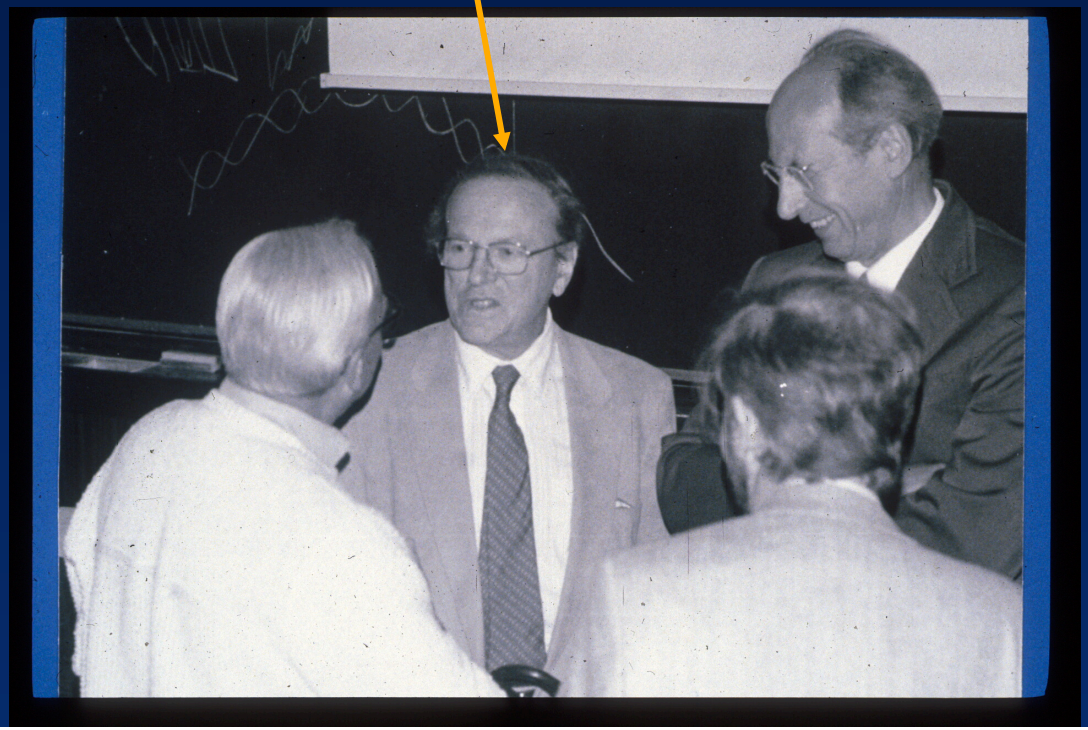
Electro-Acoustic Measurements: Otoacoustic Emissions (OAEs)

- Historical perspective
- Update on generation of OAEs: Clinical Implications
- Guidelines for OAE measurement
- Guidelines for OAE analysis
- Analysis of TEOAEs
- Analysis of DPOAEs
- Evidenced-based clinical applications in children
- Evidenced-based clinical applications in adults

George von Bekesy (1899 - 1972)
Author of *Experiments in Hearing* in 1960
Nobel Prize in Physiology or Medicine in 1961

Thomas Gold
OAE Prophet



OAEs:
Classic Quote from Yesteryear by Thomas Gold

"I had discussed at length in 1948 with von Bekesy at Harvard that the observations he made on the dead cochlea were unrepresentative. But he wouldn't have that!"

"It is shown that the assumption of a 'passive' cochlea, where the elements are brought into mechanical oscillation solely by means of the incident sound, is not tenable."

" … the nerve ending abstracts much energy from a mechanical resonator."

James W. Hall III
***Introduction to Audiology Today* (2014).**
Boston: Pearson Publishing

LEADERS AND LUMINARIES

David Kemp

David Kemp is a Professor at the University College London who founded the Ear Institute. Dr. Kemp is known for his discovery and scientific exploration of otoacoustic emissions (OAEs) as well as his invention of practical technologies for their application in screening and diagnosis. A physicist by training, Dr. Kemp gained experience in electronics and audio-frequency signals at London University England in the 1960s while researching extremely low-frequency radio waves. He found his acute hearing useful in analyzing signals and diagnosing instrument faults. Moving into audiology Kemp studied low-level auditory perceptual aberrations experienced by normally hearing subjects, concluding they were due to reflections and distortions inside the cochlea. His findings were totally at variance with contemporary auditory theories but his observations predicted acoustic emissions. Dr. Kemp subsequently recorded otoacoustic emissions. The discovery led to the identification the cochlear amplifier, nonlinear compression, a new clinical tool, and indeed a new industry. You can learn more about Dr. Kemp and this very important test technique by downloading the Story of Otoacoustic Emissions from the Otodynamics website.

Discovery of OAEs by David Kemp
(Kemp DT. Stimulated acoustic emissions from within the human auditory system. *JASA 64,* 1978.)

"A new auditory phenomenon has been identified in the acoustic impulse of the human ear…

This component of the response appears to have its origin in some nonlinear mechanism probably located in the cochlea, responding mechanically to auditory stimulation, and dependent upon the normal functioning of the cochlear transduction process…

It is tempting to suggest that one of the functions of the outer hair cell population is the generation of this mechanical energy."

Bill Brownell
"Discoverer of Outer Hair Cell Motility"

Brownell W (1990).
Outer hair cell electromotility and otoacoustic emissions.
Ear & Hearing, 11, 82-92

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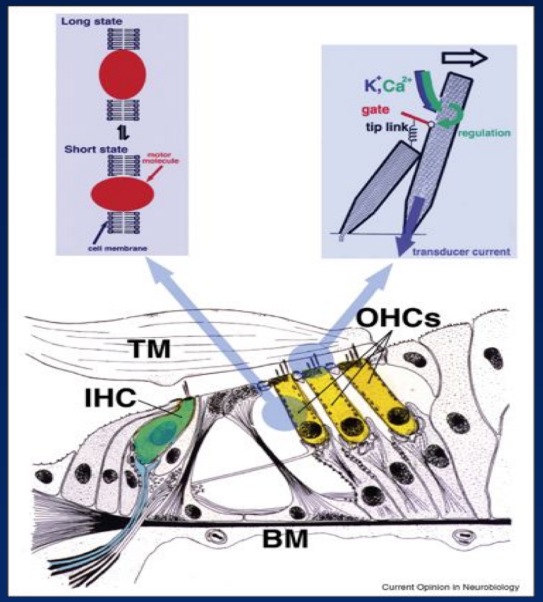
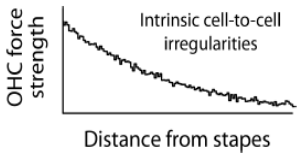
OAEs Originate in the Cochlea …
But That's Not the Entire Story



Hypothesis: Types of Otoacoustic Emissions

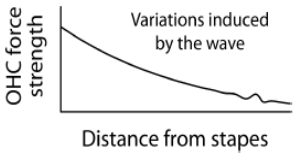
Otoacoustic Emissions

Reflection-Source



Generation requires cochlear *irregularity* (but not nonlinearity)

Distortion-Source

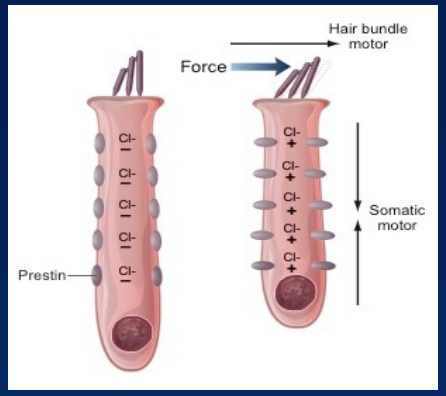


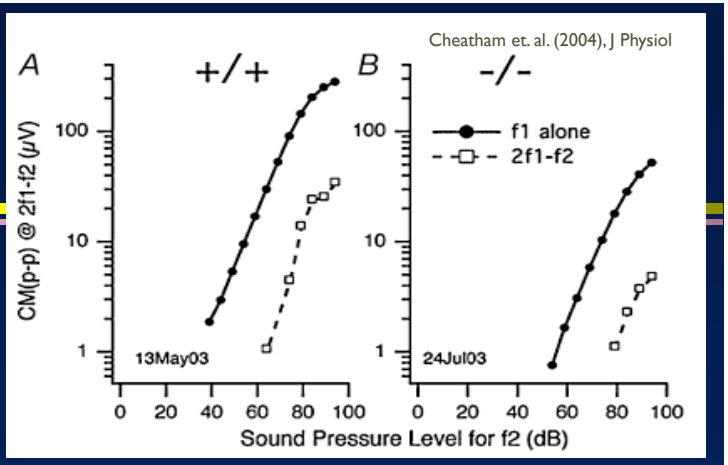
Generation requires cochlear *nonlinearity* (but not irregularity)

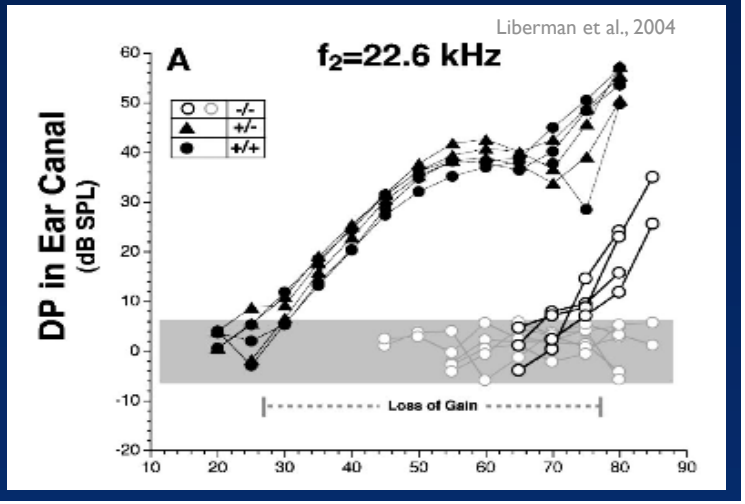
Auditory Anatomy Involved in the Generation of OAEs

- Outer hair cell motility
  - Prestin motor protein
- Stereocilia
  - Motion
  - Stiffness
- Tectorial membrane
- Basilar membrane mechanics
  - Dynamic interaction with outer hair cells
- Stria vascularis
- Middle ear (inward and outward propogation)
- External ear canal
  - Stimulus presentation
  - OAE detection

