Presentation at the Second Plenary Meeting of the Advisory Committee on Acoustic Impacts on Marine Mammals

28-30 April 2004

Arlington, Virginia

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“Noise Exposure Criteria”

Noise Exposure Criteria Group

Advisory Committee on Acoustic Impacts on Marine Mammals

Plenary Meeting Two

April 28-30, 2004

Arlington, Virginia

Noise Exposure Criteria: Presentation Outline

History and Scope of the Criteria

Structure of the Matrix

Metrics and Weighting Functions

Injury (PTS) Criteria

Behavioral Criteria

Concluding Remarks

Noise Exposure Criteria:
“History and scope of the criteria”

Roger Gentry

NOAA Fisheries Acoustics Program

History of Noise Exposure Criteria and Policy Guidelines

- 1997: HESS panel and report
- 1998: NMFS consultation on "Acoustic Criteria"
- 2002: NMFS presents draft "Acoustic Criteria" to panel for review
- 2002-2004: panel drafts its own recommended "Noise Exposure Criteria"
- 2004: NMFS begins scoping and EIS for policy guidelines
- 2004-2005: panel publishes recommended "Noise Exposure Criteria"
- 2005-2006: NMFS announces its policy guidelines

Noise Exposure Criteria Group (Authors)

- Ann Bowles
- Roger Gentry
- William Ellison*
- James Finneran
- Charles Greene*
- David Kastak
- Darlene Ketten*

*Former HESS panelist

- James Miller
- Paul Nachtigall
- W. John Richardson*
- Brandon Southall
- Jeanette Thomas
- Peter Tyack

Former Contributors

- Whitlow Au
- Sam Ridgway* (ret)
- Ron Schusterman (ret)

NMFS Charge to the Noise Exposure Criteria Group

Develop science-based criteria for the onset of tissue injury and behavioral disruption from noise exposure without considering "harassment" as defined by present law.

Potential effects of noise exposure

Distant

- Causes a behavioral reaction of some magnitude
- Masks detection of other important sounds
- Induces temporary threshold shift (TTS)
- Causes permanent threshold shift (PTS), disorientation, non-auditory injury, or death

Close

“History and scope of the criteria”

Committee Questions for Panel

Noise Exposure Criteria:
“Structure of the matrix”

Brandon Southall

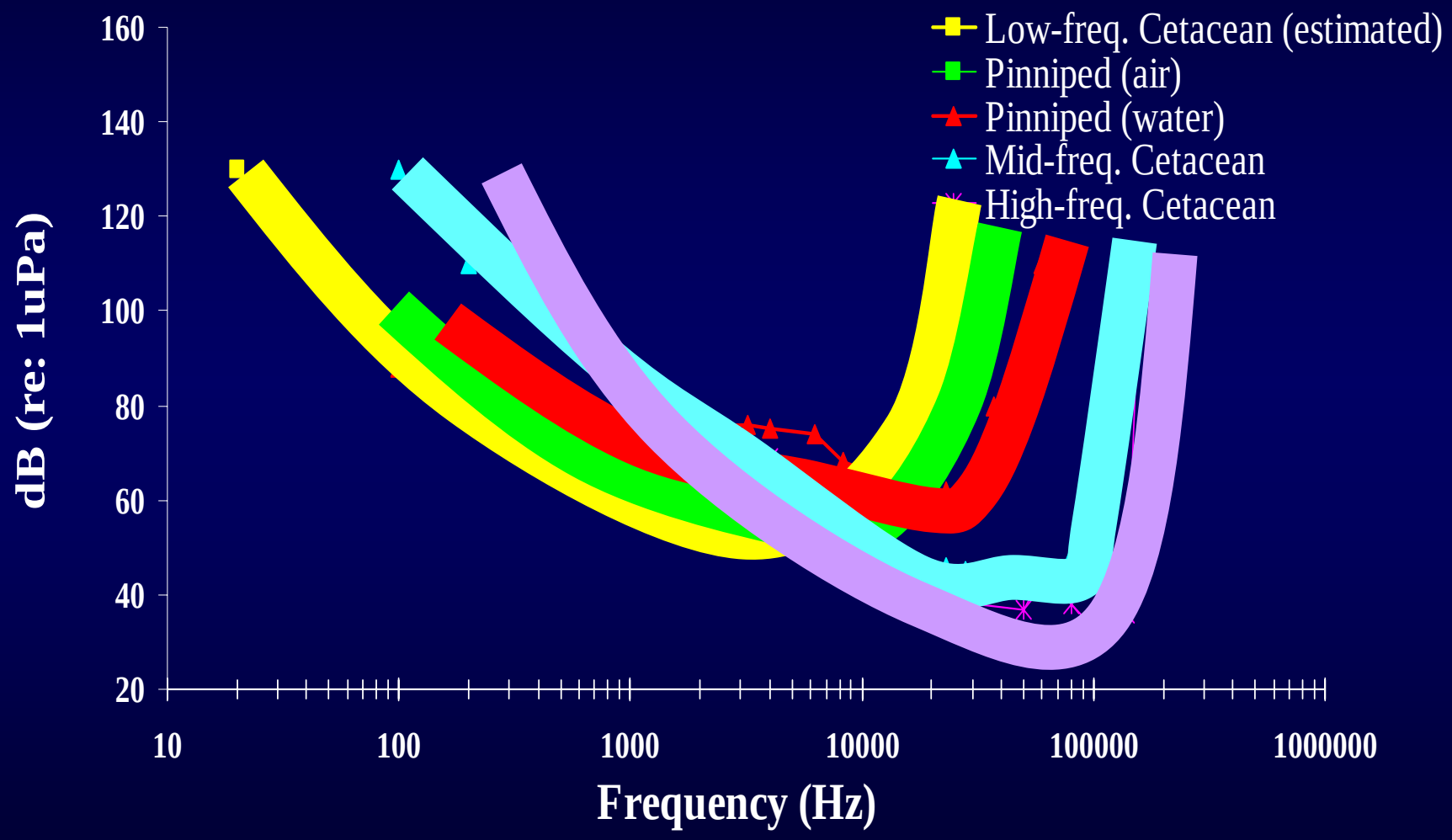
NOAA Fisheries Acoustics Program

University of California, Santa Cruz

Sound Types: Noise sources categorized based on characteristics *at the source*

Sound Type	Characteristics (at source)	Selected Examples
Single Pulse	Single sound: short duration, fast rise time	Single explosion, single airgun, watergun, or sparker pulse, single ping of certain sonars/depth sounders
Single Non-Pulse	Single sound: long duration, slow rise time	Single vessel pass, drilling event, aircraft overflight, single ping of certain sonars
Multiple Pulse	Multiple sounds: each short duration, fast rise time	Airguns, some sonar/depth sounder systems, waterguns, sparkers, pile driving, serial explosions
Multiple Non-Pulse	Multiple sounds: long duration, slow rise time	Multiple vessel/aircraft passes, certain sonar systems, tomography sources

Animal Groups: Animals categorized into functional hearing groups



Composite data (see: Richardson *et al*., 1995; Kastelein *et al*., 2002)

Impact Levels: Distinctions between noise events causing injury versus behavioral disturbance

Criteria for defining behavioral disturbance and estimated injury onset given in greater detail later in this presentation *

* If behavioral disturbance may result in injury or death (*e.g.*, beaked whales), behavioral criteria are used to conservatively set the injury criteria

<u>Exposure Metrics</u>: Dual criteria for sound pressure level (rms or peak pressure) and sound exposure level (SEL, also called energy flux density level). Threshold exceeded if **either** sound pressure level or SEL is greater than the respective criterion

Acoustic metrics relevant to the noise exposure criteria discussed in greater detail later in this presentation

Noise Exposure Criteria: General structure of the matrix

Sound Types:	4	
Animal Groups:	5	(20 cells)
Impact Levels:	2	(40 sub-cells)
Exposure Metrics:	2	(80 criteria)*

*Maximum; some may not be assigned

Noise Exposure Criteria: Specific structure of the matrix

Animal Groups	Sound Types			
	Single Pulse	**Single Non-Pulse**	**Multiple Pulse**	**Multiple Non-Pulse**
Low-frequency cetaceans	1i (Injury) 1d (Disturbance)	2i 2d	3i 3d	4i 4d
Mid-frequency cetaceans	5i 5d	6i 6d	7i 7d	8i 8d
High -frequency cetaceans	9i 9d	10i 10d	11i 11d	12i 12d
Pinnipeds in water	13i 13d	14i 14d	15i 15d	16i 16d
Pinnipeds in air	17i 17d	18i 18d	19i 19d	20i 20d

“Structure of the matrix”

Committee Questions for Panel

Noise Exposure Criteria:
“Metrics and Weighting Functions”

Charles Greene, Jr.

Greeneridge Sciences, Inc.

Ann Bowles

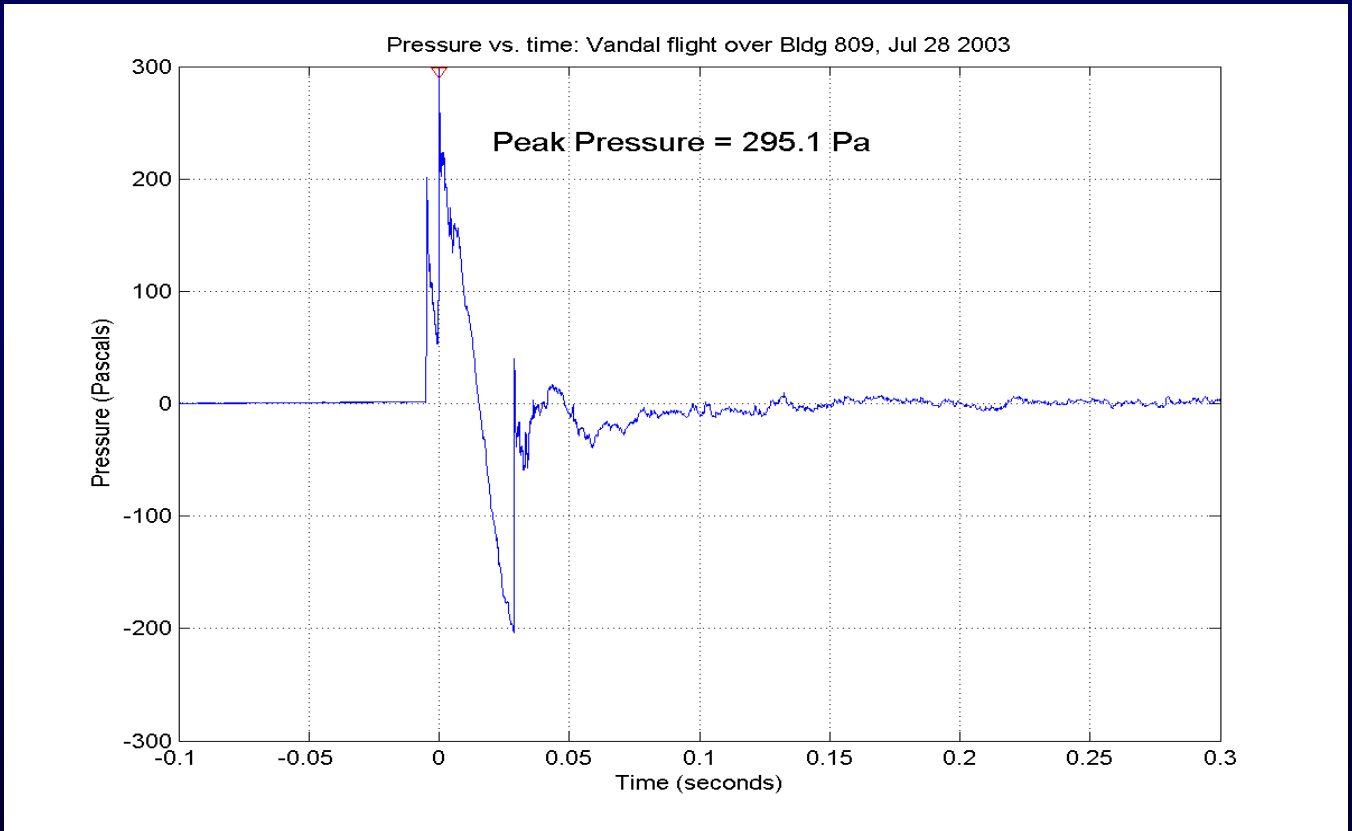
Hubbs-Sea World Research Institute

Acoustic Measures and Units

Peak pressure (μPa)

Duration (s)

Root-Mean-Square (RMS) pressure (μPa)

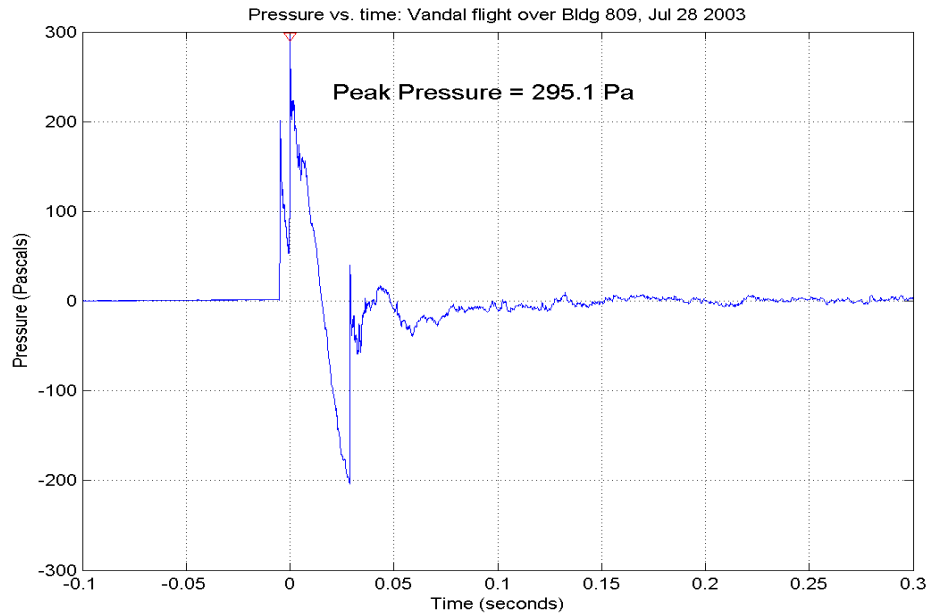


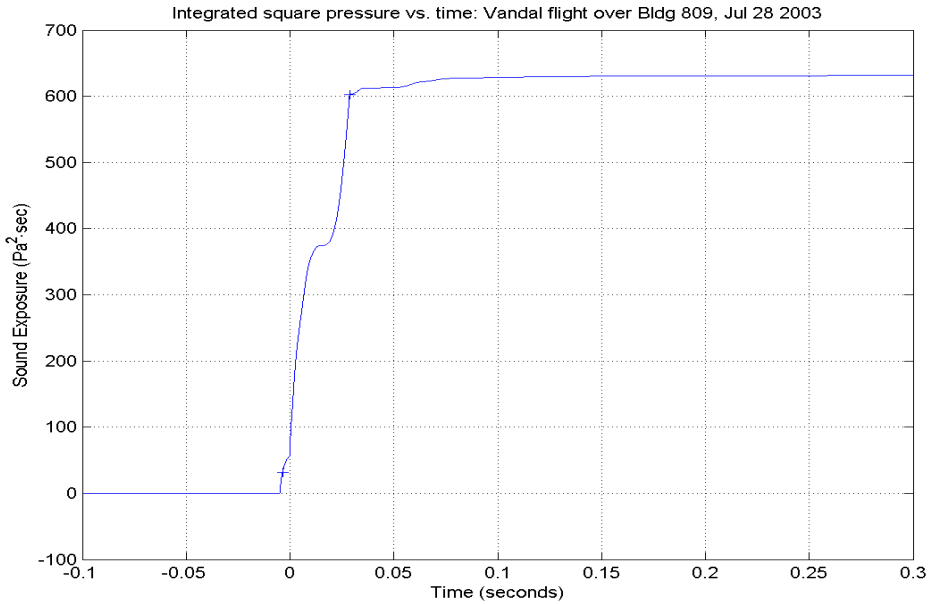
Acoustic Measures and Units

Sound Exposure

(μPa^2-s)

(Sometimes called "energy" or "energy flux density")

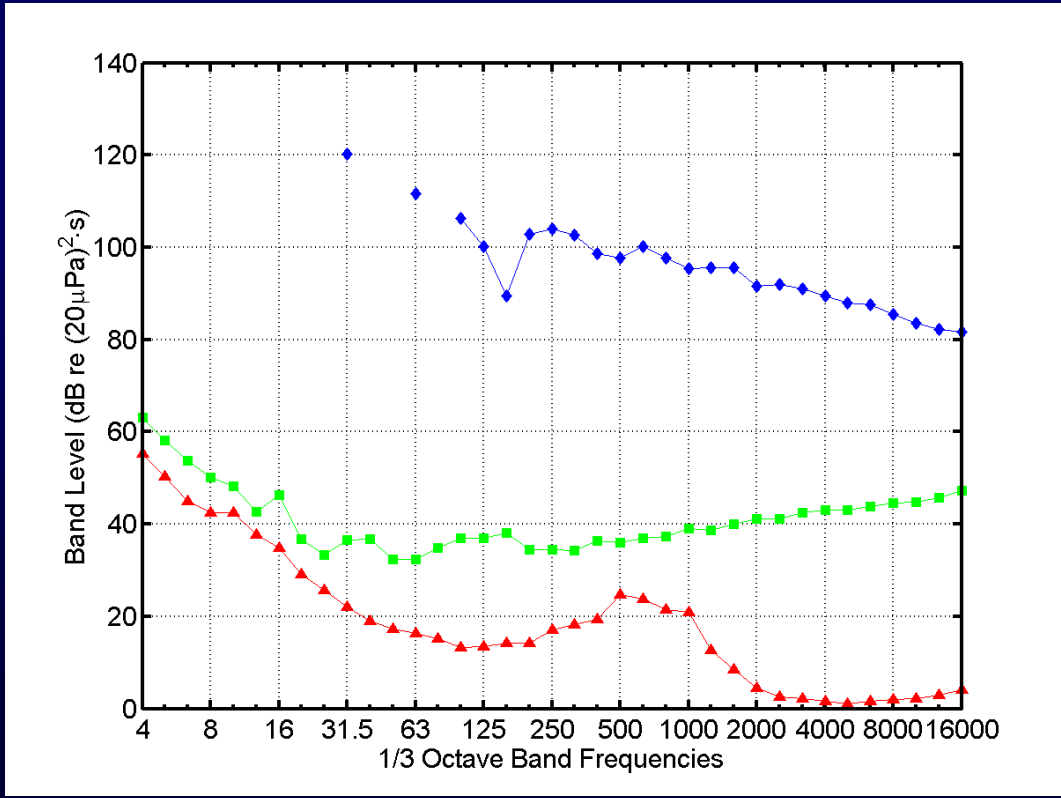




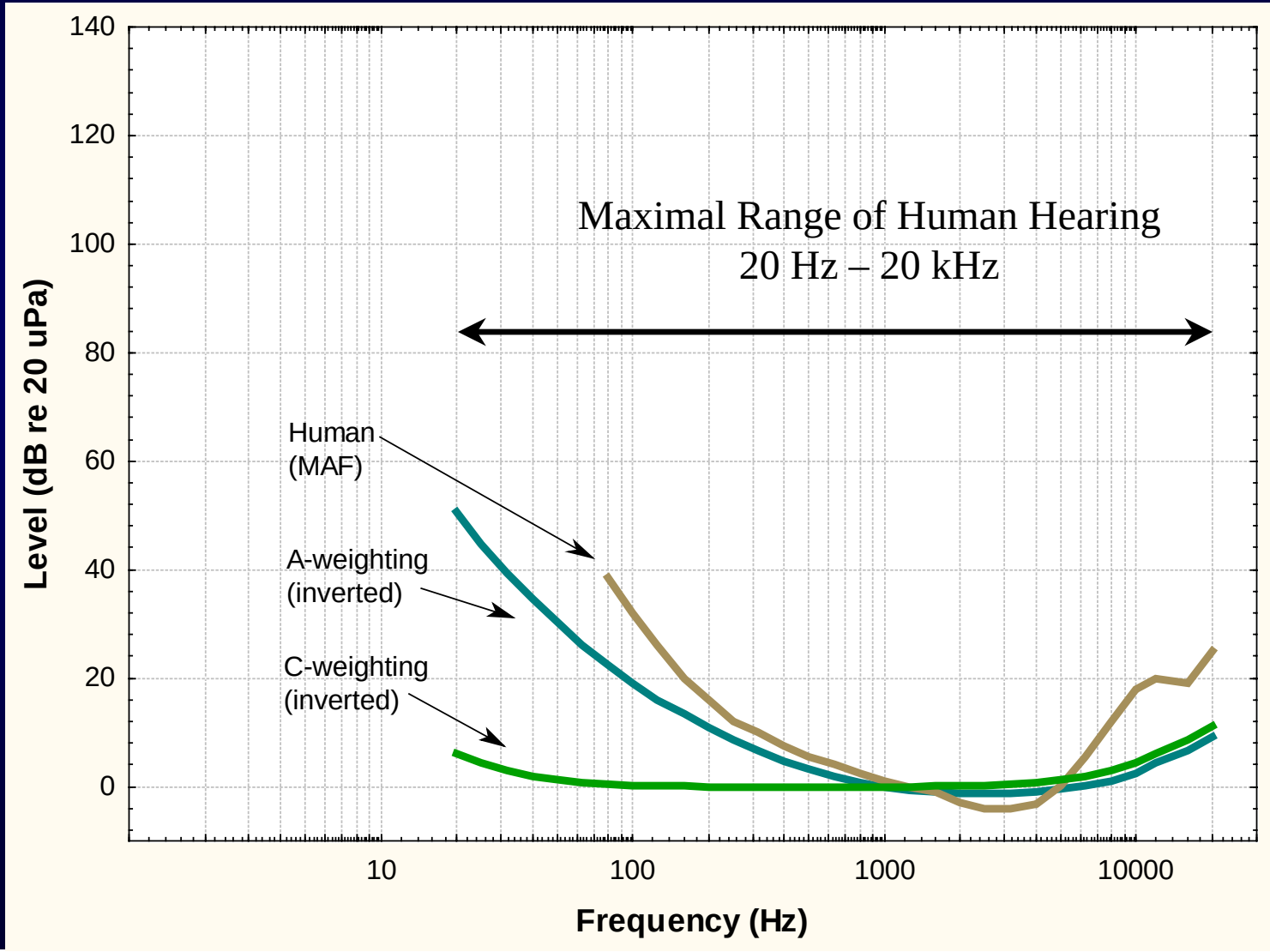
Acoustic Measures and Units

Sound pressure spectral density (μPa^2/Hz)

