MODELING NOISE HAZARD TO THE HUMAN EAR

Background and Approach
Development of the Mathematical Model
Validation of AHAA-CAT
Making the Human Model
Validation of the Model – Albuquerque Studies
Rating Impulses in the Literature
From the Model toward a DRC

Presented at the Panel Review of the HRED Method for Accessing the Risk of Auditory Injury for Hearing-Protected Soldiers Exposed to Impulse Noise
30-31 January 2001
MODELING NOISE HAZARD TO THE HUMAN EAR

THE BACKGROUND AND APPROACH
Problems with Existing Standards

• Suppose A-weighted energy used as a method for rating hazard:
  – 2000 - 3000 J/M² measured under a muff acceptable for cannon impulses (Johnson & Patterson, 1994)
  – Would allow 2000+ rounds unprotected exposure from a rifle
  – In fact, fewer than 10 rounds hazardous
Or Consider Use of Peak Pressure and Duration as in MIL STD-1474 or Pfander or Smoorenburg
Common Perceptions About Impulse Noise Hazard

Impulse noise is a special problem
Exceedingly high variability in impulse noise exposures
Pulse duration makes a difference - longer pulses better or worse depending on experiment.
Rise time and peak pressure are critical; but their effects are poorly understood
“The precise mechanism behind hearing loss is poorly understood” I. Flindell (1999)
BASIC CONSIDERATIONS IN APPROACH

• First need to understand ear’s response to intense sound
• Basic research with animal model useful in identifying issues and establishing principles (scaling another problem)
• Primary site of loss intracochlear
• Mammalian cochleas similar
BASIC CONSIDERATIONS IN APPROACH

- External and middle ears control properties of conductive path to cochlea
- A selective reading of the basic research needed to find those pieces that pin down basic mechanisms
- Should make theoretical sense
- Begin by following sound into cochlea
The External and Middle Ears

- The external ear (head reflectivity and canal and pinna resonances) provides about 20 dB of emphasis at 4 kHz (cat)
- The middle ear’s resonance is at about 1 kHz (cat)
- Low frequency sensitivity falls off at about 6 dB/Oct (too stiff)
- High frequency falls off at about 18 dB/Oct (too massive)
INSIGHTS FROM BASIC RESEARCH

• At high levels, mechanical stress at the level of the hair cell primary loss mechanism
INSIGHTS FROM BASIC RESEARCH

• At high levels, mechanical stress at the level of the hair cell primary loss mechanism
  – Tip links most vulnerable
  – Upward displacement of basilar membrane puts tissue in tension - primary failure mode
• Damage grows very rapidly at high levels
Growth of Damage

- As level goes up, loss goes from log-time to linear-time relationship
  - In the human ear
    - Ward, Selters and Glorig, 1961
    - Clicks from speaker
    - Threshold shift measure
  - In the cat ear
    - Price (1968, 1972)
    - Pure tone excitation
    - Loss in cochlear microphonic sensitivity
Growth of Damage

- Above critical level, loss grows about 7 dB per dB increase in level
  - In the human ear
    • Ward, Glorig and Sklar, 1962
    • Clicks from speaker
    • Threshold shift measure
  - In the chinchilla ear
    • Patterson et al.
    • Impulses from a speaker
    • Threshold shift, behavioral measure
Growth of Damage - Implications

- Above critical level, loss grows about 7 dB per dB increase in level
  - And in the cat ear
    - Price and Wansack (1985; 1989)
    - Impulse from primer
    - Threshold shift, evoked response measure
Growth of Damage - Implications

• Once loss begins (and middle ear is in linear range of operation and middle ear muscles are not growing in effect), in 10 - 15 dB
  – Threshold shift >80 dB
  – Outer hair cells gone
• Recovery prolonged
  – Loss may even increase for hours
    • Luz and Hodge (1971)(sunburn model)
    • Hamernik, Ahroon and Patterson (1988)
  – Presumption: mechanical repair in cochlea going on
INSIGHTS FROM BASIC RESEARCH

• At high levels, mechanical stress at the level of the hair cell primary mechanism
  – Tip links most vulnerable
  – Upward displacement of basilar membrane puts tissue in tension - primary failure mode
• Damage grows rapidly
• Stapes displacement limited by annular ligament
The Annular Ligament

- In cat, uniform width (about 40 microns)
- Promotes piston-like movement
- Tough - stapes likely to be destroyed before it can be removed from oval window
- On basis of physical considerations, not likely to displace by more than 20 microns
Annular Ligament

- In man, asymmetrical (15 microns at one end, 150 at other end)
- Promotes rocking of footplate along long axis of stapes - less efficient
- Effective maximum displacement for piston about same as cat
• Evidence for non-linearity
  – Measured by Guinan and Peake (1967)
  – Calculable from physical considerations (Price, 1974)
  – Inferable from Nixon and Sommer (1973) airbag simulation
  – Measured effect on intracochlear pressure (Dancer, 2000)
INSIGHTS CONTINUED

• Implications of limited displacement
  – Earliest non-linearity (others follow)
  – Ossicular chain stiffens
  – Peak clips intense sounds - if linear, would try to displace 2000 or more microns to large caliber weapon impulse
  – In complex sounds, low frequencies modulate higher frequencies
  – **Linear weighting schemes can’t work at very high pressures.**
Insights from Basic Research
The Middle Ear Muscles

• Middle ear muscle contraction protective
  – If elicited, too late to affect short impulse
  – If anticipatory or already elicited, protects
• Middle ear muscle reflex conditionable in cat and at least some men
• Middle ear muscle reflex also part of facial reflex
Insights -- Middle Ear Muscles

- Stimuli in impulse noise exposures 40 - 60 dB more intense than those used in the lab
- At gunfire levels, impulse also tactile
- Propose that in case where moment of firing known, should assume middle ear muscle reflex active
- A conservative assumption for a model
Insights -- Middle Ear Muscles

• Stapedius responsible for most of middle ear muscle effect
• Attached to neck of stapes, acts by rocking stapes to side
  – Incudo-stapedial joint sides, capsule deforms
  – Annular ligament stiffens
STAPEDIOUS TENDON

INCUS

ANNULAR LIGAMENT

20 MICRONS
Insights -- Middle Ear Muscles

- Stapedius responsible for most of middle ear muscle effect
- Acts by rocking stapes to side, stiffening annular ligament
- Effects proportional to displacement angle
- Action affects low frequencies most, high frequencies less
EFFECT OF STAPEDIAN CONTRACTION (CAT)
(from Pang and Peake)
The Bottom Line: To Predict Hazard We Need to Account for

• Conductive properties of the external and middle ears
• Stapes non-linearity at high displacements
• Middle ear muscle dynamics and effect
• Mechanical loss process within cochlea

A Computer Based Model Is Needed!
The Modeling Approach to a DRC: Problems and Advantages

- Relatively difficult to do well
- Makes use of a wide range of data about the ear - minimizes the arbitrary
- Theoretical basis makes for generalizability (lowers risk with new data sets)
- Simple in use
- Reduces arbitrary decisions in application
- Encourages remediation rather than palliation (fix rather than patch!)
AHAA Developed - Conformal with ear structure
Next, Development of the Model

• For DRC, could present model as fait accompli. (Once a structure is built, you tear down the scaffolding! OR Like sausage, it’s best not to watch it being made).

• But a strength of the approach is that the structure is built around theory - promotes generalizability.

