American Institute of Biological Sciences

RDECOM

U.S. Army Research, Development and Engineering Command

ARMY RESEARCH LABORATORY

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

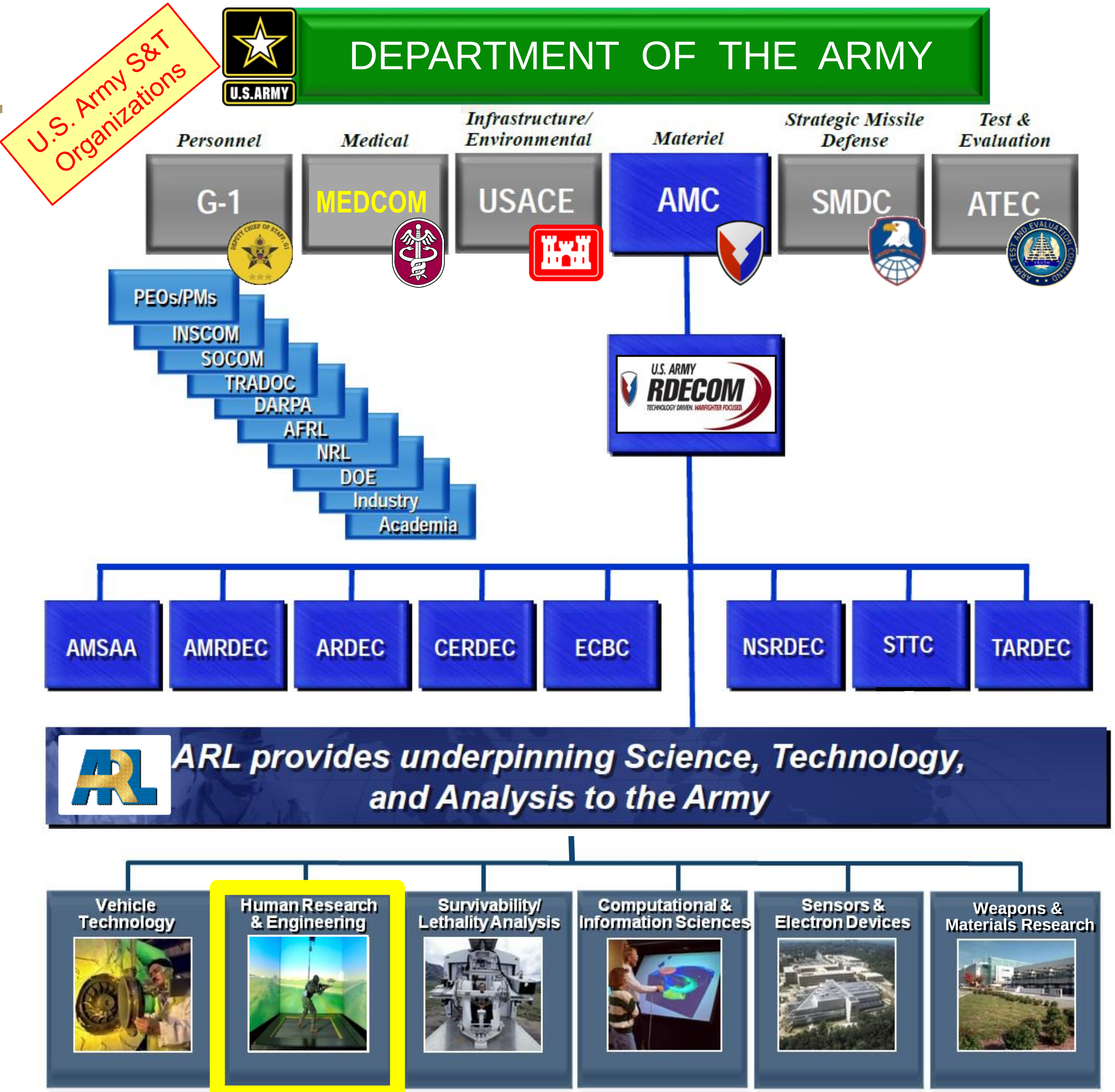
Auditory Hazard Assessment Algorithm for the Human (AHAAH)

Bruce E. Amrein

9 November 2010

U.S. Army Research Laboratory
Human Research & Engineering Directorate

HUMAN RESEARCH & ENGINEERING DIRECTORATE



1571 Technical Staff

282	Electrical/Electronics Engineers
205	Physicists/Physical Scientists
186	Mechanical Engineers
92	General/Industrial Engineers
36	Aerospace Engineers
69	Materials Engrs./Metallurgists
56	Engineering Psychologists
89	Chemical Engineers/Chemists
11	Biologists
7	Neuroscientists
54	Operations Research Analysts
154	Computer Scientists/Engineers
41	Mathematicians/Statisticians
18	Meteorologists
5	Ceramic Engineers
10	Other E&S
256	E&S Technicians

HUMAN RESEARCH & ENGINEERING

Soldier Performance

- Enhance mission effectiveness and Soldier safety in combat.
- Ensure Soldier performance requirements are adequately considered in system design and materiel development.

A Soldier's Soundscape

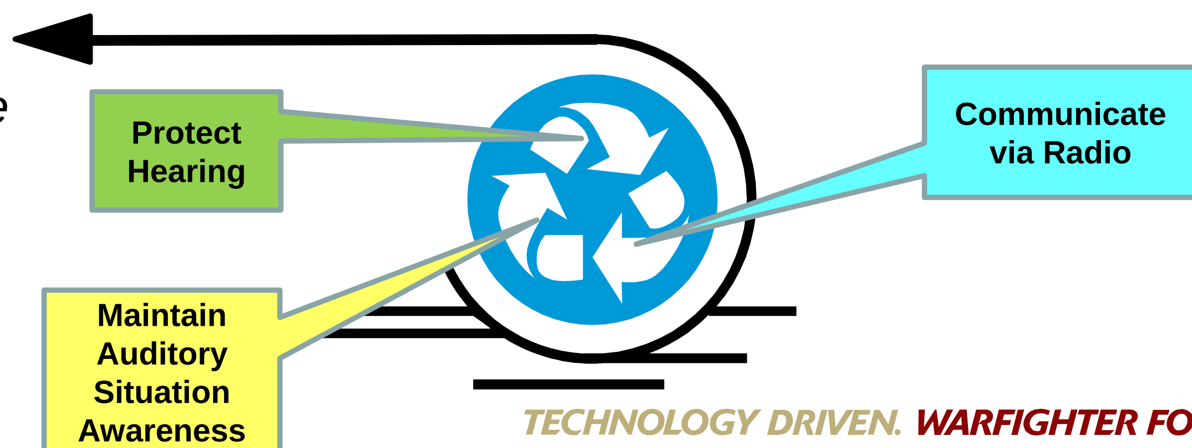
Steady-state and impulse noise levels produced by U.S. Army military equipment