Prestin Knock Out





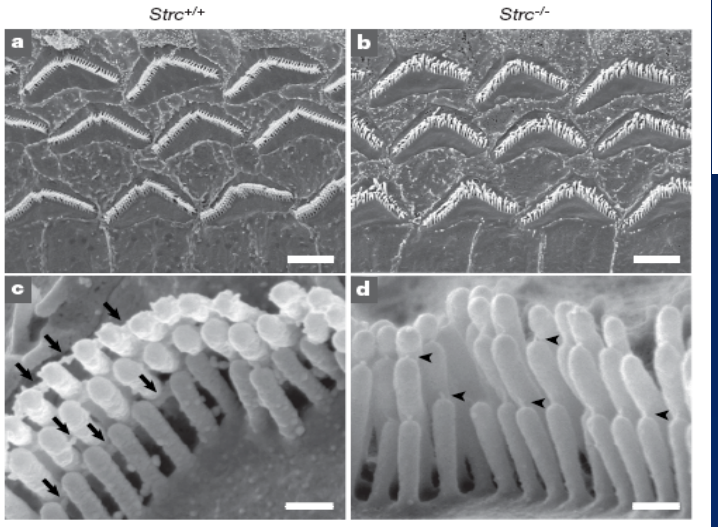


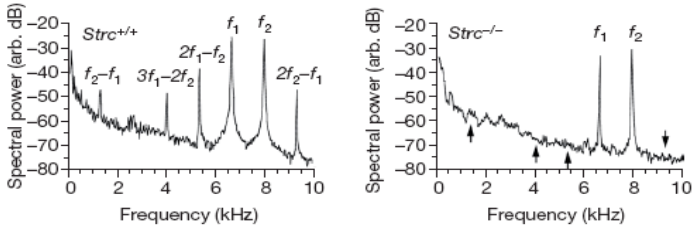
doi:10.1038/nature07380 nature

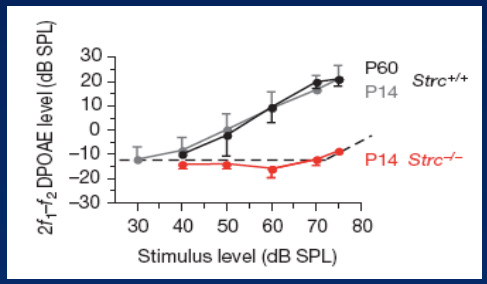
LETTERS

Stereocilin-deficient mice reveal the origin of cochlear waveform distortions

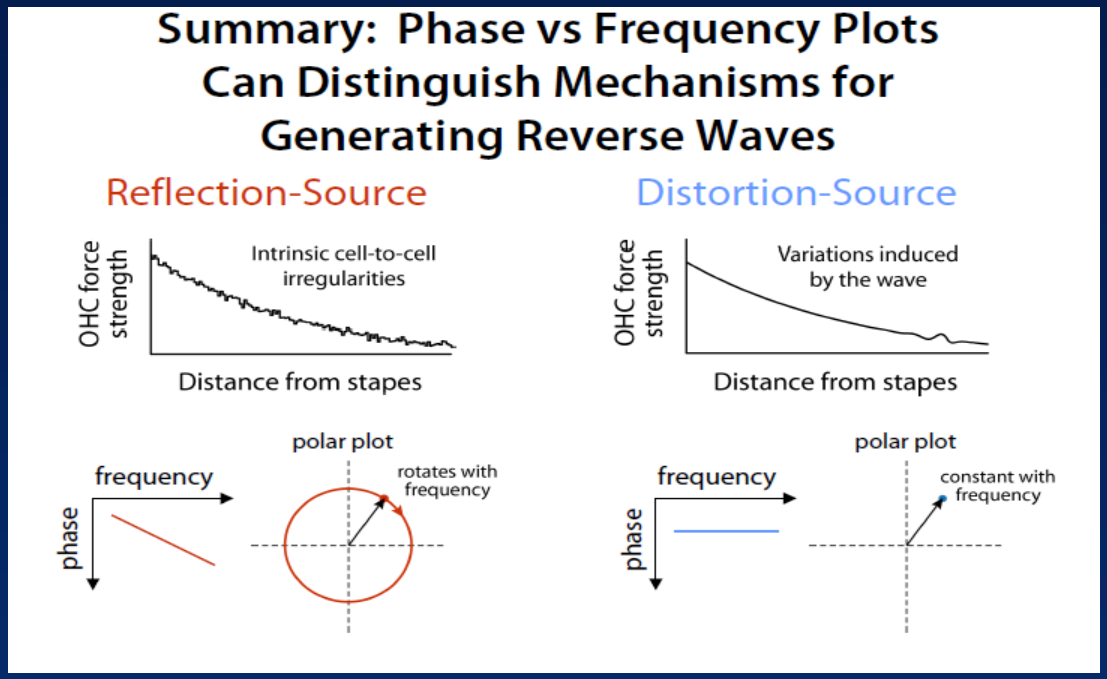
Elisabeth Verpy[1,2,3,4], Dominique Weil[1,2,3,4]*, Michel Leibovici[1,2,3,4]*, Richard J. Goodyear[5], Ghislaine Hamard[6], Carine Houdon[1,2,3,4], Gaelle M. Lefèvre[1,2,3,4], Jean-Pierre Hardelin[1,2,3,4], Guy P. Richardson[5], Paul Avan[7]* & Christine Petit[1,2,3,4]*







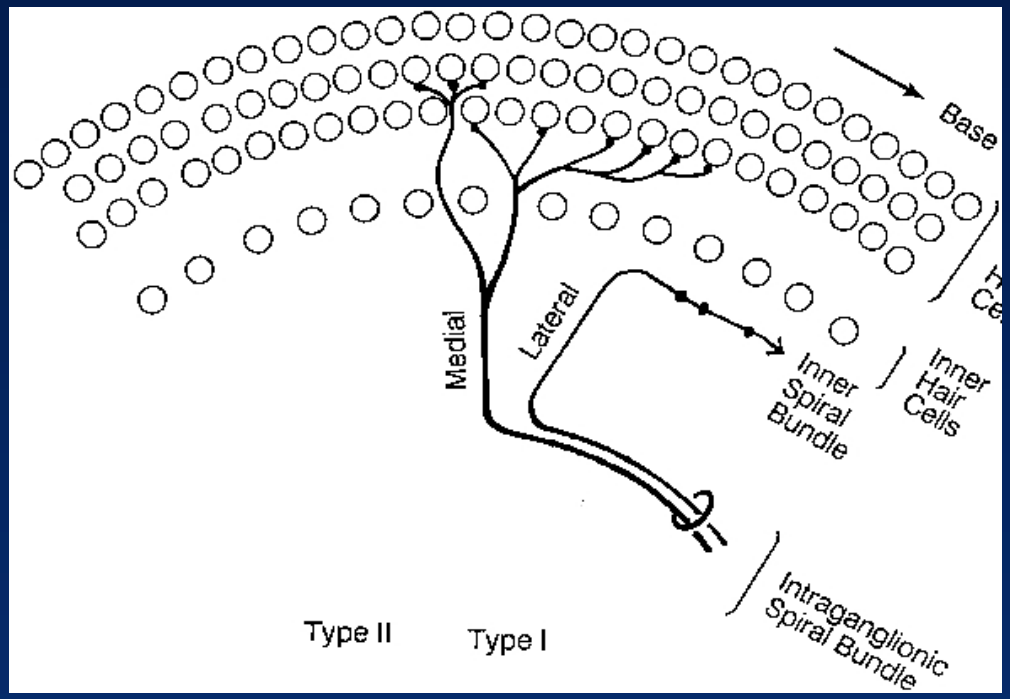
Phase is a Factor in the Generation of OAEs



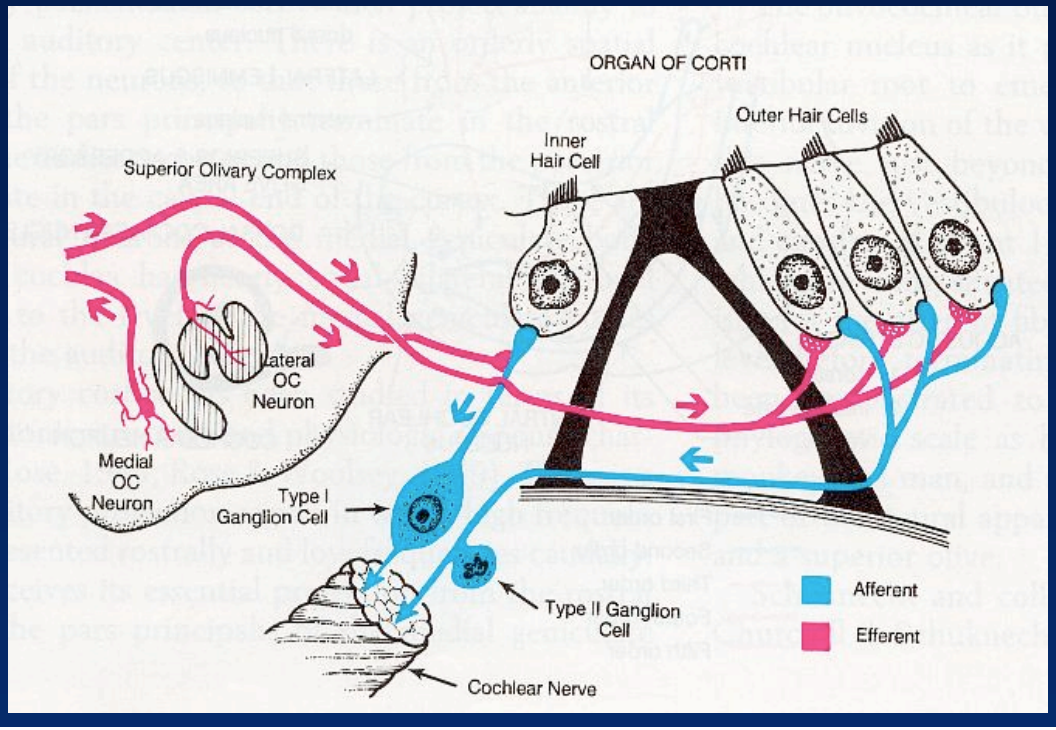
Shera, 2009

Robert Galambos, MD, PhD
Studied Efferent System and Cochlear Function
(Also contributed to discovery and pediatric application of ABR)