• Therefore, in next talks will examine the building and validation processes
Development of the Mathematical Model

The Modeling Details
Creating a Mathematical Model

• Which modeling domain?
  – Simulation
  – Mechanical
  – Finite Element
  – Electro-acoustic
Strengths of an Electroacoustic Model

- Designs microphones and loudspeakers
- Ear anatomy translates to circuit elements
- Parts of ear often modeled by circuits
- Visualize signal flow through network
- Time and frequency response calculable
- Merges signal flow in air, solid structures and liquids in cochlea
Choice of the Cat Ear

- Much detail available for cat ear
- Similar to human ear
  - Cochleas highly similar
  - Middle ears similar
    - high and low frequency slopes of sensitivity
    - tuned about 1 1/2 octaves higher
    - more absolute sensitivity
    - but less sensitive to change in frequency
- Animal already in use in lab
Goal (s) of Model

• Combine model parts into a whole
• Predict hazard to ear for any intense sound
• Work from first principles
• As complex as necessary, but not more complex
• Conformality with physiology of ear
• Provide insight into processes
• Adaptable to other species
General Modeling Approach

• Integrate existing partial models
  – Free field to ear drum - Two sound fields, three tubes
  – Middle ear
    • Two pistons, transformer, stapes limits, aural reflex, cochlear interface
  – Cochlea
    • Taper in geometry and mechanics
    • WKB solution obtained separately
Modeling specifics

• Free field to ear drum
  – Wiener - one tube becomes horn
  – HRTF at other angles of incidence

• NOTE: model can be entered at FF, ECE or EDP level - important where HPD included
Middle ear models specifics

- Tympanometry - Zwislocki, Lutman
- Bulla resonance in cat - Zwislocki
- Evidence of clipping at stapes
- Aural reflex effect on eardrum impedance
- Details of cochlear interface - annular ligament model - Nedzelnitsky, Lynch
Cochlear model(s)

- WKB vs. difference equation
- Include what WKB does, limits
- Taper feature (Type 2 cochlea)
- What about low frequency cut-off at apex?
- Active/ dead cochlea feature (Ca)
5 Unique Features of Model

1. Stapes suspension
   - Basis (Price, 1974 argument)
     • Annular ligament requires it
     • Annular ligament first/strongest non-linearity
   - Design of model
   - Effect
     • Low intensity/displacement
     • High intensity/displacement
   - Nixon & Sommer (1973) observation supports
   - Dancer (2000) measure supports
Stapes displacement peak-to-peak (microns) vs. RMS eardrum sound pressure level (dB re 0.0002 dynes/cm²).

Linear model vs. non-linear model.

Data from Guinan & Peake (1967).
Fig. 2. Load-deflection curve of a rabbit mesentery in tension. The state corresponding to the naturally spread-out mesentery is marked by the small circle. The point $l_0$ marks the relaxed length of the specimen.
$TR = \text{RISE\-TIME (MS)} = 11.7 + (113/(L-75))^3$

$\text{RESPONSE} = 100 \times (1 - \exp(-T/\text{TR}))$

$92 \ L = \text{STIMULUS LEVEL IN DB}$
Unique Features of Model

2. “Ramp” variable
   • Increase in resistance proportionate to level
   • Needed to keep model from “ringing”
   • Physiological basis
     – Middle ear suspension ‘soft’
     – Alternate modes of vibration not in conductive path possible
     – Beksey observed change in mode of stapes vibration in cadaver ear
Unique Features of Model

3. Dynamic middle ear muscle contraction
   • Stapedius contraction rocks stapes in window
   • Annular ligament in tension
   • Model increases stiffness and resistance dynamically - charging capacitor model
   • Model matches dynamic model of Dallos
Unique Features of Model

4. Model of loss within cochlea
   • Basis for loss assumed to be mechanical stress at level of hair cell
   • Keep track of number of flexes for upward displacements (puts tip-links in tension), squares peak (in microns)
   • Sums at 23 locations along cochlea
5. Movie of development of hazard
   • Data from cochlear model re-arranged
   • Played back in sequence along with waveform
   • Hazard development portrayed
   • Provides insight into processes producing damage
More Uniqueness - HPD and Azimuth Calculations

- If measures under a HPD not available
- Effects calculable two ways
- First: from attenuation data
  - REAT tests or ATF measures
  - Minimum-phase filter calculated and applied to waveform
    - Assumes linearity
    - Assumes one conduction path
  - Calculation proceeds as before
More Uniqueness - HPD and Azimuth Calculations

• Second, calculation of effect from mathematical model of HPD
• Properties of device (as fitted) must be known
• Model must be “created”
• Result calculated on waveform and new waveform applied to model.
PIECE PREPARED FOR ACTION
“A theory should be as simple as possible . . . but no simpler.”
Validation of AHAA - CAT

- Real ears tested (cat)
- Groups of 10 (2 ears tested)
- Electrophysiological measures of hearing used (BSER)
  - Etymotic headphone used
  - 1, 2, 4, 8, 16 kHz tested
- Animals anesthetized for exposure and test
  - Immobilized
  - Eliminated acoustic reflex
Validation

- Wide range of impulses challenged model
  - Primer impulses - predicted maximum susceptibility
    - Peak pressures 135, 140, 145 dB
    - 50 impulses
Validation Impulses

145 DB PRIMER

TIME IN SECONDS

PRESSURE IN PASCALS
Validation

- Wide range of impulses challenged model
  - M-16 Rifle impulses
    - At firer’s ear
      - Normal muzzle - high peak, complex, 1 impulse
      - Muzzle brake - very high peak, 1 impulse
      - Same spectrum
      - 8-10 times the energy in the high peak
Validation Impulses

M-16, FIRER’S EAR, NORMAL MUZZLE

TIME IN SECONDS

PRESSURE IN PASCALS
Validation Impulses

M-16, FIRER’S EAR

TIME IN SECONDS

PRESSURE IN PASCALS

NORMAL MUZZLE

BRL BRAKE
Validation

- Wide range of impulses challenged model
  - M-16 Rifle impulses
    - At 90 degrees
      - 140 dB peak, 50 rounds
      - 145 dB peak, 50 rounds
Validation Impulses

M-16 RIFLE, 90 DEGREES

140 dB

PRESSURE IN PA

TIME IN SEC
Validation Impulses

M-16 RIFLE, 90 DEGREES

145 dB
Validation

- Wide range of impulses challenged model
  - M-16 Rifle impulses
    - At 200 degrees
      - 142 dB peak
      - Complex wave
      - 6 and 12 rounds
Validation Impulses

M-16 RIFLE, 200 DEGREES

TIME IN SEC

PRESSURE IN PA
Validation

- Wide range of impulses challenged model
  - Airbags
    - Open compartment
    - Closed compartment
    - Sealed compartment
    - One deployment
Validation Impulses

AIRBAG, OPEN COMPARTMENT, DRIVER'S EAR
Validation Impulses

AIRBAG, CLOSED COMPARTMENT, DRIVER'S EAR

TIME IN SECONDS

PRESSURE IN PASCALS

-3000 -2000 -1000 0 1000 2000 3000 4000 5000 6000 7000 8000

0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18
Validation Impulses

AIRBAG, SEALED COMPARTMENT, DRIVER'S EAR

![Graph showing pressure impulse over time](image-url)
Validation Data: Prediction of CTS

