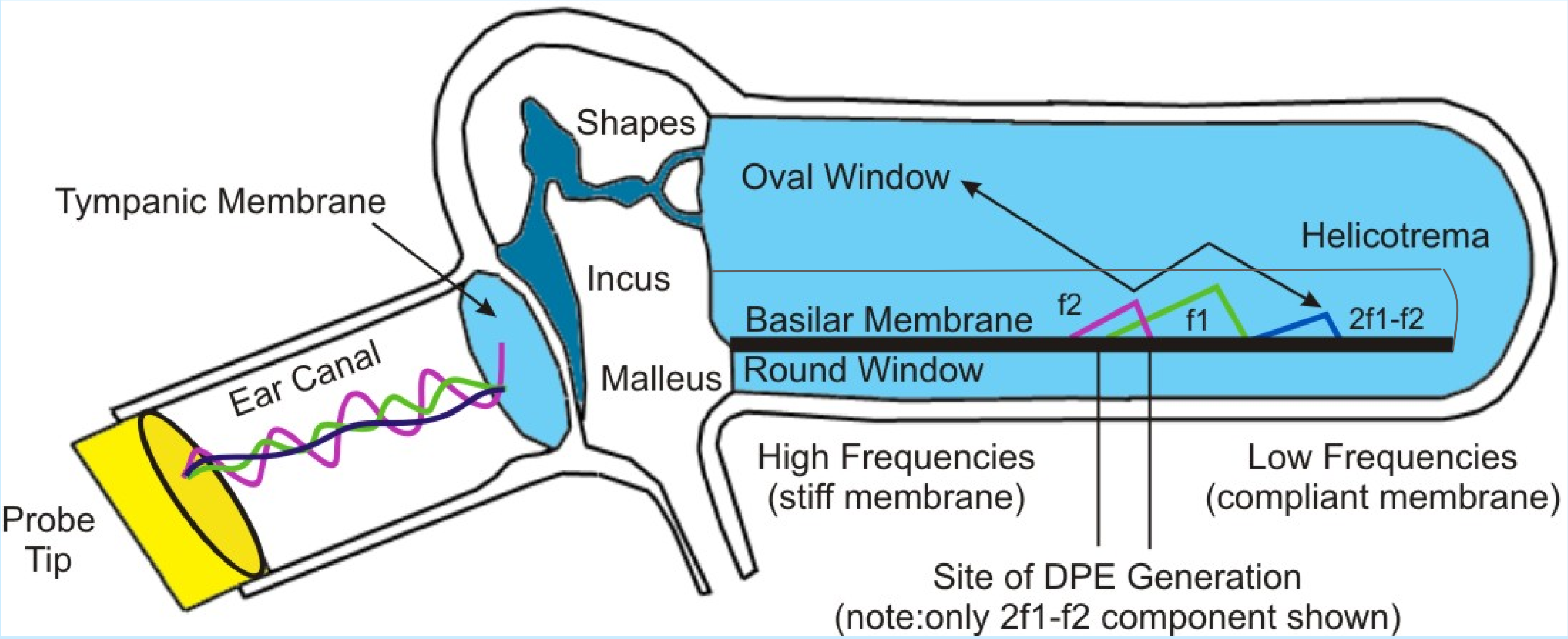
III. OAE Generation

- Evoked OAEs arise by a combination of coherent linear reflection & nonlinear distortion

- **Linear Reflection** –
  Due to coherent reflection of traveling wave from random impedance perturbations

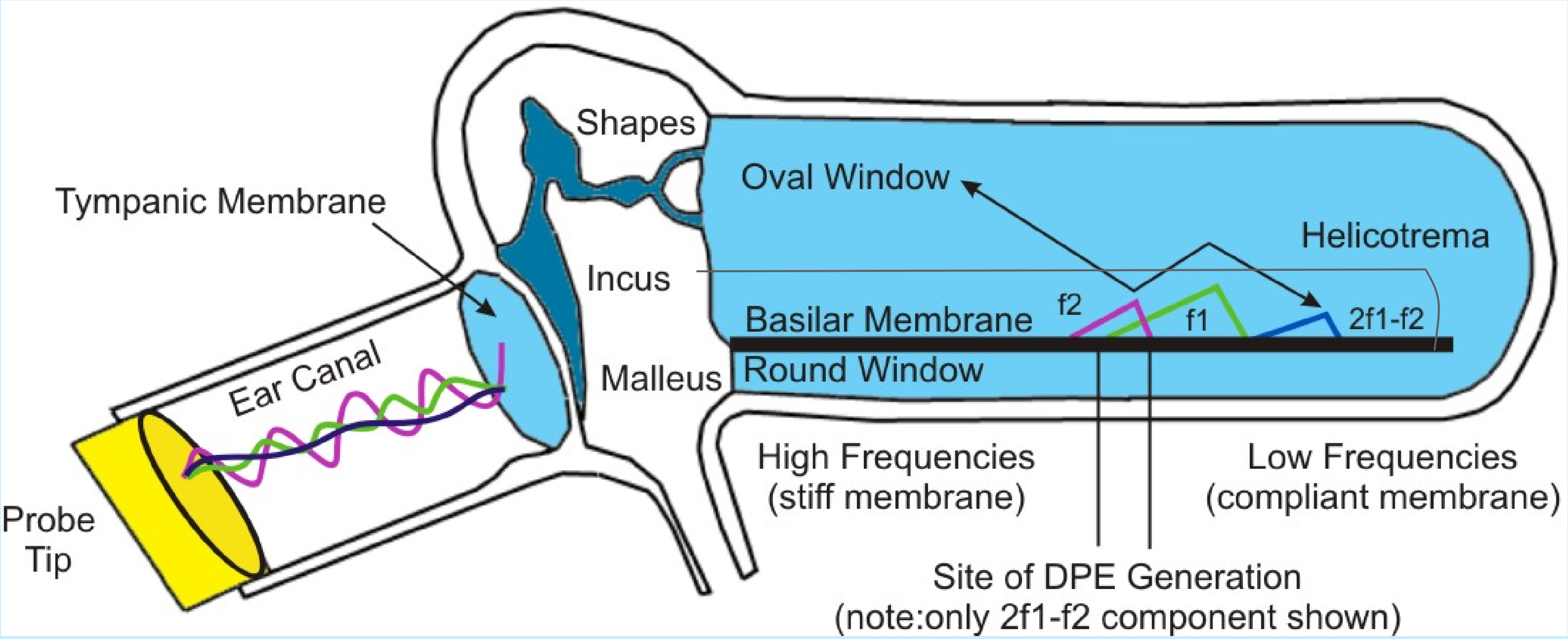
- **Nonlinear Distortion** –
  Due to nonlinearities acting as sources of cochlear traveling waves