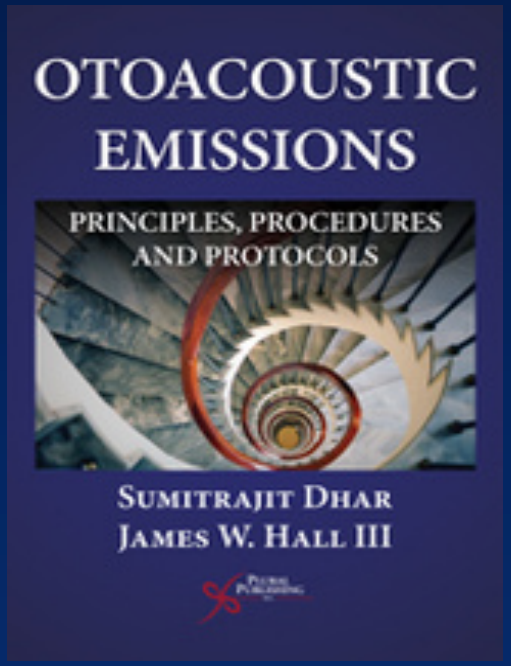
Efferent Innervation of the Cochlea: Lateral and Medial Olivocochlear Pathways



Efferent Inhibition of the Outer Hair Cells: Medial Olivocochlear Bundle



An Up-to-Date and Understandable Explanation of the Generation of OAEs and Efferent Inhibition of OAEs



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Electro-Acoustic Measurements: Otoacoustic Emissions (OAEs)

- Historical perspective
- Update on generation of OAEs: Clinical Implications
- Guidelines for OAE measurement
  - Otoscopic inspection
  - Minimizing noise
  - Test protocols
- Guidelines for OAE analysis
- Analysis of TEOAEs
- Analysis of DPOAEs
- Evidenced-based clinical applications in children
- Evidenced-based clinical applications in adults

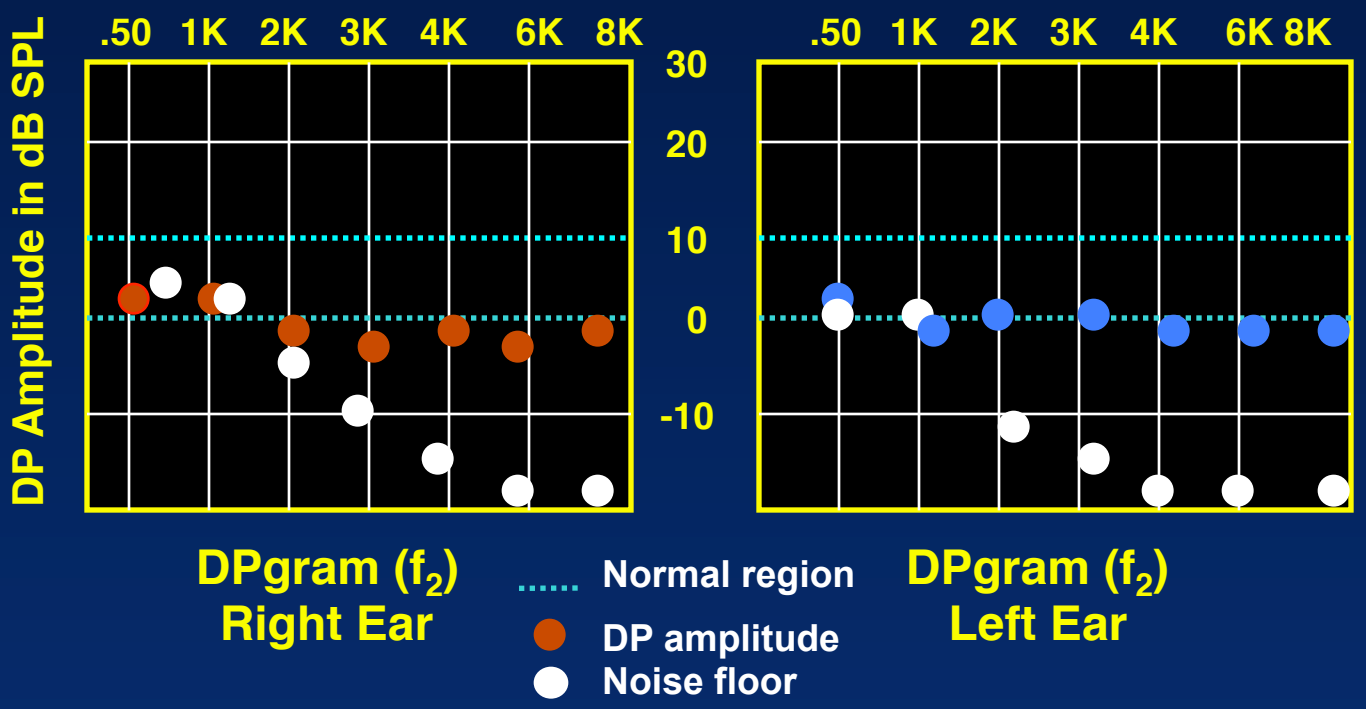
Guidelines for Measurement of Otoacoustic Emissions in Clinical Audiology

- Perform otoscopic inspection before OAE recording
- Noise floor should as low as possible
- Diagnostic DPOAE measurement should include
  - An appropriately wide frequency region
  - An adequately number of frequencies per octave
- Routinely replicate OAE recordings for each ear. *Remember*: If the OAEs do not repeat … your test is not complete.

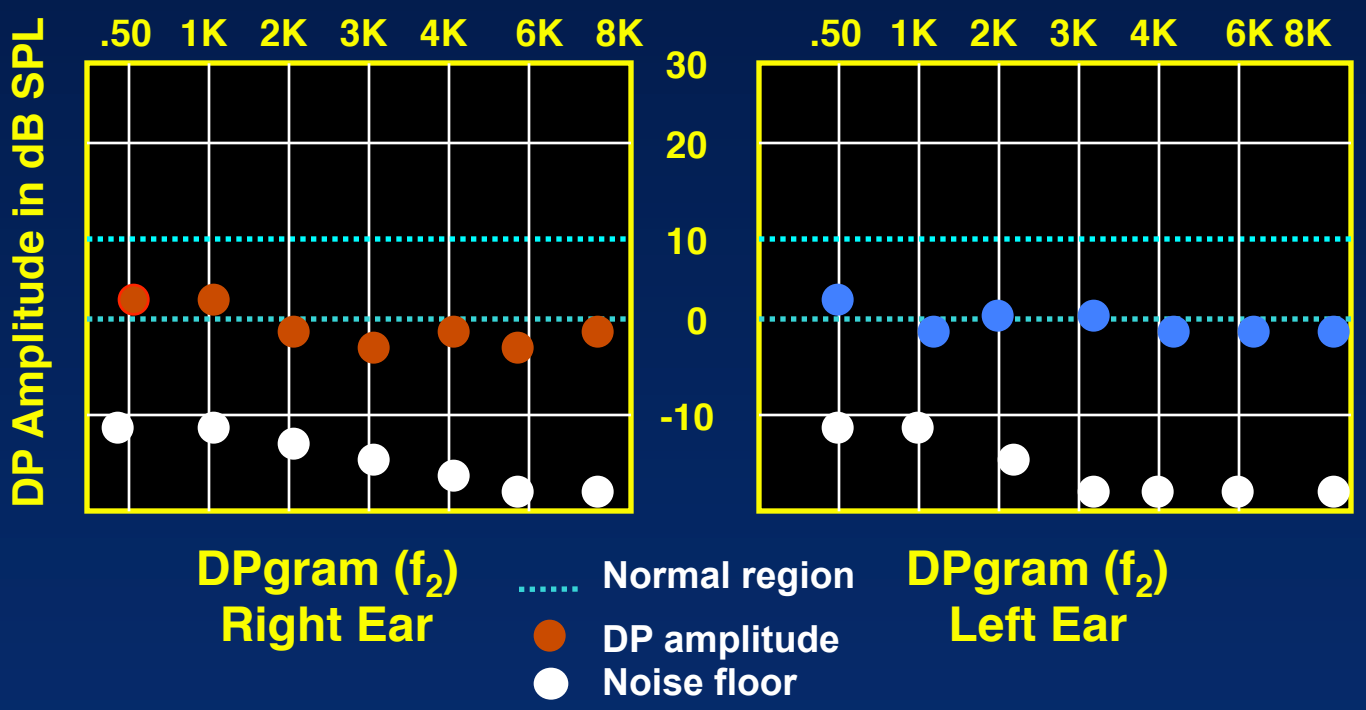
Guidelines for Measurement of Otoacoustic Emissions in Clinical Audiology

- Perform otoscopic inspection before OAE recording
  - Cerumen and debris can occlude ports in probe
  - OAE is recorded in the EAC

What Is Wrong With This DPOAE Recording?



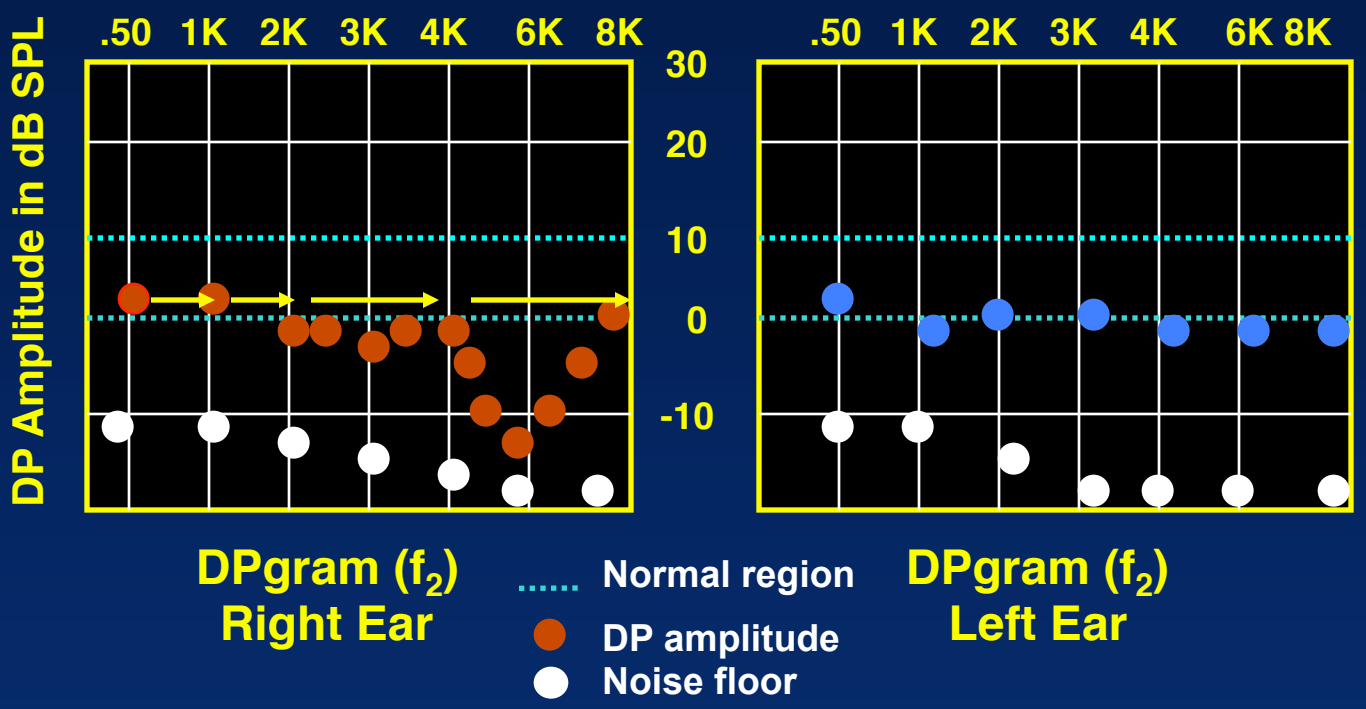
OAEs are Sound Measured in the External Ear Canal: Techniques for Lowering Noise Floor