- Mean data for group reported
- At frequency of maximum threshold shift (usually 4.0 kHz)
- Shift measured at about 1/2 hour (first measure)
- 12 Different exposures
  - 135 - 170 dB peak
  - 1, 6, 12, 50 impulses
Validation of Cat Ear Model

Validation of Cat Ear Model

$y = 26.607 \ln(x) - 140.08$

$R^2 = 0.8912$

$R = 0.94$
Validation

- Correlation very high - little variance left to explain
- Note equation relating CTS to ADUs:

\[
CTS = (26.6 \times \ln \text{ADUs}) - 140.1
\]
Validation Results

CTS-PTS

- Animals allowed to recover one - two months
- Retested (same procedure)
- Next slide shows relationship between CTS and PTS for airbag experiments
- Data points represent one ear at 4.0 kHz
- Data are “typical” for this type plot
CTS-PTS Relationship

RECOVERY AT 4.0 KHZ

SLOPE = 0.86

R = 0.76

PROBABLY SAFE
Validation Results
Histology (Location of Damage)

- On airbag tests, had CTS, PTS and histology on 16 ears
- Animals retested and sacrificed at 1 month.
- Model predicted location and amount of loss
  - Location on “dead” cochlea
  - CTS corrected to PTS (on basis of previous chart)
- Inner hair cell loss plotted (OHC similar, more loss as expected)
Location of Damage

% IHC LOSS

PTS

FREQUENCY/PLACE

PTS

64 32 16 8 4 2 1 0.5

PTS

0 10 20 30 40 50 60 70 80 90 100

% IHC LOSS

PTS

MODEL IHC

PTS

0 10 20 30 40 50 60 70 80 90 100

% IHC LOSS
So In The End

- ADUs predict CTS
- ADUs predict PTS
- ADUs predict hair cell loss
- Most variance explained

CONCLUSION: MODEL IS FUNDAMENTALLY READY!
Making the Human Model

- Assume that in most sensitive range, the stapes to basilar membrane displacement ratio is the same for cat and man.
- Adjust middle ear muscle effect to “moderately strong” (similar to effect in cat)
- Susceptibility: Modeled as an effective increase in sensitivity with a 6 dB SD, i.e. SPL increased 10 dB for 95th percentile ear.
Making the Human Model

- Model design fixed (02/26/98) before human data run through it
- Human hearing loss data not used in setting model parameters
Modeling “Susceptibility”

- For the susceptible ear, it is as though it were stimulated by a more intense impulse
- Assume susceptibility normally distributed with 6dB SD
- Operationally, raise SPL of impulse 10 dB and recalculate ADUs
Validation of Human Model

- Model’s hazard prediction had been developed with cat noise exposures
- Model adapted to human scale
- Model to be tested with human hearing loss data (data sets not used in the development of the model)
- Adjustment to follow as needed to refine and improve model
Validation of AHAAH Exposures with the Human Ear

The U. S. Army Albuquerque Studies
The Albuquerque Studies

- Aimed at definitive test of human tolerance to intense sound - both auditory and non-auditory
- Custom facility built for purpose
- Explosive sources used to simulate large caliber weapons
- 3 types of impulse in free field
  - A-durations of 2.9, 1.4 and .8 msec
  - Simulating gunfire in free field
- 1 reverberant impulse (rocket in bunker simulation)
LAYOUT OF 5 METER EXPOSURE APPARATUS
5 Meter Impulse

Free-field pressure, 5 meters, 6 level

Leaky muff toward source, 5 meters, 6 level, 270 head orientation
TOP VIEW, 3 METER EXPOSURE DEVICE ("MORTAR")
SIDE VIEW, 1 METER EXPOSURE DEVICE ("MORTAR")
1 Meter Impulse

Free-field pressure, 1 meter, 8 level

Leaky muff toward source, 1 meters, 6 level, 270 head orientation
TOP VIEW, REVERBERANT EXPOSURE CHAMBER
SIDE VIEW, REVERBERANT EXPOSURE CHAMBER
Reverberant Impulse

Reverberant Room Free-field pressure at FF5, STD Level 6

Reverberant Room, 6 level, leaky muff, PHD2, STD Level 6
The Albuquerque Studies

- 7 levels per impulse (up to 194+ dB peak free field in 3 dB steps)
- 6, 12, 25, 50, 100 round exposures
- One impulse per minute rate
- RACAL muff first level protection
  - Good but not wonderful attenuation
  - Fit under helmet
  - Had peak-limited talk-through circuit
- Count-down to exposure (Necessary!)
The Albuquerque Studies

- Audiometry
  - Automated
  - Baselines clearly established
  - Repeatability very high
  - Tested just before, immediately afterward and followed until recovery
  - Pre-test had to match baseline
The Albuquerque Studies

- Right ear exposed under muff, normal incidence
- Left had double protection, shadowed
- Protection fitted and checked
- Aimed at 60 subjects per condition
  - Interest in protecting 95%ile ear
  - Wanted 95% confidence, 95%ile ear tested
  - 95%ile ear found between 1 and 6 failures
The Albuquerque Studies

- Failure:
  - Full auditory failure (> 25dB TS)
  - Conditional failure (> 15 dB TS)
    - Implication that higher exposure might produce unacceptable TS
    - Next higher exposure not given
The Albuquerque Studies
Exposure Paradigm

• Begin at low level, single protection, 6 impulses
• Proceed upward in level until a failure occurs
• Drop in level and go to next higher number of rounds.
• If highest level reached (level 7), drop back to Level 6 and go upward in number of rounds - 12, 25, 50, 100
• Go to double protection and continue
**Pattern of Exposure**

<table>
<thead>
<tr>
<th>LEVEL</th>
<th>6</th>
<th>12</th>
<th>25</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Pattern of Exposure

- Began with long A-duration impulse (“5 meter exposures”)
- DRCs all predicted failure would occur
- Surprise outcome: NO Failures
- Strategic decision - defeat muff seal to simulate field fit and re-run study
- Muff had almost no attenuation below 1Khz, modest attenuation above
Defeated RACAL Muff
Pattern of Exposure

- 5 meter condition re-run (new Ss),
  - Some failures
  - Single protection only
- 3 meter condition run
  - More failures
  - Single protection only
- 1 meter condition run
  - Many more failures
  - Single protection only
The Problem of the Defeated Muff

• Almost all HPDs linear with respect to amplitude at all pressures
• BUT:
Hearing Protector Performance

MUFF ATTENUATION

ATTENUATION IN DB (A-WT SEL)

LEVEL

1 METER

5 METER - GOOD MUFF

3 METER

5 METER - DEFEATED MUFF
The Problem of the Defeated Muff

- The defeated muff became non-linear (got better at as level rose)
  - 4.6 dB (5M)
  - 5.3 dB (3m)
  - 10.9 dB (1M)

- Even the good muff became non-linear (got worse as level rose)
  - 5.4 dB (5M)
Analysis of the Data with AHAAH

- Presume middle ear muscles contracted before pulse arrives (Warned ear)
- Use under-muff pressure histories and enter AHAAH at ECE
- Failure taken as more than 500 ADUs
- Given failure at ‘N’ impulses, presumptive failure at > N impulses
- But failure at one level not counted as failure at higher level - growth of ADUs not monotonic with level
5 Meters - Good Muff

PATTERSON AND JOHNSON
5 METER DATA

LINEAR RESPONSE

ENERGY

ADUS

A-WT ENERGY IN DB RE: LEVEL1

FREE FIELD SPL IN DB

ADUS PER IMPULSE
5 Meters - Defeated Muff

PATTERSON AND JOHNSON
PHD DATA

LINEAR RESPONSE

ADUS

ENERGY UNDER MUFF

FREE FIELD SPL IN DB

A-WT ENERGY IN DB RE: LEVEL 1

ADUS PER IMPULSE
3 Meter Data

PATTERSON AND JOHNSON
3 METER DATA

LINEAR RESPONSE

ENERGY

ADUS
1 Meter Data

PATTERSON AND JOHNSON
1 METER DATA

ADUS
LINEAR RESPONSE
ENERGY

A-WT ENERGY IN DB RE: LEVEL1

PEAK SPL IN DB

ADUS PER IMPULSE
Does Non-Monotonicity Make Sense?