DPOAE



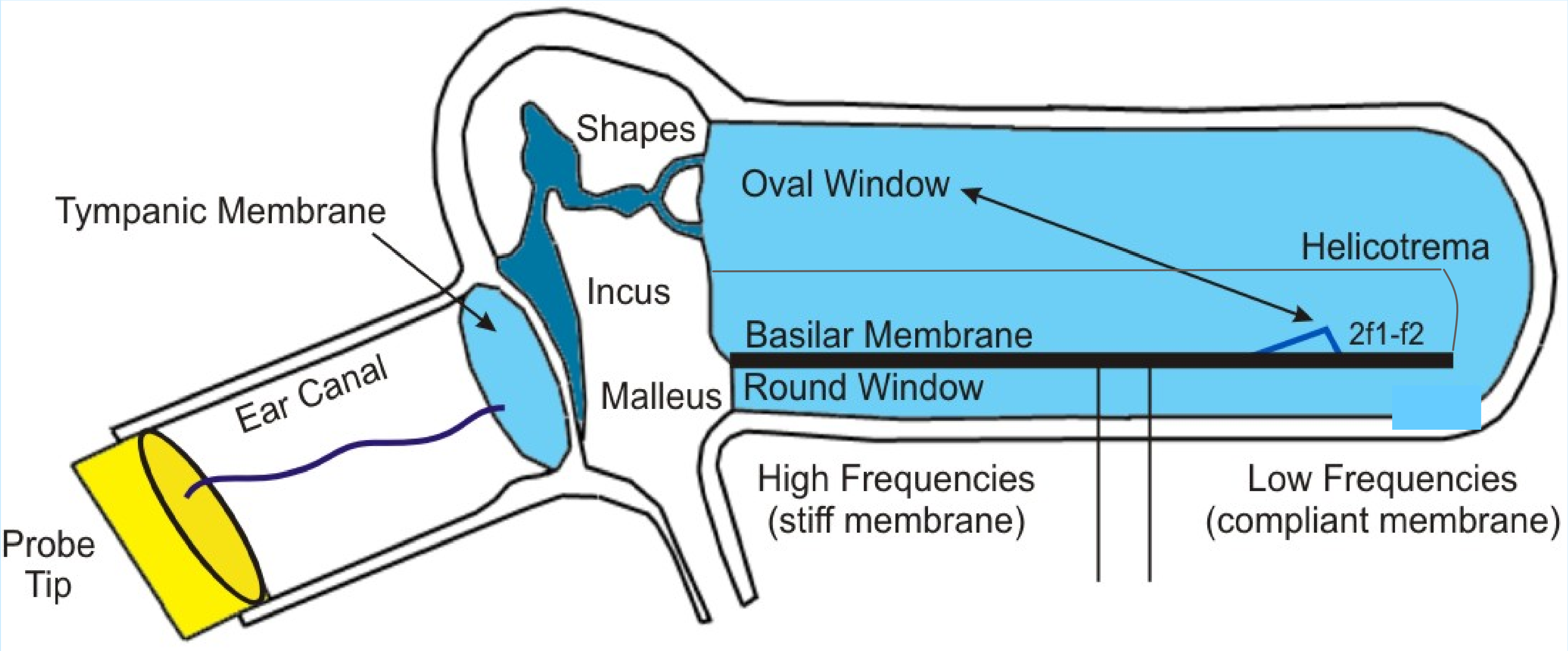
- Basilar membrane function is nonlinear in normal ears, i.e., output is distorted version of input
- Nonlinear interaction between stimulus frequencies generates distortion at $2f1$-$f2$
- This “distortion emission” is emitted from the f_2 place

DPOAE



- Some DP energy will travel (apically) to the basilar membrane place tuned to the DP frequency ($2f1$-$f2$)
- Elicits a "reflection emission" from the $2f1$-$f2$ place
- DPOAE distortion & reflection sites about ½ octave apart

SFOAE



- Due to coherent linear reflection of forward-traveling basilar membrane response near TW peak
- Reflection might be caused by slight anatomical abnormalities present in normal ears

I. OAE Generation (differences)

- Stimulus frequencies –

  DPOAEs = two different frequencies

  SFOAEs = one frequency (or two very similar frequencies)

- Dominant generation mechanism (?) –

  DPOAEs = both mechanisms (at least at low levels)

  SFOAEs = linear reflection (at least at low levels)