Type of noise	Vehicle or Weapon	Noise level
Steady-state	HMMWV	94 dB in crew position at 55 mph
	CH-47 helicopter	102.5 dB in the cockpit
	UH-60 helicopter	106 dB at the pilot/co-pilot positions
Impulse	M16A2 rifle	157 dB @ shooter's ear
	M249 machinegun	159.5 dB @ gunner's ear
	Javelin missile	172.3 dB @ gunner's fighting position
	81 mm mortar	178.8 dB @ 1 m from the muzzle, 0.9 m above ground, 135° azimuth

Reference: http://chppm-www.apgea.army.mil/hcp/NoiseLevels.aspx

The Triad Challenge

MISSION SUCCESS:
Locate, close with and destroy the enemy by fire and maneuver



A Soldier's Soundscape

A Soldier's Soundscape


jdw.janes.com • VOLUME 43 • ISSUE 30 • 26 JULY 2006

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DEFENCE WEEKLY

In deeper

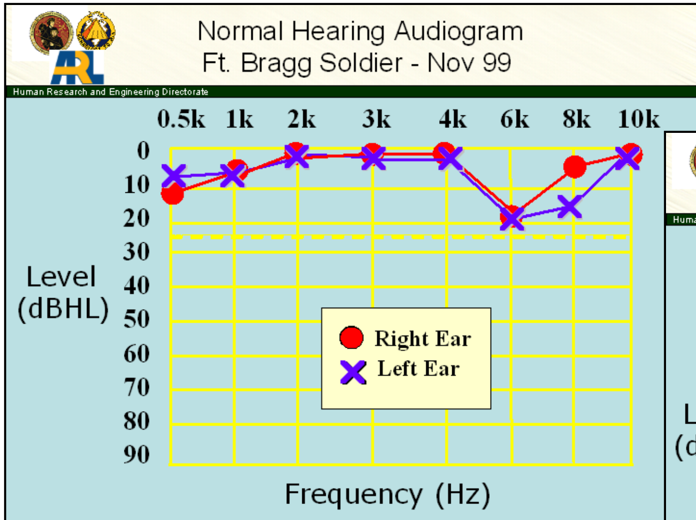
Israel tightens grip on Lebanon

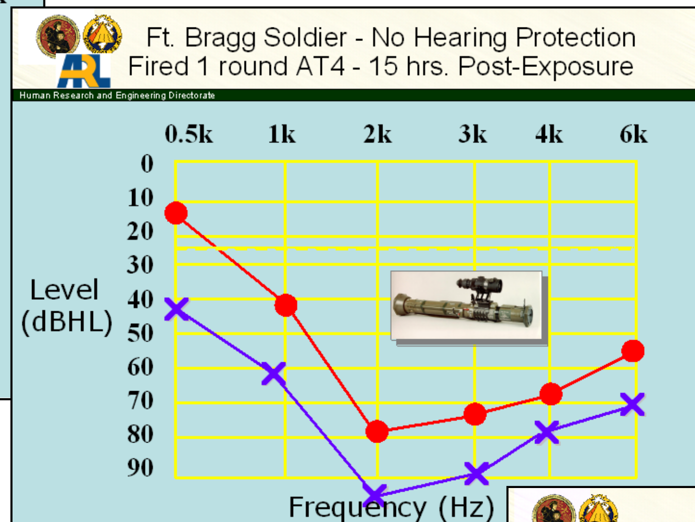
A Soldier's Soundscape

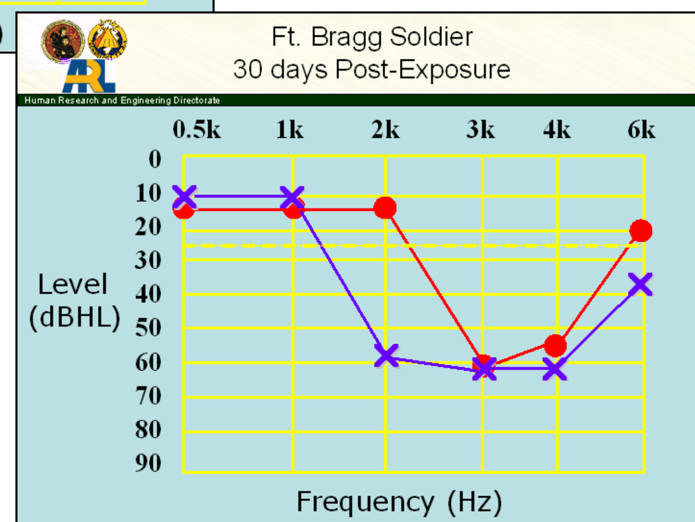
A Soldier's Soundscape

Ft. Bragg Soldier - No Hearing Protection Fired 1 round with an AT4

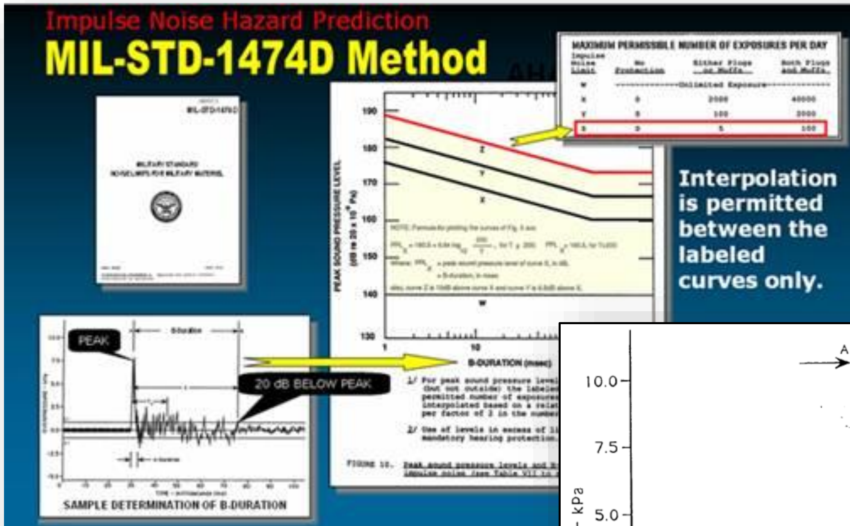
Ft. Bragg Soldier - No Hearing Protection Fired 1 round with an AT4