Guidelines for Measurement of Otoacoustic Emissions in Clinical Audiology

- Two sources of noise
  - Acoustic
  - Physiologic
- Techniques for minimizing noise in the EAC
  - Reduce ambient noise
  - Tight probe fit
  - Deep probe insertion
  - Locate patient away from OAE equipment
  - Modify test protocol

OAEs are Highly Frequency Specific: Probe Inter-Octave Cochlear Function



Create DPOAE Test Protocols for Specific Clinical Applications

Test Parameters	Diagnostic			Screening	
	General	HF	LF	Newborn	School
L_1/L_2 intensity (dB)	65/55*	65/55*	65/55	65/55	65/55
F_2/F_1 ratio	1.20	1.20	1.20	1.20	1.20
F_2 range (Hz)	0.5-8K	2-10K	0.5-1K	2-5K	2-8K
F_2 / octave	5 - 8	8	5	4	3
Averaging		Less	More	More	
Example of application	Basic test Tinnitus	Ototox. NIHL	MD		

** Decrease intensity to increase test sensitivity*

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- Historical perspective
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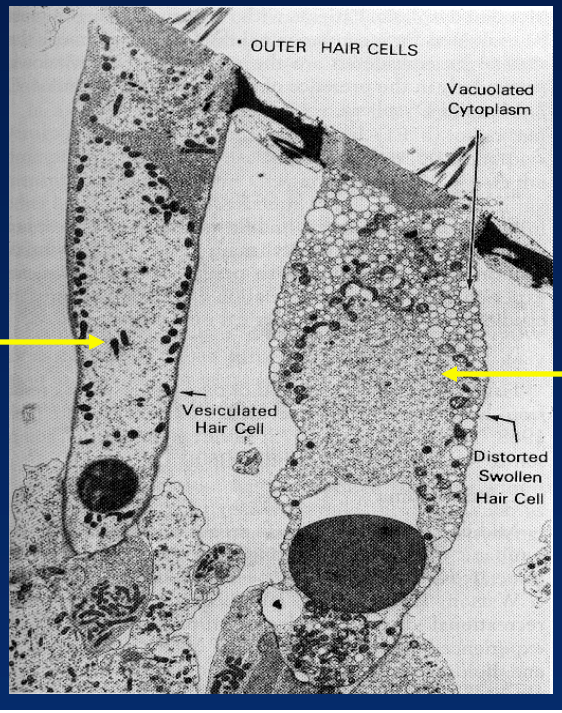
- Guidelines for OAE analysis
  - Rationale for OAE analysis
  - Steps in Analysis
  - Factors in Analysis
  - What do absent OAEs mean?
- Analysis of TEOAEs
- Analysis of DPOAEs
- Evidenced-based clinical applications in children
- Evidenced-based clinical applications in adults

OAEs in Early Detection of Outer Hair Cell Dysfunction: *Rationale Underlying Many Clinical Applications*

Normal OHC (OAEs)



Abnormal OHC (OAEs)

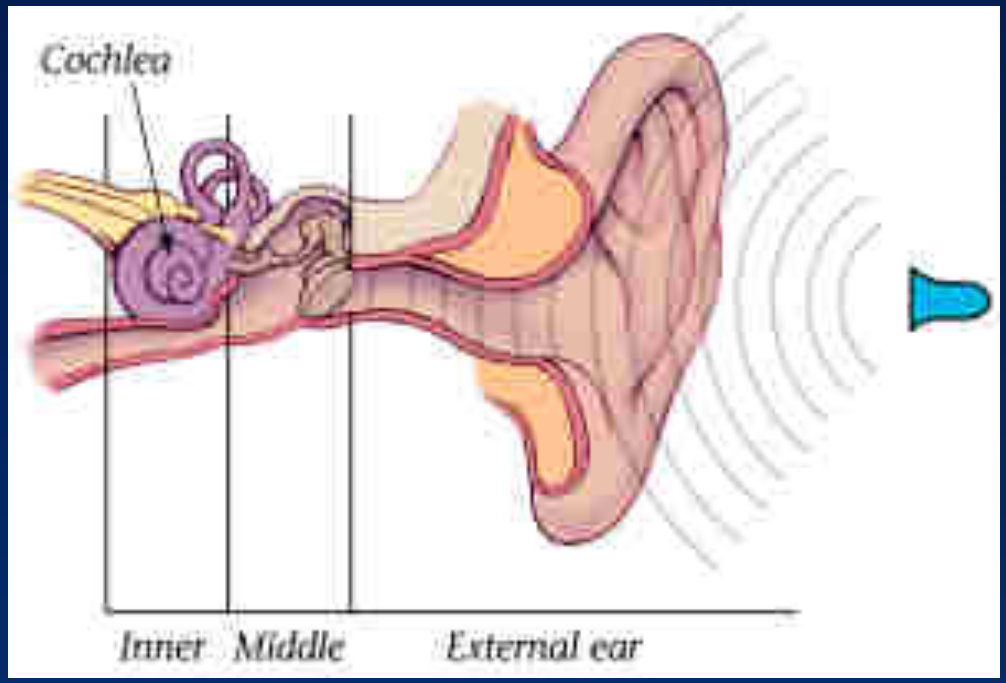
General Steps in Analysis of TEOAE or DPOAE Findings

- Verify adequately low noise floor (< 90% normal limits)
- Perform analysis at all test frequencies
- Verify repeatability of TEOAE or DPOAE amplitude (+/- 2 dB) from at least two runs
- Is OAE - NF difference > 6 dB?
  - Yes? OAEs are present
  - No? There is no evidence of OAEs
- Is DP amplitude within normal limits?
  - Yes? OAEs are normal
  - No? OAEs are abnormal (but present)

Non-Factors in OAE Interpretation

- Diurnal effects (time of day)
- Body temperature
- Body position
- Anesthetic agents (assuming normal middle ear status
- State of arousal (awake or asleep)
- Attention to stimulus
- Listener variables
  - Motivation
  - Cognitive status
  - Language abilities

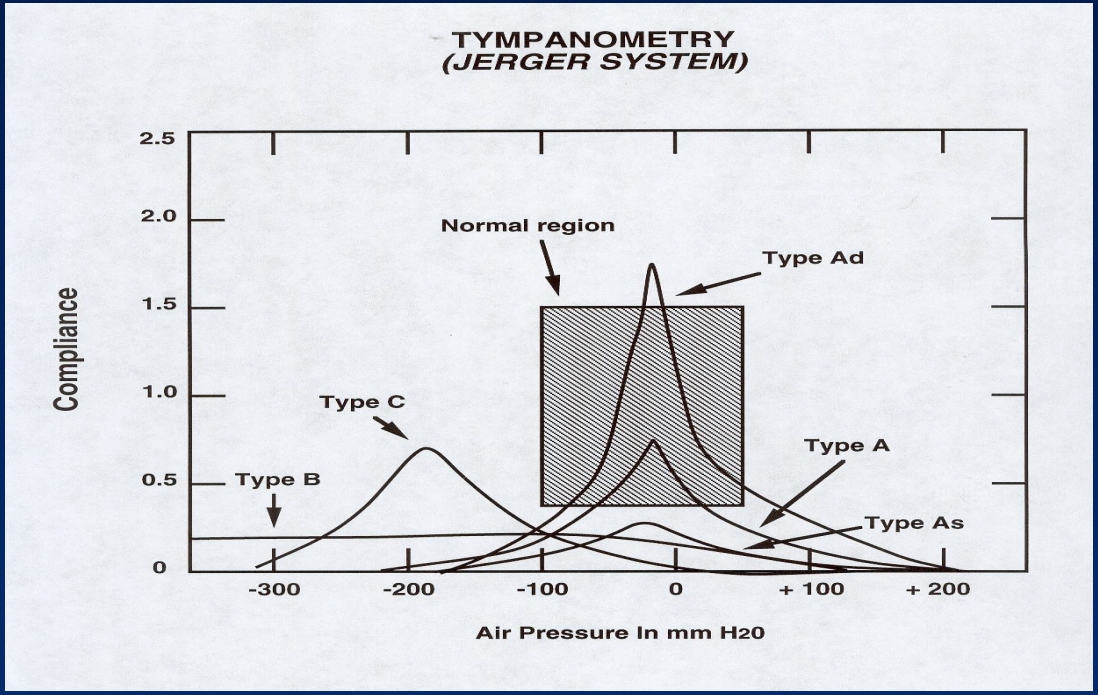
Absent OAEs?
Find an Explanation



Absent OAEs: Technical Problem or Evidence of A Non-Cochlear Abnormality?

