Application of Acoustic Immittance Measures in Audiology Today

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Electroacoustic Measurements:
A New Look at Some Old Procedures

- Immittance/Admittance Measurements
  - Tympanometry
    - Conventional (226 Hz)
    - High frequency
    - Theta Y (θY)
    - Gradient
  - Acoustic reflexes
    - Ipsilateral versus contralateral
    - Pure tone versus noise signals
- Wide-band reflectance (WBR)
- Otoacoustic emissions
Rationale … Why are electro-acoustic measures important in audiology today?

1. Abundant clinical evidence in support of the diagnostic value of electro-acoustic measures
   - 30+ years of clinical experience
   - Hundreds of publications in peer-reviewed journals
   - Electro-acoustic measures add value to the clinical test battery

2. Numerous clinical advantages of electro-acoustic measures
   - Fast
   - Objective
   - Non-invasive
   - Clinical available to all audiologists
   - Portable devices
   - No need for sedation
   - In U.S.A.
     - Equipment is approved by FDA
     - CPT codes available for billing
Rationale … Why are electro-acoustic measures important in audiology today? (2)

- Electro-acoustic measures are highly sensitive to peripheral auditory dysfunction
  - Problems with integrity of tympanic membrane
  - Mechanical abnormalities of the middle ear
  - Cochlear abnormalities (inner and outer hair cell)
  - 8th cranial nerve dysfunction
  - Auditory neuropathy
- Most hearing loss in children or adults is caused by peripheral auditory dysfunction
- Peripheral hearing loss is most effectively treated medically or non-medically (audiologically)
- Electro-acoustic measurement can contribute to better patient outcome
Electroacoustic Measurements: A New Look at Some Old Procedures

- **Imittance/Admittance Measurements**
  - Tymanometry
    - Conventional
    - High frequency
    - Theta Y ($\Theta Y$)
    - Gradient
  - Acoustic reflexes
    - Ipsilateral versus contralateral
    - Pure tone versus noise signals
- Wide-band reflectance (WBR)
- Otoacoustic emissions
AURAL IMMITTANCE MEASUREMENT: 
Historical Perspective

- **Luscher (1929)** in Germany observed acoustic reflex
- **Otto Metz (1946)** in Denmark developed mechano-acoustic impedance bridge and measured impedance and acoustic reflexes clinically
- **Jepsen (1951)** confirmed stapedius muscle acoustic reflex
- **Knut Terkildson (1956)** developed electro-acoustic impedance device
- **Josef Zwislocki (1962)** introduced mechano-acoustic impedance bridge to U.S.A.
- **James Jerger (1970)** applied electro-acoustic impedance device clinically in U.S.A.
“In October 1943, just as the Nazis were preparing to intern all Jews in Denmark, Otto Metz had the good fortune to be one of the more than 6,000 Jews spirited across the sea to Sweden by the Danish Resistance. Thus escaping capture, Metz was able to continue his pioneering research at the University Hospital of Lund.

After returning safely to Copenhagen in 1945, Metz formulated the basic principles of tympanometry in his dissertation of 1946: “The acoustic impedance measured on normal and pathological ears”. This constituted the earliest substantial set of acoustic impedance measurements in normal and pathological ears – and obtained using a mechanical bridge.

Continuing this work at Rigshospitalet, Metz also published the seminal “Threshold of reflex contractions of muscles in the middle ear and recruitment of loudness” in the Archives of Otolaryngology in 1952. This was the first study of the acoustic stapedius reflex in patients with ear disease.” (GN Otometrics Website)
Aural Immittance (Impedance) Historical Perspective:
Otto Metz (1905-1995)
Scott-Nielsen and Terkildsen
With Madsen ZO61 Impedance Bridge
James Jerger
“Father of Diagnostic Audiology”
Observed Impedance Measurements in 1960 in Denmark
AURAL IMMITTANCE MEASUREMENT:
Relations among impedance components