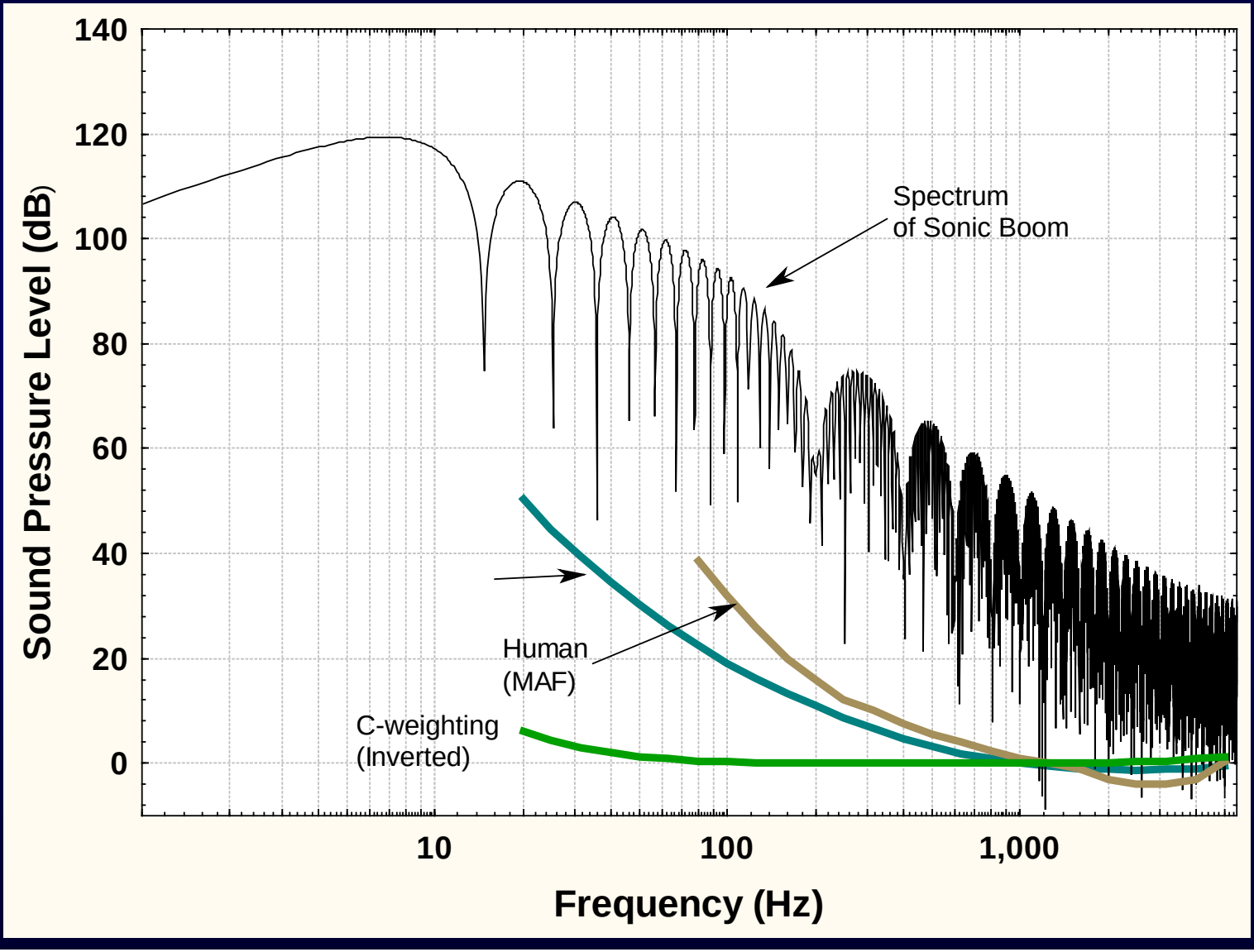
One-third octave band pressures (μPa)



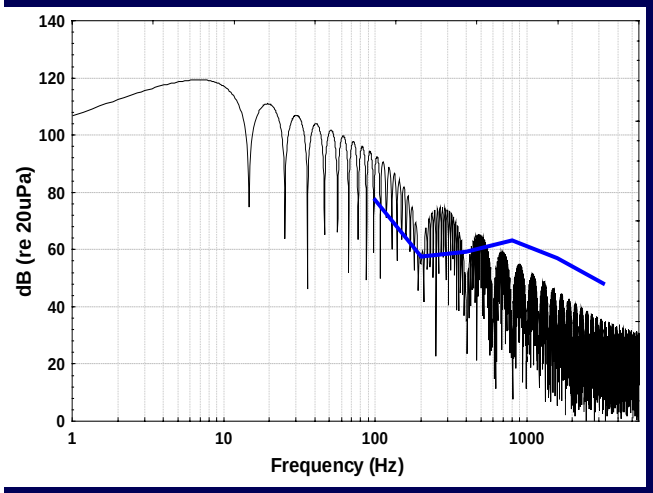
Human Hearing: Weighting Functions



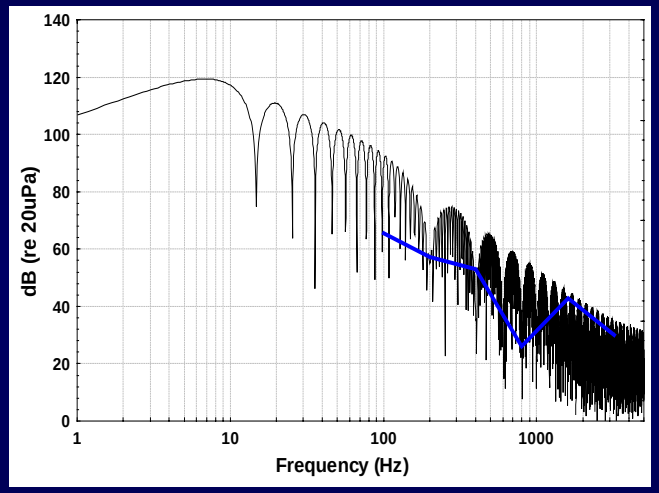
Example of sound exposure relative to human hearing and frequency weighting



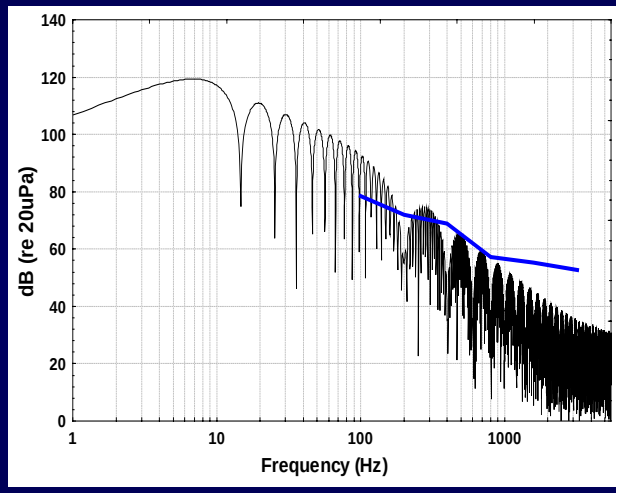
Example of sound exposure relative to marine mammal hearing



California Sea Lion



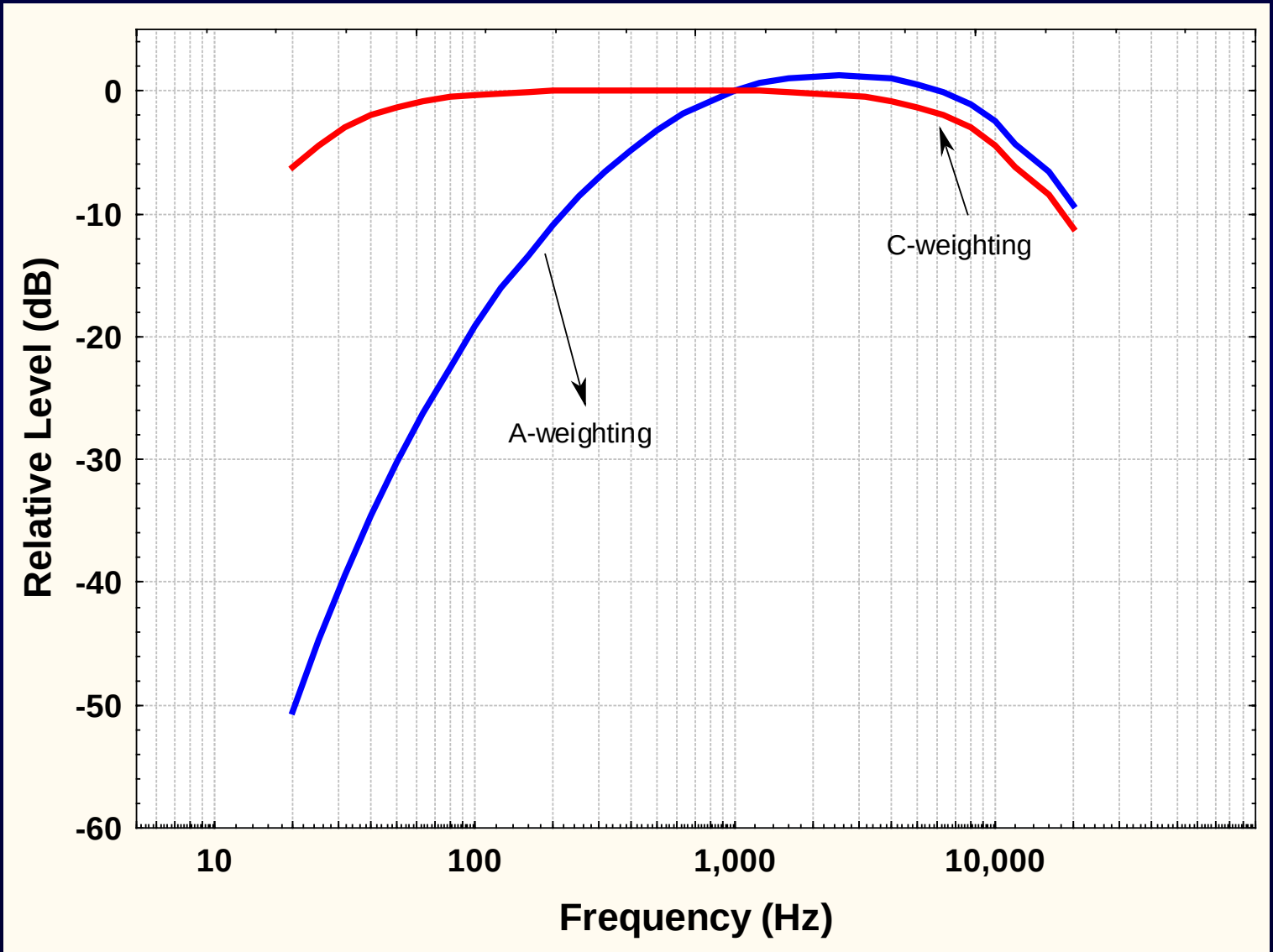
Harbor Seal



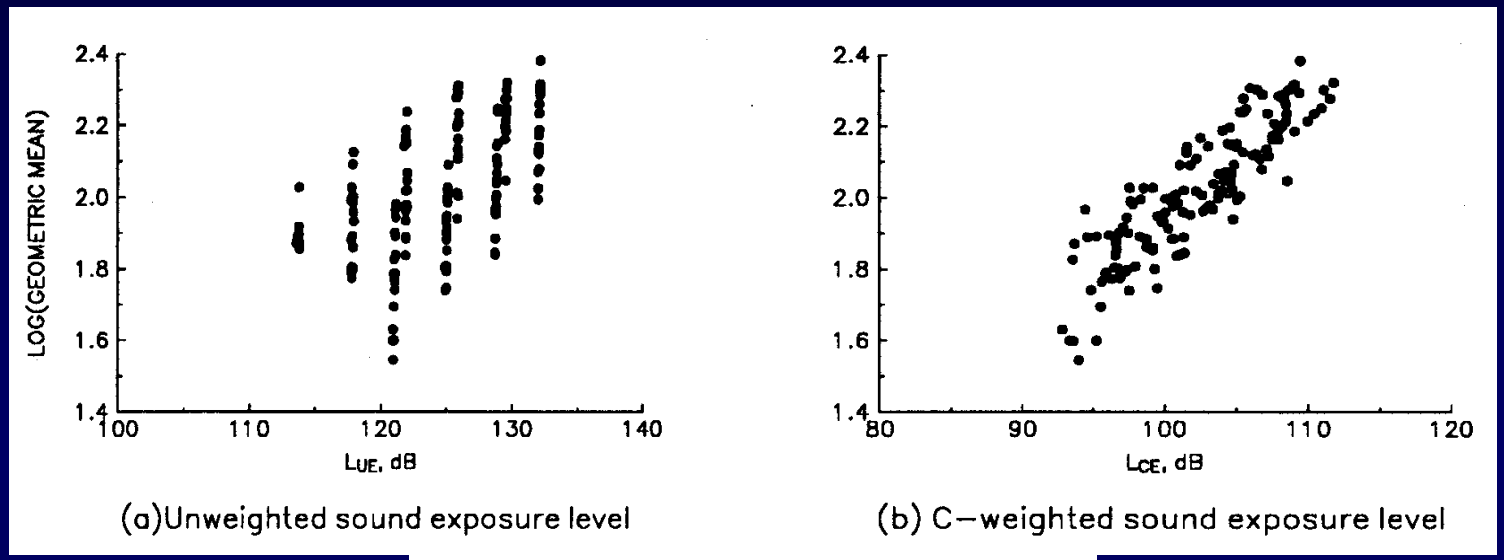
Northern Elephant Seal

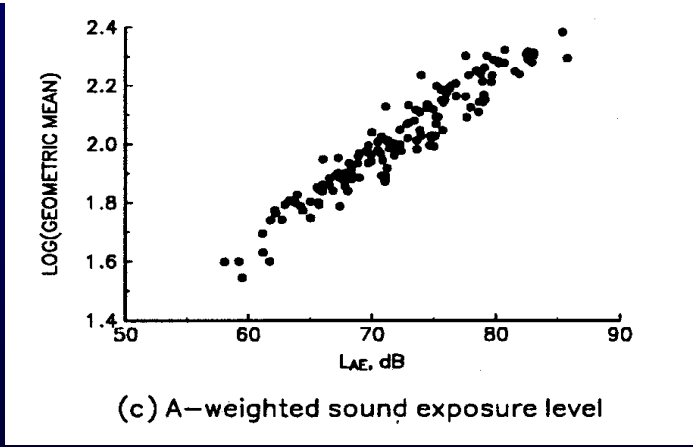
Pinniped threshold data from: Kastak, D. and R.J. Schusterman. 1998. Low-frequency amphibious hearing in pinnipeds: methods, measurements, noise and ecology. Journal of the Acoustical Society of America 103(4): 2216 – 2228

Human Frequency Weighting Networks



Use of frequency weighting for assessing human noise exposure

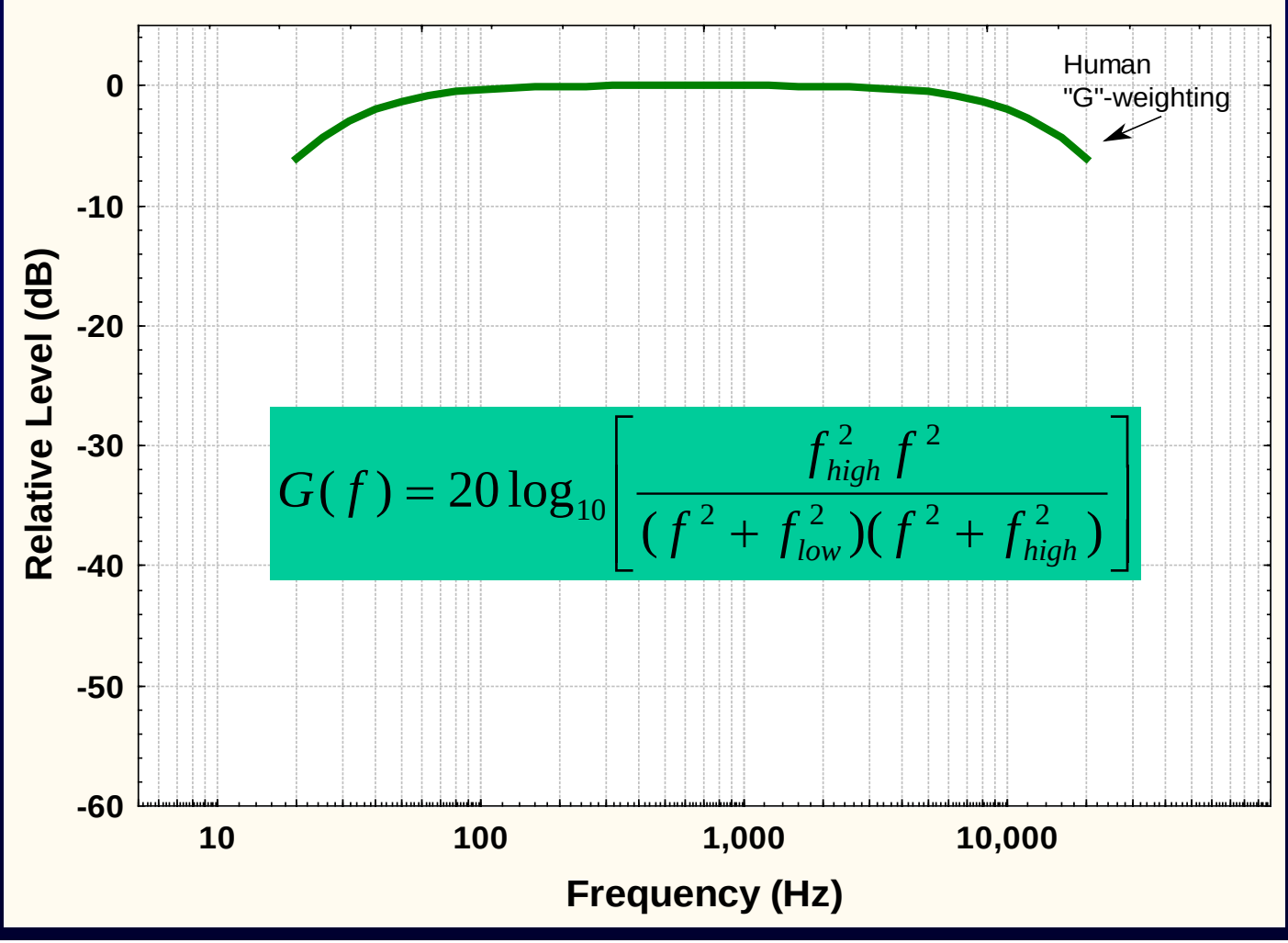




Leatherwood, J.D., B.M. Sullivan, K.P. Shepherd, D.A. McCurdy, and S.A. Brown. 2002. Summary of recent NASA studies of human response to sonic boom. Journal of the Acoustical Society of America 111(1, pt. 2): 566–598.