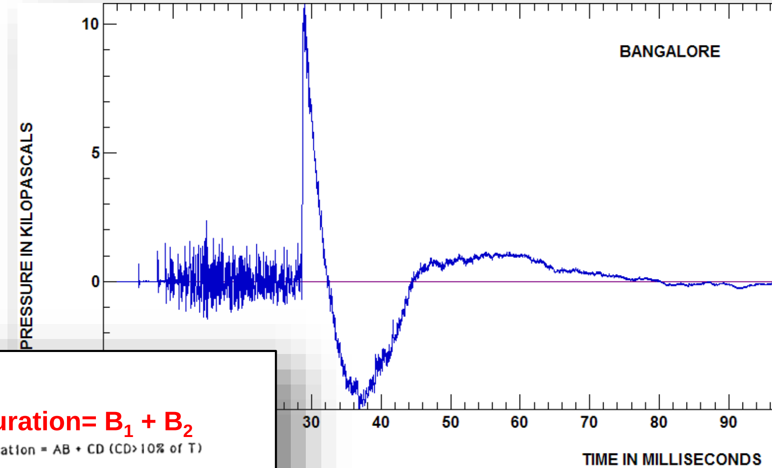


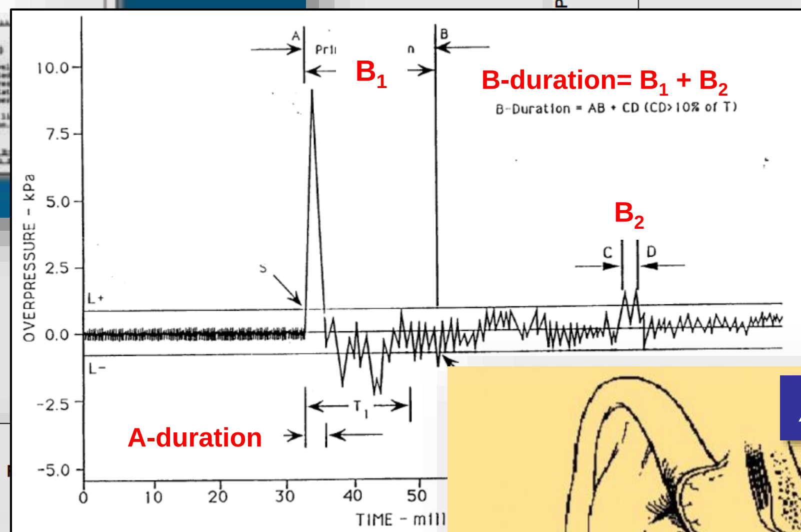


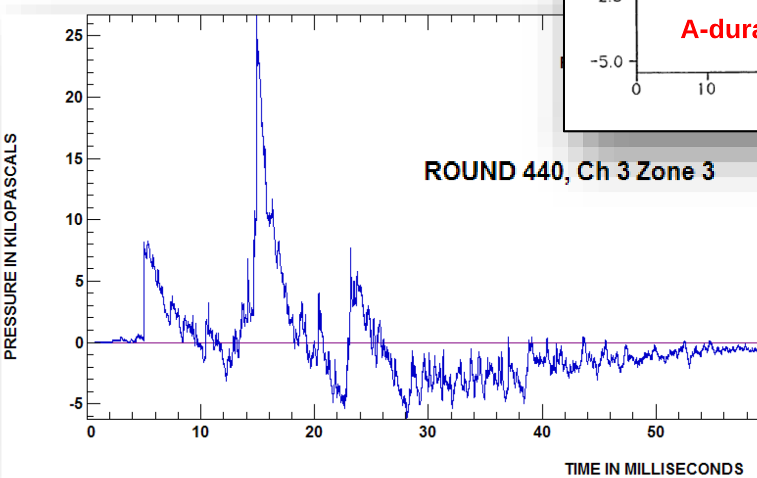


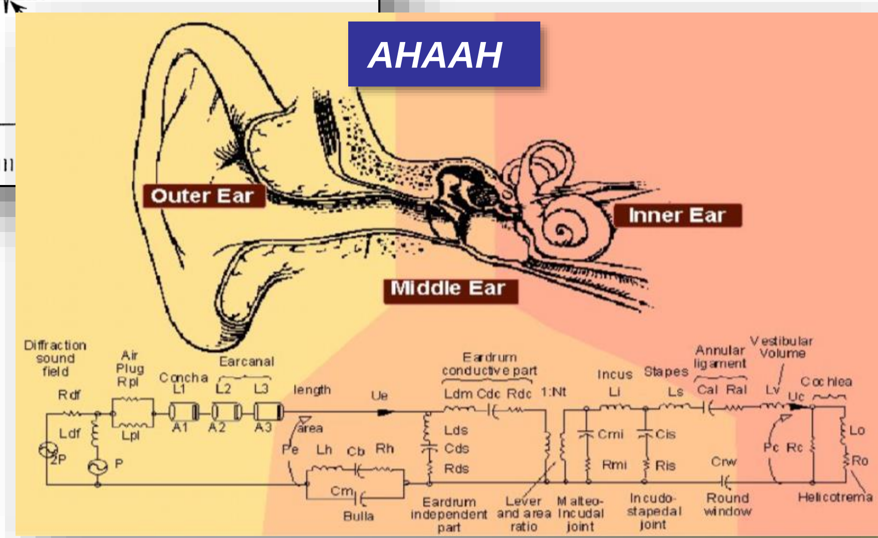
Auditory Hazard Assessment Algorithm for the Human (AHAAH)











The "Science" Behind the MIL-STD 1474 Method

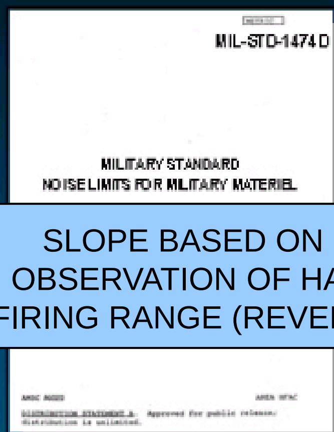
CORRECTION FOR NUMBER OF ROUNDS BASED ON COMMITTEE "ESTIMATE"

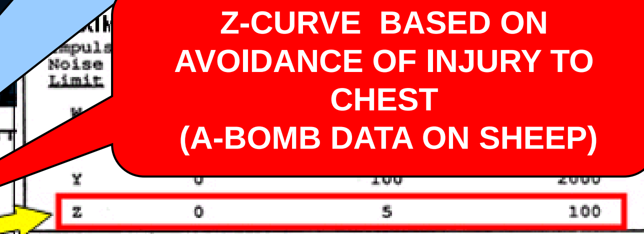
LEVEL OF CURVE = COLES, *ET AL*. PLUS 29 DB PROTECTION – EMPIRICALLY DETERMINED (LAW EXPOSURES)