- $Z_a = \sqrt{R_a^2 + X_a^2}$, where $X_a = 2\pi f M (-k/2\pi f)$

  - $R_a = \text{acoustic resistance, i.e., impedance due to friction}$

  - $X_a = \text{acoustic reactance, i.e., impedance due to mass and stiffness (or compliance) components}$
Early Impedance Devices ("Bridges")

- GSI 1720 Immittance Meter
- Madsen ZO 70
- American Electromedics
- Amplaid
Impedance Audiometry Ushers in the Modern Era of Audiology (1975)
AURAL IMMITTANCE MEASUREMENT:
Definitions

- Immittance = \textbf{impedance} + admittance

- Impedance \((Z_a)\) = opposition to acoustic energy flow through middle ear system (in acoustic ohms)

- Admittance \((Y_a)\) = ease of acoustic energy flow through middle ear system (in acoustic mmhos); reciprocal of \(Z_a\)
AURAL IMMITTANCE MEASUREMENT: Relations among admittance components

\[ Y_a = \sqrt{G_a^2 + B_a^2}, \text{ where} \]

Y phase angle = arctan \( \frac{B_a}{G_a} \)

- \( G_a = \text{acoustic conductance (admittance due to friction)} \)
- \( B_a = \text{acoustic susceptance, i.e., admittance due to mass and stiffness (or compliance) components} \)
AURAL IMMITTANCE MEASUREMENT:  
Clinical Measurements

- Instrumentation
- Ear canal volume
- Static compliance
- Tympanometry
  - 220 vs. 1000 Hz probe tones for adults vs. neonates
  - Toynbee and Valsalva procedures
  - Fistula test acoustic reflexes
- Acoustic reflexes
  - ipsi - and contralateral
  - reflex decay
ELECTROACoustic IMMITTANCE METER

Oscillator (220 Hz) → Potentiometer → Loudspeaker → Pinna → External ear canal → Middle ear

Air Pump → Manometer

Reference Voltage → Amplifier → Balance Meter → Bridge Circuit
A Simple System for Categorizing Tympanograms

TYMPANOGRAMMETRY
(JERGER SYSTEM)

Compliance

Air Pressure In mm H2O

Normal region

Type Ad

Type C

Type B

Type A

Type As
### Tympanogram Type as a Function of Pressure Change Direction in 186 Ears (Hall & Chandler, 1994)

<table>
<thead>
<tr>
<th>Descending Pressure (+ to -)</th>
<th>A</th>
<th>As</th>
<th>Ad</th>
<th>B</th>
<th>C</th>
<th>Cpos</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>123</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>As</td>
<td>7</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ad</td>
<td>1</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>17</td>
<td>0</td>
</tr>
<tr>
<td>Cpos</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
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</tbody>
</table>
Tympanogram Gradient

- Computation of tympanogram admittance relative to pressure range

- First reported by
  - Cooper et al, 1982
  - de Jonge, 1986
  - Koebsell & Margolis, 1986
  - Tompkins & Hall, 1990

- A half-amplitude admittance ($Y$) point is determined on the positive and negative side of the tympanogram
  - Total amplitude on each side is divided by two
  - The difference in air pressure between each of these points on the slope of the tympanogram is referred to as delta (difference) pressure ($dP$) and expressed in daPa
Tympanogram Gradient

GdP = Pb - Pa

Ad
Lower GdP

As or B
Higher GdP

Compliance mm
Air Pressure (daPa)
Multicomponent Tympanograms: Admittance (Y), Susceptance (B), Conductance (G)
“Distribution of Theta $Y_{226}$ in A Clinical Population”
(Bishop & Church, JAAA 19: 2008)
Toynbee and Valsalva Tests