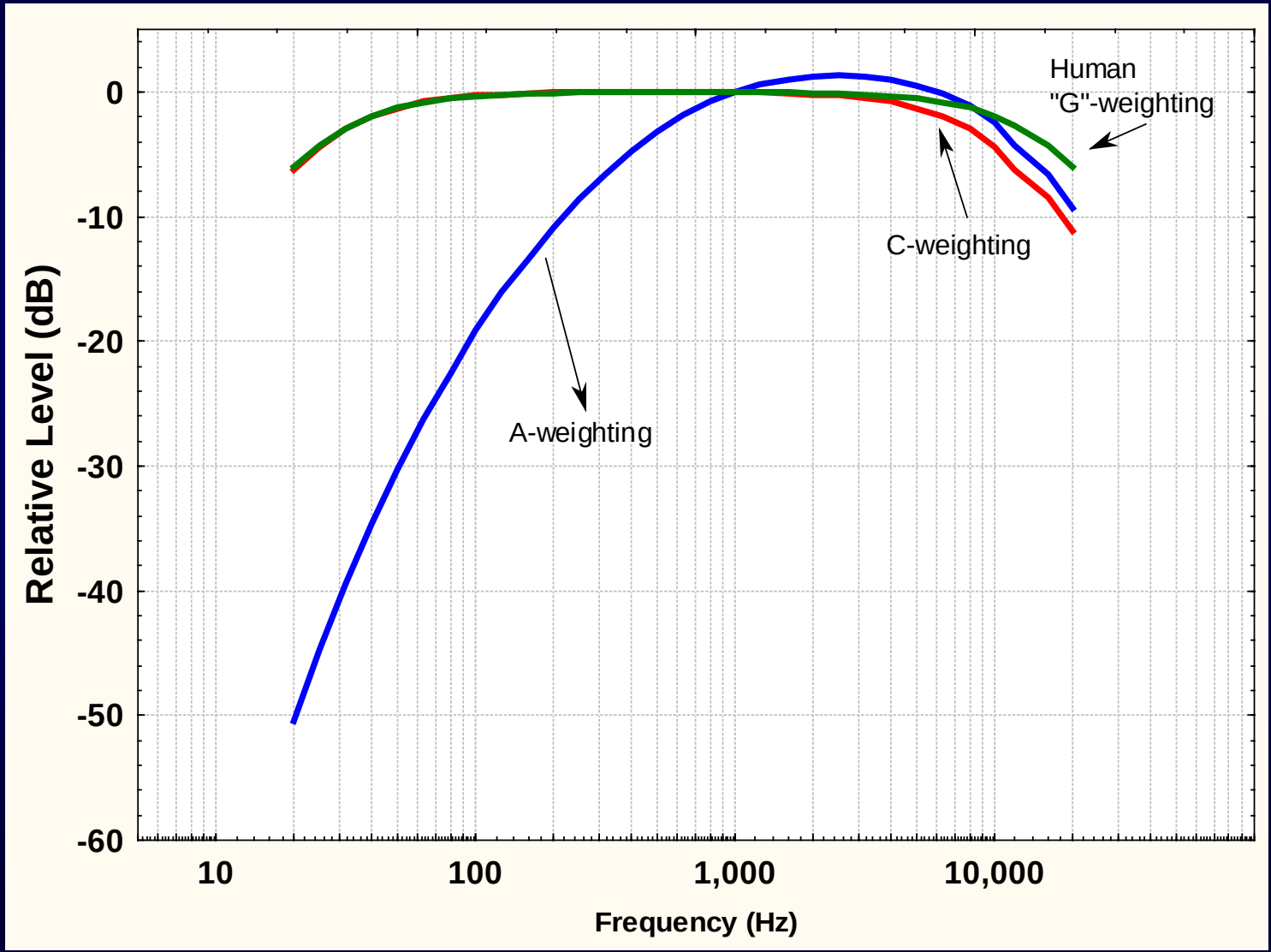
“G-weighting” function: a C-weighting approximation

(Miller unpub.)

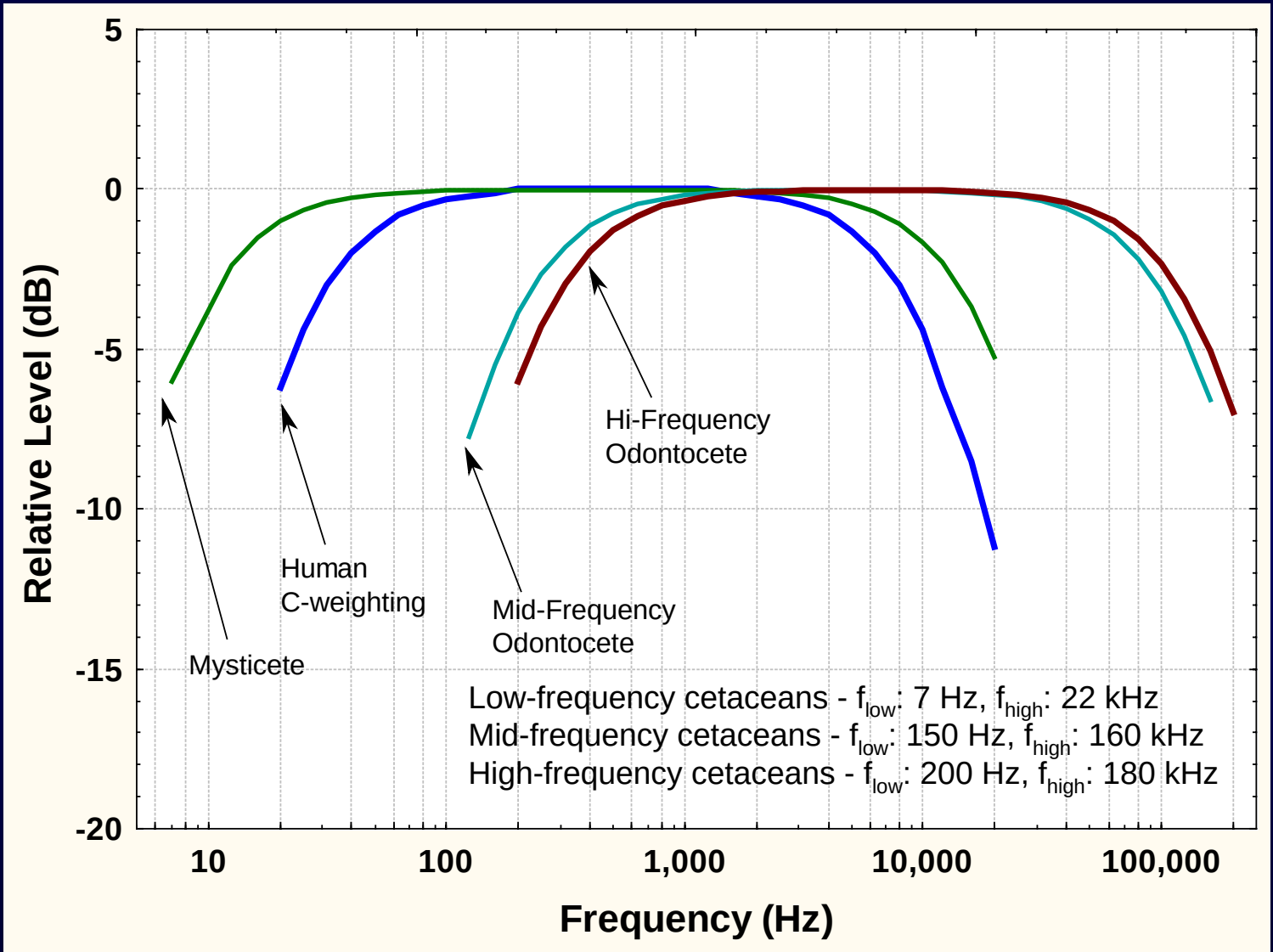


$$G(f) = 20\log_{10}\left[\frac{f_{high}^{2} f^{2}}{(f^{2} + f_{low}^{2})(f^{2} + f_{high}^{2})}\right]$$

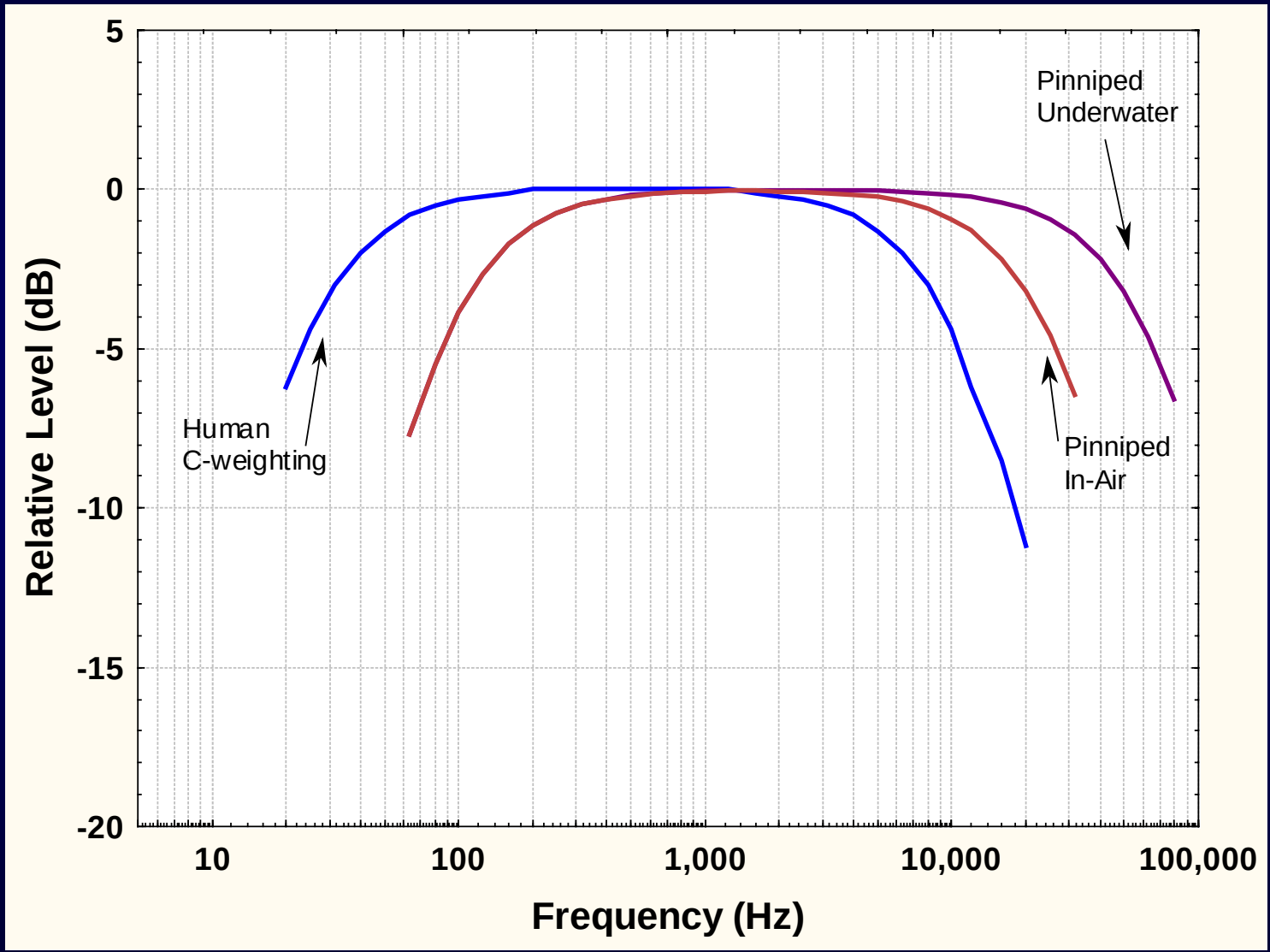
“G-weighting” for human hearing



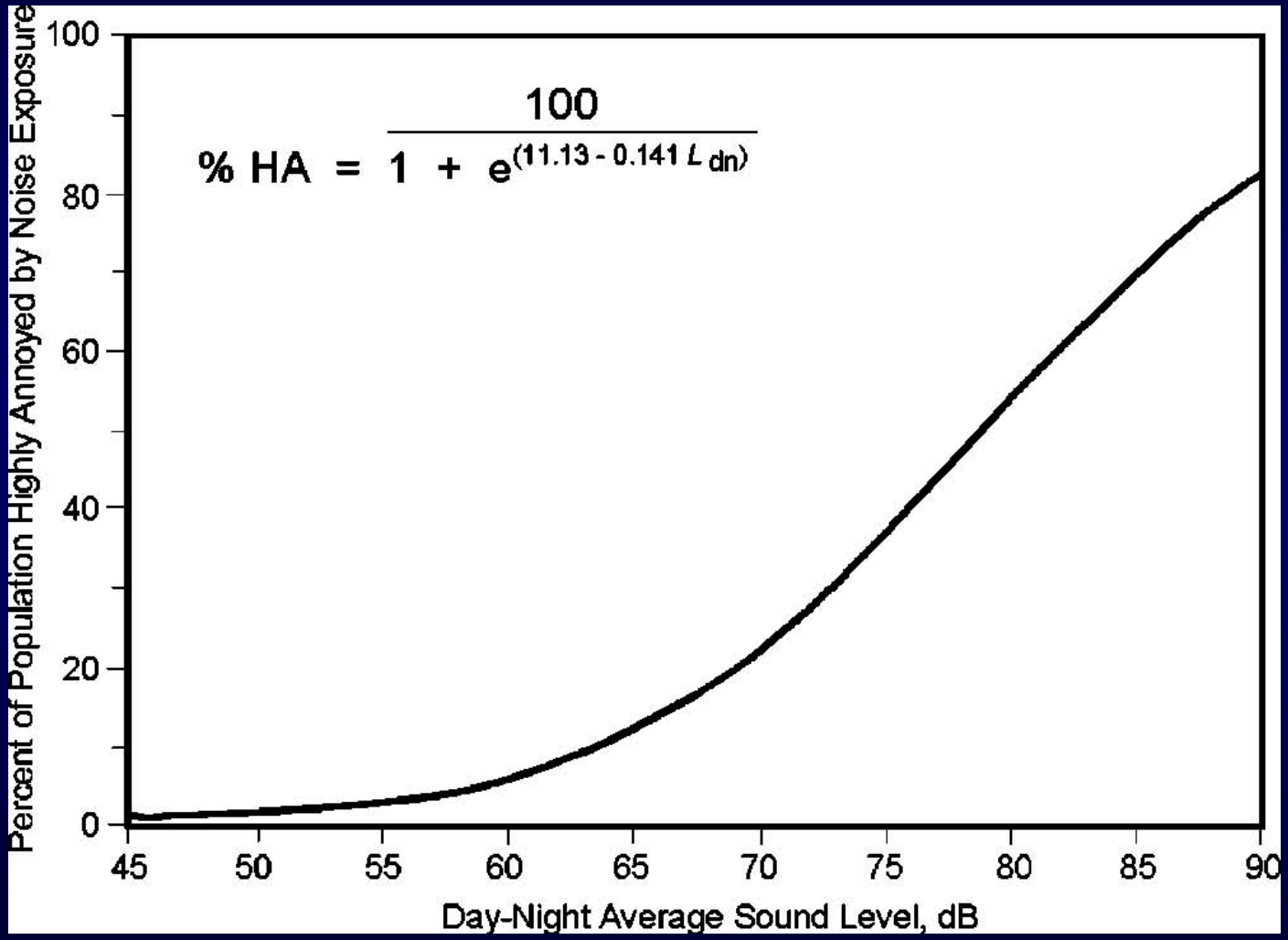
“G-weighting” for cetacean hearing



“G-weighting” for pinniped hearing



Schulz Curve (as modified by FICON/USAF, 1992)



From: Fidell, S. 2003. The Schulz curve 25 years later: A research perspective. Journal of the Acoustical Society of America 114(6): 3007 – 3015.

“Metrics and Weighting Functions”

Committee Questions for Panel

Noise Exposure Criteria: "Injury (PTS) Criteria"

D.R. Ketten

Woods Hole Oceanographic Institution

Harvard Medical School

Jim Finneran

Space and Naval Warfare Systems Center, San Diego

ACOUSTIC TRAUMA: PTS vs TTS

Level, duration, duty cycle, spectra

permanent vs. temporary, mechanisms and patterns

NIHL – why there is no single sound byte

Species and individual differences

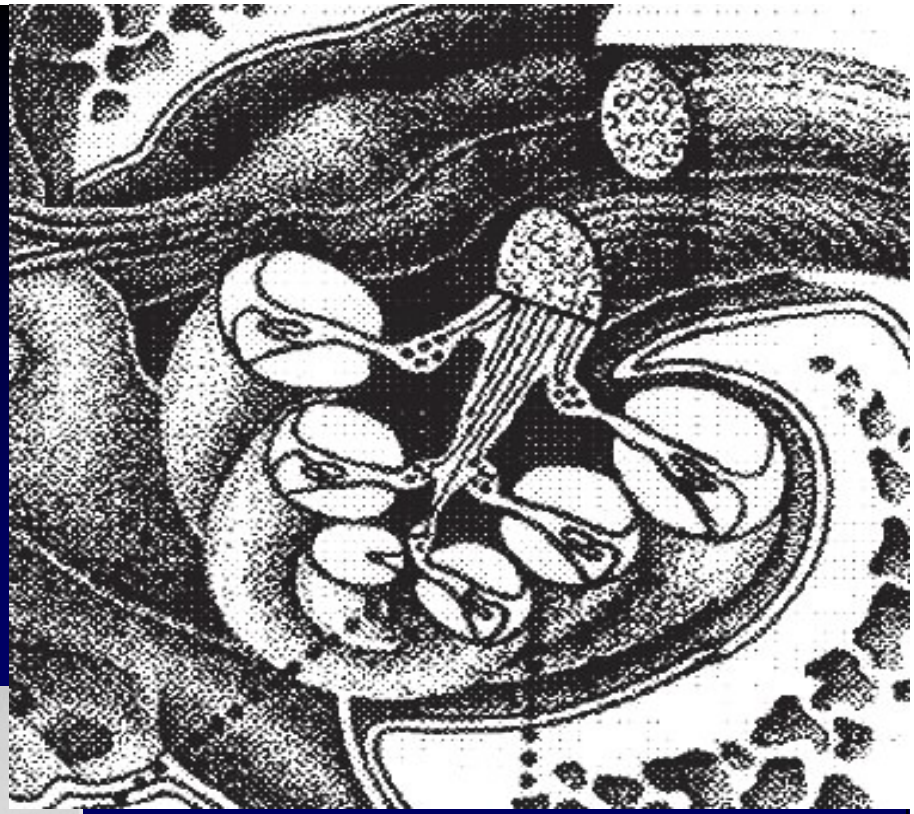
MARINE MAMMAL EARS

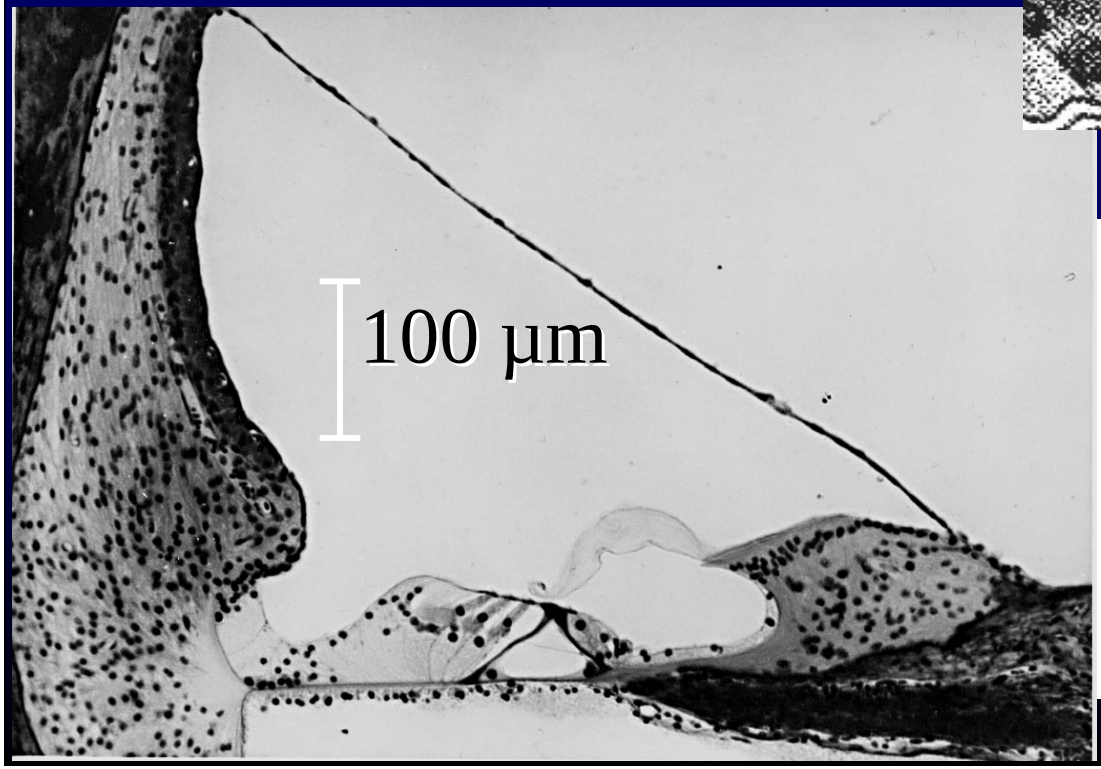
Acoustic and structural categorizations

Acknowledgements

Charles Liberman, Joseph Nadol (HMS)
Staff of Eaton Peabody Laboratory of Auditory Physiology (MIT/HMS)
William Yost (Parmley Laboratory for Hearing Research)
Barbara Bohne (Washington Univ. Medical School)