- Peak pressure did rise in free-field, though less under the muff
- But ‘interior’ details of waveform changed
- Model suggests clipping affects stapes displacement and driving of cochlea
- Result, for 1 Meter condition, for example, Level 4 worse than Level 7
Model Analysis Shows

LEVEL 4 IMPULSE

Leaky muff toward source, 1 meters, 4 level, 270 head orientation
Model Analysis Shows
LEVEL 7 IMPULSE

Leaky muff toward source, 1 meters, 7 level, 270 head orientation
Analysis of the Threshold Shift Data

• Samples of 5 or more waveforms used where available
• Mean ADUs established
• Exposure = ADUs/impulse x Number
• If >500, failure predicted
• Full audiometric failure and presumptive failures both counted as failures
<table>
<thead>
<tr>
<th>LEVEL</th>
<th>NUMBER OF IMPULSES</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>12 25 50 100</td>
</tr>
<tr>
<td>7</td>
<td>56\2</td>
</tr>
<tr>
<td>6</td>
<td>59\0 56\2 54\8 49\10 37\13</td>
</tr>
<tr>
<td>5</td>
<td>63\1 3\2 4\2 7\5 12\9</td>
</tr>
<tr>
<td>4</td>
<td>64\0</td>
</tr>
<tr>
<td>3</td>
<td>64\0</td>
</tr>
<tr>
<td>2</td>
<td>65\2</td>
</tr>
<tr>
<td>1</td>
<td>66\0</td>
</tr>
<tr>
<td>LEVEL</td>
<td>NUMBER OF IMPULSES</td>
</tr>
<tr>
<td>-------</td>
<td>--------------------</td>
</tr>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>56\2</td>
</tr>
<tr>
<td>6</td>
<td>62\2</td>
</tr>
<tr>
<td>5</td>
<td>66\2</td>
</tr>
<tr>
<td>4</td>
<td>69\1</td>
</tr>
<tr>
<td>3</td>
<td>68\0</td>
</tr>
<tr>
<td>2</td>
<td>68\0</td>
</tr>
<tr>
<td>1</td>
<td>68\0</td>
</tr>
<tr>
<td>LEVEL</td>
<td>NUMBER OF IMPULSES</td>
</tr>
<tr>
<td>-------</td>
<td>--------------------</td>
</tr>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>57\0</td>
</tr>
<tr>
<td>6</td>
<td>60\1</td>
</tr>
<tr>
<td>5</td>
<td>60\1</td>
</tr>
<tr>
<td>4</td>
<td>61\0</td>
</tr>
<tr>
<td>3</td>
<td>61\0</td>
</tr>
<tr>
<td>2</td>
<td>61\0</td>
</tr>
<tr>
<td>1</td>
<td>61\0</td>
</tr>
<tr>
<td>LEVEL</td>
<td>NUMBER OF IMPULSES</td>
</tr>
<tr>
<td>-------</td>
<td>--------------------</td>
</tr>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>49\0</td>
</tr>
<tr>
<td>6</td>
<td>58\0</td>
</tr>
<tr>
<td>5</td>
<td>59\0</td>
</tr>
<tr>
<td>4</td>
<td>62\0</td>
</tr>
<tr>
<td>3</td>
<td>62\0</td>
</tr>
<tr>
<td>2</td>
<td>62\0</td>
</tr>
<tr>
<td>1</td>
<td>62\0</td>
</tr>
<tr>
<td>LEVEL</td>
<td>NUMBER</td>
</tr>
<tr>
<td>-------</td>
<td>--------</td>
</tr>
<tr>
<td>7</td>
<td>59\0</td>
</tr>
<tr>
<td>6</td>
<td>59\0\59\0\58\1</td>
</tr>
<tr>
<td>5</td>
<td>61\0</td>
</tr>
<tr>
<td>4</td>
<td>61\0</td>
</tr>
<tr>
<td>3</td>
<td>63\0</td>
</tr>
<tr>
<td>2</td>
<td>63\0</td>
</tr>
<tr>
<td>1</td>
<td>64\0</td>
</tr>
</tbody>
</table>
Evaluation Diagram

<table>
<thead>
<tr>
<th>Prediction</th>
<th>Outcome</th>
<th>Correct Rating</th>
<th>Under-Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safe</td>
<td>Safe</td>
<td></td>
<td>Auditory Casualties</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Poorer Commo</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mission Endangered</td>
</tr>
<tr>
<td>Hazardous</td>
<td>Hazardous</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Correct Rating</td>
<td>Mission Endangered</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Excess Casualties</td>
</tr>
</tbody>
</table>
Rating Hit or Miss

• If a rating scheme said hazardous level had been reached and
  – No subject had failed - over-prediction
  – One or more had failed - correct
• If a rating scheme said “safe” and
  – Up to six failed - correct
  – More than six failed - under-prediction
Rating Schemes

- Three rating schemes compared
  - MIL-STD 1474
  - A-Weighted Energy
    - 8.7 J/m² safe (85 dB $L_{A\text{EQ8HR}}$)
  - AHAAH
**EVALUATION BY MIL STD-1474**

<table>
<thead>
<tr>
<th>PREDICTION</th>
<th>outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAFE</td>
<td>HAZARDOUS</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>01 T1 T2</td>
<td></td>
</tr>
<tr>
<td>F1 F2 F3</td>
<td></td>
</tr>
<tr>
<td>G1 G2 G3</td>
<td></td>
</tr>
<tr>
<td>R1 R2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>O2 O3 O4 O5 O5 O7 O8</td>
</tr>
<tr>
<td></td>
<td>T3 T4 T5 T6 T7 T8</td>
</tr>
<tr>
<td></td>
<td>F4 F5 F6 F7 F8 F9</td>
</tr>
<tr>
<td></td>
<td>G4 G5 G6 G7 G8 G9 GF</td>
</tr>
<tr>
<td></td>
<td>GH R3 R4 R5 R6 R7 R8</td>
</tr>
</tbody>
</table>

| O9 OF OH |
| T9 TF TH |
| FF FH    |
| R9       |
### Evaluation Based on A-Weighted Energy

<table>
<thead>
<tr>
<th>Prediction Safe</th>
<th>Outcome Safe</th>
<th>Hazardous</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1 G2 G3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O1 O2 O3 O4 O5 O6 O7 O8</td>
<td>O9 OF OF</td>
<td>T9 TF TH</td>
</tr>
<tr>
<td>T1 T2 T3 T4 T5 T6 T7 T8</td>
<td>T9 TF TH</td>
<td>FF FH F9</td>
</tr>
<tr>
<td>F1 F2 F3 F4 F5 F6 F7 F8</td>
<td>FF FH F9</td>
<td></td>
</tr>
<tr>
<td>R2 R3 R4 R5 R6 R7 R8 R9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G4 G5 G6 G7 G8 G9 GF GH</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Evaluation by AHAHAH