R = RESTING PRESSURE
T = PRESSURE AFTER TOYNBEE
T1 = PRESSURE AFTER ONE OPEN-NOSE SWALLOW
T2 = RESIDUAL PRESSURE AFTER MULTIPLE OPEN-NOSE SWALLOWS
V = PRESSURE AFTER VALSALVA
V1 = PRESSURE AFTER ONE SWALLOW
V2 = RESIDUAL PRESSURE AFTER MULTIPLE SWALLOWS

UNIT

T T1 T2 R V2 V1 V

mm H20
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
Low (226 Hz) versus High (1000 Hz) Probe Tone for Infant Tympanometry
Tympanometry in Infants and Young Children: Clinical Recommendations and Cautions

- The middle ear system of a newborn infant is mass dominated with a lower resonant frequency (Kei et al, 2007)
- The adult middle ear system is stiffness dominated with a higher resonance frequency
- External ear canals of neonates “are distensible under applied air pressure because of the underdeveloped osseous portion of the ear canal” (Kei et al, 2007)
- “Compensating for the ear canal contribution by making measurements of admittance at extreme ear canal static pressures (i.e., +200 or - 400 daPa) may introduce errors in estimating the static admittance.” (Kei et al, 2007)
- Use a 1000 Hz probe tone with infants up to the chronological age of at least 4 months
- Calculate ear canal volume with a 226 Hz probe tone
- Ear canal volume measurements at extreme positive or negative pressures may not be accurate in neonates.
New concept for middle ear assessment
Wideband power reflectance (impedance and admittance)
Uses broad band stimulus
Measured at ambient pressure or with induced ear canal pressure
Takes a few seconds to record averaged response
Wideband Power Reflectance (WBR):
Measurements in 6 Domains

- Power reflectance (%)
- $|R|^2$ Power absorption (%)
- $1 – |R|^2$ Transmittance (dB)
- $0 \times \log_{10}[1 – (|R|^2)]$ Normalized resistance (real (Re) component)
- $[\text{Re}(Z) / Z_c]$ Normalized reactance (imaginary (Im) component)
- $[\text{Im}(Z) / Z_c]$ Normalized impedance magnitude ($|Z / Z_c|$)
What is Power Reflectance?

- Sound enters ear canal, propagates down the ear canal, and is partially reflected from the ear drum.
- Power reflectance = energy reflectance
- Reflectance = reflected power / incident power
Reflectance = \frac{\text{Reflected Power}}{\text{Incident Power}}

Transmittance = \text{Absorbed Power}
Wideband Reflectance $|R(f)|$

$R(f)$ depends on frequency

Hunter, AAA convention 2005
Reflectance Measurement

- Probe calibration
- Obtain patient measurement
- Evaluation of results
Probe Calibration

Characterize the probe acoustics properties via four cavities

Cavity pressures  Calibration pass

Earphone  L4  L3  L2  L1  FOUR CAVITIES  Cavity set
Obtain patient measurement

- Select the probe tip
- Place the probe in the patient’s ear canal
- Specify the probe tip size
- Initiate the canal pressure measurement
- Parameters:
  - Stimulus type (Chirp or tone)
  - Stimulus duration (sec)
Measure Reflectance

- Ear tip size
- Stimulus type
- Ear to be measured
- Reflectance plot
Bilateral Sensorineural Hearing Loss (SNHL)

Feeney, JSHR, 2003
Four Ears with Otitis Media with Effusion (OME)

Feeney, JSHR, 2003
Ossicular Discontinuity

Feeney, JSR, 2003
Tympanic Membrane Perforation

Feeney, JSHR, 2003
Wideband Power Reflectance (WBR): Findings in Healthy Newborn Infants (Hunter et al, 2007)

- Strong relationship between WBR and referred DPOAEs
- Reflectance and OAEs combined in portable device
- FDA approved instrument (Mimosa Hear-ID)
- Reflectance is broad-band across entire audiometric range
- Measurement is rapid and easy to complete in neonates
Acoustic Stapedial Reflex
(Anatomy adapted from Borg)
Patterns of Acoustic Reflex Deflections: Normal and Abnormal