Mammalian Cochlear Dynamics

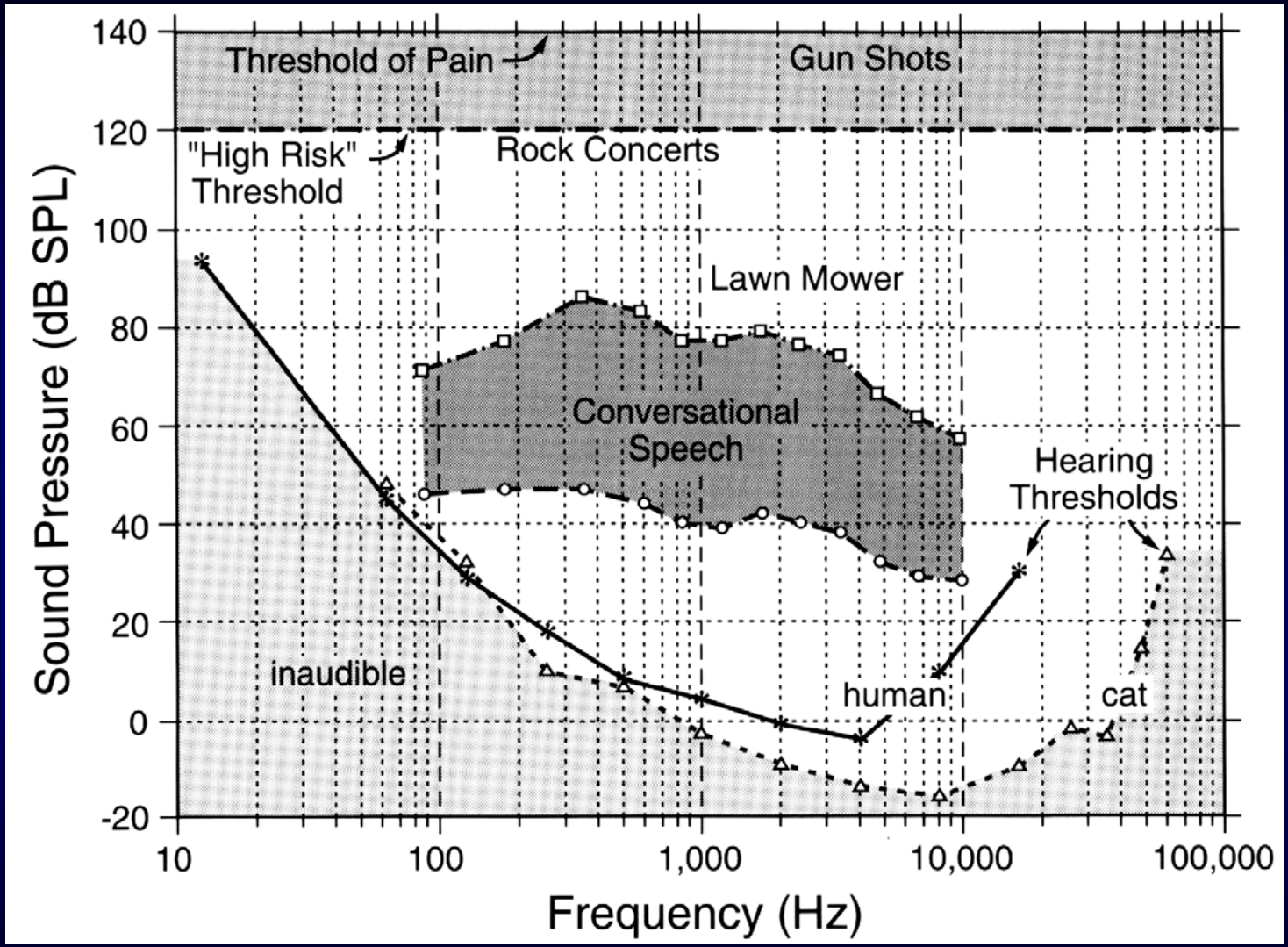




Membrane Displacements:
0 dB SPL at 4 kHz,
sensation = H atom diameter

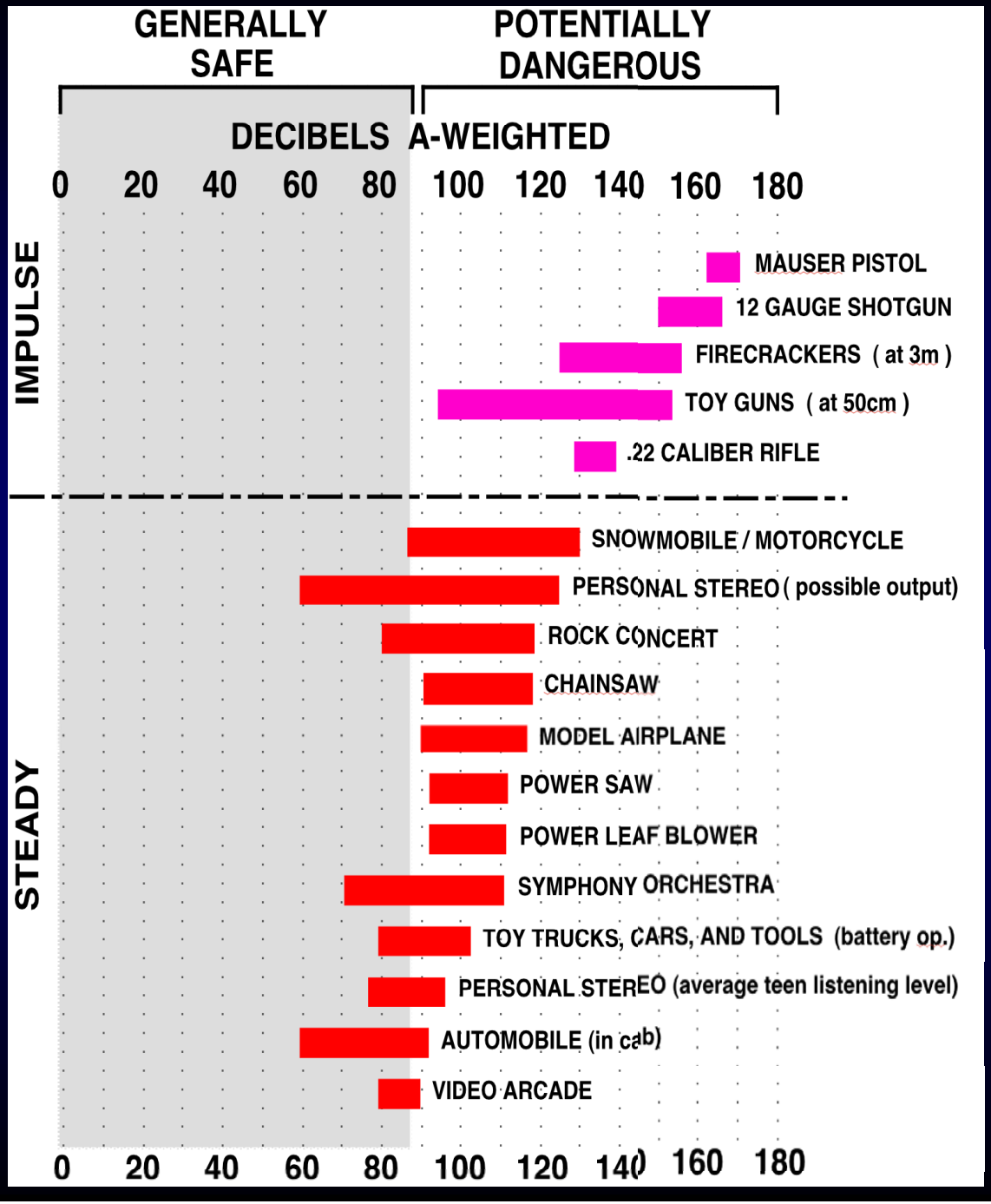
80 dB SPL ~ 100 nm
100 dB SPL ~ 1 µ

Thresholds of Hearing, Damage and Pain



Temporary (TTS)
Permanent (PTS)

Exposures studied primarily in cat, guinea pig, chinchilla, mouse



OSHA Guidelines

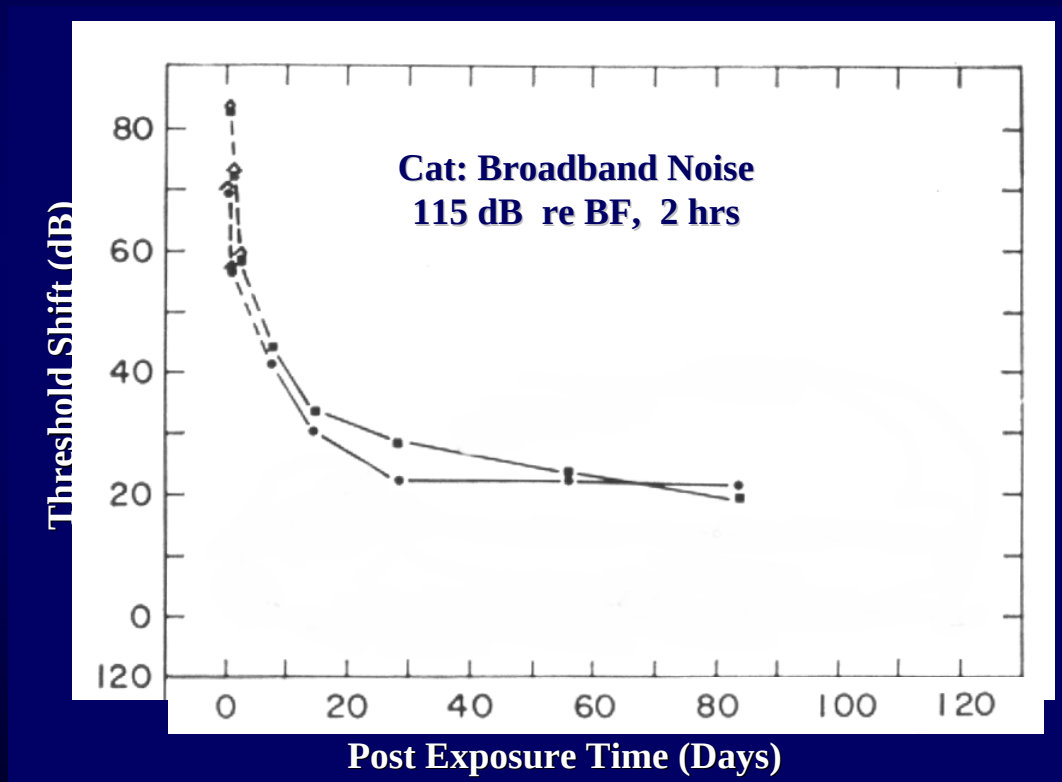
(re ANSI standard human thresholds)

OSHA GUIDELINES - STEADY NOISE

NOISE LEVEL dB (A)	ALLOWABLE DURATION (per day, 5 days/week)
90	8 hours
95	4 hours
100	2 hours
105	1 hour
110	30 minutes
115	15 minutes
120	7.5 minutes

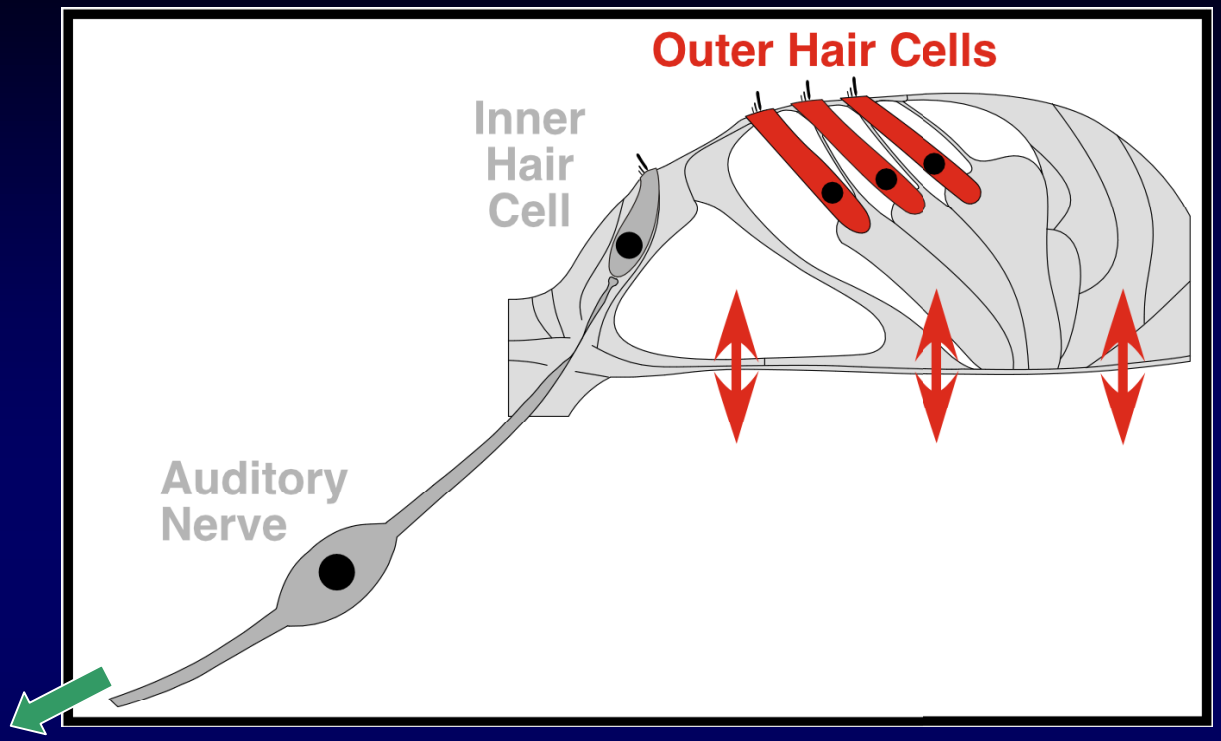
Permanent Threshold Shift (PTS):

"Permanent increase in the threshold of audibility for an ear at a specified frequency above a previously established reference level." (Yost, 2000)



Miller Watson and Covell, 1963

Normal Hair Cell Function



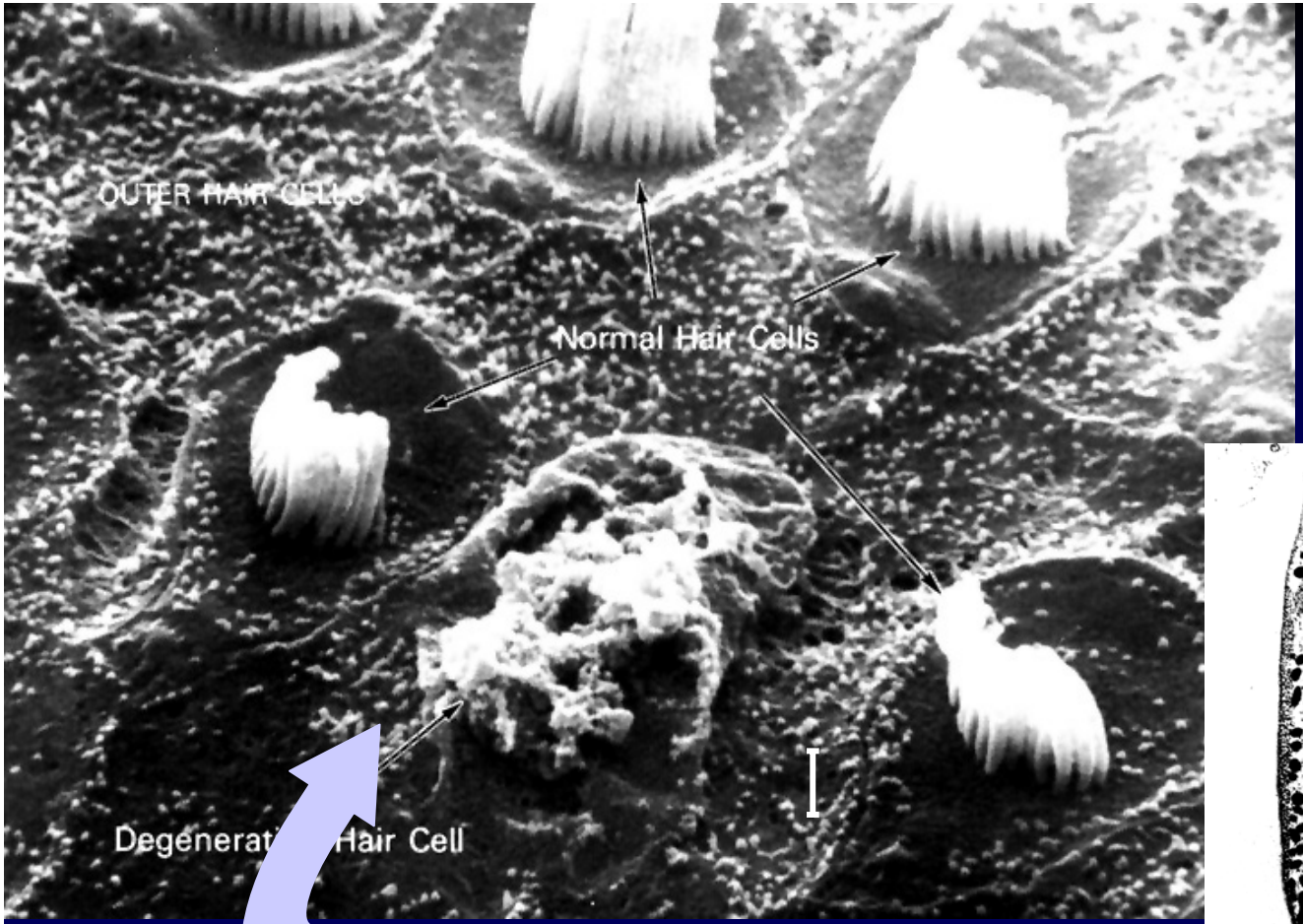
Sound pressure generates motion

Outer Hair Cells amplify motion

Inner Hair Cells transduce motion into electricity

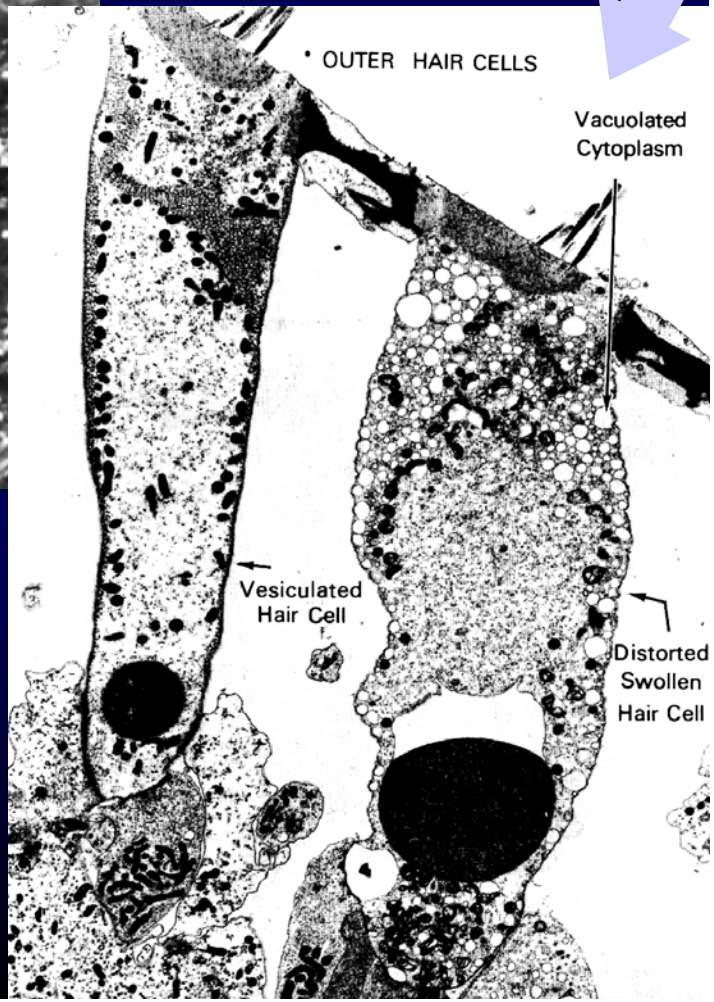
Auditory Nerve transmits electrical activity to the brain