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Safe</th>
<th>Hazardous</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>O1 O2 O3 O4 O5 O6 O7 O8</td>
<td>O9 OF OH T9 TF TH F9 FF FH R9</td>
</tr>
<tr>
<td>Safe</td>
<td>T1 T2 T3 T4 T5 T6 T7 T8</td>
<td>G1 G2 G3 G4 G5 G6 G7 G8 GF GH</td>
</tr>
<tr>
<td>Hazardous</td>
<td>F1 F2 F3 F4 F5 F6 F7 F8</td>
<td>R1 R2 R3 R4 R5 R6 R7 R8</td>
</tr>
</tbody>
</table>

### Prediction

<table>
<thead>
<tr>
<th>Safe</th>
<th>Hazardous</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1 O2 O3 O4 O5 O6 O7 O8</td>
<td>O9 OF OH T9 TF TH F9 FF FH R9</td>
</tr>
<tr>
<td>T1 T2 T3 T4 T5 T6 T7 T8</td>
<td>G1 G2 G3 G4 G5 G6 G7 G8 GF GH</td>
</tr>
<tr>
<td>F1 F2 F3 F4 F5 F6 F7 F8</td>
<td>R1 R2 R3 R4 R5 R6 R7 R8</td>
</tr>
</tbody>
</table>

**Note:** The table structure is designed to show the evaluation criteria for outcomes and predictions, indicating whether they are safe or hazardous.
<table>
<thead>
<tr>
<th>CODE</th>
<th>CONDITION</th>
<th>LEVEL/RDS</th>
<th>CODE</th>
<th>CONDITION</th>
<th>LEVEL/RDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1</td>
<td>1-METER</td>
<td>L1/6</td>
<td>F6</td>
<td>5-METER</td>
<td>L6/6</td>
</tr>
<tr>
<td>O2</td>
<td>1-METER</td>
<td>L2/6</td>
<td>F7</td>
<td>5-METER</td>
<td>L7/6</td>
</tr>
<tr>
<td>O3</td>
<td>1-METER</td>
<td>L3/6</td>
<td>F8</td>
<td>5-METER</td>
<td>L6/12</td>
</tr>
<tr>
<td>O4</td>
<td>1-METER</td>
<td>L4/6</td>
<td>F9</td>
<td>5-METER</td>
<td>L6/25</td>
</tr>
<tr>
<td>O5</td>
<td>1-METER</td>
<td>L5/6</td>
<td>FF</td>
<td>5-METER</td>
<td>L6/50</td>
</tr>
<tr>
<td>O6</td>
<td>1-METER</td>
<td>L6/6</td>
<td>FH</td>
<td>5-METER</td>
<td>L6/100</td>
</tr>
<tr>
<td>O7</td>
<td>1-METER</td>
<td>L7/6</td>
<td>G1</td>
<td>5-M GOOD MUFF</td>
<td>L1/6</td>
</tr>
<tr>
<td>O8</td>
<td>1-METER</td>
<td>L6/12</td>
<td>G2</td>
<td>5-M GOOD MUFF</td>
<td>L2/6</td>
</tr>
<tr>
<td>O9</td>
<td>1-METER</td>
<td>L6/25</td>
<td>G3</td>
<td>5-M GOOD MUFF</td>
<td>L3/6</td>
</tr>
<tr>
<td>OF</td>
<td>1-METER</td>
<td>L6/50</td>
<td>G4</td>
<td>5-M GOOD MUFF</td>
<td>L4/6</td>
</tr>
<tr>
<td>OH</td>
<td>1-METER</td>
<td>L6/100</td>
<td>G5</td>
<td>5-M GOOD MUFF</td>
<td>L5/6</td>
</tr>
<tr>
<td>T1</td>
<td>3-METER</td>
<td>L1/6</td>
<td>G6</td>
<td>5-M GOOD MUFF</td>
<td>L6/6</td>
</tr>
<tr>
<td>T2</td>
<td>3-METER</td>
<td>L2/6</td>
<td>G7</td>
<td>5-M GOOD MUFF</td>
<td>L7/6</td>
</tr>
<tr>
<td>T3</td>
<td>3-METER</td>
<td>L3/6</td>
<td>G8</td>
<td>5-M GOOD MUFF</td>
<td>L6/12</td>
</tr>
<tr>
<td>T4</td>
<td>3-METER</td>
<td>L4/6</td>
<td>G9</td>
<td>5-M GOOD MUFF</td>
<td>L6/25</td>
</tr>
<tr>
<td>T5</td>
<td>3-METER</td>
<td>L5/6</td>
<td>GF</td>
<td>5-M GOOD MUFF</td>
<td>L6/50</td>
</tr>
<tr>
<td>T6</td>
<td>3-METER</td>
<td>L6/6</td>
<td>GH</td>
<td>5-M GOOD MUFF</td>
<td>L6/100</td>
</tr>
<tr>
<td>T7</td>
<td>3-METER</td>
<td>L7/6</td>
<td>R1</td>
<td>REVERBERANT</td>
<td>L1/1</td>
</tr>
<tr>
<td>T8</td>
<td>3-METER</td>
<td>L6/12</td>
<td>R2</td>
<td>REVERBERANT</td>
<td>L2/1</td>
</tr>
<tr>
<td>T9</td>
<td>3-METER</td>
<td>L6/25</td>
<td>R3</td>
<td>REVERBERANT</td>
<td>L3/1</td>
</tr>
<tr>
<td>TF</td>
<td>3-METER</td>
<td>L6/50</td>
<td>R4</td>
<td>REVERBERANT</td>
<td>L4/1</td>
</tr>
<tr>
<td>FH</td>
<td>3-METER</td>
<td>L6/100</td>
<td>R5</td>
<td>REVERBERANT</td>
<td>L5/1</td>
</tr>
<tr>
<td>F1</td>
<td>5-METER</td>
<td>L1/6</td>
<td>R6</td>
<td>REVERBERANT</td>
<td>L6/1</td>
</tr>
<tr>
<td>F2</td>
<td>5-METER</td>
<td>L2/6</td>
<td>R7</td>
<td>REVERBERANT</td>
<td>L7/1</td>
</tr>
<tr>
<td>F3</td>
<td>5-METER</td>
<td>L3/6</td>
<td>R8</td>
<td>REVERBERANT</td>
<td>L6/2</td>
</tr>
<tr>
<td>F4</td>
<td>5-METER</td>
<td>L4/6</td>
<td>R9</td>
<td>REVERBERANT</td>
<td>L6/3</td>
</tr>
<tr>
<td>F5</td>
<td>5-METER</td>
<td>L5/6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Accuracy for the Albuquerque Data Set

• 53 different exposures evaluated

• Mil STD-1474 - 37.7% correct
  – Errors often large

• A-Weighted Energy - 24.5% correct
  – Errors often very large

⭐ AHAAH - 96.2% correct
Rating Impulses in the Literature

Free-field Impulses (Mostly)
New Look at Old Data

• Need good waveform for AHAHH analysis
  – Published waveforms usually don’t have enough detail

• Data reported vary with study - model can calculate equivalent data for comparison