- Normal: typical
- Normal: atypical
- Abnormal: early otosclerosis
Acoustic Reflex Decay: A Retrocochlear Finding

**ACOUSTIC REFLEX DECAY**

- **Time in Seconds**
- **Compliance in cc**
- **Impedance**

**1000 Hz**

- Normal finding: no decay
- Abnormal finding: > 50% decay
PLOTTING ACOUSTIC REFLEXES

RIGHT EAR
Frequency in Hz

125  250  500  1000  2000  4000  8000

Right ear ipsilateral (stimulus right)
Right ear contralateral (sound right)
Left ear contralateral (sound left)

Tympanometry
Earphone
Contralateral
Ipsilateral

Acoustic Reflex
Crossed uncrossed

Tympanometry
Earphone

Left ear ipsilateral (stimulus left)
Left ear contralateral (sound left)
Right ear contralateral (sound right)

Compliance (c) mmH2O

0  20  40  60  80  100

dB HL

0  250  500  1000  2000  4000  8000

Left ear ipsilateral (stimulus left)
Left ear contralateral (sound left)
Right ear contralateral (sound right)

Compliance (c) mmH2O

normal abnormal absent
### Plotting the Results of Acoustic Reflex Measurements

**Acoustic reflex patterns ("faces")**
- Conductive/fferent pattern
- Sensory pattern
- Neural pattern
- Brainstem pattern

<table>
<thead>
<tr>
<th></th>
<th>Right</th>
<th>Left</th>
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<tbody>
<tr>
<td><strong>Crossed (contralateral)</strong></td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>Sound in ear</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th></th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Uncrossed (ipsilateral)</strong></td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>Probe and sound in ear</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
</tbody>
</table>
Ipsilateral (Uncrossed)
Sound Right
Probe Right

Contralateral (Crossed)
Sound Right
Probe Left

Abnormal Acoustic Reflex

Vertical pattern
• Mild conductive hearing loss pattern or efferent (7th CN) pattern (normal tymp and no air bone gap) on right ear

Ipsilateral (Uncrossed)
Sound Left
Probe Left

Contralateral (Crossed)
Sound Left
Probe Right
Ipsilateral (Uncrossed) Sound Right Probe Right

Contralateral (Crossed) Sound Right Probe Left

Abnormal Acoustic Reflex

*Inverted “L” pattern*
- Moderate or severe conductive hearing loss on right ear

Contralateral (Crossed) Sound Left Probe Right

Ipsilateral (Uncrossed) Sound Left Probe Left
Ipsilateral (Uncrossed)
Sound Right
Probe Right

Contralateral (Crossed)
Sound Right
Probe Left

Contralateral (Crossed)
Sound Left
Probe Right

Ipsilateral (Uncrossed)
Sound Left
Probe Left

Abnormal Acoustic Reflex

Diagonal pattern
- Severe sensory hearing loss or 8th nerve auditory dysfunction on right ear
Ipsilateral (Uncrossed)
Sound Right Probe Right

Contralateral (Crossed)
Sound Right Probe Left

Abnormal Acoustic Reflex

Horizontal pattern
• Brainstem auditory dysfunction

Right

<table>
<thead>
<tr>
<th>Abnormal Acoustic Reflex</th>
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</thead>
<tbody>
<tr>
<td>Horizontal pattern</td>
</tr>
<tr>
<td>• Brainstem auditory dysfunction</td>
</tr>
</tbody>
</table>

Left

Ipsilateral (Uncrossed)
Sound Left Probe Left

Contralateral (Crossed)
Sound Left Probe Right
Estimation of Hearing Sensitivity with Acoustic Reflex Thresholds for Pure Tones versus Broad Band Noise (BBN): Simplified SPAR (Sensitivity Prediction by the Acoustic Reflex)