- Non-pathologic explanations
  - Probe tip placement, size, or condition
  - Standing wave interference
  - Cerumen or debris
    - ✓In ports of probe
    - ✓Occluding external ear canal
  - Vernix casseous (healthy newborn infants)
- Pathologic explanations
  - Stenosis
  - External otitis
  - Middle ear dysfunction

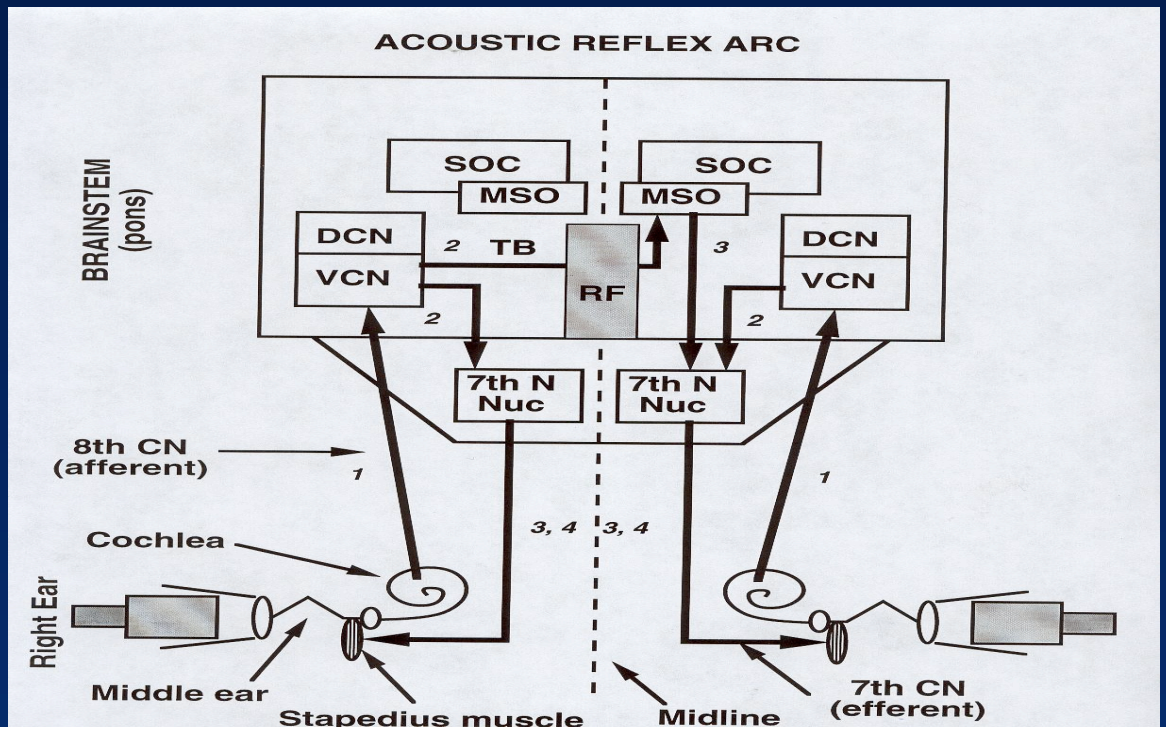
Acoustic Immittance Measurements and OAEs:
Perform Tympanometry



Diagnosis of Hearing Loss: Protocol for Confirmation of Hearing Loss in Infants and Toddlers (0 to 6 months)
Year 2007 JCIH Position Statement

- Child and family history
- Otoacoustic emissions
- ABR during initial evaluation to confirm type, degree & configuration of hearing loss
- Acoustic immittance measures (including acoustic reflexes) *using high frequency (1000 Hz) probe tone*
- Supplemental procedures (insufficient evidence to use of procedures as "sole measure of auditory status in newborn and infant populations")
  - Auditory steady state response (ASSR)
  - Acoustic middle ear reflexes for infants < 4 months
  - Broad band reflectance
- Behavioral response audiometry *(if feasible)*
  - ✓ Visual reinforcement audiometry *or*
  - ✓ Conditioned play audiometry
  - ✓ Speech detection and recognition
- Parental report of auditory & visual behaviors
- Screening of infant's communication milestones

Acoustic Stapedial Reflex: A Valuable Tool in Assessing Middle Ear Status (and so much more)



What About Tympanostomy (Ventilation) Tubes?
Can OAEs Be Recorded?

- Daya et al. (1966). Otoacoustic emissions: Assessment of hearing after tympanostomy tube insertion. Clin Otolaryngol 21: 492-494.
- Owens, McCoy, Lonsbury-Martin, Martin. (1993). Otoacoustic emissions in children with normal ears, middle ear dysfunction, and ventilating tubes. Amer J Otol 14: 34-40.
- Tilanus. Stenis, Snik.(1995). Otoacoustic emission measurements in evaluation of the effect of ventilation tube insertion in children. Annals of ORL 104: 297-300.
- Richardson, Elliott, Hill. (1996). The feasibility of recording transiently evoked otoacoustic emissions immediately following grommet insertion. Clin Otolaryngol 21: 445-448.
- Cullington, Kumar, Flood. (1998). Feasibility of otoacoustic emissions as a hearing screen following grommet insertion. Brit J Audio 32: 57-62.

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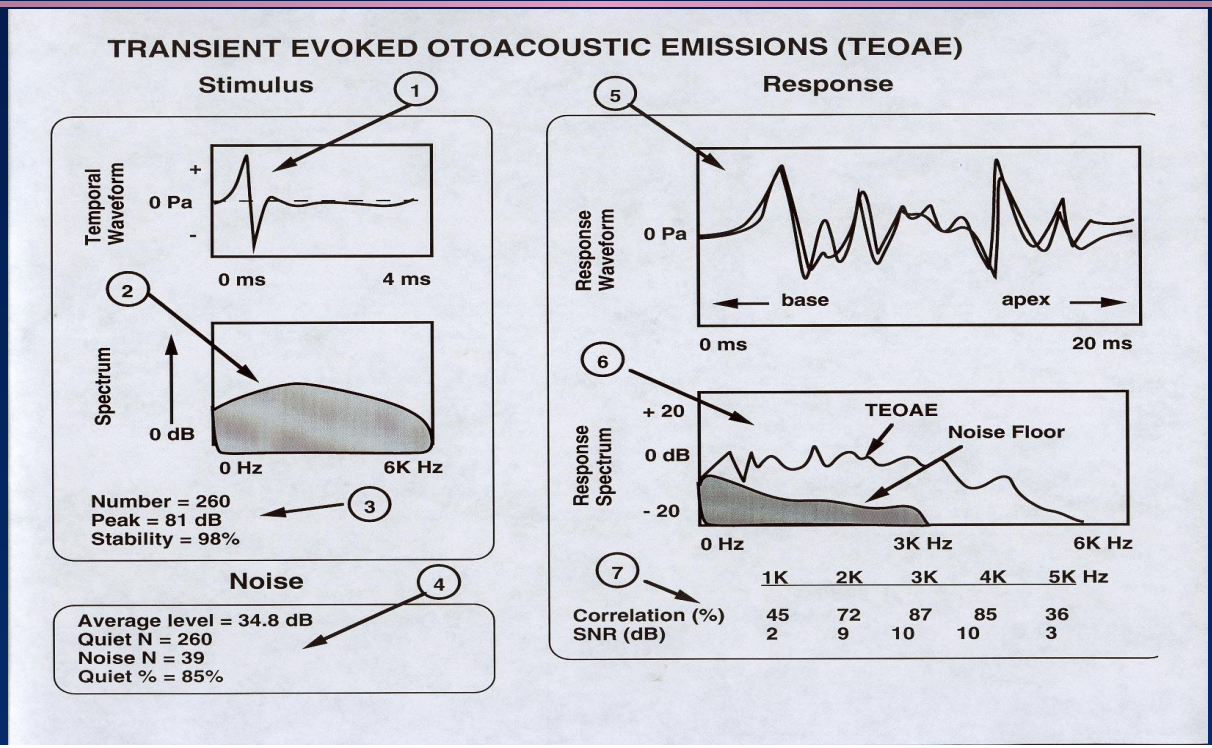
Analysis of Transient Evoked Otoacoustic Emissions (TEOAEs)




CAPELLA OAE [Sample Patient]
NOAH File Setup Mode View Ear
Help
[mPa]
[uPa]
1.0
-1.0
100
-100
(A+B)/2
(A-B)/2
0.0
5.0
10.0
15.0
[ms]
[dB]
0
-10
-20
Resp.
Noise
1.0
2.0
3.0
4.0
5.0
[kHz]
Scale
Statistics
Correlation:
97 %
96 %
96 %
Emission strength:
12.2 dB
11.9 dB
15.0 dB
S/N ratio:
19.0 dB
16.8 dB
17.8 dB
0.5-2kHz
2-13kHz
Overall
Sweeps
Accepted:
3000
Rejected:
3648
% Comp:
100 %
Meas. No.
1
Fit
Cursor
A+B:
0.10 mPa
7.76 ms
Mode
Linear
Non-linear
Stimulus
80 dB
Action
Start
Pause
Stop
Measured: 4/24/00
Stimulus adjust: coupler referenced
Ear: Left
TEOAE mode