• Keep criterion of 25 dB threshold shift as hazardous
7.62 mm Rifle Exposures

- Impulse used by Hodge et al. 1964-1966
- Unprotected left ear exposed
- 50 or 25 impulses
- 5 sec inter-pulse interval - automated
- 155 and 158 dB peak pressure
- Subjects seated (ear at 62” height) to side of muzzle, 7’4” and 11’1” away
- Varying numbers of Ss (7, 12, 28)
- Report extremes, mean, median, quartiles
- Shift data ‘corrected’ to TTS$_2$
Threshold Shift Data

• The 3 conditions produced large shifts
  – 50 rounds at 155 dB
  – 50 rounds at 158 dB
  – 25 rounds at 158 dB
• Shifts of 40, 50, 70 dB - third quartile above 25 dB -- all 3 rate as hazardous
• Noted 25 impulses at 158 dB less hazardous than 50 impulses at 155 dB (no statistical test)
7.62 MM M-60 Exposure

HODGE ET AL., TM15-64

N=12

50 ROUNDS, 155 DB PEAK PRESSURE

UPPER LIMIT

QUARTILE 3

MEAN

N=12

100 1000 10000

FREQUENCY IN HZ

0 10 20 30 40 50 60 70 80

THRESHOLD SHIFT IN DB

10 20 30 40 50 60 70 80

FREQUENCY IN HZ
7.62 MM M-60 Exposure

HODGE ET AL, TM 3-65

N=28

50 ROUNDS AT 155 DB

UPPER LIMIT

3RD QUARTILE

MEAN

FREQUENCY IN HZ

THRESHOLD SHIFT IN DB
7.62 MM M-60 Exposure

HODGE ET AL. TM 15-64

N=7

50 ROUNDS, 158 DB

UPPER LIMIT

3RD QUARTILE

MEAN
7.62 MM M-60 Exposure

HODGE AND MCCOMMONS, TM 3-66

N=28

25 ROUNDS, 158 DB PEAK PRESSURE

UPPER LIMIT

3RD QUARTILE

MEAN

FREQUENCY IN HZ

THRESHOLD SHIFT IN DB

FREQUENCY IN HZ

100

1000

10000
Analysis of 7.62mm Rifle Impulses with AHAHAH

- Timing of impulses warrants “warned” calculation (for second and later impulses)
- 155 dB peak pressure
  - 16.6 ADUs/impulse (W); 118 ADUs(U)
  - 50 impulses = 830 ADUs (hazardous)
- 158 dB peak pressure
  - 22.3 ADUs/impulse (W); 153 ADUs(U)
  - 25 impulses = 558 ADUs (hazardous)
  - 50 impulses = 1115 ADUs (hazardous)
Summary of Predictions

• 7.62mm, 50 at 155 - correct
• 7.62mm, 25 at 158 - correct
• 7.62mm, 50 at 158 - correct
FNC Rifle Analysis

• Brinkmann (2000) re-measured Belgian Rifle
  – 51 subjects fired 6 rounds standing
  – 53 subjects fired 5 rounds standing
  – Data reported
    • Primarily, time to recover
    • Some clues as to amount of TS
• Case 1:
  – 11 Ss shifts > 25 dB (hazardous)
• Case 2:
  – 9 Ss shifts >25 dB (hazardous)
• Recovery times 30 minutes to 16 hours
FNC Rifle Analysis with AHAAH

- Brinkmann supplied recorded waveform
- Soldiers fired own weapon - warned exposure
- Average of 156.8 ADUs per impulse
- Exposures of 940 and 784 ADUs
- Matches threshold shift data
FNC Rifle Analysis with A-weighted Energy

- Impulses contained 1.4 j/m$^2$
- Exposures contained 8.4 and 7 j/m$^2$
- Both rated as safe
- Were hazardous - only case of under-conservative criterion!
Summary of AHAAH Predictions

- 7.62mm, 50 at 155 - correct
- 7.62mm, 25 at 155 - correct
- 7.62mm, 25 at 158 - correct
- FNC 6 rounds - correct
- FNC 5 rounds - correct
G3 Rifle

- Pfander (1974) reported
- 78 soldiers fired 5 rounds
- No protection
- Some threshold shifts of 30, 50 dB
- Recovery times of 3-6 days (N=16)
- A hazardous exposure
Analysis by AHAHAH

- Brinkmann supplied recorded impulse
- Soldier fired own weapon - warned exposure
- Impulse contained 178.3 ADUs (W)
- Exposure = 892 ADUs (hazardous)
Summary of AHAAH Predictions

- 7.62mm, 50 at 155 - correct
- 7.62mm, 25 at 155 - correct
- 7.62mm, 25 at 158 - correct
- FNC 6 rounds - correct
- FNC 5 rounds - correct
- G3 5 rounds - correct
M 72 LAW Impulse

- Garinther and Hodge used LAW as impulse source
- Exposure at grazing incidence, unprotected
  - 43 Subjects tested (86 ears)
  - 161 dB (8m to left rear)
  - Fired by remote control with some countdown
  - Loss within CHABA limits - considered safe
M 72 LAW Impulse

- Exposure to 1 impulse at firer’s ear position, unprotected
  - 28 Subjects tested (test cut short)
  - 179 dB peak
  - Self-fired
- **Large** threshold shifts resulted (very hazardous)
M 72 LAW Impulse

• Exposure to 1 impulse to rear side, V-51R protection
  – 175, 179.6 and 184 dB peak
  – 40, 38, 31 Subjects tested respectively
  – All exposures safe
Analysis with AHA AH

- One waveform from LAW, not sure where recorded. **Not truly adequate for purposes.**
- Slow recovering Ss dropped from study!
- **Use this analysis for ball-park value only**
- Pulse adjusted for 161 dB peak (unprotected):
  - 105 ADUs(W), 516 ADUs(UW) - just safe (correct)
- If adjusted for 179 dB peak (unprotected)
  - 921 ADUs(W) and 4217 ADUs (UW) Hazardous! (correct)
LAW IMPULSE, NO PROTECTION

GARINTHER AND HODGE, 1971

95%ILE CTS

50%ILE CTS

AHAHAH

AHAHAH

CTS IN DB

FREQUENCY

GARINTHER AND HODGE, 1971
Analysis with AHAAH

• If adjusted for 175, 179.6 and 184 dB peak (protected with V-51R):
  – <7.3 ADUs(W); <35 ADUs(UW) - safe (correct)

• Conclusion: AHAAH in correct ball park
Summary of AHAHAH Predictions

- 7.62mm, 50 at 155 - correct
- 7.62mm, 25 at 155 - correct
- 7.62mm, 25 at 158 - correct
- FNC 6 rounds - correct
- FNC 5 rounds - correct
- G3 5 rounds - correct
- LAW 1 round - correct on 5 different exposures
FLETCHER AND LOEB SPARK GAP IMPULSES
Spark Gap Impulses
Fletcher and Loeb

• Peak pressures all 166 dB
• 6 gap impulse spectral peak at 3.0 kHz
• 3 gap impulse spectral peak near 8.0 kHz
• Exposure to 1/sec in anechoic chamber
• 72 Ss, no hearing protection
• Stopped when TS exceeded 30 dB (tested up to 16 kHz)
• Can’t specify 95%ile ear from data
Spark Gap Impulses
Fletcher and Loeb

• Interesting data nevertheless:
  – For 6 gap pulse
    • 1 pulse was enough for some ears
    • Median number to criterion was 4 pulses
  – For 3 gap pulse
    • Some reached criterion in 11 impulses
    • Median number to criterion was 88 pulses
Spark Gap Impulses
Analysis with AHAHA