- Space between sources –

  DPOAE = ½ octave apart

  SFOAE = very close together

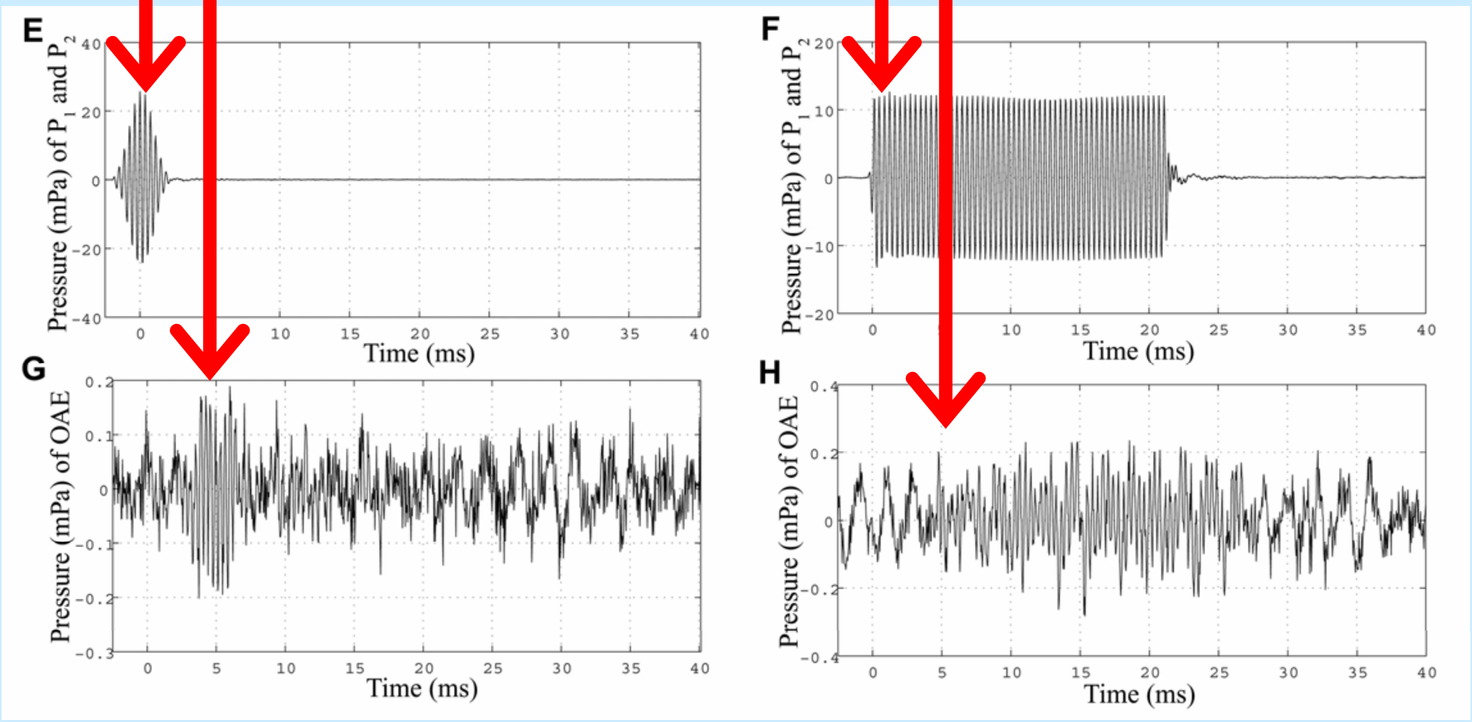
IV. OAE Latency

Time difference at peak SPL

Time difference at 6 dB down point

Stimulus

OAE



Tone-Pip-Evoked

Gated-Tone-Evoked

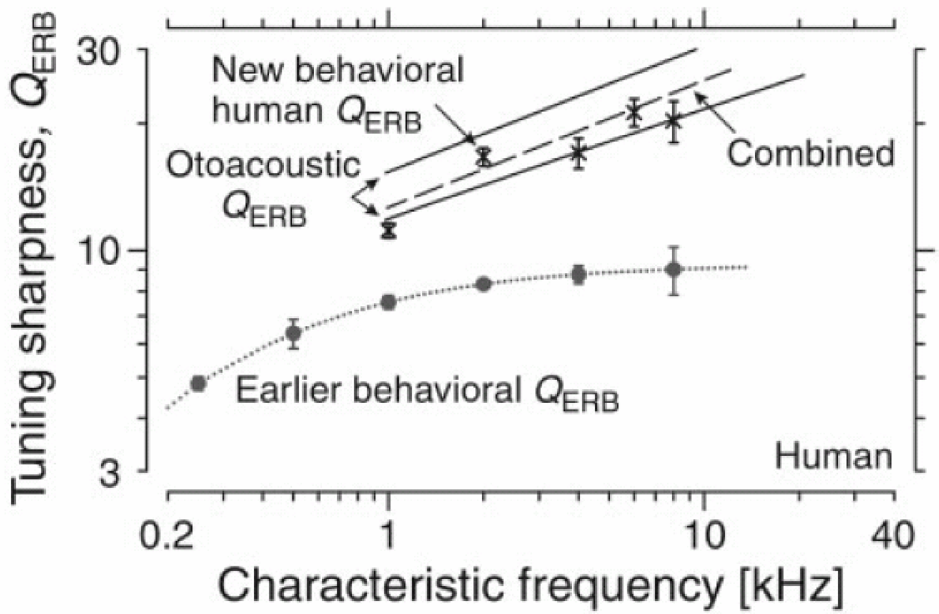
IV. OAE Latency

Relation to Traveling Wave Delay

- Theory indicates SFOAEs at low-mod levels arise near the peak of basilar membrane traveling wave
- Basilar membrane at low levels like a bank of overlapping minimum phase-shift filters
  - Bandwidths and delays inversely related
- Thus, SFOAE and basilar membrane latencies should be linked

IV. OAE Latency

Relation to Frequency Tuning



*Q*erb = *kTf/2*, in which *k(f)* varies with *f*.

Fig. 4 from Shera, Guinan & Oxenham, 2002, PNAS 99, 3318-23.

IV. OAE Latency

Relation to Frequency Tuning

- SFOAE group delays (latencies) at 40 dB SPL predicted behavioral tuning curve data from 1- 8 kHz in normal ears (Shera et al., 2002)
- Pip-evoked OAE latencies did not vary with SNHL (Prieve et al., 1995)
- Distortion emissions predicted to have short group delays, which may not depend on cochlear tuning (Talmadge et al., 1999)

Research Questions

For SFOAE & DPOAE latencies, measured directly in the time domain

1) Do they vary with level and hearing status?
2) Do they allow separation of multiple components (e.g., reflection and distortion components, multiple internal reflections)?
3) Are they consistent with model results

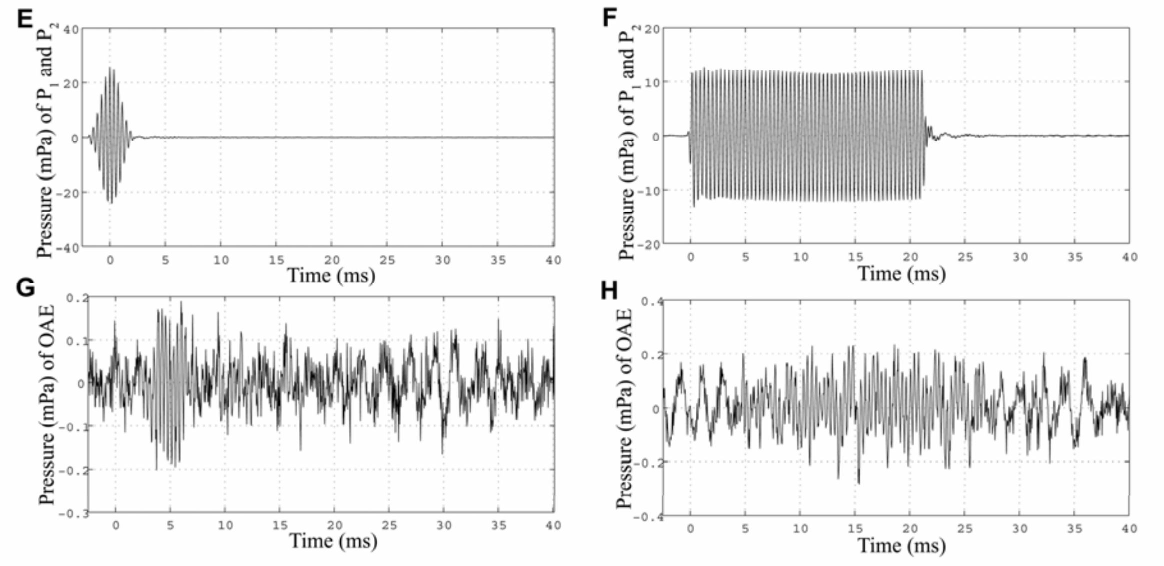
Methods

Subjects

- 17 normal-hearing subjects
  - pure-tone thresholds 15 dB HL or better at half-octave frequencies from 0.25 to 8.0 kHz)
- 10 subjects with impaired hearing
  - 10 had thresholds > 20 dB HL at 4 kHz
  - 9 had thresholds > 20 dB HL at 3 kHz
- All subjects had normal 226-Hz tympanometry at time of testing

Stimuli: Types of Transients

- Tone pip pairs (pp), band-limited impulses
- Gated tone pairs (gg), well-defined onset, steady state and decay
- Continuous plus gated tones (cg), (DPOAE only)



Tone-Pip-Evoked   Gated-Tone-Evoked

DPOAE Stimuli

- $f_1 < f_2$, with $f_2 / f_1 = 1.2$
- $f_2 = 4000$ Hz
- $L_1 = L_2$ for ppDPOAE
- $L_1 = L_2 + 10$ dB for ggDPOAE, cgDPOAE
  - Not optimal based on Kummer et al., 1998, in which $L_1 = 0.4L_2 + 39$ dB for $L_2 < 65$ dB SPL
- L_2 varied from about 35 to 70 dB SPL, depending on transient type