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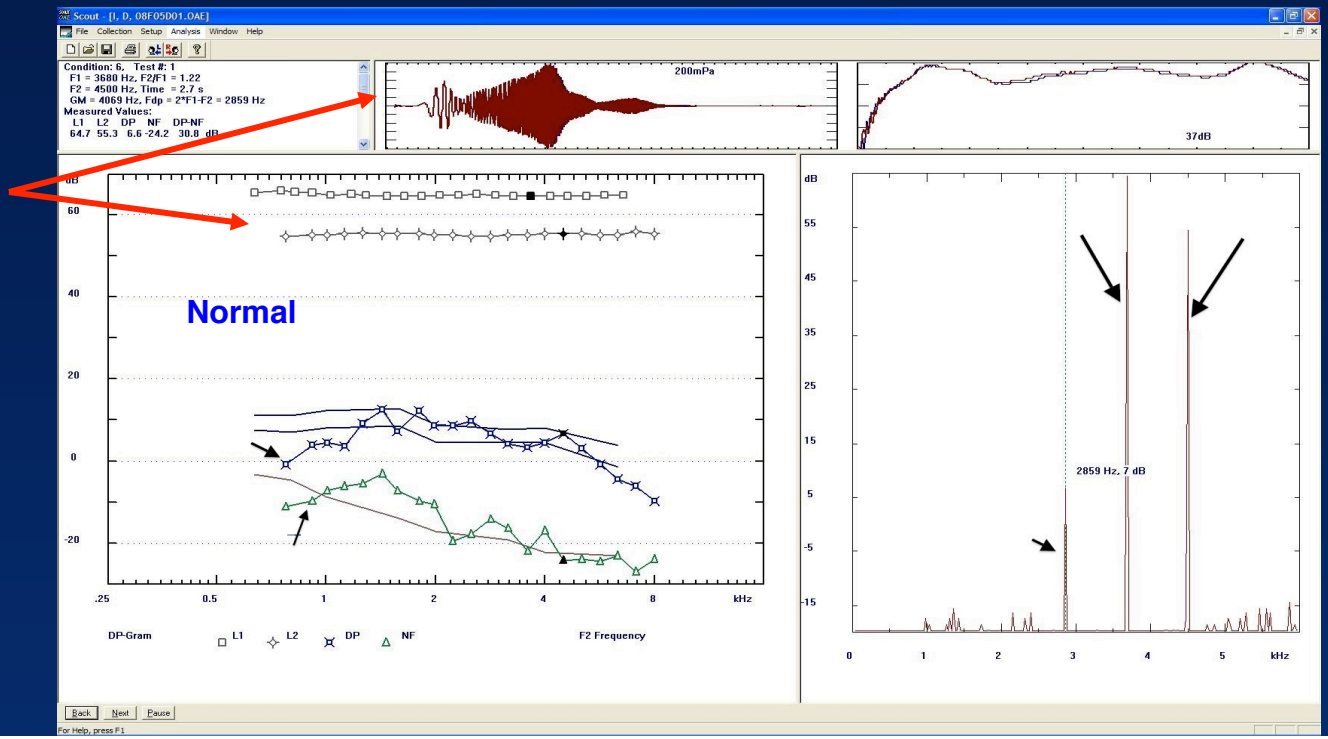
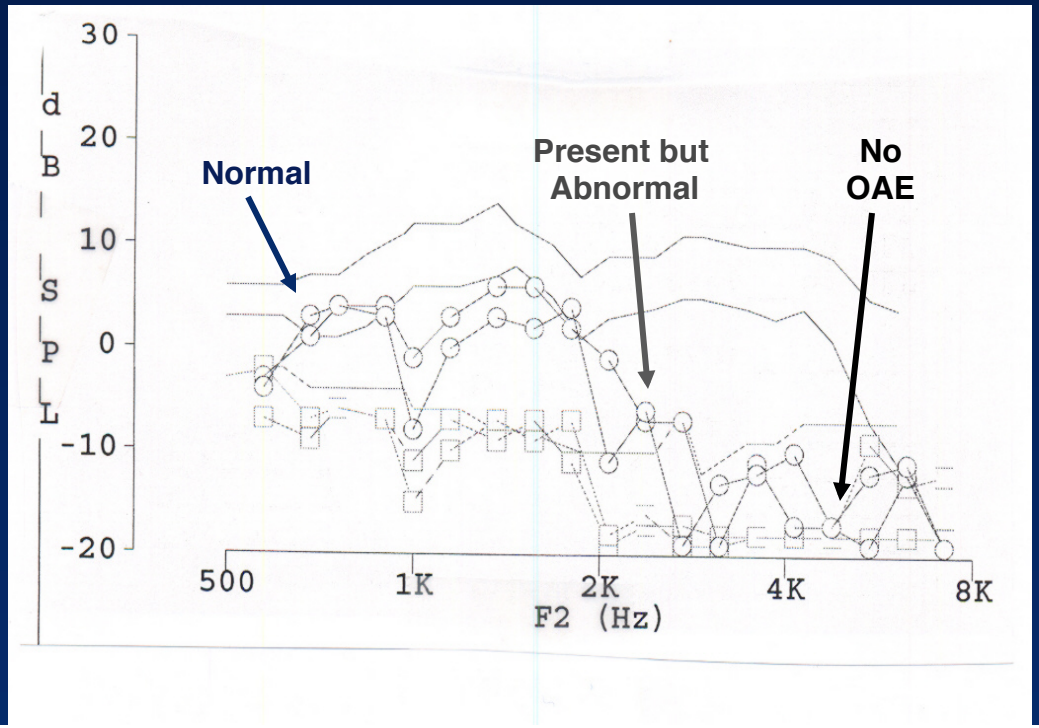
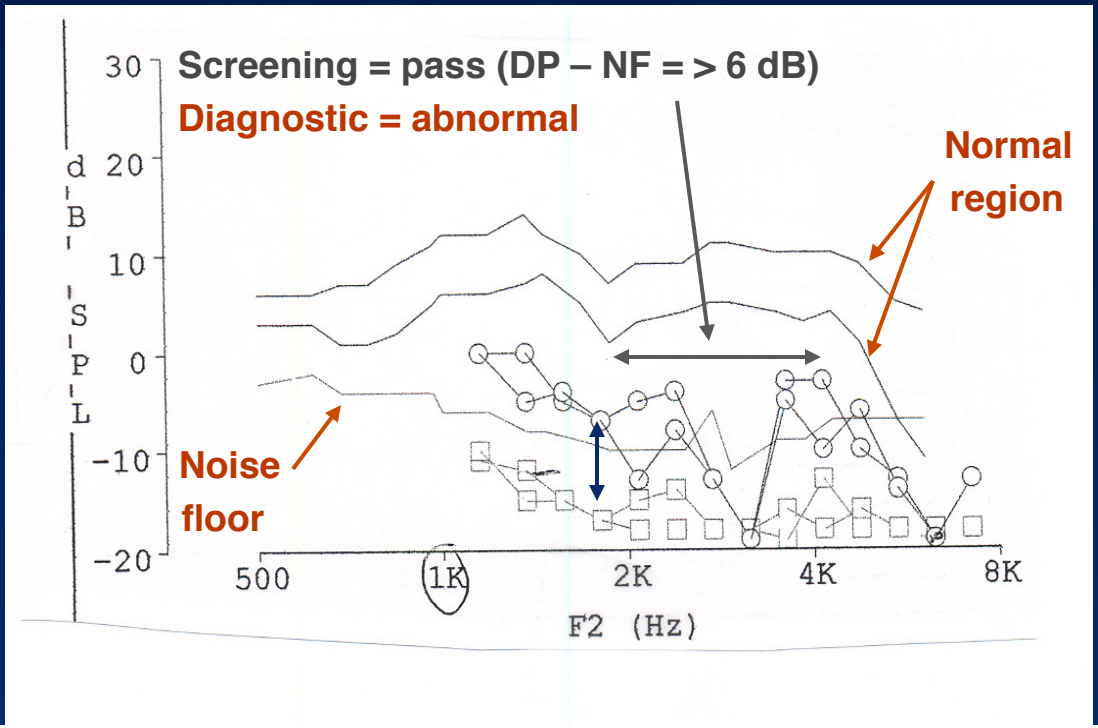
Analysis of Distortion Product Otoacoustic Emissions (DPOAEs)

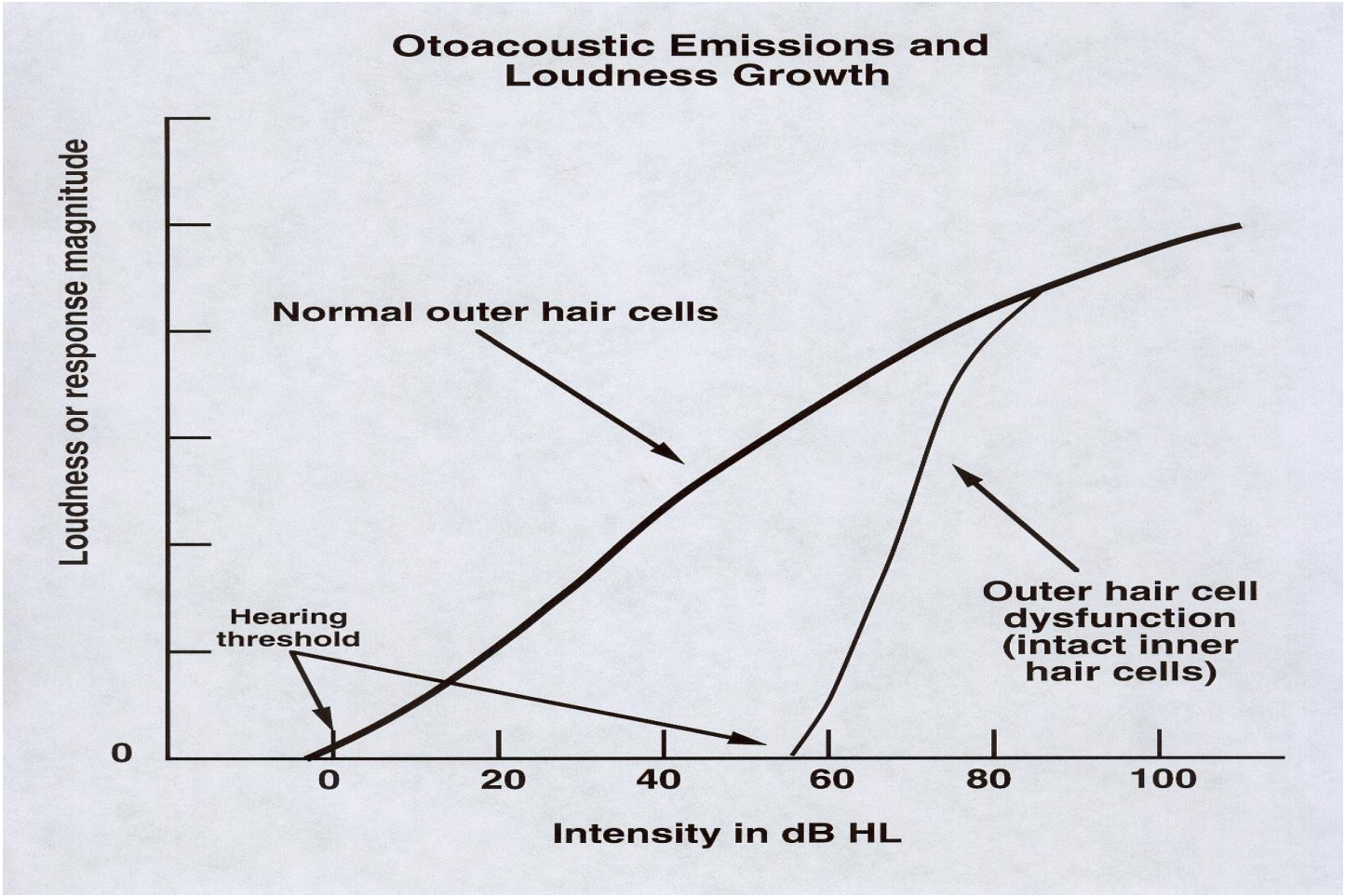


Analysis of Distortion Product Otoacoustic Emissions (DPOAEs)



Diagnostic Application of OAEs: Findings for Multiple Frequencies vs. Normal Region




Otoacoustic Emissions and
Loudness Growth
Loudness or response magnitude
Normal outer hair cells
Hearing
threshold
Outer hair cell
dysfunction
(intact inner
hair cells)
0
0
20
40
60
80
100
Intensity in dB HL

OAEs:
Abnormal OHCs and loudness recruitment

"The phenomenon of loudness recruitment appears to be the psychoacoustic expression of the loss of a large component of outer hair cells and the concurrent preservation of a large component of inner hair cells and type I cochlear neurons."