• For rate of 1/sec, presume warned exposure for second and successive impulses
  – For 6 gap pulse
    • 176.1 ADUs (W); 995.4 ADUs (UW)
      – Predicts 44 dB CTS for 1 pulse (correct for some)
    • 56 ADUs (W); 342 ADUs (UW) (Median ear)
      – 1(UW)+3(W)= 510 ADUs (26 dB CTS) (Correct)
Spark Gap Impulses
Analysis with AHA AH

– For 3 gap pulse
  • 31.6 ADUs (W); 186 ADUs (UW)(95%ile ear)
    – 186+ 10 x 31.6 = 502 ADUs (26 dB CTS) (correct)
  • 6.5 ADUs (W); 186 ADUs(UW) (Median ear)
    – 1(UW)+87(W)=751.5ADUs (36 dB CTS) (Correct)
Summary of AHAHAH Predictions

- 7.62mm, 50 at 155 - correct
- 7.62mm, 25 at 155 - correct
- 7.62mm, 25 at 158 - correct
- FNC 6 rounds - correct
- FNC 5 rounds - correct
- G3 5 rounds - correct
- LAW 1 round - correct on 5 different exposures
- Spark Gap impulses - correct on 4 predictions
The Horn That Did Some Damage

HORN IN FREE FIELD

155.8 DB PEAK

TIME IN SECONDS

PRESSURE IN PASCALS
Exposure to Horn

- Report of Royster et al. (1999) 39 month old boy exposed self to several toots - complained of ear pain and tinnitus
- At 6 days 50 dB HL (10 dB at 4Khz 3 mos earlier) and 20 dB PTS at 6 mos
- Model shows any number of scenarios (angles, distances, susceptibility, number) producing this effect
Conclusions About Old Data and AHAHAAH’s Predictions

• For six unprotected exposures to rifles, data were adequate for analysis and AHAHAAH was correct in each case.

• For ten additional predictions, the data were less than desired; but AHAHAAH was correct in all those cases as well.

• If 16 correct predictions added to the 51 (of 53) from the Albuquerque study, then AHAHAAH has achieved a 97% hit rate - without adjustment of original model.
From the Model Toward a DRC

The details
Issues to Be Settled

• Percentage of population to be protected
• Correction for angle of incidence?
• Use of hearing protector(s)
• Allowance for ‘field fit’ with a protector
• Instrumentation requirements for acoustic measurements
• What about variability in impulse measures?
• Assumptions with respect to middle ear muscle response
• Which manikin or ATF should be used?
Percentage Protected

• Customary to aim for 95%ile ear
• Experience suggests that occasional shifts of 20-25 dB from intense impulses recover
• Caveat: threshold shift from high level impulse is evidence of mechanical disruption
  – Recovery longer
  – Daily exposure at limit probably not OK.
• In model terms: 500 ADUs a limit
  200 ADUs “safe”
Correction(s) for Angle of Incidence

• Given a source always at particular azimuth
  – Left ear of right handed firer faces source
  – Outside ear faces side airbag
• Head-related transfer function (HRTF) applies
• Two alternatives:
  – From free-field pressure, AHAHAH calculates waveform at ear using HRTF
  – Measure waveform with manikin
Correction for Angle of Incidence cont.

• If complex field, random incidence
• Two choices:
  – Use manikin, measure waveform at ECE or drum position
  – Use FF measure and calculate waveform using worst case angle of incidence
• Calculate hazard with AHAHAH
Handling Hearing Protection

• For the military, most ears will be exposed while wearing protection.
• In past, 29 dB attenuation assumed for all protectors (35.5 dB for double protection)
  – Details of protector fit and character ignored
  – No incentive to improve designs
• Hearing protection (and use) an important variable in determining hazard
  – Need to protect
  – Need to communicate, stay aware
Handling Hearing Protection CONTINUED

- AHA AH needs a pressure history to calculate
- AHA AH handles protection three ways:
  1. Pressure measurement on a manikin
  2. Calculation from free field pressure and attenuation data
  3. Mathematical model of the protector applied to free-field pressure
Handling Hearing Protection CONTINUED

(1) Measurement on a manikin (or subject)
   – Measure at canal entrance or ear drum
   – Corrects for incidence
   – Includes subtleties of fit - friction, band pressure, etc.
   – Non-linearities evaluated in the measure
   – Manikin design and standardization a problem
(2) Calculation from free-field pressure and attenuation data

- REAT tests commonly available
- Attenuation and its variability evaluated
- AHAAH creates minimum-phase digital filter matching given attenuation
- Filter can be de-rated to match field fit.
- Filter is applied to free-field waveform to calculate effective waveform at ear
- Presumes only one conductive path and a linear protector
(3) Create mathematical model of the protector and process free-field pressure

- If behavior of protector fully known, modeling possible
- Model calculation quick and precise
- Discovering behavior of protector at all levels a non-trivial problem
- Modeling a high level technical skill
Recommendations for Hearing Protection in DRC Formulation

- Allowance for hearing protection- measured effect:
  - For muff, prescribe measurement at ECE on manikin head or on subject
    - Placed at user head location
    - Blocked ear canal acceptable
    - Oriented for worst case presentation if location not fixed
Recommendations for Hearing Protection in DRC Formulation

- Allowance for hearing protection- measured effect:
  - For plug, prescribe measurement of EDP on manikin head
    - Placed at user head location
    - Oriented for worst case presentation if location not fixed
Recommendations for Hearing Protection in DRC Formulation

• Allowance for hearing protection- calculated effect from free-field measure:
  – For muff or plug, prescribe free-field pressure measurement at center of head location (head absent)
  – Calculate effective pressure with 90 degree azimuth, unless other can be justified
Recommendations for Hearing Protection in DRC Formulation

- De-rating protector -
  - Use worst-case angle of incidence
  - Raise measured or calculated level under protector by 6dB (or average standard deviation for device in REAT tests)
Dealing with Measurement Variability

- Analyze all impulses measured for a condition (artifacts rejected)
- Use average ADUs as estimate of hazard for a round/weapon/condition
- Allowable number of rounds = 500/ADUs
Measurement Instrumentation and Conventions

• Measurement system:
  – sampling rate at least 44kHz
  – 16 bit digitization (12 bit or better used)
  – linear up to highest pressure measured (195 dB under protector)
  – linearity: 0.1 Hz to 20 kHz (low frequency limit 20 Hz if lower frequency not in signal)
  – Digitized waveforms stored in ASCII format
Recommendations

- Numbers stored are pressure in Pascals
- Digitizing rate reported (or time column included in file)
- Measurement procedures shall follow best acceptable practice.
  - Mike a blunt cylinder
  - Grazing orientation
  - Minimum 5 impulses per condition measured
Recommendations for Middle Ear Muscle Calculation

• In analysis consider muscles “warned” if:
  – Individual fires own weapon or
  – Firing signal clearly discernable e.g. vocal command, visual signal, etc.
  – Second and successive impulses normally follow closely (as in machine gun).