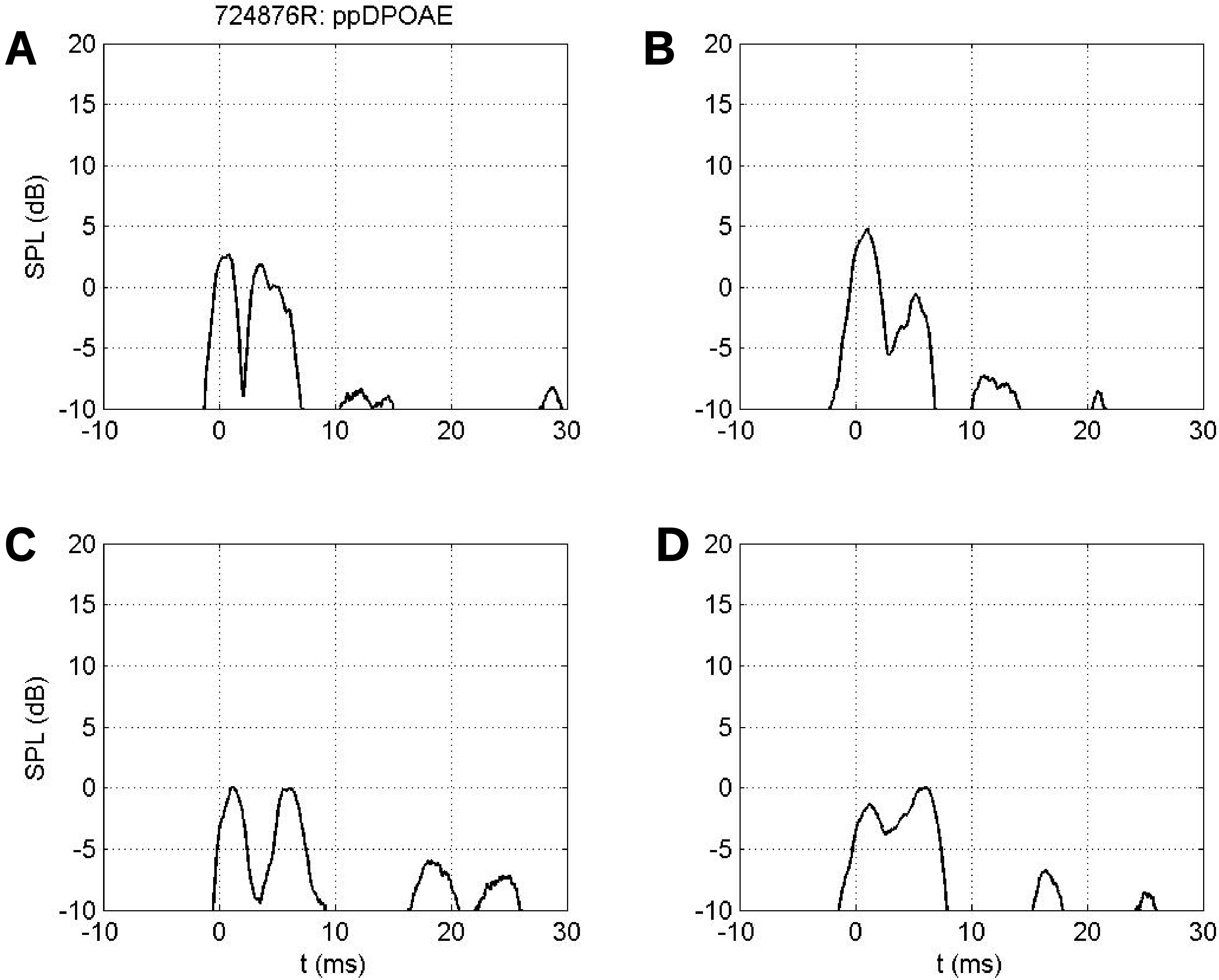
SFOAE Stimuli

- $f_1 = f_2$ (Equal-frequency)
- f_2 = 2.7 kHz and 4.0 kHz
- $L_1 = L_2$ (Equal-level)
- L_2 varied from about 30 to 75 dB SPL in 5-dB steps

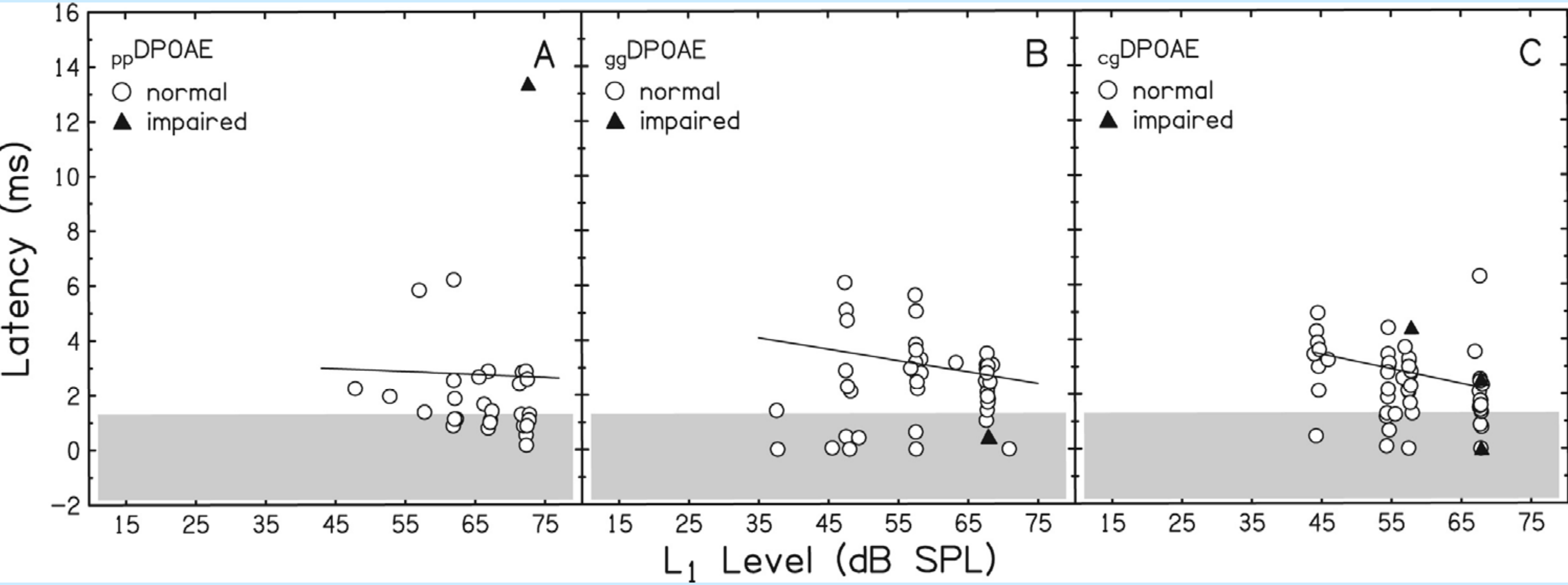
OAE Recording and Analysis

- SFOAE and DPOAE responses recorded in the time domain
  - Narrow-band filtered (Kaiser) at SF or DP frequency,
  - and envelopes extracted (Hilbert transform)
- For SFOAE, equivalent auditory filter bandwidth calculated ($e\mathrm{Q}_{\mathrm{ERB}}$)
  - eQerb = $kTf/2$
  - k values were 2.15 for 2.7 and 2.09 for 4.0 kHz
- Synchronous SOAEs measured to assess their contribution to SFOAE and DPOAE