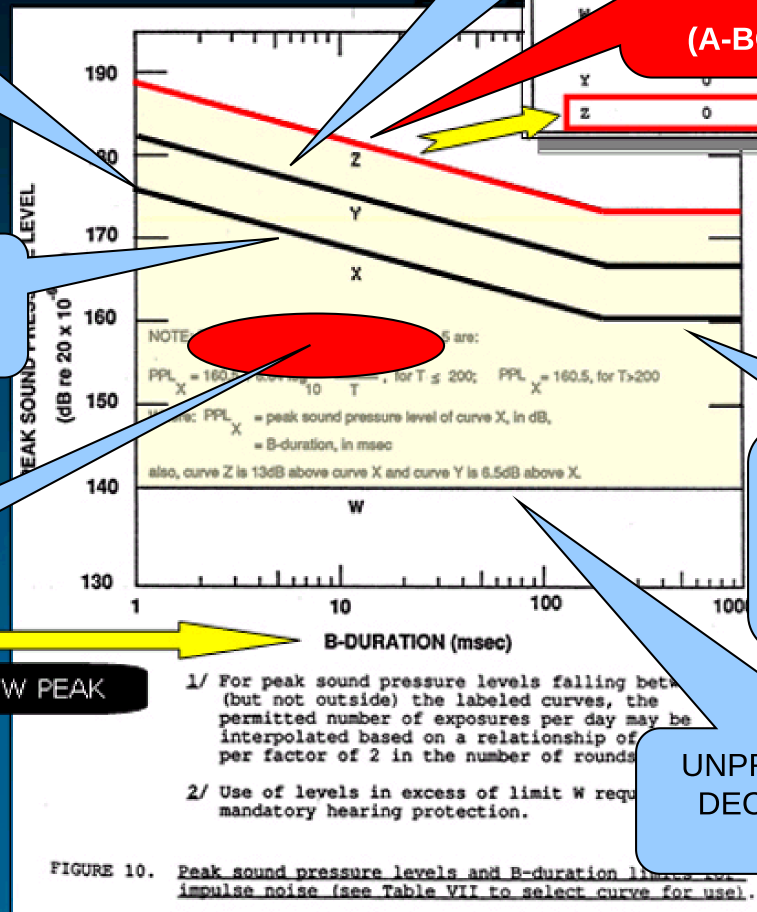
I Prediction

MIL-STD- 4D Method

Z-CURVE BASED ON AVOIDANCE OF INJURY TO CHEST (A-BOMB DATA ON SHEEP)



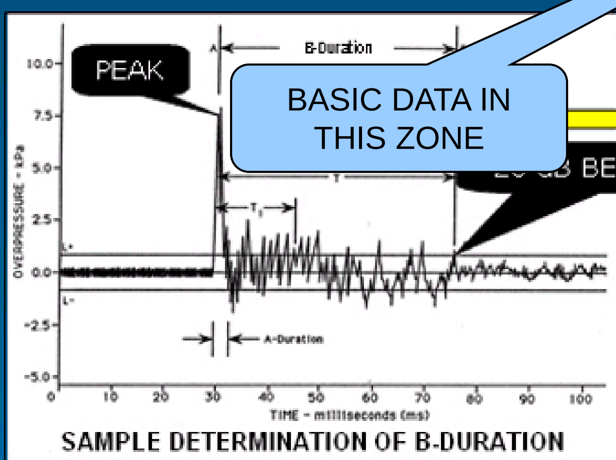




Interpolation is permitted between the labeled

SLOPE BASED ON COLES OBSERVATION OF HAZARD IN FIRING RANGE (REVERBERANT)

LEVELS INCORRECT BECAUSE OF ASSUMED MIDDLE EAR MUSCLE REFLEX 'STOPPING' HAZARD

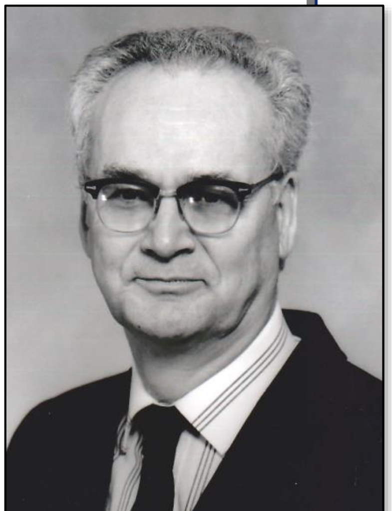


SAMPLE DETERMINATION OF B-DURATION

BASIC DATA IN THIS ZONE

UNPROTECTED CURVE – DECREE OF SURGEON GENERAL

Auditory Hazard Assessment Algorithm for the Human (AHAAH)



AMSRD-ARL-HR-SD 10 Nov 04

MEMORANDUM FOR RECORD

Subject: The history and the future of the Impulse Noise Criterion of MIL-STD 1474

1. The Impulse Noise Damage Risk Criterion for limiting the noise level of weapons originated at the U.S. Army Human Engineering Laboratory (HEL), now the Army Research Laboratory's Human Research & Engineering Directorate (ARL-HRED). Prior to that time there was no scientific guidance for limiting the noise levels and the acceptable number rounds that could safely be fired by artillery, small arms, rocket launchers, etc. The first study (TM 1-65), was conducted, in 1964, by Dr. Karl Kryter and the undersigned. The exposure criterion for this study was based upon the CHABA Working Group 46 criterion (Hazardous Exposure to intermittent and steady-state noise, dated 1965). This criterion states that temporary hearing loss measured 2 minutes after exposure to noise shall not exceed 10 dB at and below 1000 Hz, 15 dB at 2000 Hz, and 20 dB at and above 4000 Hz. This criterion postulates that repeated exposures, for many years of habitual exposure, will result in a permanent hearing loss of the same magnitude.

2. The results of this report were also presented at the International Congress on Acoustics held in Belgium in 1965. After presenting my paper, Dr. Ross Coles (whom I had not previously met) came to me and said that he was presenting a paper on the same topic. Dr. Coles was a Commander and physician in the British Royal Navy and had been assigned to the University of Southampton to conduct research on the hearing hazard of gunfire. After his presentation, he and I discussed our respective research and decided to write a joint US-British report with Dr. David Hodge of HEL and Dr. Christopher Rice of the University of Southampton. Following the publication of this joint report, HEL with the cooperation of the Army Environmental Hygiene Agency published, in 1965, the first standard (HEL Standard S1-63B) which provided impulse noise limits for weapons. Several years later, this HEL standard was elevated to a DOD Military Standard (MIL-STD-1474).

3. Through the years this standard has been very helpful in providing materiel design limits for impulse noise and limiting hearing loss among soldiers. It has been determined, however, that the limits are somewhat overly restrictive.

4. Over the last 15 years Dr. G. Richard Price and Dr. Joel T. Kalb (ARL-HRED) have been developing an improved computer model for assessing the potential hearing hazard resulting from exposure to impulse noise. Essentially the model calculated stress in the inner ear due to the following: head orientation, hearing

AMSRD-ARL-HR-SD
Subject: The history and the future of the Impulse Noise Criterion of MIL-STD 1474

protection [manikin or Real-Ear-Attenuation-at-Threshold (REAT) measurements], aural reflex, and stapes displacement limitation. This model calculates risk based upon a hypothesis that damage to the hair cells in the cochlea correlates to a mathematical function of the number and amplitude of basilar membrane displacements in a manner analogous to mechanical fatigue of solid materials.