Schuknecht HF. Pathology of the Ear (2nd ed). 1993, p. 91

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CLINICAL APPLICATION OF OTOACOUSTIC EMISSIONS (OAE): General advantages

- Highly sensitive to cochlear (outer hair cell function)
- Site specific (to outer hair cells)
- Do not require behavioral cooperation or response
- Ear specific
- Highly frequency specific
- Do not require sound-treated environment
- Can be quick (< 30 seconds)
- Portable (handheld devices)
- Relatively inexpensive

CLINICAL APPLICATION OF OTOACOUSTIC EMISSIONS (OAE): Possible Disadvantages

- Susceptible to effects of noise
- Affected greatly by middle ear status
- Provide cochlear information only about outer hair cells
- May be abnormal or not detected with normal audiogram
- Are not detectable with hearing loss > 40 dB HL
- Cannot be used to estimate degree of hearing loss
- Not a measure of neural or CNS auditory function
- Not a test of hearing

Selected Clinical Applications of OAEs in Pediatric Populations

- Pediatric Applications
  - Infant hearing screening
  - Diagnosis of auditory dysfunction in infants and young children
    - ✓Confirm or rule out outer hair cell dysfunction
    - ✓Identification of ANSD
  - Monitoring ototoxicity
  - Pre-school/school screenings
  - Identification of false or exaggerated hearing loss

Grandson Charlie Hall (age 2 weeks)

Year 2007 Position Statement: Principles and Guidelines for Early Hearing Detection and Intervention Programs

Joint Committee on Infant Hearing (JCIH). *Pediatrics 120*: 898-921

- "Physiologic measures must be used to screen newborns and infants for hearing loss. Such measures include OAE and automated ABR testing." (p. 903)
- "Both OAE and automated ABR techniques provide noninvasive recordings of physiologic activity underlying normal auditory function." (p. 903)
- "Neural conduction disorders or auditory neuropathy/dysschrony without concommitant sensory dysfunction will not be detected by OAE testing."
- "The JCIH recommends ABR technology as the only appropriate screening technique for use in the NICU." (p/ 904)
- "Some programs use a combination of screening techniques (OAE and ABR) to decrease the fail rate at discharge." (p. 904)

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- Parental report of auditory & visual behaviors
- Screening of infant's communication milestones

Identification and Diagnosis of Auditory Neuropathy Spectrum Disorder (ANSD): Minimal Test Battery (2008 ANSD Guidelines)

- Tests of cochlear hair cell function
  - Otoacoustic emissions (OAEs)
  - Cochlear microphonic (ECochG and ABR)
    - ✓ CM may be present when OAEs are absent (e.g., with middle ear dysfunction)
- Tests of auditory nerve function
  - ABR for high intensity click stimulation (e.g., 80 to 90 dB nHL) with separate averages for:
    - ✓ Rarefaction stimulus polarity
    - ✓ Condensation stimulus polarity
- Additional tests
  - Acoustic reflex measurement (generally acoustic reflexes are absent in ANSD)
  - Suppression of otoacoustic emissions (abnormal, e.g, no suppression in ANSD)

Selected Clinical Applications of OAEs in Pediatric Populations

(See Chapter 9 in Dhar & Hall, 2012)

- Pediatric Applications
  - Infant hearing screening
  - Diagnosis of auditory dysfunction in infants and young childre
    - Confirm or rule out outer hair cell dysfunction
    - Identification of ANSD
  - Monitoring ototoxicity
  - Pre-school/school screenings
  - Identification of pseudohypacusis

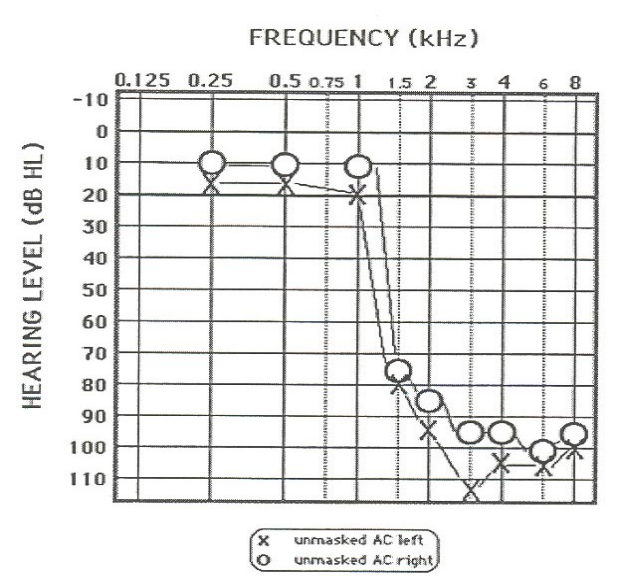
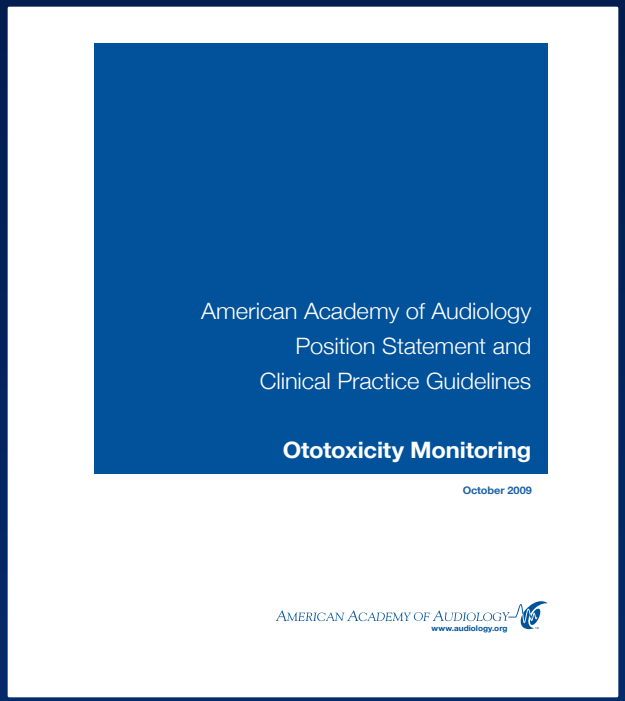


FIG. 1. This 24-year-old woman with cystic fibrosis received frequent tobramycin therapy since her diagnosis at the age of 3 months. Her audiogram shows a hearing loss at high frequencies.

Clinical Guidelies for Ototoxicity Assessment and Monitoring



- Task Force Members
  - John Durrant (Chair)
  - Kathleen Campbell
  - Stephen Fausti
  - O'Neil Guthrie
  - Gary Jacobson
  - Brenda Lonsbury-Martin
  - Gayla Poling

Current Trends in Ototoxicity Assessment and Monitoring
(American Academy of Audiology Position Statement and Clinical Practice Guidelines for Ototoxicity Monitoring, 2009)

- **Assessment and Monitoring Techniques**
  - **Pure tone audiometry**
    - ✓**Conventional test frequencies**
    - ✓**High frequency audiometry (HFA)**
  - **Distortion product otoacoustic emissions (DPOAEs)**
    - ✓**Determine reliability during baseline measurement**
    - ✓**High frequency protocol with many frequencies/octave**
  - **Frequency-specific electrophysiological measures as indicated**
    - ✓**ABR (tone burst and chirp stimuli)**
    - ✓**ASSR**

OTOTOXICITY:
Rationale for Monitoring with DPOAEs (*not* TEOAEs)

- Highly sensitive to cochlear (outer hair cell) dysfunction
- Most ototoxic drugs first damage outer hair cells
  - Aminoglycosides (e.g., gentamicin)
  - Loop diuretics (lasix or furosemide)
  - Cisplatin
- Objective (can be performed on sick patients)
- Brief test time (one or two minutes)
- High degree of frequency detail (selectivity)
- High frequency limit up to 10,000 Hz (DPOAEs only … TEOAE limit is about 5000 Hz)
- Earlier detection of cochlear auditory dysfunction compared to audiogram

OAEs in Monitoring For Ototoxicity: Recording and Analysis

- Utilize distortion product otoacoustic emissions versus TEOAEs to reach higher frequency region
  - Record to highest available test frequencies (≥ 8K Hz)
  - Sensitive stimulus intensity levels (L1 = 65 dB; L2 = 55 dB)
  - Use multiple frequencies/octave (> 5)
  - Replicate DPgrams to determine normal variability
- Analysis
  - Verify the presence of DPOAEs for each frequency
  - Compare average amplitude for replications for baseline versus post-drug recordings
  - Report any decrease in amplitude exceeding variablity

Selected Clinical Applications of OAEs in Pediatric Populations

- Pediatric Applications
  - Infant hearing screening
    - ✓Confirm or rule out outer hair cell dysfunction
    - ✓Diagnosis of ANSD
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  - Pre-school/school screenings
  - Identification of false or exaggerated hearing loss

Otoacoustic Emissions in Audiology Today: Pre-school and school age hearing screening

- Few published papers on pre-school or kindergarten age hearing screening with OAEs (despite widespread use of OAEs in Head Start hearing screening programs)
- Screening auditory function in first grade children (≥ 6 years old)
  - Lyons A, Kei J & Driscoll C. DPOAEs in children at school entry: A comparison with pure-tone screening and tympanometry results. *JAAA 15: 2004* (Univ. of Queensland, Brisbane, Australia)
    - ✓ N = 1003 children
    - ✓ "When the results of a test protocol which incorporates both DPOAEs and tympanometry were used in comparison with the gold standard of pure tone screening plus tympanometry, test performance was enhanced. The use of a protocol that includes both DPOAEs and tympanometry holds promise as a useful tool in hearing screening of schoolchildren, including difficult-to-test children" (p. 702).