Results

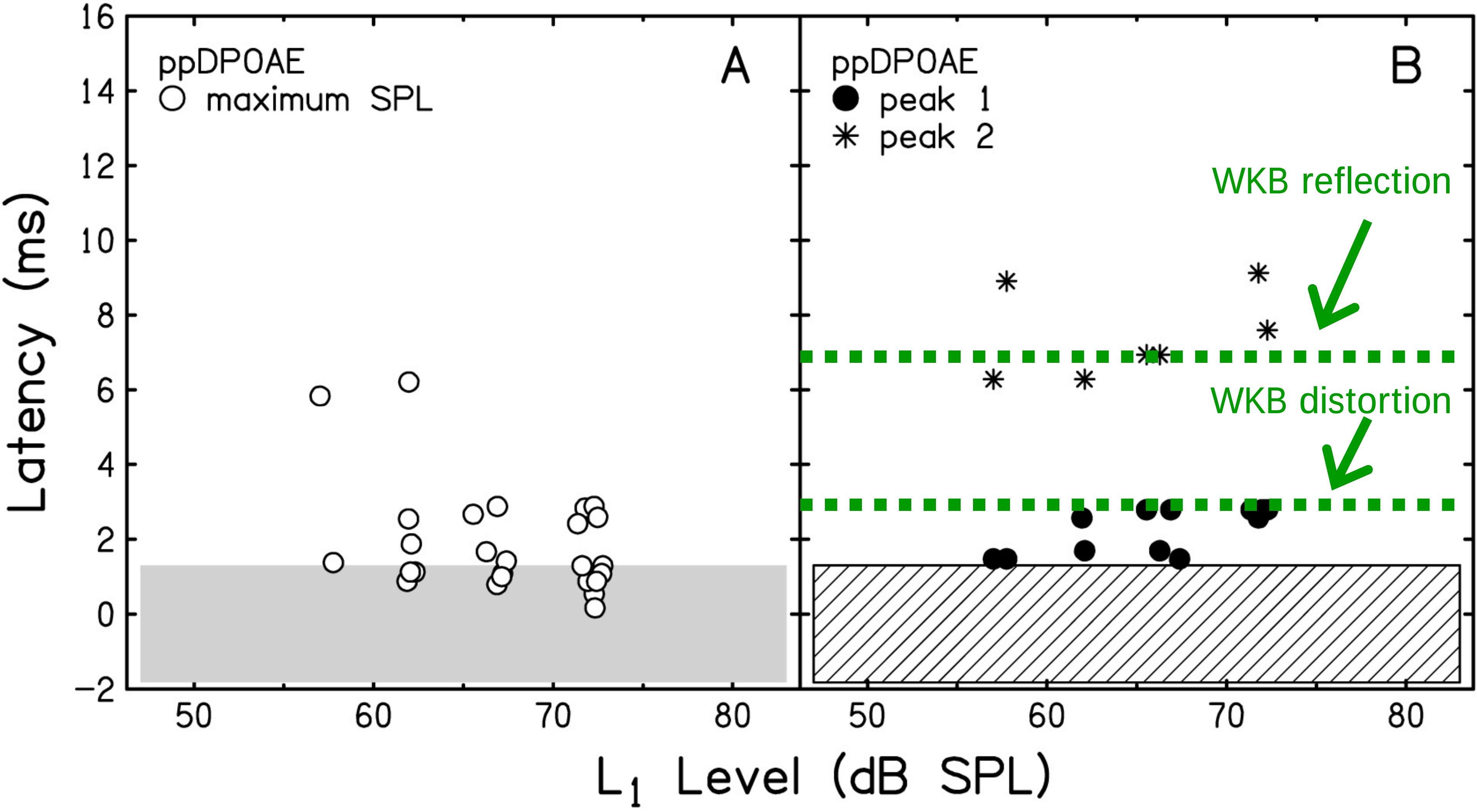

724876R: ppDPOAE
A
B
C
D
SPL (dB)
t (ms)
20
15
10
5
0
-5
-10
-10
0
10
20
30

Effect of Stimulus Level



- Valid responses (shown) had a 6 dB SNR
- Excluded latencies shorter than T_{min}, since they could possibly be related to artifact

Effect of Stimulus Level



Results

Envelopes of ppDPOAE provide evidence for two $2f_1$-f_2 DPOAE sources.

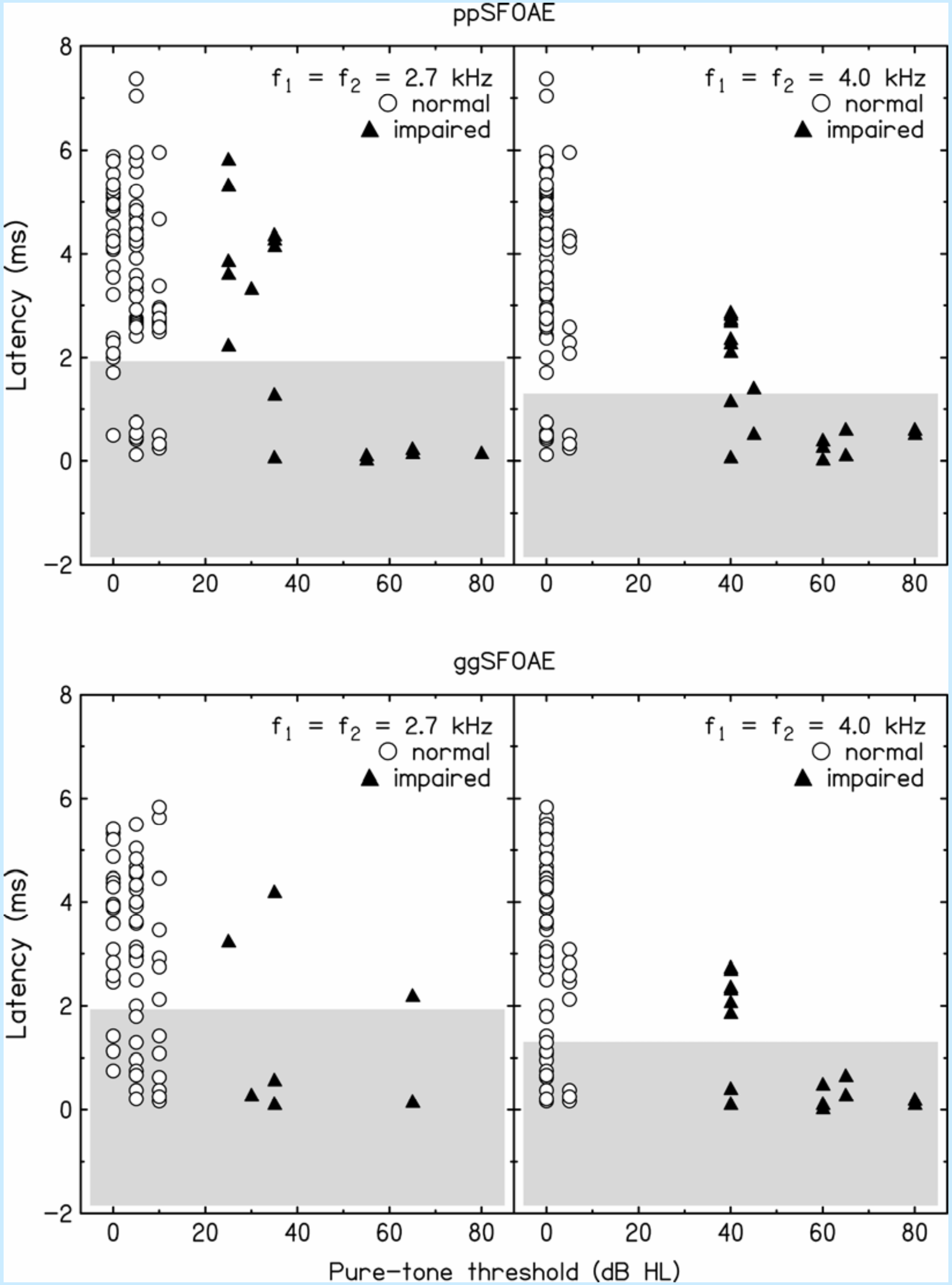
Latency variations explained in part by variations in the dominant generator source.