This model has been reviewed by a Peer Review Panel convened by the American Institute of Biological Sciences. The Panel concluded that the Ear Model "represents a significant improvement over the limits specified by MIL-STD-1474, and that the model was validated by a human exposure experiment conducted in Albuquerque, New Mexico"

In my opinion, this model is significantly more accurate than the existing criterion, and takes into account all aspects of the hearing mechanism. In addition to being more accurate, the acceptable levels predicted by this model are also slightly less restrictive than the limits specified by MIL-STD-1474 .

It is my opinion, therefore, that the impulse noise limits stipulated in MIL-STD 1474 should be upgraded to the limits predicted by this new computer model.

/s/
GEORGES R. GARINTHER
Guest Researcher
Human Research & Engineering Directorate

"It is my opinion, therefore, that the impulse noise limits stipulated in MIL-STD 1474 should be upgraded to the limits predicted by this new computer model." *Georges Garinther, November 2004*

The 1960s: MIL-STD 1474 (Requirement 4) is developed:

- Very limited database of impulses (small arms only)
- Correction for number of rounds a guess by committee
- No allowance for waveform spectrum
- Calculation of duration required judgment by user
- **But it was the best thing available at the time**
- **It was useful --- used for Health Hazard Assessments (HHA) "until something better comes along."**

The 1970s: Basic Research Continued:

- **At high levels, mechanical stress at the level of the hair cell is the primary loss mechanism**
- Conductive path emphasizes the mid-range
- Middle ear muscles exert large variable influence
- **Stapes non-linearity is a major influence at high intensity noise levels**
- As level goes up, loss goes from log-time to linear-time relationship (demonstrated in human and cat ears)
- Above critical level, loss grows very rapidly - about 7 dB per dB increase in level (demonstrated in human, chinchilla, and cat ears)

Auditory Hazard Assessment Algorithm for the Human (AHAAH)
Fifty Years of Basic Research

In the 1980s:

- **Computational capacity exploded**
- Wave motion in the cochlea could be calculated
- Transfer functions from free-field to stapes displacement became available
- **Measurement techniques improved**
- **Digitized pressure histories became available**
- Electrophysiological measurement of hearing sensitivity became possible

The 1990s: AHAAH was slowly born:

- Developed as an electro-acoustic analog of the ear
  - Parallelism between physiology and model elements
  - Promoted both generality and insight- works in the time domain
- **Developed and validated first for the cat ear; predicted CTS, PTS and hair cell loss**
- **Model parameters changed to reflect values for human ear**
- AHAAH validated for human ear
  - Comparison of transfer functions with measured data (conductive path OK)
  - **Comparison of predicted hearing loss for available human data**
  - Provided temporal analysis of action (movie)

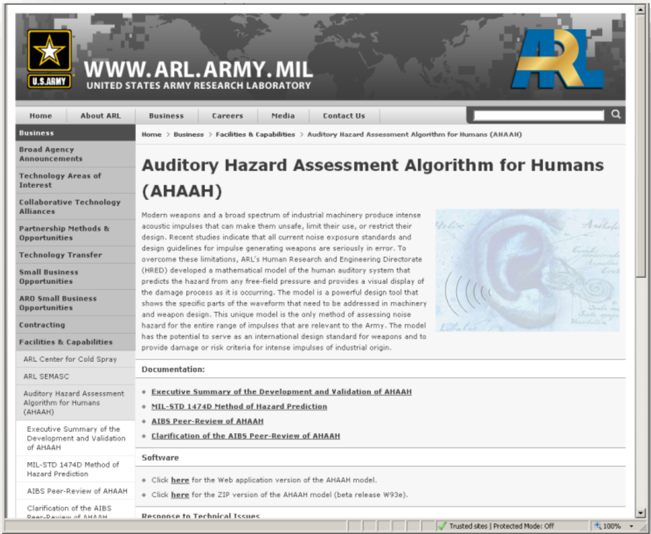
CHRONOLOGY OF RECENT SIGNIFICANT EVENTS

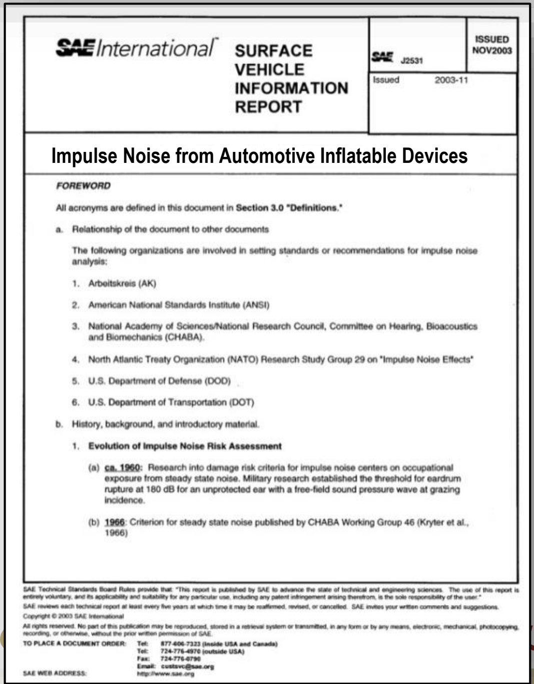
- **American Institute of Biological Sciences (2001)** concluded that the AHAAH Ear Model “represents a significant improvement over the limits specified by MIL-STD-1474.”

- **AHAAH Website** created (2003): http://www.arl.army.mil/ahaah/

- **Society of Automotive Engineers** (SAE) recommends use of AHAAH; publishes “Impulse Noise from Automotive Inflatable Devices” (2003).

- **“Validation of the auditory hazard assessment algorithm for the human with impulse noise data”** (2007), published in J. Acoust. Soc. Am. **122** 5.





SAE International SURFACE VEHICLE INFORMATION REPORT

SAE J2531 ISSUED NOV2003

Issued 2003-11

Impulse Noise from Automotive Inflatable Devices

FOREWORD

All acronyms are defined in this document in Section 3.0 "Definitions."

a. Relationship of the document to other documents

The following organizations are involved in setting standards or recommendations for impulse noise analysis:

1. Arbeitskreis (AK)
2. American National Standards Institute (ANSI)
3. National Academy of Sciences/National Research Council, Committee on Hearing, Bioacoustics and Biomechanics (CHABA).
4. North Atlantic Treaty Organization (NATO) Research Study Group 29 on "Impulse Noise Effects"
5. U.S. Department of Defense (DOD)
6. U.S. Department of Transportation (DOT)

b. History, background, and introductory material.

1. **Evolution of Impulse Noise Risk Assessment**

(a) ca. 1960: Research into damage risk criteria for impulse noise centers on occupational exposure from steady state noise. Military research established the threshold for eardrum rupture at 180 dB for an unprotected ear with a free-field sound pressure wave at grazing incidence.