PTS: Inner and/or Outer Hair Cells die



Metabolic

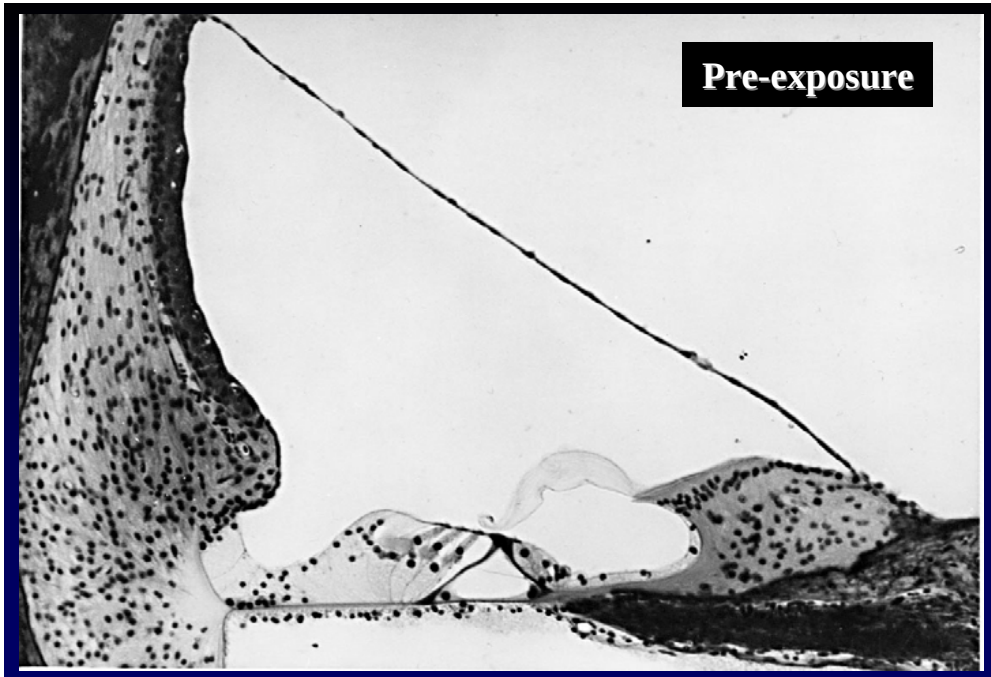
mitochondria
lytic mixing



Mechanical

stereocilia/plate
hair cells/organ of Corti
membranes

Lim in Schuknecht, 1993



TTS

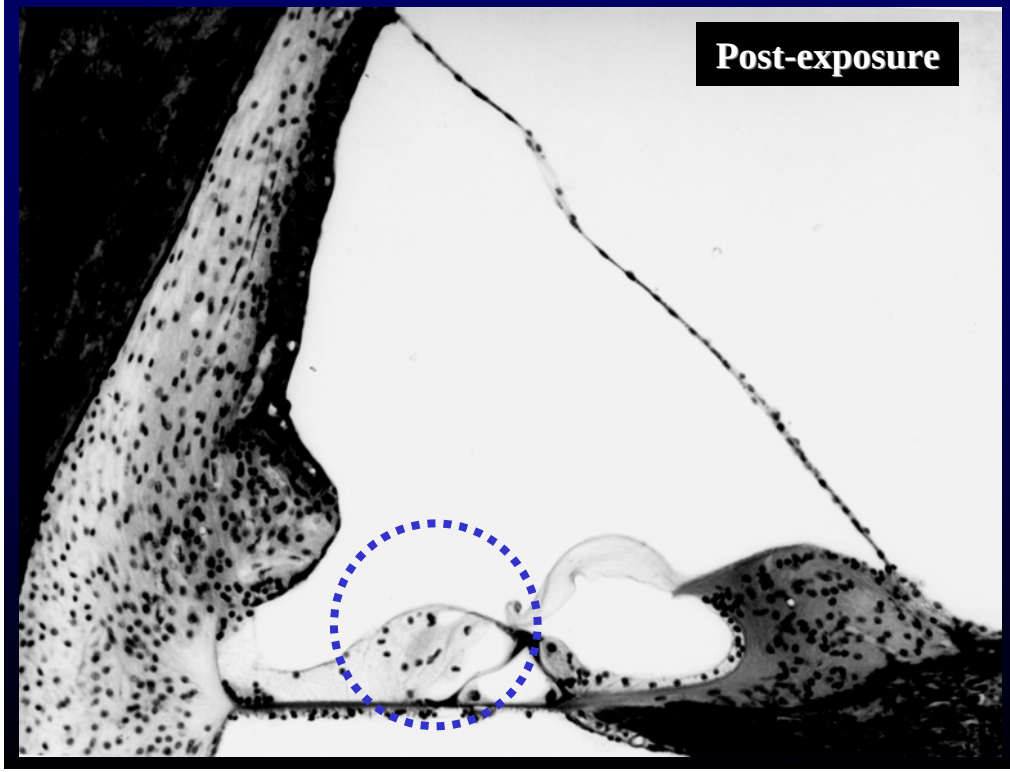
OHC damage

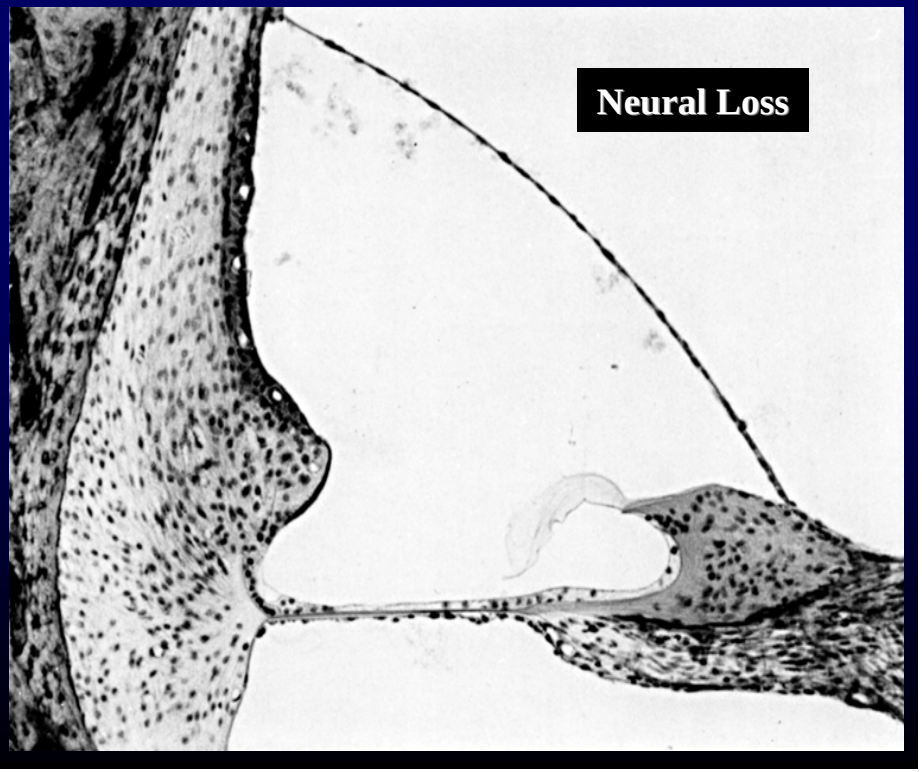
Support cell damage

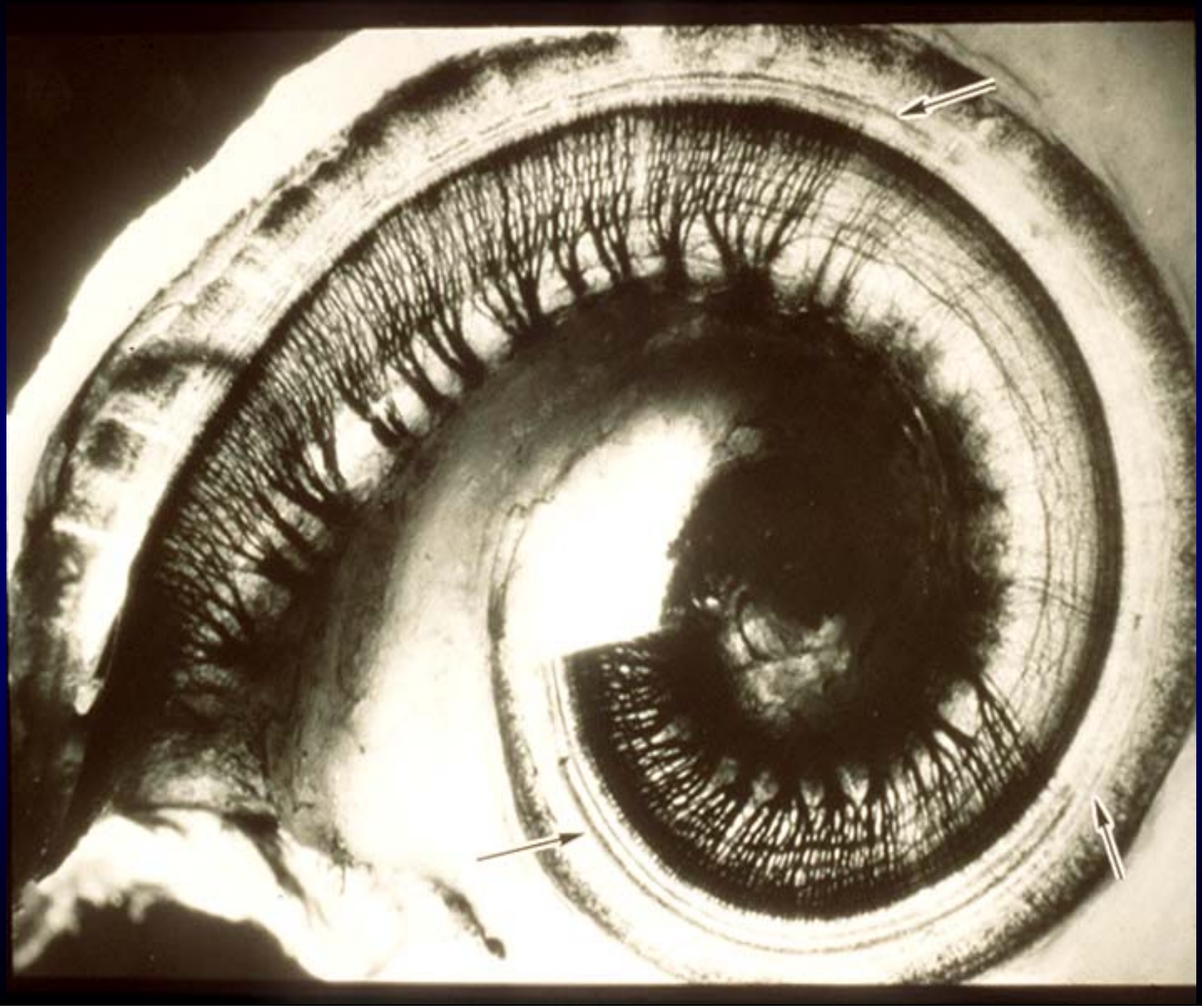
IHC/ Metabolic damage

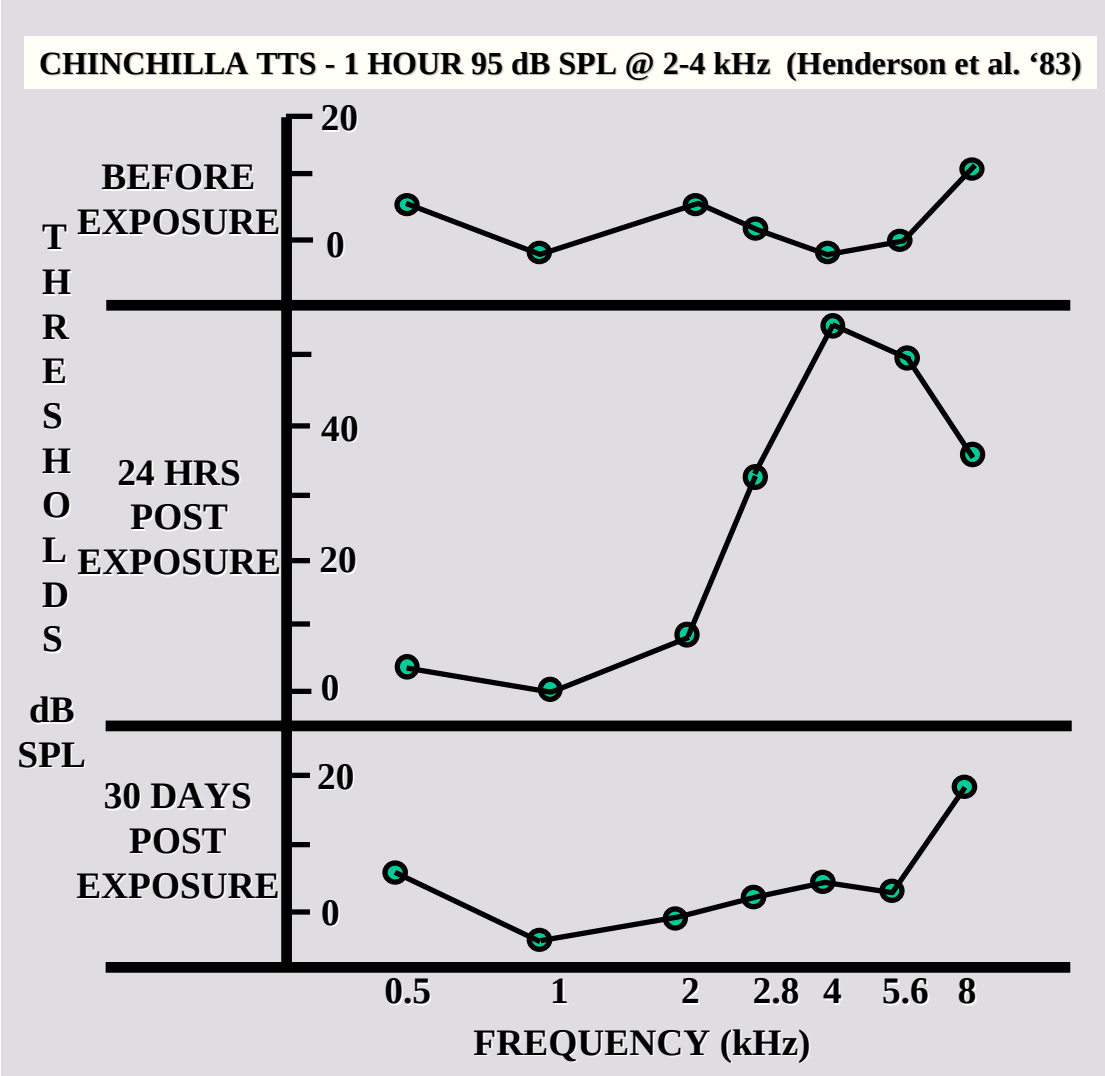
Retrograde neuronal loss

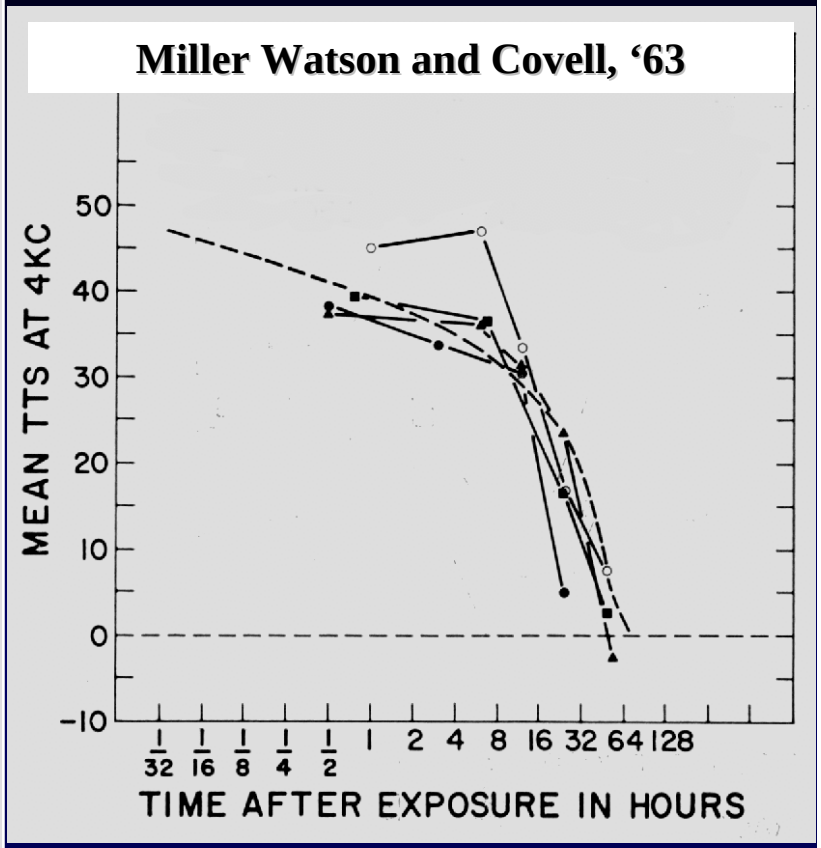
PTS









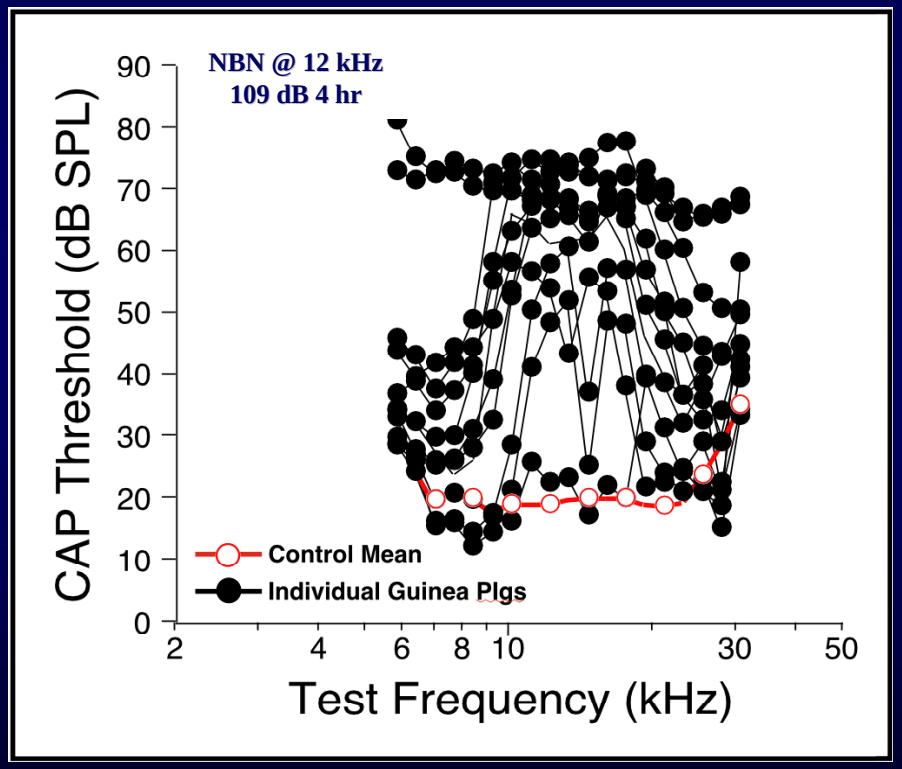


<u>Temporary Threshold Shift (TTS)</u>: temporary change in hearing sensitivity that is non-injurious and fully reversible