Latencies of transient DPOAE were consistent with model predictions.

Effect of Hearing Status on SFOAE Latencies

	ppSFOAE		ggSFOAE	
	2.7 kHz	*4.O kHz*	*2.7 kHz*	*4.O kHz*
normal hearing	16/17	16/17	14/17	14/17
impaired hearing	5/9	4/10	3/9	2/10

Proportion of subjects with valid tone pip (pp) and gated tone (gg) SFOAEs.



ppSFOAE
f1 = f2 = 2.7 kHz
normal
impaired
f1 = f2 = 4.0 kHz
normal
impaired
Latency (ms)
ggSFOAE
f1 = f2 = 2.7 kHz
normal
impaired
f1 = f2 = 4.0 kHz
normal
impaired
Latency (ms)
Pure-tone threshold (dB HL)

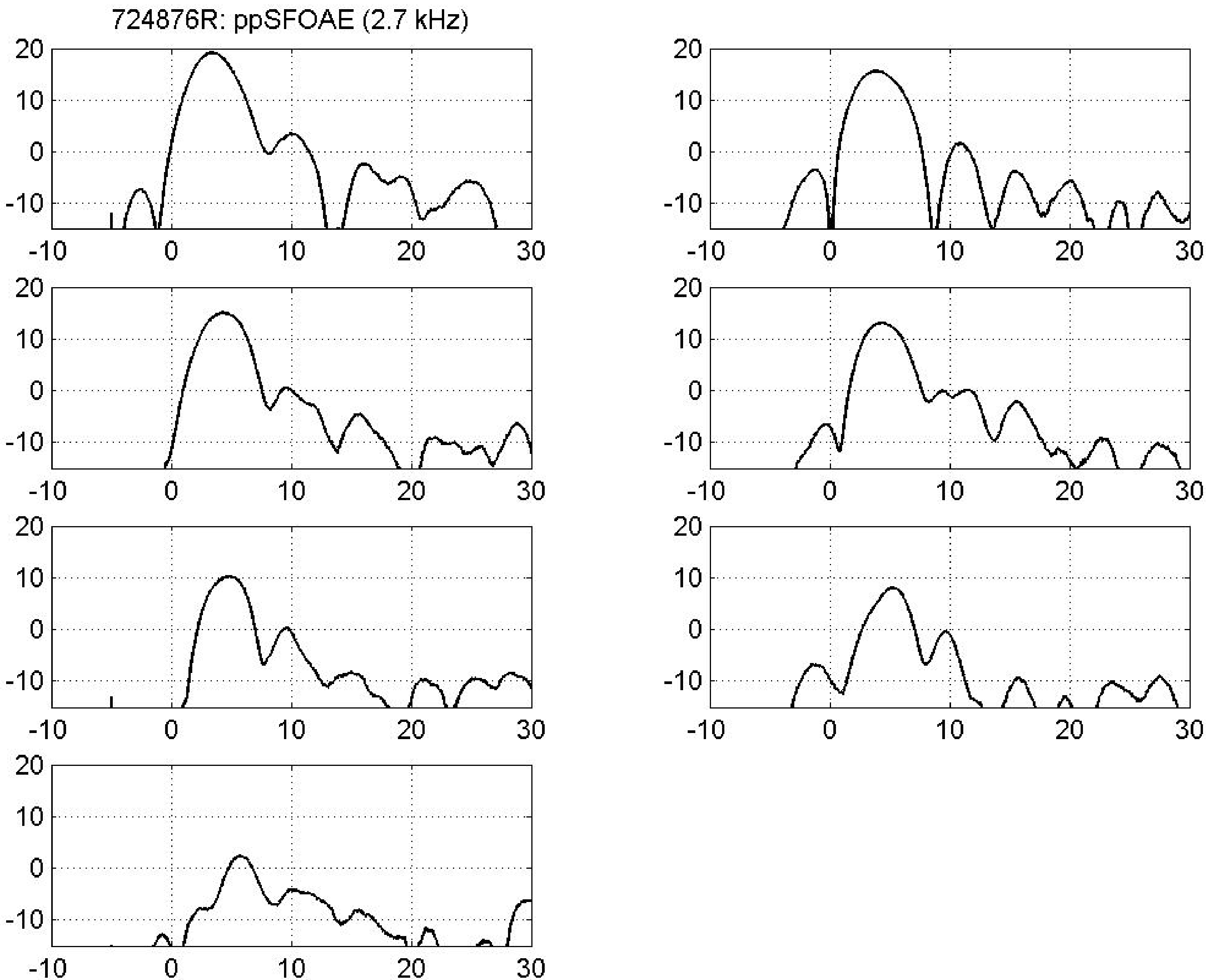
Results

Responses with 6 dB signal to noise ratio (SNR) obtained for a wide range of audiometric threshold levels.

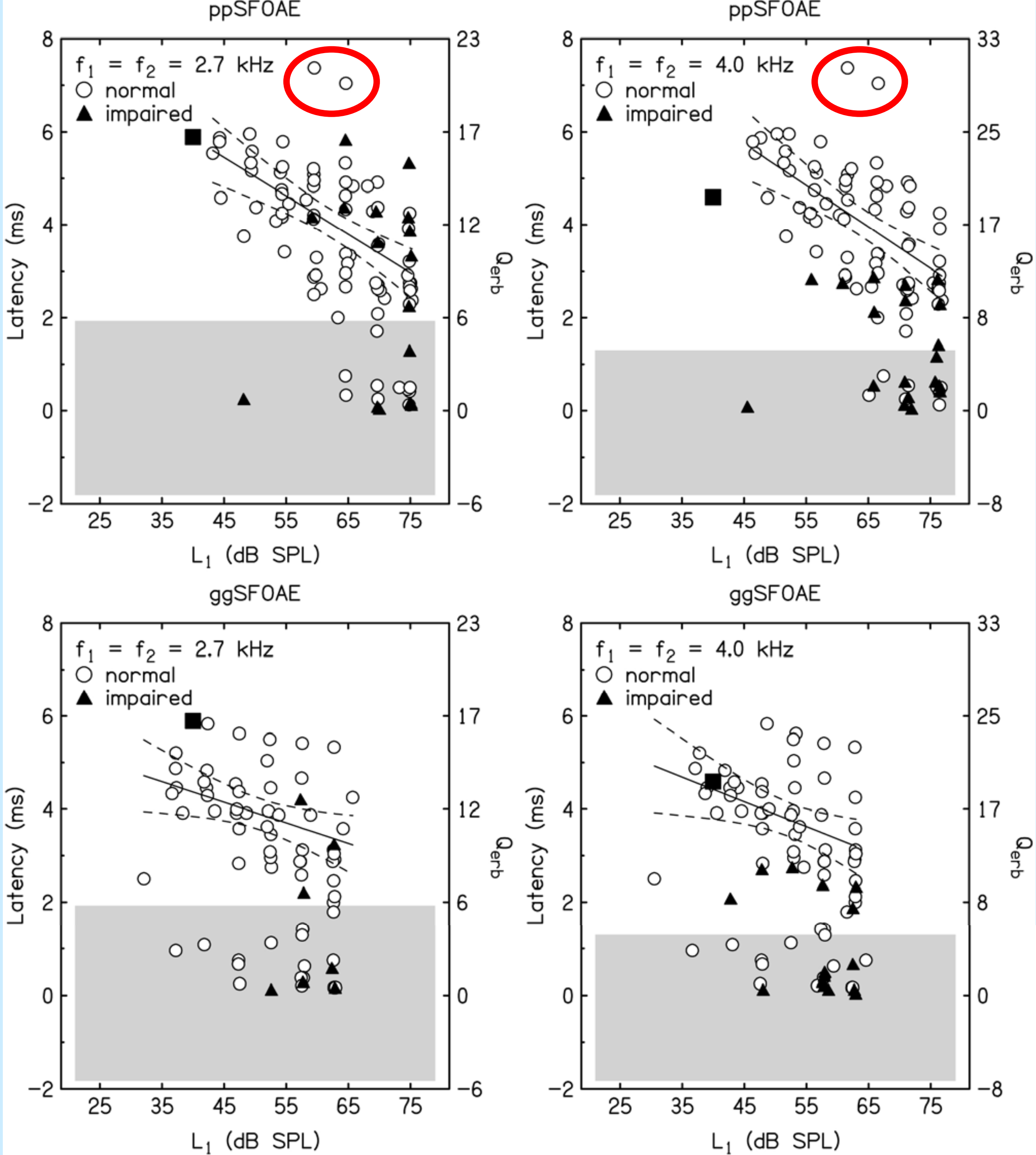
However, valid latencies ($> T_{min}$) were obtained only in subjects with pure-tone thresholds below about 45 dB HL.