(b) 1966: Criterion for steady state noise published by CHABA Working Group 46 (Kryter et al., 1966)

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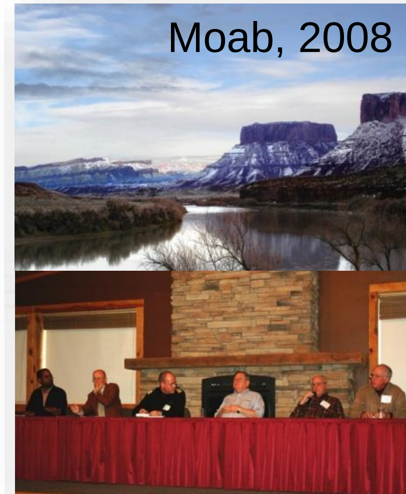
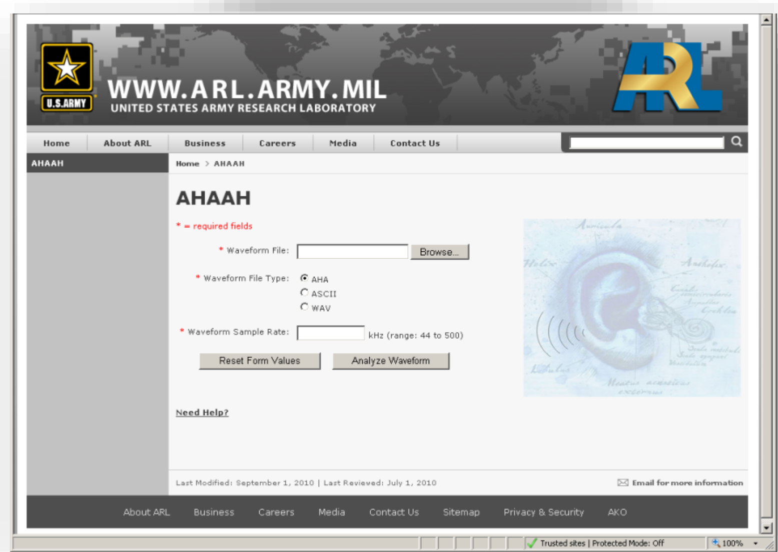
Auditory Hazard Assessment Algorithm for the Human (AHAAH)

CHRONOLOGY OF RECENT SIGNIFICANT EVENTS (Continued)

- **Air Force Research Laboratory (AFRL)** convenes "Effects of High Intensity Continuous, Impulse and Blast Noise on Humans Workshop" in Moab, Utah (2008).
- **AHAAH web-based analysis tool** goes on-line (2008) http://www.arl.army.mil/AHAAH/
- **ARL publishes** "Using the Auditory Hazard Analysis Algorithm for Humans (AHAAH) software, beta release W93e." ARL-TR-4987 (2009)
- **American National Standards Institute** (ANSI) reinstates the ANSI/ASA Working Group S3/WG 62 "Impulse Noise with Respect to Hearing Hazard" and chartered it with the development of the scientifically valid and practically accepted model of hearing hazard (2010).





Responses to questions posed by the AIBS panel:

Is the assessment method based on sound scientific principles?

- **The method is a theoretically-based approach.**
- The model:
  - uses physical laws to obtain a set of proven algorithms which are used to determine the percentage of the population that would sustain a permanent threshold shift based on impulsive sound measurement under a variety of exposure conditions.
  - accounts for impulse noise measurements:
    - under free field conditions
    - at the ear canal entrance
    - at the tympanic membrane, at probe tip location,
    - and while using a variety of hearing protection devices.

Is the assessment method based on sound scientific principles?

- Specific anatomical and physiological aspects of the ear canal model are based on scientific principles including:
  - effect of pinnae and external auditory canal as an exponential horn
  - two-piston model of the tympanic membrane
  - pars flaccida and pars tensa
  - an ossicular chain which includes compliant malleo-incudo and incudo-stapedial joint
- **AHAAH correctly accounts for the nonlinear behavior of the ear (annular ligament, stapes activity).**
- The cochlea is modeled using the Wentzel–Kramers–Brillouin (WKB) method; dividing the basilar membrane into 23 "bins" or segments where acoustic energy accumulates.
- The model's explanation of head related transfer function (HRTF) is scientifically based.

Auditory Hazard Assessment Algorithm for the Human (AHAAH)

Does the method adequately protect the noise-exposed population from a well-defined auditory injury?

- **AHAAH predicts the probability of PTS with 96% accuracy.**
- This model is unable (as is MIL-STD 1474D) to account for Soldiers who are not allowed adequate recovery time (estimated at least 24 hours) between consecutive periods of exposure to high level sounds.

Has the method been validated by the existing human exposure data sets?

- **The model's predictions are in agreement with the results of all data sets analyzed (small arms weapons, Albuquerque Studies; automotive airbags).**

- Within the parameters in which the model will be used, the model is valid.

Is the accuracy of the method in determining acceptable exposure conditions adequate for use as an occupational exposure standard?

- **The method is a powerful tool ready for use as a standard.**

- Accurately predicts exposure under the conditions specified in the model (such as proper fit and wearing of HPDs).

Auditory Hazard Assessment Algorithm for Humans (AHAAH)

- A unique, non-linear hearing protector was used in the Albuquerque Studies (AS).
- Many analyzes of the AS data were conducted assuming linear (non level dependent) behavior of the hearing protector.
- **Assuming linear hearing protection when analyzing Albuquerque Studies hearing loss data is inappropriate.**

Albuquerque Studies:
Defeated (non-linear) RACAL Muff

Will the method remain valid and retain necessary accuracy as the impulse noise characteristics change (e.g., longer and shorter sound pressure wave duration, complex and reverberate environments) and as the hearing protection devices change?

- AHAAH provides a realistic and flexible assessment of auditory risk from impulsive noise events (with or without hearing protection).

- **Unlike MIL-STD-1474D:**
  - **the model does not assume a specific shape of sound impulse.**
  - **the model does not rely on determining parameters such as duration that are difficult to measure consistently.**
  - **removes subjective interpretation of waveforms that are different from the norm.**

- AHAAH collocates well with all available datasets; no false negatives.

Does the method provide clear guidance on the hearing protection devices that will be acceptable under the conditions assessed?

AHAAH can be used to assess the relative effectiveness of any HPD, or combinations of HPDs.

Is AHAAH, in its current state and using sound pressure data as weapon developers currently collect it, a suitable replacement for MIL-STD 1474D for general application in limiting exposure of hearing-protected soldiers to impulse noise?

AHAAH is a suitable replacement of MIL-STD 1474D in the application of limiting exposure of hearing protected Soldiers to impulse noise.