Selected Literature:
Pre-School and School Age Hearing Screening with OAEs
(See Chapter 7 in Dhar & Hall, 2012)

- Lyons et al (2004)
  - N = 1003
  - Age: 4-8 years
  - DPOAE: 90% hit rate (for 20 dB HL hearing loss)
- Sideris & Glattke (2006)
  - N = 200
  - Age: 2-6 years
  - TEOAE: 21% refer rate
- Berg et al (2006)
  - N = 4003
  - Age: 2-9 years
  - DPOAE: 13.6%

Selected Literature:
Pre-School and School Age Hearing Screening with OAEs

- Dille et al (2007)
  - N = 33
  - Age: 0.5-4 years
  - TEOAE & DPOAE: Failure rates > 40%
- Hunter et al (2007)
  - N = 421
  - Age: 0-2 years
  - DPOAE: 30% (high rate of otitis media)
- Psillis et al (2007)
  - N = 76
  - Age: 1-5 years
  - DPOAE

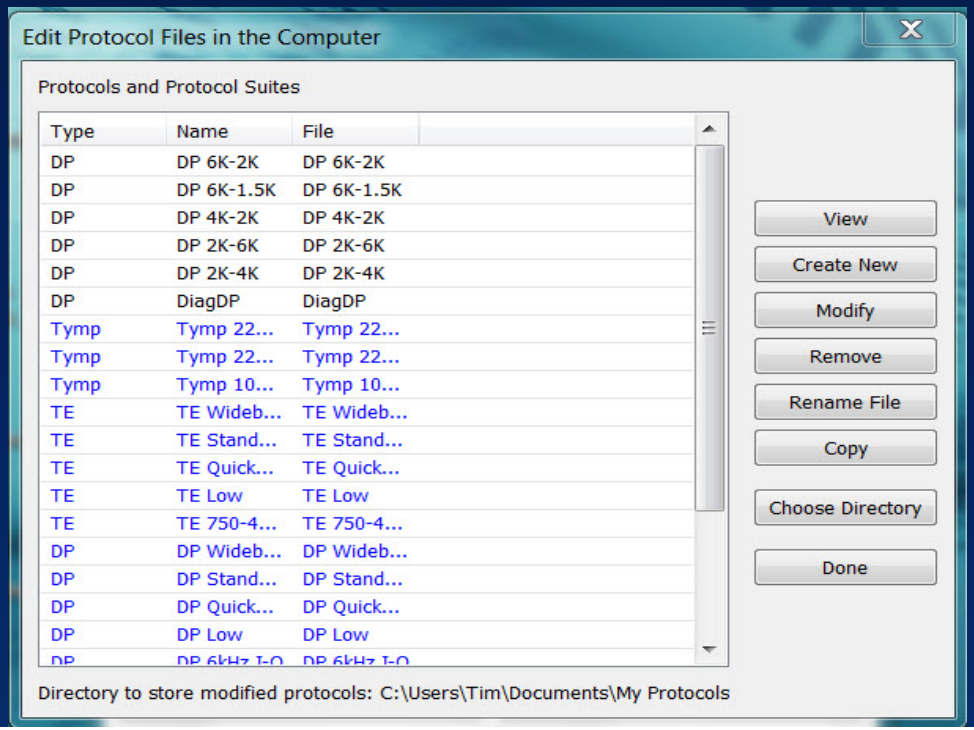
Selected Literature:
Pre-School and School Age Hearing Screening with OAEs

- Eiserman et al (2008)
  - N = 4591
  - Age: ≤ 3 years
  - DPOAE: Refer rate 18%
- Georgalas et al (2008)
  - N = 196
  - Age: 6-12 years
  - TEOAE: Refer rate 32%
- Hild et al (2008)
  - N = 512
  - Age: 10-69 years
  - DPOAE: Refer rate 24%
- Yin et al (2009)
  - N = 744
  - Age: 2-6 years
  - TEOAE: Refer rate 5.5%

Hearing Screening in the Head Start Population: Equipment

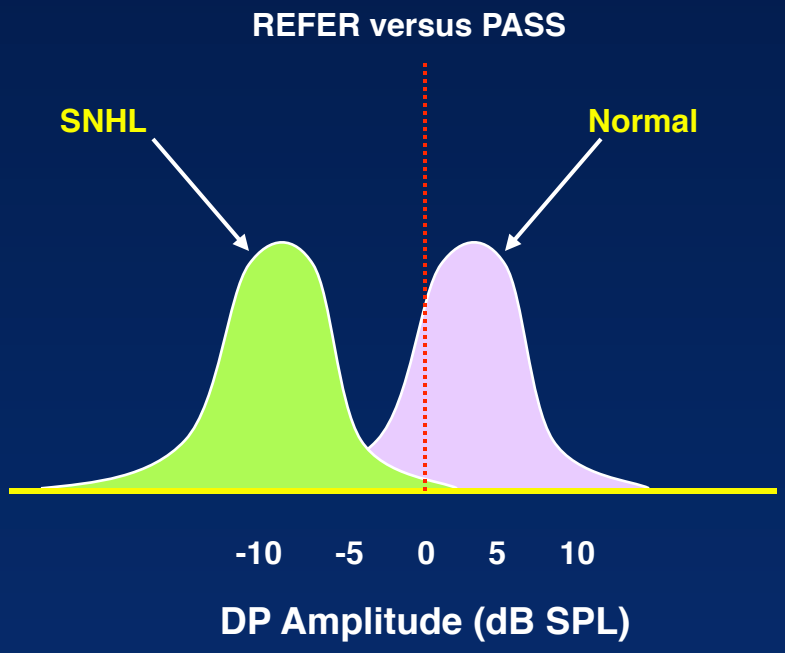
Hearing Screening in a Pre-School (Head Start) Population: Distortion Product OAEs (≥ 2000 Hz)

Pre-School Hearing Screening with DPOAEs: Creating and Evidence-Based Protocol

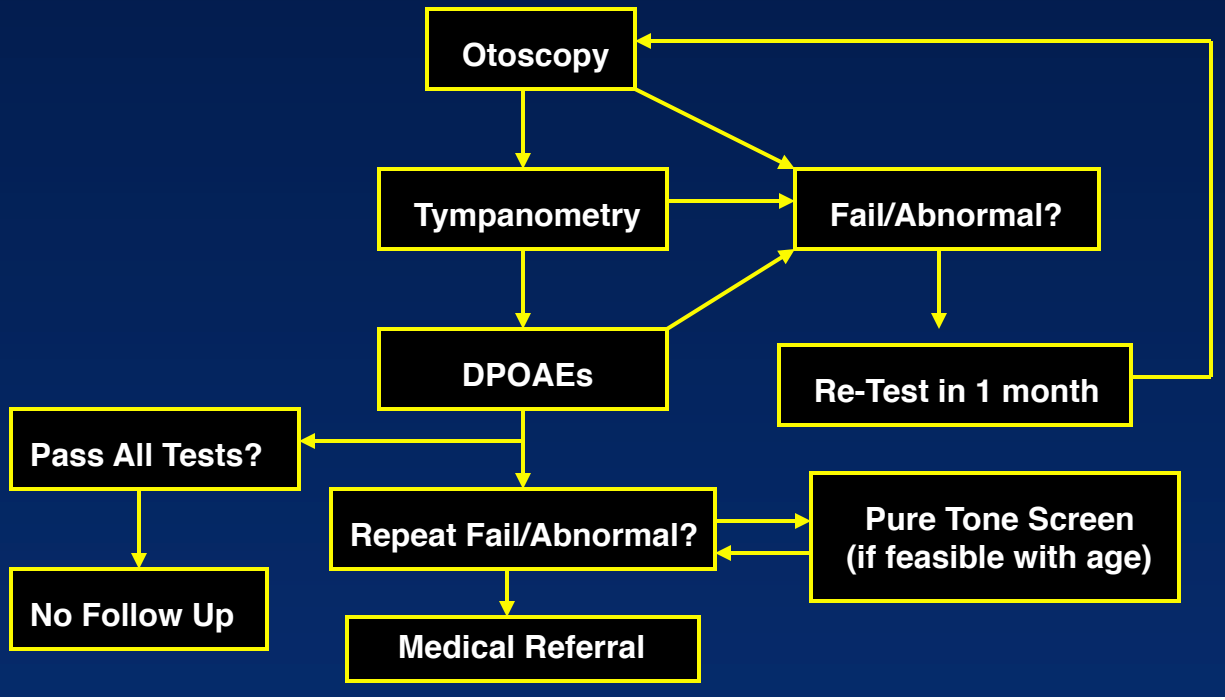


OAE Screening in Pre-School and School Age Children: Criterion for PASS versus REFER

(Data from Gorga, Stover & Neely, 1996)



Hearing Screening with Tympanometry and OAEs Versus Pure Tones in the Pre-School Population



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- Pediatric Applications
  - Infant hearing screening
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  - Pre-school/school screenings
  - Identification of false or exaggerated hearing loss

Selected Literature: Detection and Diagnosis of Pediatric Pseudohypacusis with OAEs

- Balatsouras et al (2003)
  - At risk children include those with emotional trauma
  - Tendency to more common in adolescent girls
  - OAE findings contribute to increased cooperation and valid behavioral thresholds
- Saravanappa et al (2005)
  - OAEs contribute to quicker, easier, and more confident diagnosis
  - Patient and parent awareness of OAE findings results in “improvement” in hearing and disappearance of condition
- Holenweg & Kompis (2010)
  - Without evaluation with OAEs, one-out-of-five children with pseudohypacusis were fit with hearing aids

Selected Literature: Detection and Diagnosis of Pediatric Pseudohypacusis with OAEs

- **Morita et al (2010)**
  - **Late or misdiagnosis can lead to**
    - ✓ **Increase cost of health care**
    - ✓ **Litigation**
    - ✓ **Inappropriate medical (e.g., steroid) treatment**
- **Ioannis et al (2009**
  - "Otoacoustic emissions were used in all children who participated in this study and in some cases their role as 'lie detector' produced a striking and immediate result."

Electro-Acoustic Measurements: Otoacoustic Emissions (OAEs)

- Historical perspective
- Update on generation of OAEs: Clinical Implications
- Guidelines for OAE measurement
- Guidelines for OAE analysis
- Analysis of TEOAEs
- Analysis of DPOAEs
- Evidenced-based clinical applications in children
- Evidenced-based clinical applications in adults

OAEs: Clinical Applications in Adults

- Sensitive measure of middle ear status
- Noise/music exposure
- Malingerers
- Cochlear versus retrocochlear dysfunction
- Assessment of tinnitus & hyperacusis
- Auditory processing disorders (r/o cochlear deficit)
- Industrial hearing screening and conservation

Thank You!
Questions?