Impaired ears were more likely to have SFOAEs present than DPOAEs present.

Effect of Stimulus Level on SFOAE Latencies



724876R: ppSFOAE (2.7 kHz)
20
10
0
-10
-10
0
10
20
30


ppSFOAE
f1 = f2 = 2.7 kHz
normal
impaired
ppSFOAE
f1 = f2 = 4.0 kHz
normal
impaired
ggSFOAE
f1 = f2 = 2.7 kHz
normal
impaired
ggSFOAE
f1 = f2 = 4.0 kHz
normal
impaired
Latency (ms)
Qerb
L1 (dB SPL)

Results

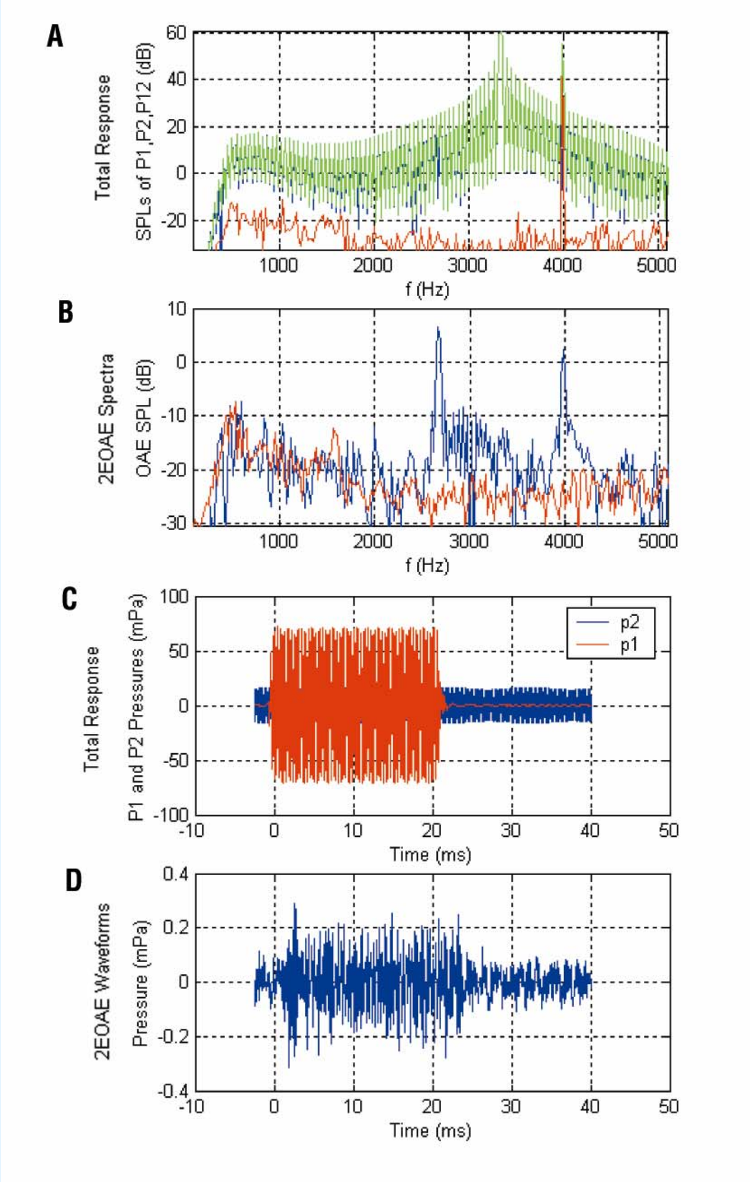
Increasing the stimulus level decreases ggSFOAE & ppSFOAE latencies.

Valid impaired-ear latencies were similar or shorter compared to normal-ear latencies at equal SPL.

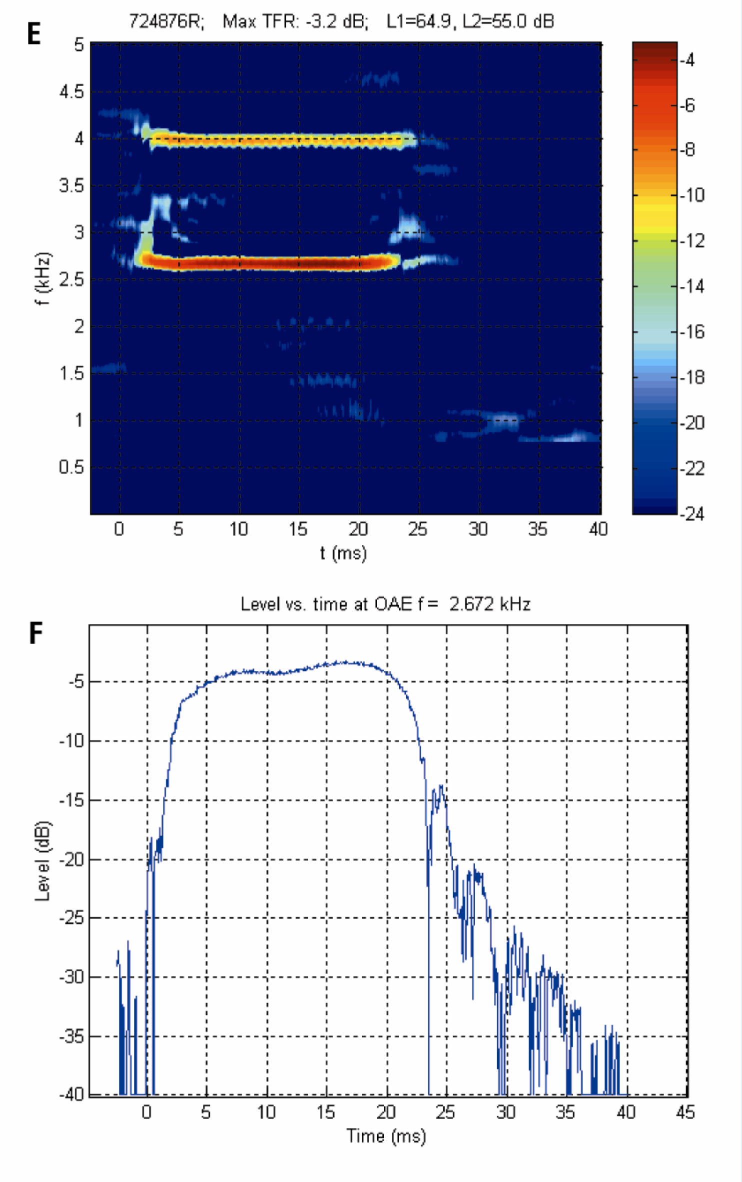
Low-level SFOAE latencies consistent with model predictions for reflection mechanism; high-level latencies consistent with distortion mechanism