Border of reversibility: <50 dB TS post exposure; 2-4 days recovery

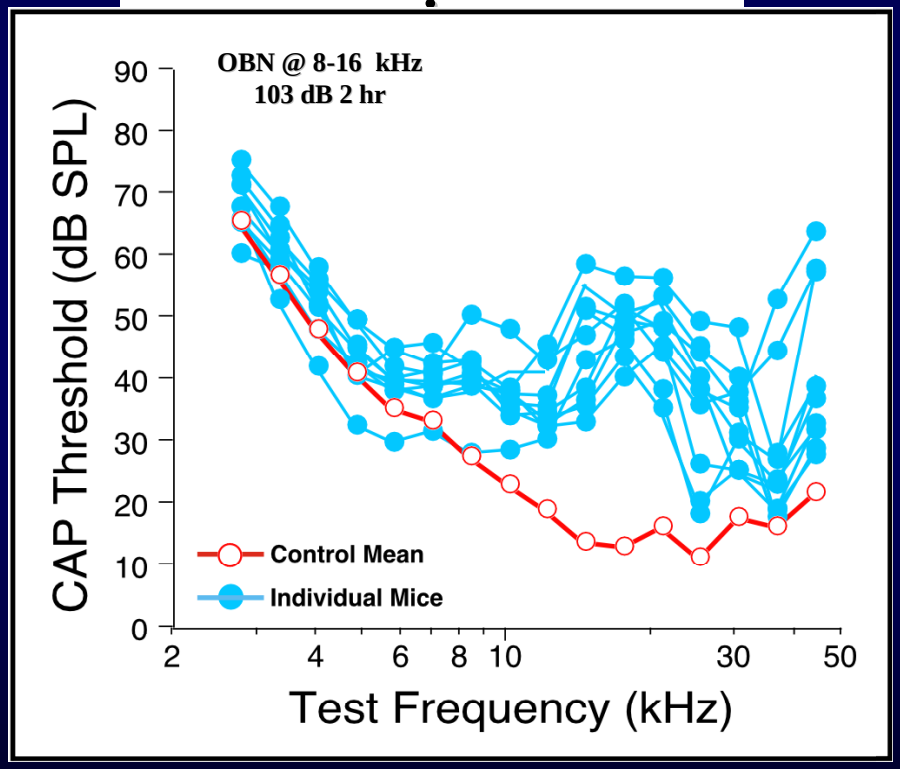
Intersubject Variability in NIHL

12 identically exposed Guinea Pigs

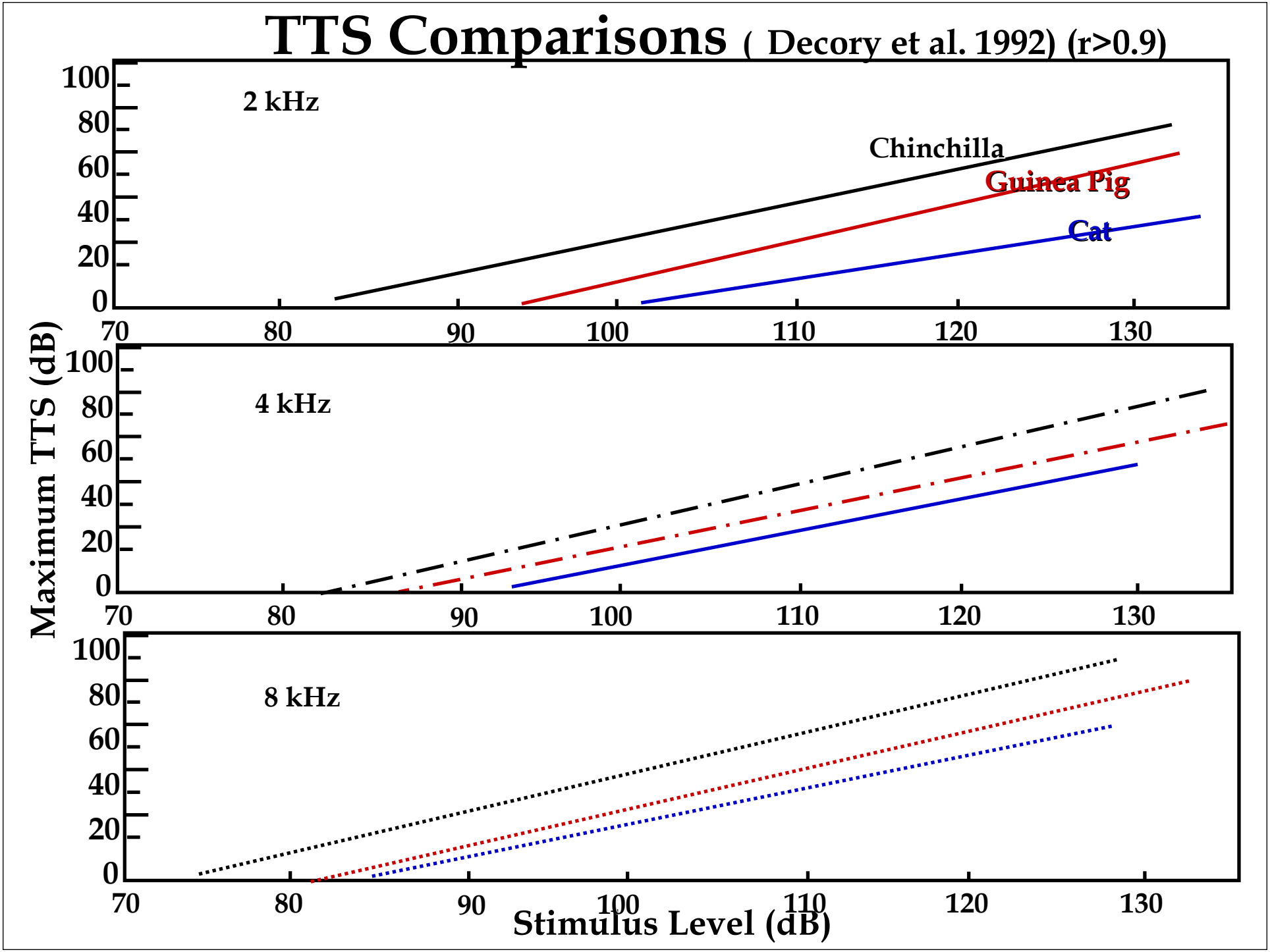


Kujawa and Liberman 1996

12 identically exposed CBA/CaJ



Yoshida and Liberman 2000


TTS Comparisons (Decory et al. 1992) (r>0.9)
2 kHz
Chinchilla
Guinea Pig
Cat
4 kHz
8 kHz
Maximum TTS (dB)
Stimulus Level (dB)
0
20
40
60
80
100
70
80
90
100
110
120
130

Acoustic Trauma

1. Damage is roughly proportional to total energy
2. Interrupted exposure less risk than continuous
3. Impulse more hazardous than non-impulsive
4. High frequency more hazardous than low
5. Narrow-band: maximum loss center frequency
6. Pure-tone: maximum 1/2 octave above
7. Broad-band: maximum loss mid frequencies

NIHL: PTS vs. TTS

1. Organ of Corti is fundamental site of injury in PTS.

2. Earliest stage PTS (>50 dB TS) is at stereociliary level; progresses to hair cell and neural loss with intensity and time.

3. No consistent structural correlates of moderate or low TTS have been found.

4. Large subject and species differences in noise susceptibility

Are cats, chinchillas, tigers, or bears - oh my - good surrogates?

Domestic Cat

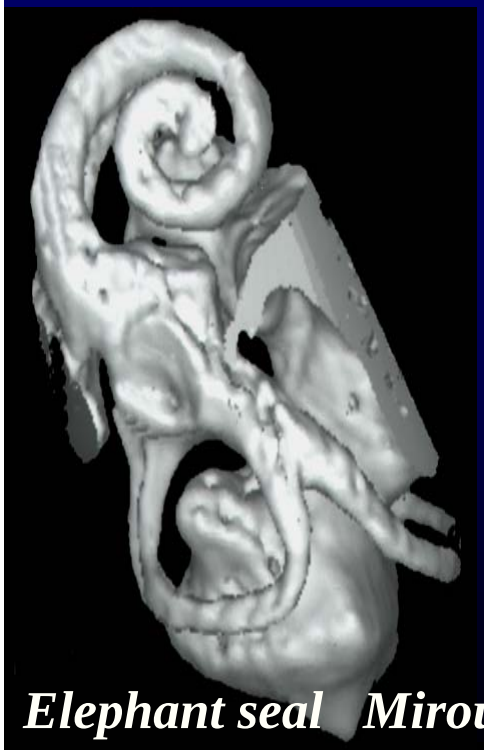
Basilar Membrane Length = 25 mm
0.2 – 60 kHz

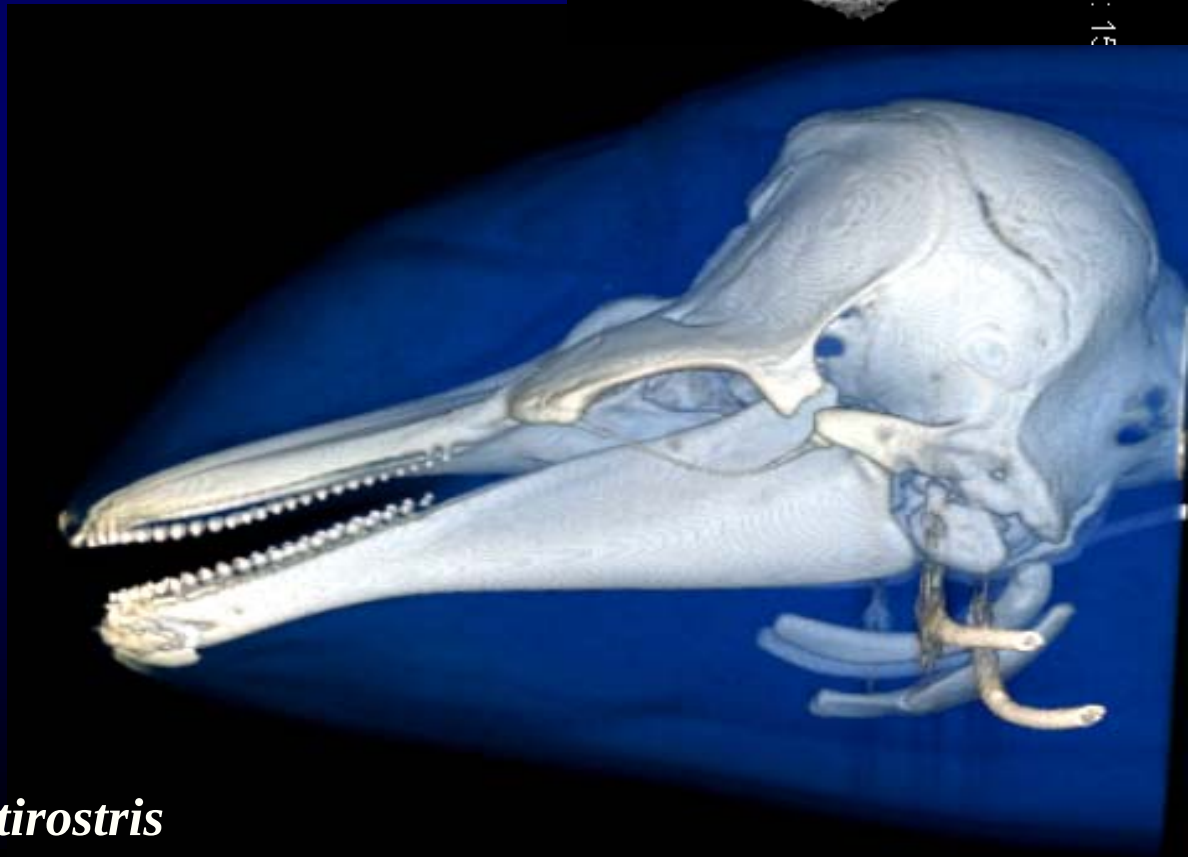
Harbour Porpoise

Basilar Membrane Length = 25 mm
0.15 to 200 kHz

Beaked whale Mesoplodon europaeus

Seal and whale auditory systems:
126 Species
Air to fully aquatic
Wide hearing range (IS to US; 6 to 12 octaves)
Wide dynamic range (100 dB)
Wide sensitivity (40 to 80 dB re 1 µPa at BF)





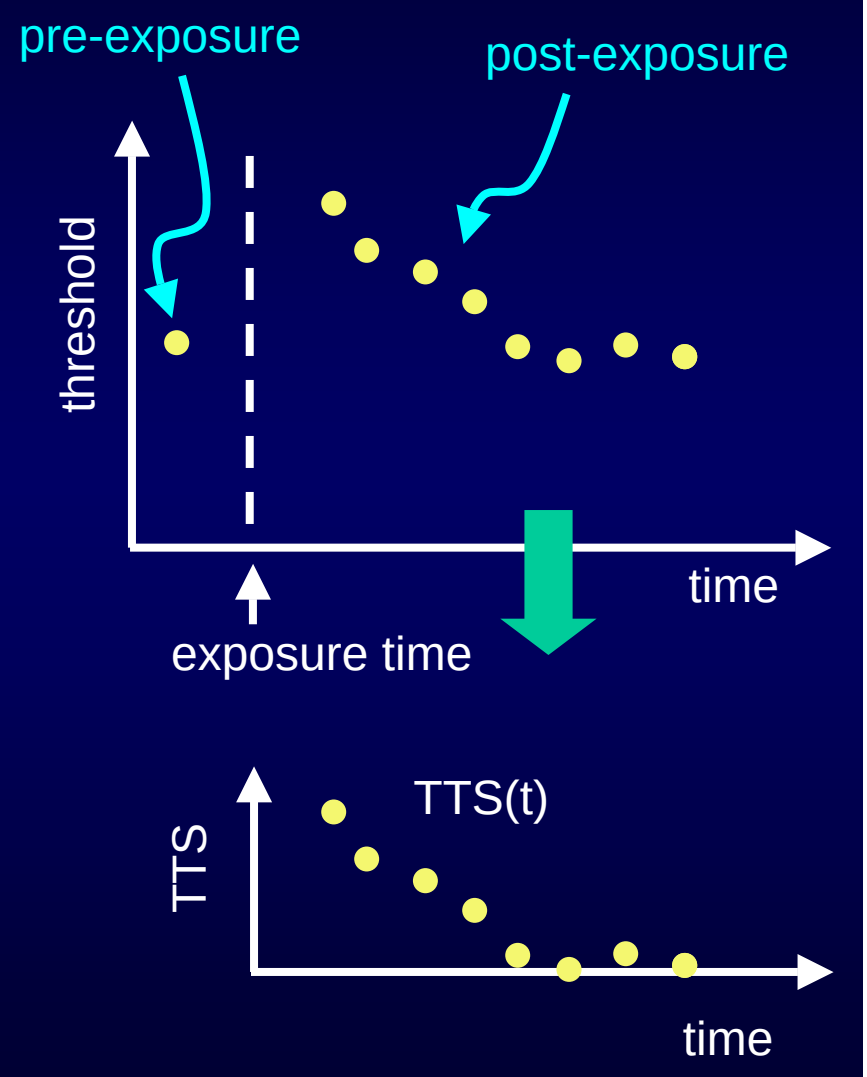
Elephant seal Mirounga angustirostris

Estimating Numerical Values for Injury Thresholds

- Most appropriate data would be PTS measurements from all species for all sound types, frequencies, levels
- Impossible to obtain these measurements
  - PTS testing in available subjects is unacceptable
  - Many species are not available
  - Impossible to test every possible sound type
- Extrapolation is necessary
  - Extrapolate from TTS measurements with similar species (groups)
  - Use terrestrial data to estimate some relationships (e.g., TTS vs. PTS onset) but not directly for impact thresholds

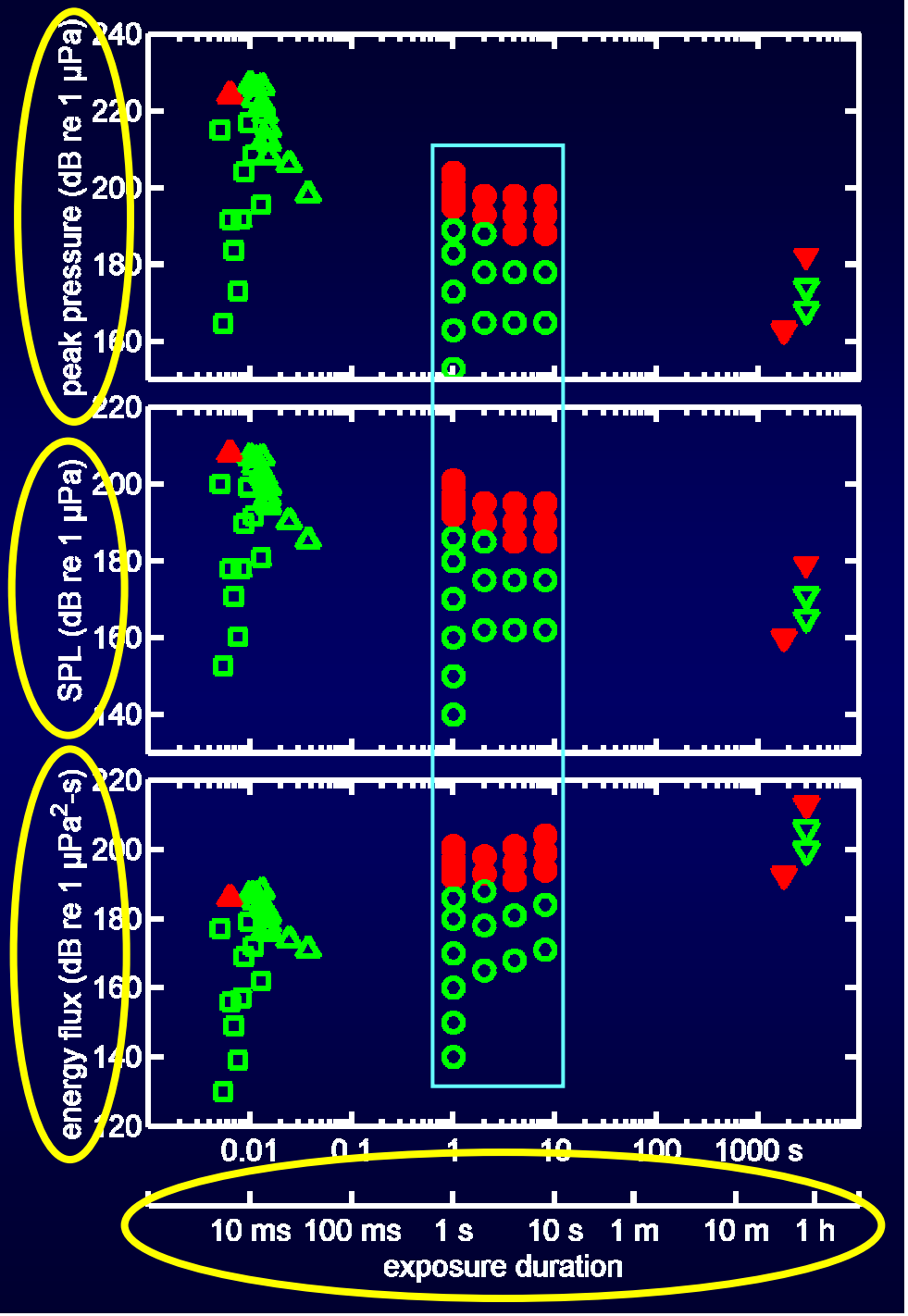
Measuring TTS in Marine Mammals

- Compare hearing thresholds before and after exposure
  - Difference (in dB) is the amount of TTS
  - Need to specify when the TTS was measured
- Hearing thresholds are measured using
  - Behavioral response paradigm
    - Trained to perform a specific action when they hear a sound
  - Electrophysiological method (AEP)
    - Measure small voltages generated by the brain in response to sounds
  - Record response at various sound levels to estimate threshold



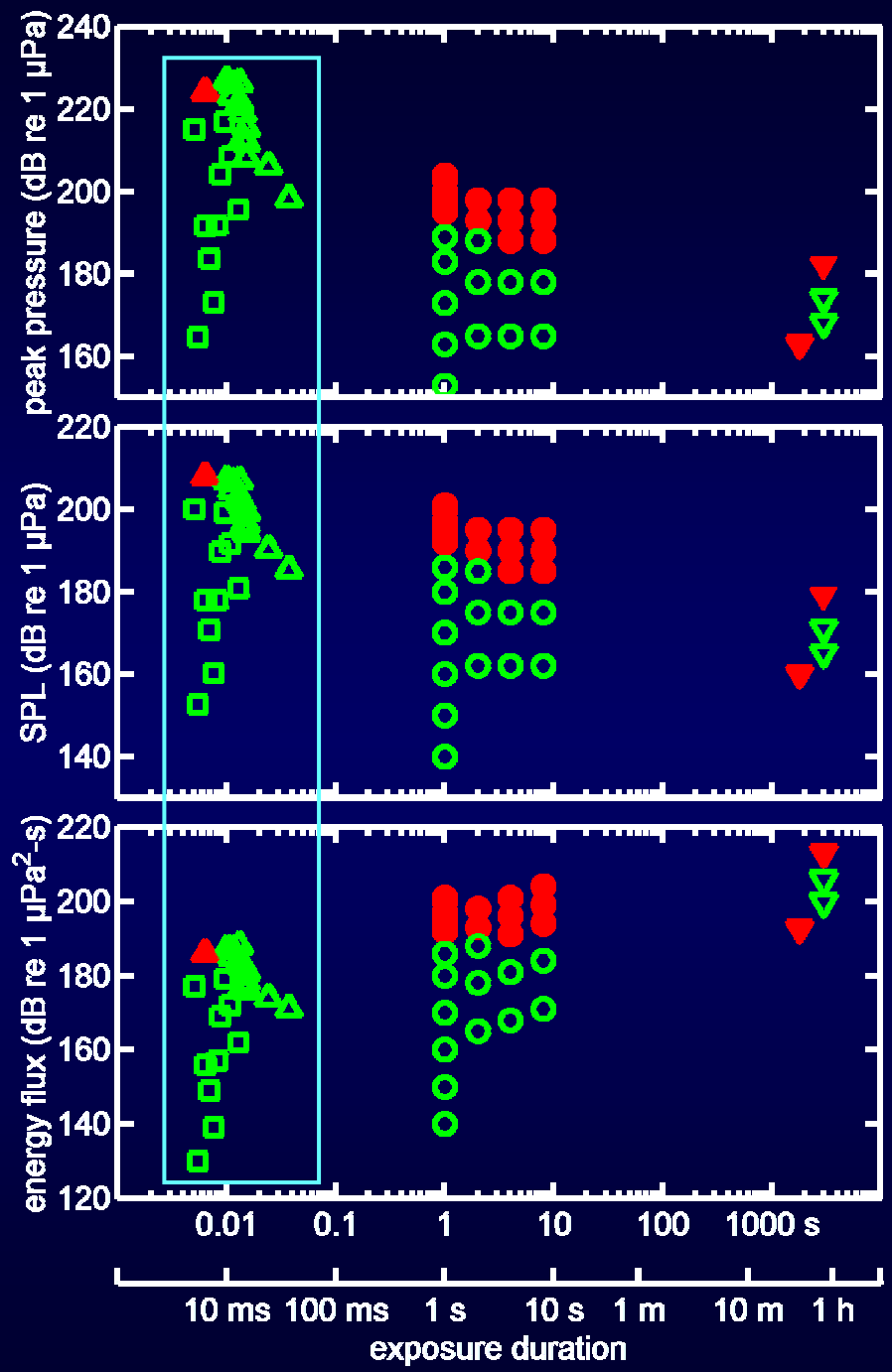
TTS Data:
Mid-Freq. Cetaceans

- Tones ("Non-pulses")
- 1-s tones at 3, 10, 20 kHz
  - 5 dolphins
    2 white whales
  - Schlundt et al. (2000)
- 1, 2, 4, 8-s tones at 3 kHz
  - 1 dolphin
  - Finneran et al. (2001, 2003)