• Otherwise assume “unwarned”
The Problem of An ATF or Manikin

• Several manikins exist
  – ISL “French Head” (limited numbers)
  – Bruel developing a meter incorporating a head
  – Kemar
  – Head acoustics (AACHEN HEAD)
  – Other
• Recommend interim use of ISL Head
• Recommend development of new manikin
ISL Manikin
ISL Manikin in Use
Desiderata in a Manikin

- Head should be sized to simulate 50%ile (alternate sizes desirable)
- Shaped like real head shape to allow mounting of helmet, muffs, masks, etc.
- Pinna and ear canal matching an average ear
- Pinna surround and ear canal of material with near skin characteristics
- Ear canal allow insertion of a plug
- Back path to microphone more attenuating than protectors
Desiderata in a Manikin

- Ear canal terminated with proper impedance
- Body temperature ear canal
- Microphone(s) at
  - Ear canal entrance (blocked canal)
  - Ear drum position
- Microphone characteristics:
  - Small size (ECE Mike)
  - High stability
  - DC to 20+kHz response
  - Linear up to 195+dB
  - Removable for calibration and repair
Effect of Speech Intelligibility on Mission Success

SIMPLE TASKS

COMPLEX TASKS
<table>
<thead>
<tr>
<th>CODES</th>
<th>LOCATION</th>
<th>DISTANCE</th>
<th>VALUE</th>
<th>J/M²</th>
<th>ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1</td>
<td>ALBUQUERQUE</td>
<td>ONE METER</td>
<td>L1/6</td>
<td>15.01</td>
<td>90.06</td>
</tr>
<tr>
<td>O2</td>
<td>ALBUQUERQUE</td>
<td>ONE METER</td>
<td>L2/6</td>
<td>22.7</td>
<td>136.2</td>
</tr>
<tr>
<td>O3</td>
<td>ALBUQUERQUE</td>
<td>ONE METER</td>
<td>L3/6</td>
<td>29.32</td>
<td>175.92</td>
</tr>
<tr>
<td>O4</td>
<td>ALBUQUERQUE</td>
<td>ONE METER</td>
<td>L4/6</td>
<td>43.73</td>
<td>262.38</td>
</tr>
<tr>
<td>O5</td>
<td>ALBUQUERQUE</td>
<td>ONE METER</td>
<td>L5/6</td>
<td>44.29</td>
<td>265.74</td>
</tr>
<tr>
<td>O6</td>
<td>ALBUQUERQUE</td>
<td>ONE METER</td>
<td>L6/6</td>
<td>59.77</td>
<td>358.62</td>
</tr>
<tr>
<td>O7</td>
<td>ALBUQUERQUE</td>
<td>ONE METER</td>
<td>L7/6</td>
<td>79.48</td>
<td>476.88</td>
</tr>
<tr>
<td>O8</td>
<td>ALBUQUERQUE</td>
<td>ONE METER</td>
<td>L6/12</td>
<td>44.29</td>
<td>531.48</td>
</tr>
<tr>
<td>O9</td>
<td>ALBUQUERQUE</td>
<td>ONE METER</td>
<td>L6/25</td>
<td>44.29</td>
<td>1107.3</td>
</tr>
<tr>
<td>OF</td>
<td>ALBUQUERQUE</td>
<td>ONE METER</td>
<td>L6/50</td>
<td>44.29</td>
<td>2214.5</td>
</tr>
<tr>
<td>OH</td>
<td>ALBUQUERQUE</td>
<td>ONE METER</td>
<td>L6/100</td>
<td>44.29</td>
<td>4429</td>
</tr>
<tr>
<td>T1</td>
<td>ALBUQUERQUE</td>
<td>THREE METER</td>
<td>L1/6</td>
<td>3.8</td>
<td>22.8</td>
</tr>
<tr>
<td>T2</td>
<td>ALBUQUERQUE</td>
<td>THREE METER</td>
<td>L2/6</td>
<td>7.59</td>
<td>45.54</td>
</tr>
<tr>
<td>T3</td>
<td>ALBUQUERQUE</td>
<td>THREE METER</td>
<td>L3/6</td>
<td>20.14</td>
<td>120.84</td>
</tr>
<tr>
<td>T4</td>
<td>ALBUQUERQUE</td>
<td>THREE METER</td>
<td>L4/6</td>
<td>23.57</td>
<td>141.42</td>
</tr>
<tr>
<td>T5</td>
<td>ALBUQUERQUE</td>
<td>THREE METER</td>
<td>L5/6</td>
<td>35.42</td>
<td>212.52</td>
</tr>
<tr>
<td>T6</td>
<td>ALBUQUERQUE</td>
<td>THREE METER</td>
<td>L6/6</td>
<td>49.1</td>
<td>294.6</td>
</tr>
<tr>
<td>T7</td>
<td>ALBUQUERQUE</td>
<td>THREE METER</td>
<td>L7/6</td>
<td>53.9</td>
<td>323.4</td>
</tr>
<tr>
<td>T8</td>
<td>ALBUQUERQUE</td>
<td>THREE METER</td>
<td>L6/12</td>
<td>49.1</td>
<td>589.2</td>
</tr>
<tr>
<td>T9</td>
<td>ALBUQUERQUE</td>
<td>THREE METER</td>
<td>L6/25</td>
<td>49.1</td>
<td>1227.5</td>
</tr>
<tr>
<td>TF</td>
<td>ALBUQUERQUE</td>
<td>THREE METER</td>
<td>L6/50</td>
<td>49.1</td>
<td>2455</td>
</tr>
<tr>
<td>TH</td>
<td>ALBUQUERQUE</td>
<td>THREE METER</td>
<td>L6/100</td>
<td>49.1</td>
<td>4910</td>
</tr>
<tr>
<td>F1</td>
<td>ALBUQUERQUE</td>
<td>FIVE METER</td>
<td>L1/6</td>
<td>0.63</td>
<td>3.78</td>
</tr>
<tr>
<td>F2</td>
<td>ALBUQUERQUE</td>
<td>FIVE METER</td>
<td>L2/6</td>
<td>0.78</td>
<td>4.68</td>
</tr>
<tr>
<td>F3</td>
<td>ALBUQUERQUE</td>
<td>FIVE METER</td>
<td>L3/6</td>
<td>1.51</td>
<td>9.06</td>
</tr>
<tr>
<td>F4</td>
<td>ALBUQUERQUE</td>
<td>FIVE METER</td>
<td>L4/6</td>
<td>3.36</td>
<td>20.16</td>
</tr>
<tr>
<td>F5</td>
<td>ALBUQUERQUE</td>
<td>FIVE METER</td>
<td>L5/6</td>
<td>10.14</td>
<td>60.84</td>
</tr>
<tr>
<td>F6</td>
<td>ALBUQUERQUE</td>
<td>FIVE METER</td>
<td>L6/6</td>
<td>19.67</td>
<td>118.02</td>
</tr>
<tr>
<td>F7</td>
<td>ALBUQUERQUE</td>
<td>FIVE METER</td>
<td>L7/6</td>
<td>54.41</td>
<td>326.46</td>
</tr>
<tr>
<td>F8</td>
<td>ALBUQUERQUE</td>
<td>FIVE METER</td>
<td>L6/12</td>
<td>19.67</td>
<td>236.04</td>
</tr>
<tr>
<td>F9</td>
<td>ALBUQUERQUE</td>
<td>FIVE METER</td>
<td>L6/25</td>
<td>19.67</td>
<td>491.75</td>
</tr>
<tr>
<td>FF</td>
<td>ALBUQUERQUE</td>
<td>FIVE METER</td>
<td>L6/50</td>
<td>19.67</td>
<td>983.5</td>
</tr>
<tr>
<td>FH</td>
<td>ALBUQUERQUE</td>
<td>FIVE METER</td>
<td>L6/100</td>
<td>19.67</td>
<td>1967</td>
</tr>
</tbody>
</table>