Comparing Temporal Details of DPOAE Waveforms: Narrow-band filtering vs. time-frequency response (TFR) technique

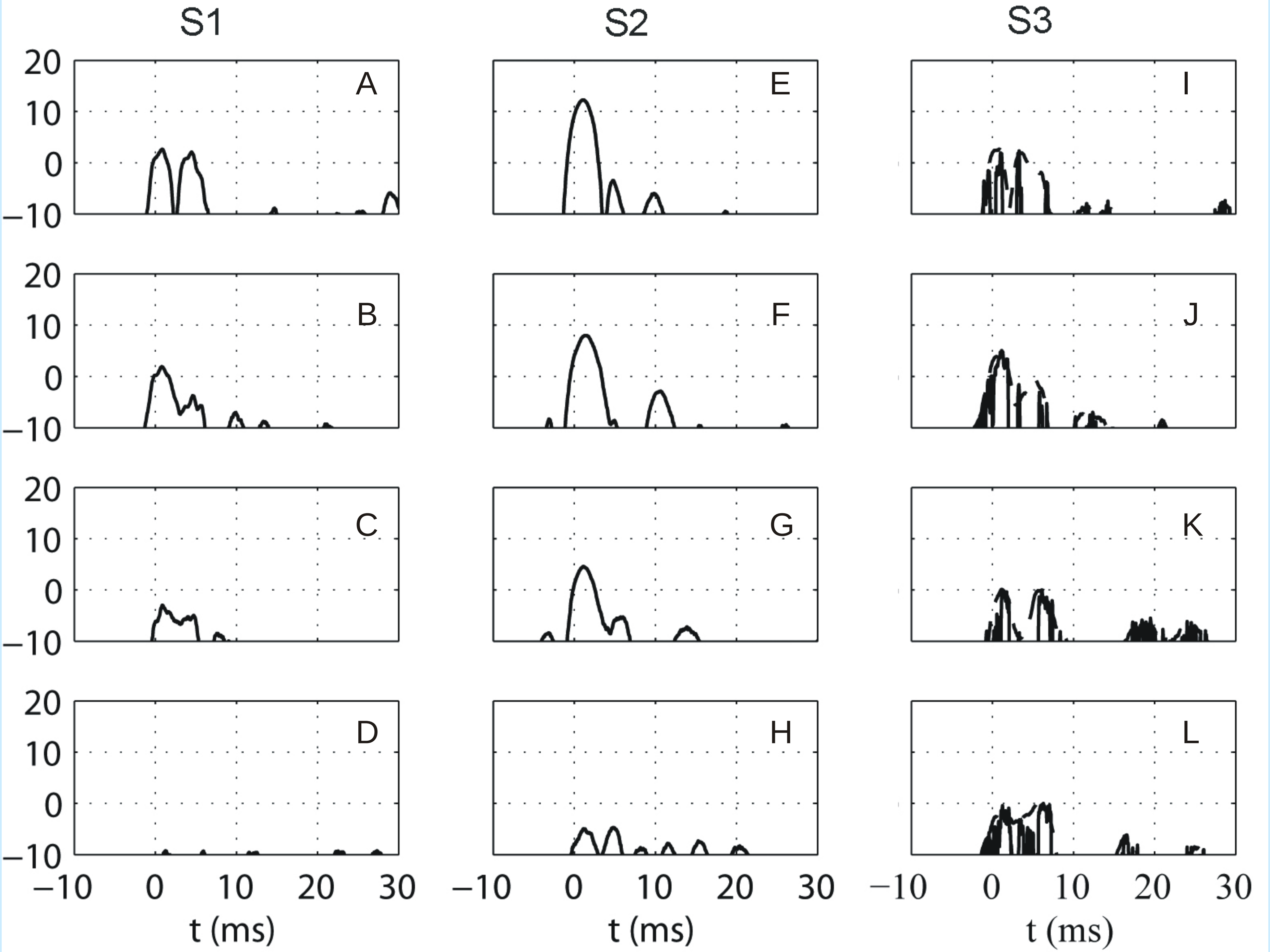
DPOAE



A
Total Response
SPLs of P1,P2,P12 (dB)
f (Hz)
B
2EOAE Spectra
OAE SPL (dB)
f (Hz)
C
Total Response
P1 and P2 Pressures (mPa)
p2
p1
Time (ms)
D
2EOAE Waveforms
Pressure (mPa)
Time (ms)



E
724876R; Max TFR: -3.2 dB; L1=64.9, L2=55.0 dB
f (kHz)
t (ms)
F
Level vs. time at OAE f = 2.672 kHz
Level (dB)
Time (ms)


S1
S2
S3
A
B
C
D
E
F
G
H
I
J
K
L
20
10
0
−10
−10
0
10
20
30
t (ms)

Results

Good correspondence between temporal envelopes using narrow-band filtering and TFR analysis

Conclusions

Conclusions

SFOAE latency variation with level and hearing status are consistent with expected changes in BM traveling wave under the same conditions. Thus, transient-evoked SFOAE may provide a rapid, non-invasive measure of cochlear tuning.

Transient-evoked DPOAE may provide a means for separately evaluating distortion and reflection components

TFR technique valid for exploring OAE elicited by complex stimuli

Future Directions

Determine the extent to which temporal (time) and spectral (frequency) analysis are abnormal in the auditory periphery of older adults

Isolate cochlea and auditory nerve using OAE and CAP measurements

Determine the functional (behavioral) consequences of abnormal temporal and frequency analysis for processing of speech

(1) temporal speech cues (VOT)
(2) isolated (time-gated) words

Full Citations

Konrad-Martin, D, & Keefe, D.H. (2003). Time-frequency analyses of transient-evoked stimulus-frequency and distortion-product otoacoustic emissions: Testing cochlear model predictions. J. Acoust. Soc. Am. 114, 2021-2043.

Konrad-Martin, D, & Keefe, D.H. (2005). Transient-evoked stimulus-frequency and distortion-product otoacoustic emissions in normal and impaired ears. J. Acoust. Soc Am. (in press).