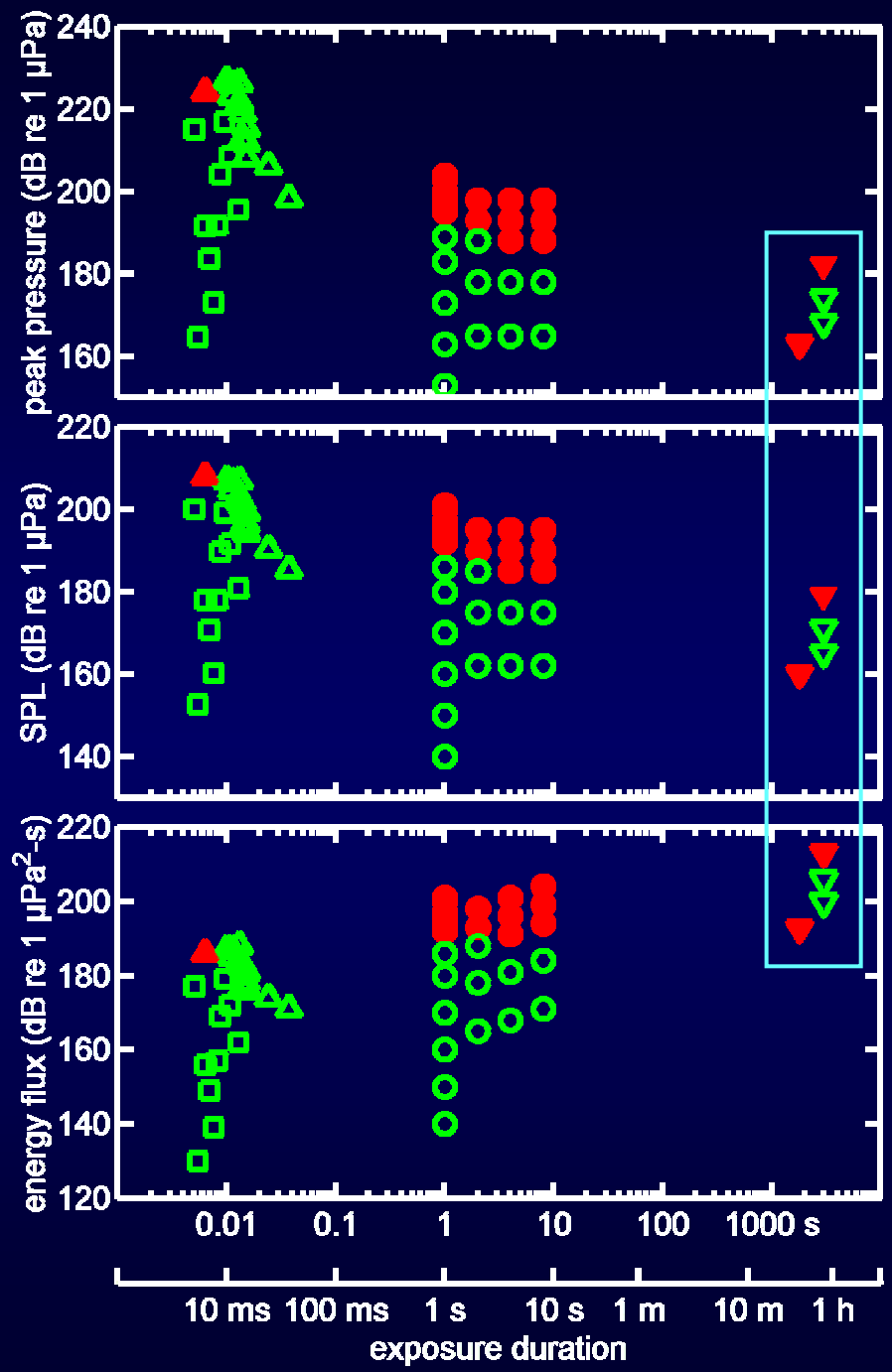
TTS Data:
Mid-Freq. Cetaceans

- "Pulse" Sounds
- "Explosion simulator"
  - 2 dolphins
    1 white whale
  - Finneran et al. (2000)
- Seismic watergun
  - 1 dolphin
    1 white whale
  - Finneran et al. (2002)



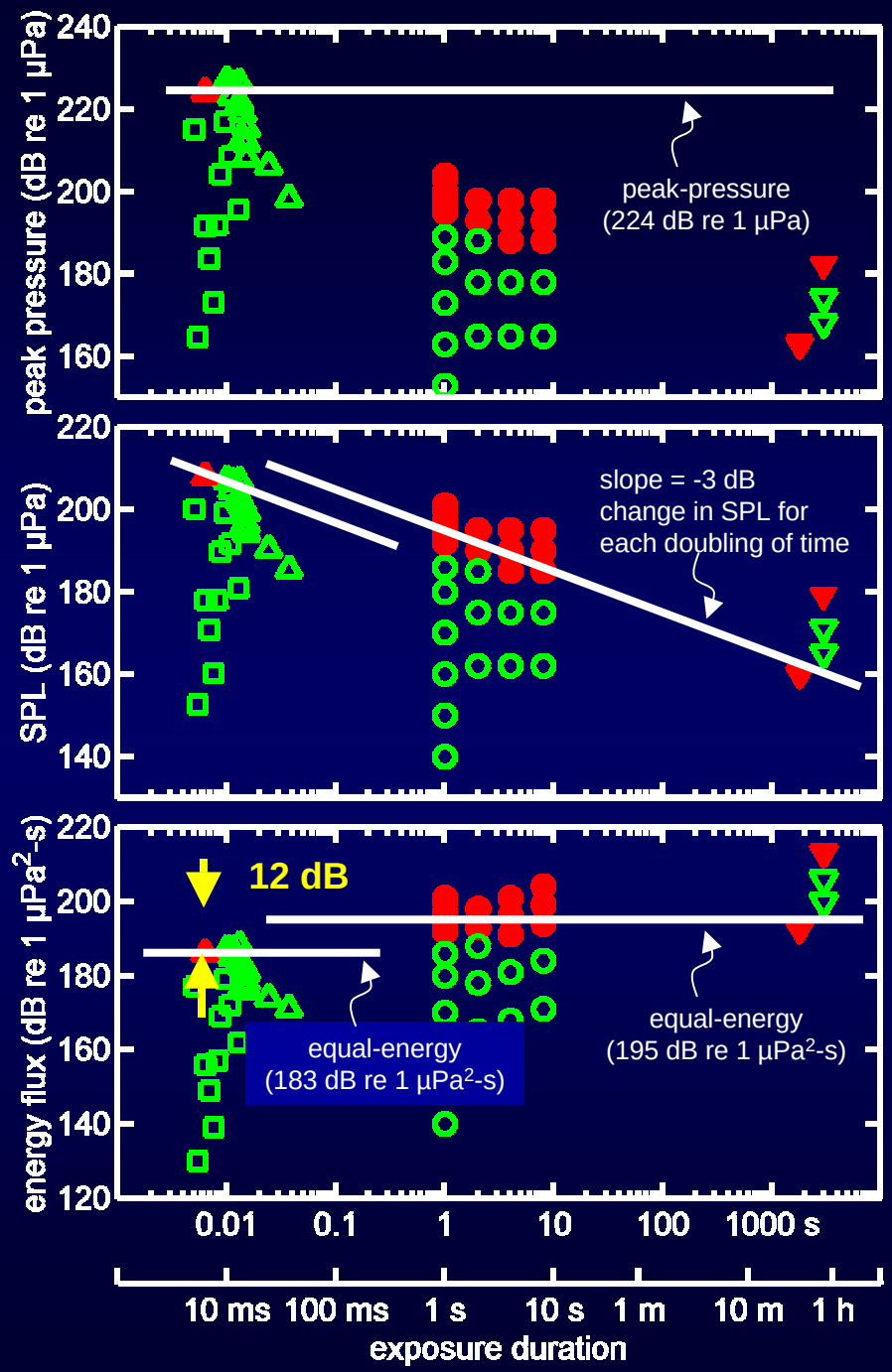
TTS Data:
Mid-Freq. Cetaceans

- Octave-band noise
- 30-50 minutes of noise
  - 7.5 kHz center, octave-band
  - 1 dolphin
  - Nachtigall et al. (2003)



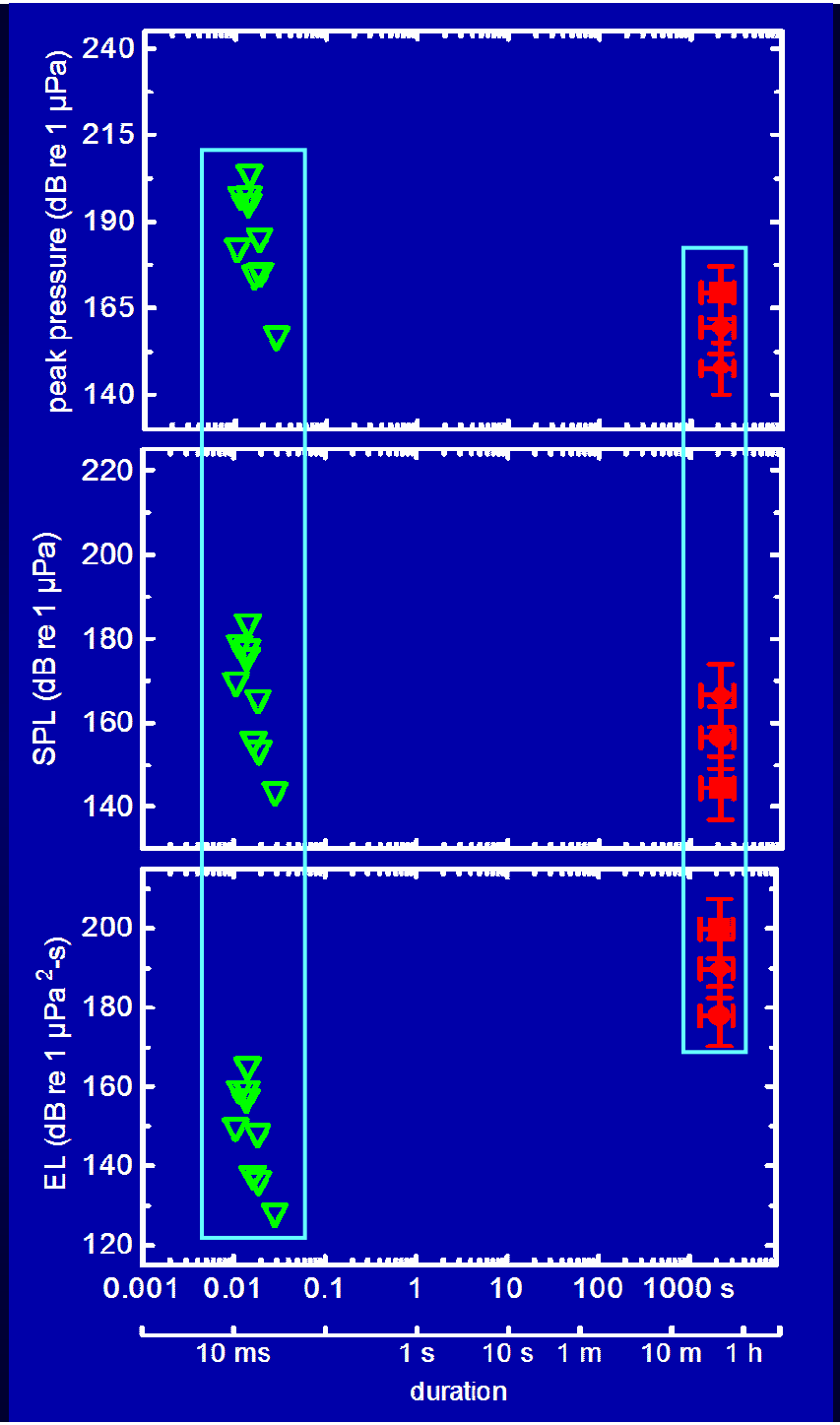
TTS Criteria:
Mid-Freq. Cetaceans

- SEL-based (Energy-based)
  - Slope of -3 dB SPL per doubling of time fits existing data
    - "equal-energy" line
  - "Non-pulses"
    - 195 dB re 1 μPa^2-s (w)
  - "Pulses"
    - 183 dB re 1 μPa^2-s (w)
- Peak pressure-based
  - 224 dB re 1 μPa
  - "ceiling" limit for sound pressure
- TTS assumed if either number is exceeded



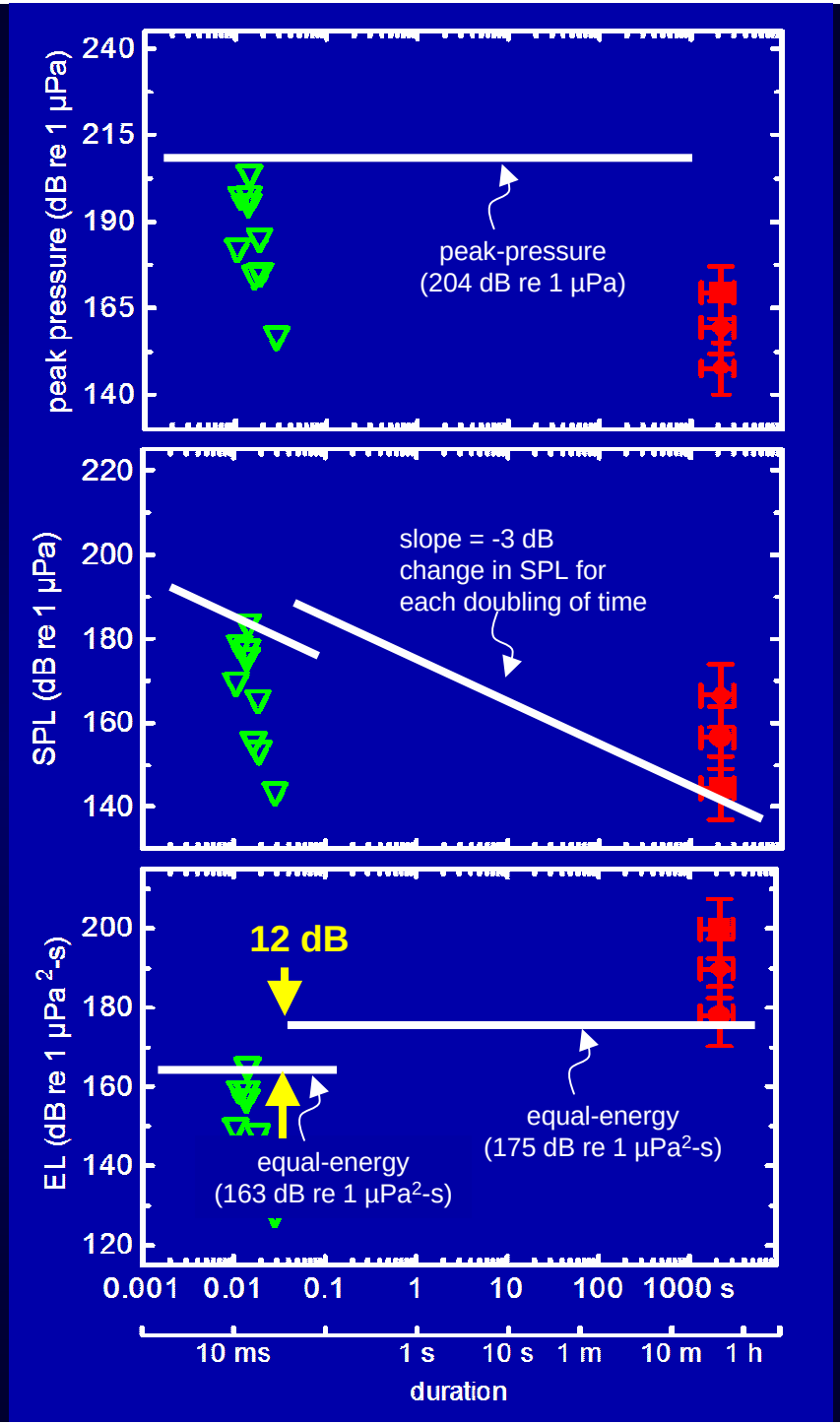
TTS Data:
Pinnipeds (underwater)

- 22-50 minutes of octave-band noise
  - 1 C. sea lion
  - 1 N. Elephant seal
  - 1 Harbor seal
  - Kastak *et al*. (1999)
- "Pulse" sounds (arc-gap transducer)
  - 2 C. sea lions
  - Finneran *et al*. (2003)



TTS Criteria:
Pinnipeds (underwater)

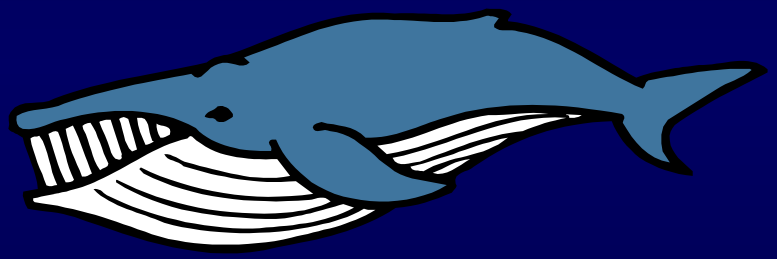
- SEL-based (Energy-based)
  - "Non-pulses"
    - 175 dB re 1 μPa^2-s (w)
    - Precautionary – based on most susceptible of species tested (Harbor seal)
  - "Pulses"
    - 163 dB re 1 μPa^2-s (w)
    - Extrapolated from pinniped "non-pulse" data and MF cetacean "pulse"/"non-pulse" relationship
- Peak pressure-based
  - 204 dB re 1 μPa$_{peak}$
  - Extrapolated using relationship between MF cetacean ceiling peak pressure and relationship between pinniped/MF cetacean SEL criteria



Estimating PTS from TTS

- Since PTS is used for injury impact criteria, need to estimate onset-PTS from TTS data

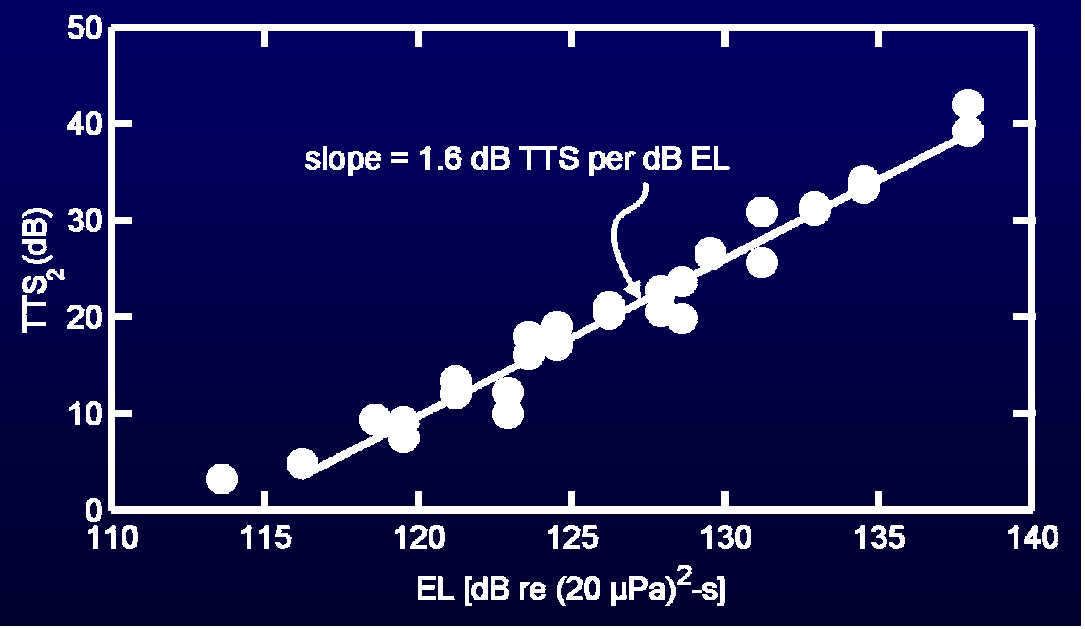
- This is done using
  - Marine Mammal TTS data
  - Terrestrial mammal data relating TTS and PTS
    - How much TTS before PTS?
    - How does TTS increase with increases in exposure level?