Overall Strengths and Weaknesses of AHAAH

Strengths

AHAAH is a flexible assessment of auditory risk which:

- accommodates changes in impulse noise characteristics and hearing protection devices.
- is based on scientific research and can determine auditory injury, as well as account for impulse noise measurements under free field conditions, at the ear canal entrance, at the tympanic membrane, at probe tip location, and while using a variety of hearing protection devices.
- **uses well established theories to account for physiological activity and sound processing in the inner ear.**
- correctly accounts for the nonlinear nature of annular ligament and stapes activity.
- assumes the basilar membrane is acting nonlinearly at levels which the ear can be damaged.
- **has been validated against all available human impulse noise exposure data.**

Overall Strengths and Weaknesses of AHAAH

Weaknesses

- AHAAH (or any other damage risk criterion) is not able to account for the temporal pattern of exposure of Soldiers who are not allowed adequate recovery time between consecutive periods of exposure to high level sounds.

- **Details of the effects of the acoustic reflex at high levels of impulse noise are not well known; however treatment of the acoustic reflex in AHAAH has been shown to be predictive of actual hearing loss.**

AHAAH– Recent Developments

ISRAEL DEFENSE FORCES
Medical Corps Headquarters
Occupational Health Frame
September 30 2009

To:
U.S. Army, USACHPPM –
LTC Eric Fallon, Mr. Charles Jokel
U.S. Army, ARL – Mr. Bruce Amrein

SUBJECT: IMPULSIVE NOISE HAZARDS REGULATIONS

Dear colleagues,

We wish again (on behalf of myself and Mr. Philip Hopstone from RAFAEL) to thank you for your hospitality and the productive meeting at Aberdeen, May 11-14, 2009 and for sharing the information with us. There is no replacement for a direct discussion.

Secondly, although the meeting was productive and demonstrated the efforts made by the US Army to develop a unique approach for impulsive noise hazard risk evaluation and to verify its accuracy, it also demonstrated the need for world-wide guidelines. At this point it is seems reasonable to us to adopt the US Army approach, however we see also a need that this approach will be approved in-house (i.e., adopted by the US Army as a standard) and by NATO.

At this point, and due the reasons mentioned, we (the IDF Medical Corps) have chosen a conservative approach, of adopting the AHAAH model (due to its "army noise ear response approach" and the including of non-linear behavior elements), and applying the equal energy principle, as proposed by NATO RTO-017 (as a possibility, with extrapolation to some exposures not covered by NATO, according to ACGIH), and adopting of $L_{AEQ,8h}$ of 85 dBA (90 dBA for blast noise with protected ears by

At this point, and due the reasons mentioned, we (the IDF Medical Corps) have chosen a conservative approach, of adopting the AHAAH model (due to its "army noise ear response approach" and the including of non-linear behavior elements), …

toward some agreement soon, knowledge may be lost and there will be fewer chances for having internationally accepted guidelines.

Hence we propose proceeding with the process towards establishing a single, internationally accepted document (with the "best available knowledge"). Interim steps would involve a forum discussion via E-mail to establish the proposed document, prior to ratification.

Best regards,

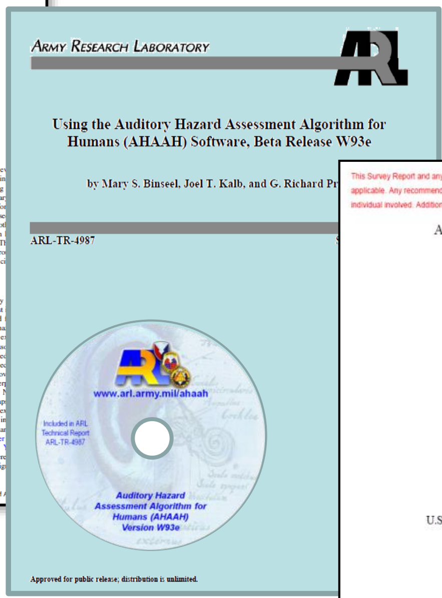
A. Duvdevany
LTC Dr. Amnon Duvdevany
Head of Acoustics and EMR Section
Occupational Health Frame
IDF Medical Corps

CC: IDF Surgeon General, IDF Surgeon General Deputy, RAFAEL - Mr. Philip Hopstone

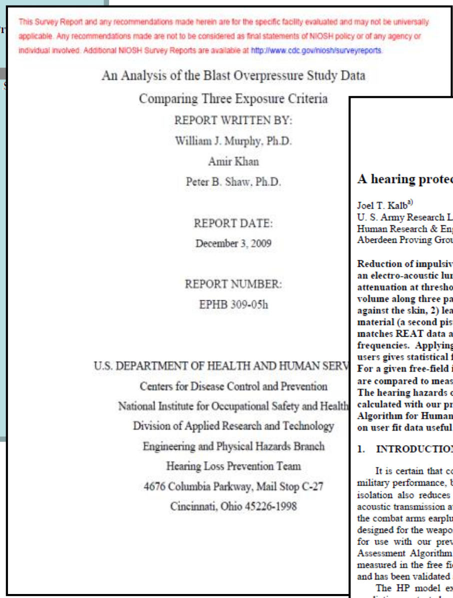
30 September 2009:
Israel Defense Forces Adopt AHAAH for Impulse Noise Hazard Evaluation

Recent AHAAH-related Publications

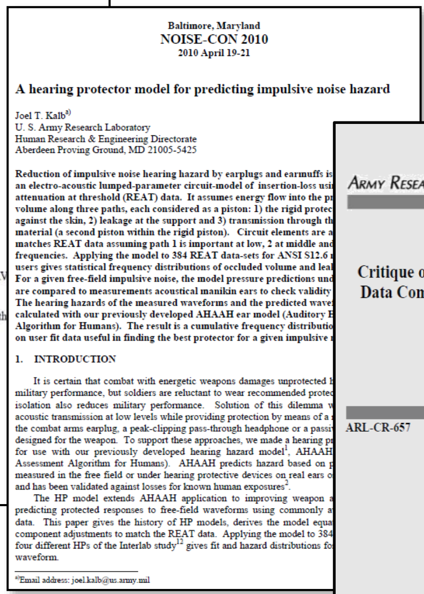
2007



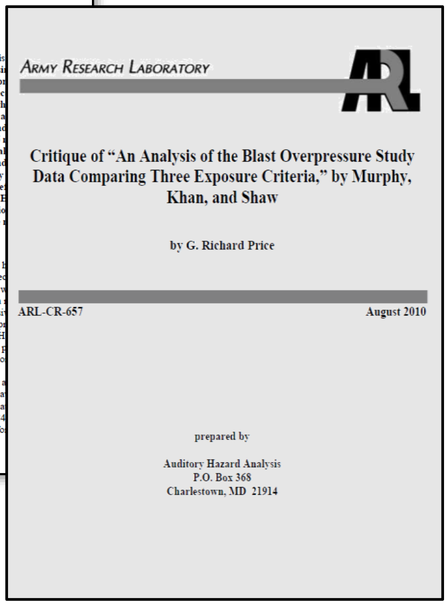
2009



2009



2010



2010

Auditory Hazard Assessment Algorithm for the Human (AHAAH)

MIL-STD 1474D

PREDICTED \ OUTCOME	SAFE	HAZ
SAFE	11	0
HAZ	33	9

A-WEIGHTED ENERGY

PREDICTED \ OUTCOME	SAFE	HAZ
SAFE	4	0
HAZ	40	9

AHAAH

PREDICTED \ OUTCOME	SAFE	HAZ
SAFE	41	0
HAZ	3	9

Albuquerque Studies Data: MIL-STD 1474D, A-weighted Energy, AHAAH

MIL-STD-1474D was correct in its evaluation of 22 of the exposures and incorrect in 31, an accuracy of 42%.

- ✓ Its errors were all in the direction of *overpredicting* hazard.

A-weighted energy was correct in 13 cases out of 53, an accuracy of 25%.

- ✓ This method also erred in *over-predicting the true hazard.*
- ✓ The amount of error in the over-prediction was sizable, often 10–20 dB.

The AHAAH model was correct in all but three cases for an overall accuracy of 94%.

- ✓ **Its three errors were also in the direction of *over-predicting hazard.***

G. Richard Price: Validation of auditory hazard algorithm
J. Acoust. Soc. Am., Vol. 122, No. 5, November 2007

Auditory Hazard Assessment Algorithm for Humans (AHAAH)

SUMMARY

1. Are there deficiencies with the current impulse noise requirement of MIL-STD 1474D?

   YES– acknowledged for 10-years

2. If so, what are the deficiencies that need to be addressed?
   - **Not scientifically based.**
   - **It is overly restrictive (its errors were all in the direction of overpredicting hazard)**
   - **Fails to properly handle non-standard waveforms**
   - **Many weapons systems are granted waivers to exceed the "Z-curve"**

3. Do any of the following models/approaches adequately address all of the current MIL-STD deficiencies?

   AHAAH Model **YES**

4. If so, is this model sufficiently tested and proven to be applied?

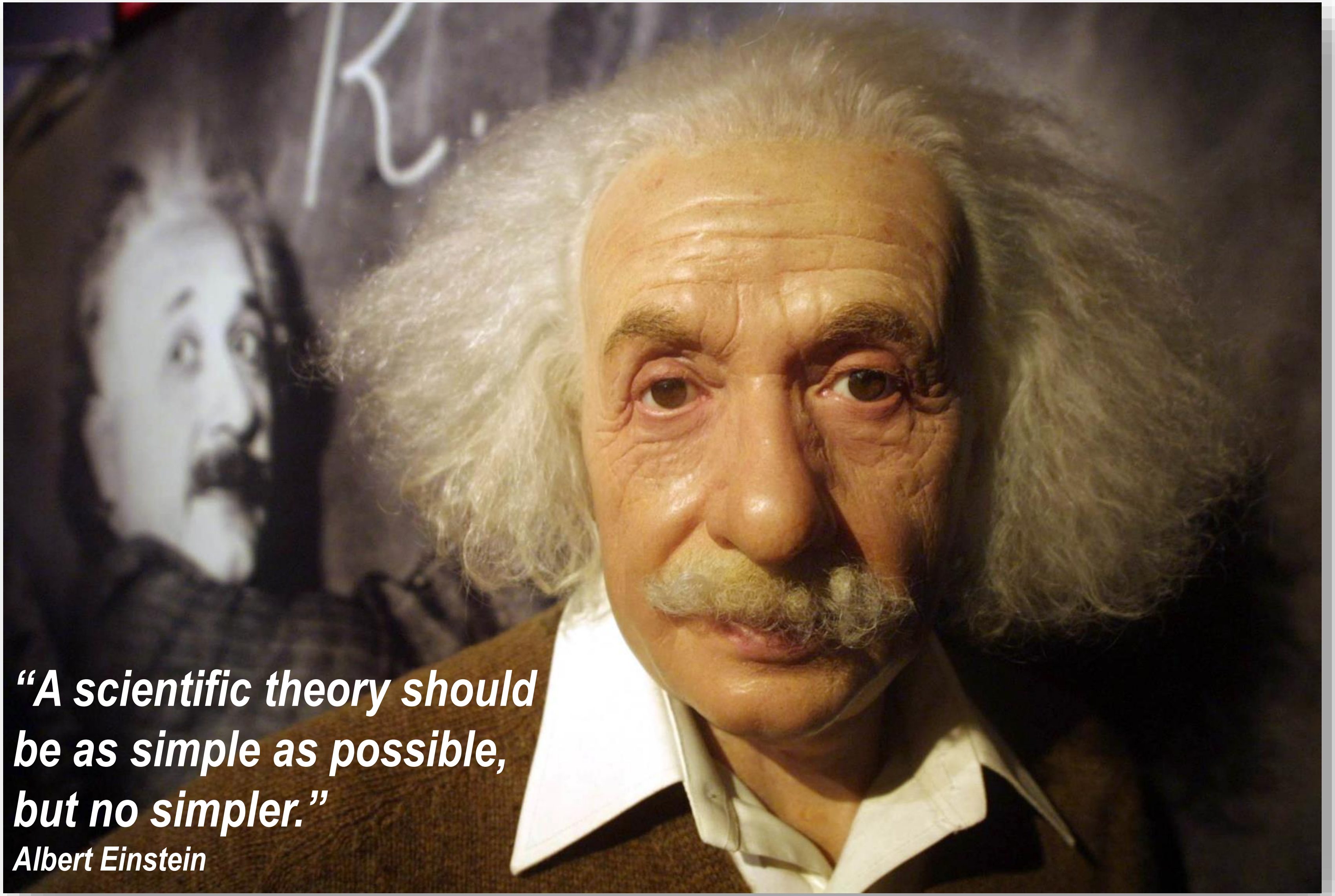
   YES; AHAAH has been validated against all available human exposure data.

American Institute of Biological Sciences

…concluded that the AHAAH Ear Model "represents a significant improvement over the limits specified by MIL-STD-1474"

April 2, 2001

Auditory Hazard Assessment Algorithm for Humans (AHAAH)



LIFETIME ACHIEVEMENT

G. RICHARD PRICE IS AWARDED THE 2010 ARL AWARD FOR LIFETIME ACHIEVEMENT. DURING HIS 50-YEARS OF RESEARCH IN AUDITION AND HEARING LOSS HE DEVELOPED A THEORETICAL UNDERSTANDING OF THE EAR'S FUNCTION AT HIGH NOISE INTENSITIES, VALIDATED AND TRANSITIONED IT INTO A UNIQUE MATHEMATICAL MODEL OF THE EAR.
IN PARALLEL, HE CREATED BASIC UNDERSTANDINGS OF THE EFFECTS OF CHANGES IN HEARING ON MILITARY PERFORMANCE, WHICH HAVE MATERIALLY AFFECTED HEARING CONSERVATION WITHIN THE ARMED FORCES. DR. PRICE'S OUTSTANDING WORK REFLECTS GREAT CREDIT UPON HIM, ARL, RDECOM, AND THE DEPARTMENT OF THE ARMY.