Estimating PTS: “Non-pulses”

- Terrestrial mammal data show
  - > 40 dB of TTS before PTS
  - Growth of TTS with exposure is about 1.6 dB TTS per dB SEL (energy flux density level) Ward et al. (1958, 1959)

- Estimate PTS (SEL) threshold at 20 dB above TTS threshold



Estimating PTS: “Pulses”

- Relationship between TTS and PTS is not as clear for “pulse” sounds
  - Terrestrial mammal data support > 40 dB TTS before PTS
  - However, growth of TTS with increased SEL (energy) is uncertain; slope may be steeper
- SEL (Energy-based) criteria
  - Not yet established
- Peak pressure limit
  - Set 6 dB above TTS onset value for impulse as a precautionary approach
  - Applies to both “pulses” and “non-pulses” to protect against pulse-like components of non-pulse exposures

Injury (PTS) Criteria: Example 1

- Mid-Freq. Cetaceans – Single “non-pulse”
  - SEL (Energy-based)
    - 215 dB re 1 μPa^2-s SEL

      = 195 dB dB re 1 μPa^2-s (measured TTS-onset)

      + 20 dB (estimated PTS-onset from TTS-onset)
  - Peak pressure limit
    - 230 dB re 1 μPa peak pressure

      = 224 dB re 1 μPa (measured TTS-onset)

      + 6 dB (allowable increase in peak pressure from TTS-onset)

Injury (PTS) Criteria: Example 2

- Mid-Freq. Cetaceans – Multiple "non-pulse"
  - SEL (Energy-based)
    - 215 dB re 1 μPa^2-s EFD level

      = 195 dB re 1 μPa^2-s (measured TTS-onset)

      + 20 dB (estimated PTS-onset from TTS-onset)
    - Duty cycle affects way that energy is accumulated
      - Duty cycle > 20%
        - » Assume no recovery during quiet periods
        - » EL = $10\log_{10}$(sum of E)
      - Duty cycle < 20%
        - » Assume some recovery during quiet periods
        - » EL = $10\log_{10}$[(sum of E^2)]
  - Peak pressure limit
    - 230 dB re 1 μPa peak pressure

      = 224 dB re 1 μPa (measured TTS-onset)

      + 6 dB (allowable increase in peak pressure from TTS-onset)

Injury (PTS) Criteria: Example 3

- Mid-Freq. Cetaceans – Single “pulse”
  - SEL (Energy-based)
    - Not established yet

      = 183 dB re 1 μPa^2-s (measured TTS-onset)

      + ? dB (estimated PTS-onset from TTS-onset)
  - Peak pressure limit
    - 230 dB re 1 μPa peak pressure

      = 224 dB re 1 μPa (measured TTS-onset)

      + 6 dB (allowable increase in peak pressure from TTS-onset)

Injury (PTS) Criteria: Example 4

- Pinnipeds under water – Single "pulse"
  - SEL (Energy-based)
    - Not established yet

      = 175 dB re 1 μPa^2-s (measured TTS-onset)

      - 12 dB (estimated TTS-onset for impulse)

      + ? dB (estimated PTS-onset from TTS-onset)
  - Peak pressure limit
    - 210 dB re 1 μPa peak pressure

      = 204 dB re 1 μPa (estimated TTS onset)

      + 6 dB (allowable increase in peak pressure from TTS-onset)

“Injury (PTS) Criteria”

Committee Questions for Panel

Noise Exposure Criteria:
“Behavioral Criteria”

W. John Richardson

LGL Ltd. environmental research associates

Peter Tyack

Woods Hole Oceanographic Institution

Biological Significance in Context of Human Noise Exposure

- NRC panel is explicitly considering this issue
- In the interim, the Noise Exposure Criteria Group interprets **behavioral disturbance** as "behavioral changes that may have a biologically significant effect, i.e., effects on reproduction and/or survival at the individual or population level."
- Brief and infrequent responses, startle or otherwise, that are unlikely to affect growth, reproduction or survival of individuals (and thus of the population) are not considered significant.

Behavioral Disturbance Criteria: 24-hour Rule

We recommend a "24 hour/one time only" exclusion in considering whether behavioral disturbance is significant.

If a behavioral disruption resulting from noise exposure lasts <24 hours and, for a given individual, occurs only once in an extended period, the disturbance would not be considered biologically significant unless there is specific contrary evidence.

Variability in behavioral responses

- Individuals change in responsiveness over time depending on season, context, previous exposure (e.g., habituation or sensitization), etc.
- Individuals differ by age and sex classes, inherent variability in responsiveness, etc.
- Species within the same functional hearing group of marine mammals may differ in response.
- Responses may vary to different sounds from the same category of sound types.

Alternate approaches to dealing with behavioral variability

- Single criterion approach
- Dose-response function

Establishing disturbance criteria: Single criterion alternative

- Proposed "single number" criteria, are precautionary.
- Recommended criteria < 50% probability of response, but generally are not the minimum sound levels at which disruption might occasionally occur
- The single criterion approach is applied in the case of single “pulse” exposures
- No final decision on whether a single criterion will apply for any other types of exposures

Alternative views of Criterion Level:

- 50% of exposed animals expected to respond?
- de minimus pressure level or SEL above which there may be a take depending upon context?
- For species and situations where specific behavioral data exist and indicate response levels other than “typical” levels, that information should be used lieu of the general guidelines.

Behavioral Disturbance Criteria: Single Pulse Exposures

- Exposure to single pulses rarely causes a biologically significant behavioral response (except for pinnipeds exposed to aerial “pulses” during the breeding season)
- To be precautionary, the sound level causing TTS onset (in either peak pressure or energy flux density) is taken as the level above which significant behavioral disturbance might occur.

Behavioral Disturbance Criteria: Single Pulse Exposures

- Low, mid, and high frequency cetaceans (measured or estimated TTS onset)
  - Pressure: 224 dB re: $1\mu Pa_{peak}$
  - Sound exposure level: 183 dB re 1 μPa^2-s
- Pinnipeds in water (estimated TTS onset)
  - Pressure: 204 dB re: $1\mu Pa_{peak}$
  - Sound exposure level: 163 dB re 1 μPa^2-s
- Pinnipeds in air (based on field observations; sub-TTS levels during breeding season)
  - Pressure: 109 dB re: $20\mu Pa_{peak}$
  - Sound exposure level: 100 dB re: $(20\mu Pa)^2$-s

Establishing disturbance criteria: Dose response function

- For most noise exposures, there is no single pressure or sound exposure level above which significant behavioral disruption always occurs and below which it never occurs.
- Rather, the proportion of mammals showing significant responses depends on many factors, but tends to be higher with higher sound exposure.
- This argues for a dose response type of approach to account for the quantitative relationship between sound exposure and the probability of significant disturbance

Establishing disturbance criteria: Advantages of dose response function

- More representative of graduated way animals react to noise exposure than single criterion approach.
- Precedent for this type of risk approach for human reactions such as “annoyance”.

Establishing disturbance criteria: Limitations to dose response function

- There are few combinations of sound type and marine mammal type for which there is quantitative information concerning probability of behavioral disruption relative to sound exposure.
- Establishing a realistic "slope“, for this relationship has a large effect on the numbers predicted to respond significantly.

Importance of Exposure Duration

- Duration of exposure (as well as sound level) is relevant in assessing probability of a significant behavioral response.
- Significant disturbance will be more likely when marine mammals are exposed to a given sound level for a longer time, or for a higher proportion of the time.
- The panel has not reached a conclusion regarding how best to quantify the interrelated factors of sound duration and sound level for purposes of predicting behavioral response.

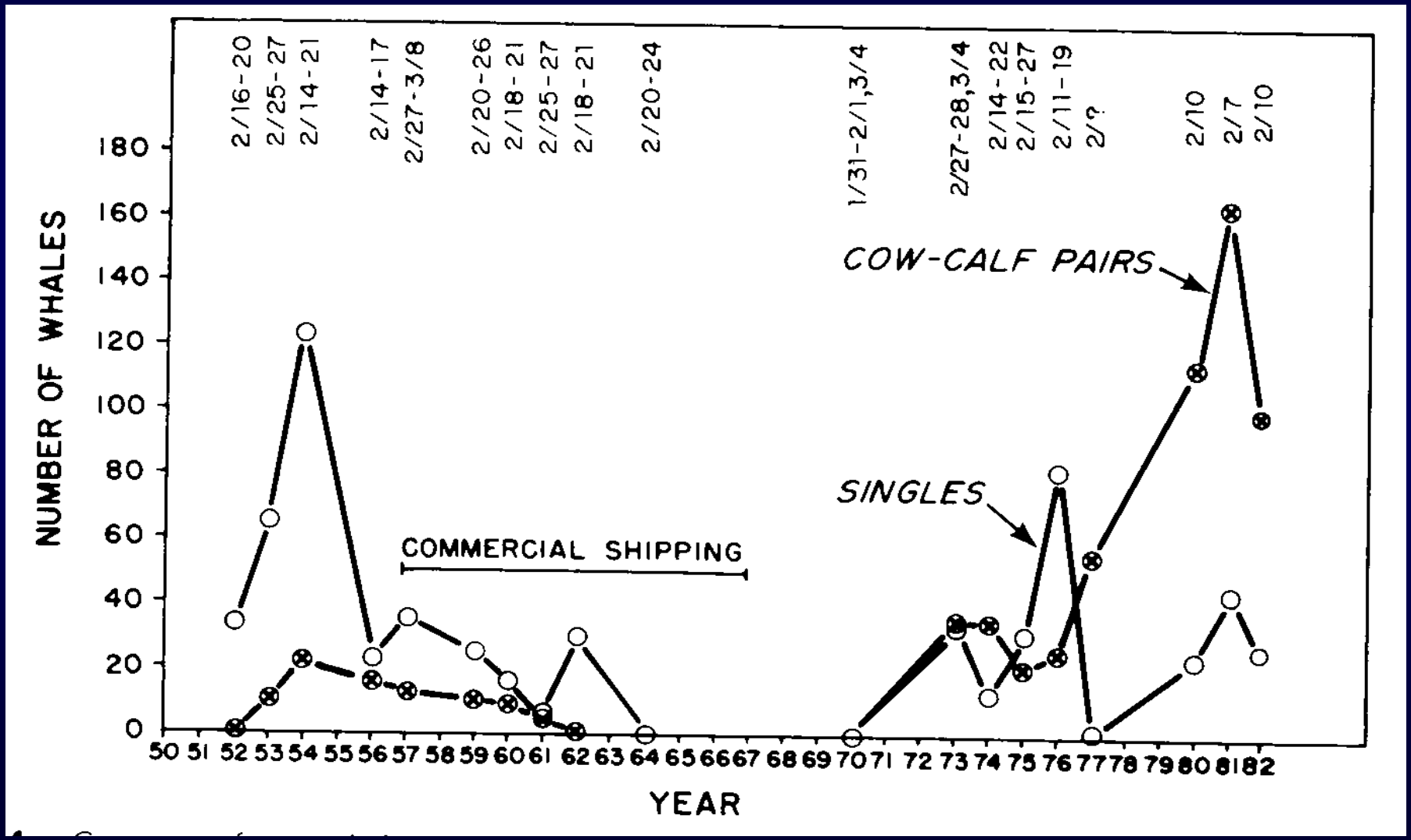
Behavioral Responses of Biologically Significant activities that can be related to adverse impact

- Basic issues are demographic – effects on growth, survival, and reproduction
- Growth: Feeding and energetics
- Survival: strandings (may involve behavioral reaction, but impact is injury or worse)
- Reproduction: mating behavior
- Avoidance and habitat quality

Examples of Avoidance Behavior

- Significance must be evaluated on case-by-case basis
  - How critical is affected habitat?
  - How much of critical habitat is affected?
- Avoidance includes a good example where risk function has been calculated
- Data on habituation of avoidance behavior

Gray whales abandon breeding lagoon during shipping/dredging



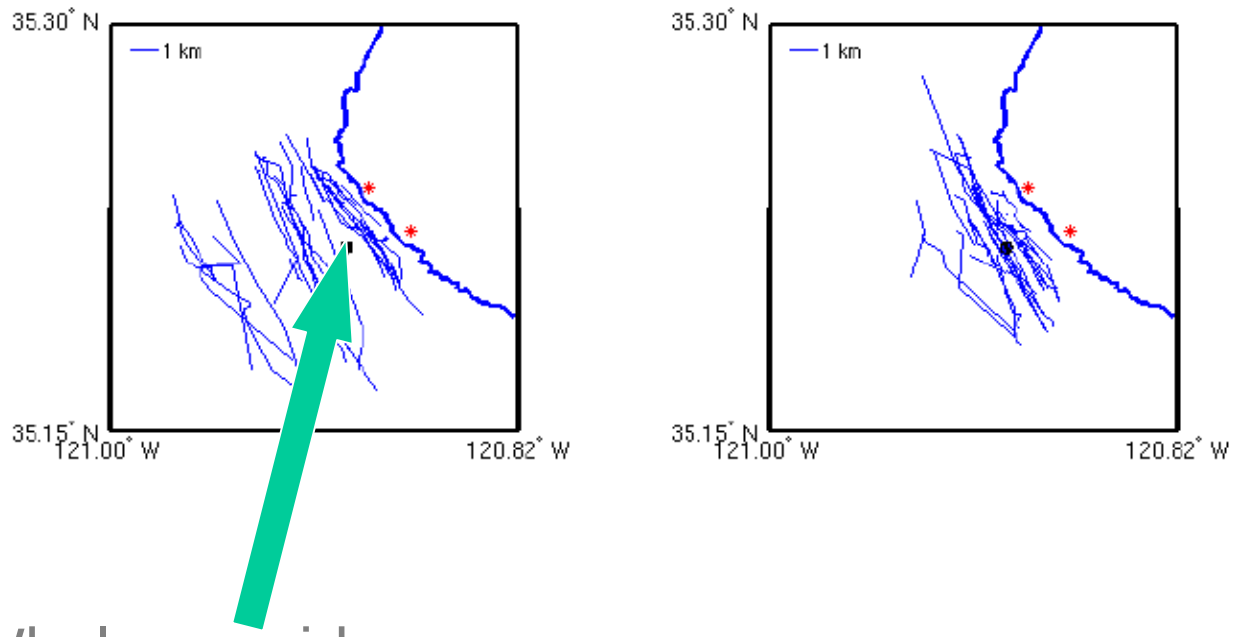
We can all agree we want to avoid abandonment of critical habitat

- But long term ("epidemiological") studies seldom measure dosage and have weak predictive power
- We do not want to design experimental studies that may have adverse impact
- Design shorter term studies to study relationships between acoustic exposure and behavioral response and results must be extrapolated to novel conditions based upon temporal and spatial aspects.

Measuring Avoidance Responses of Migrating Gray Whales

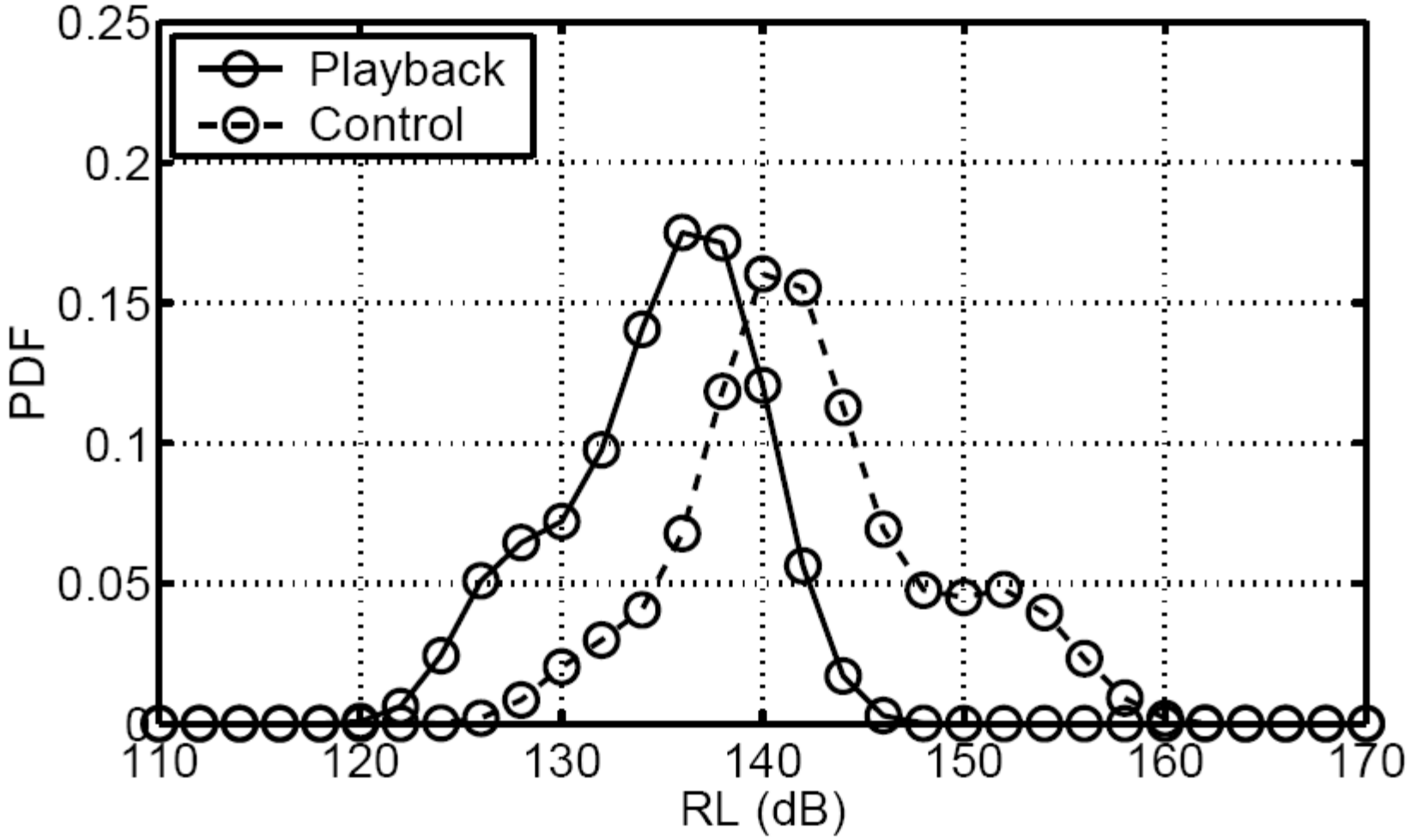
LFA Inshore

Source Level = 185 dB re 1 µPa @ 1m



Whales avoid area near source

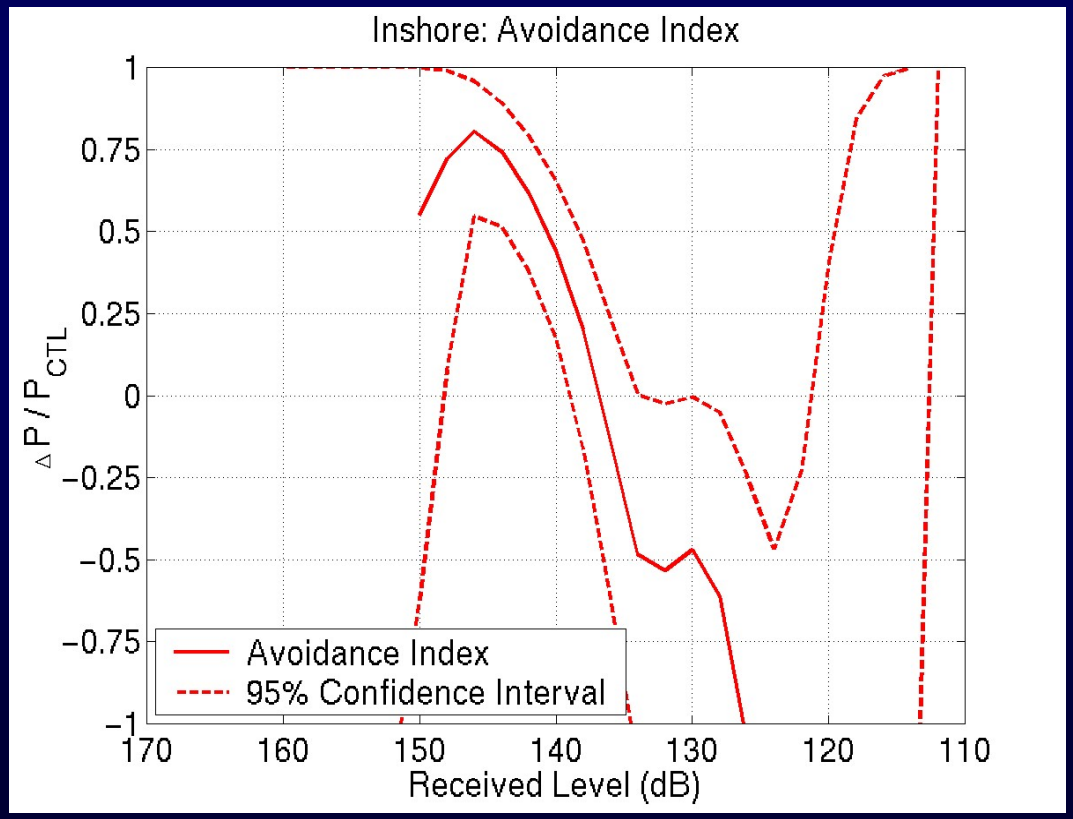
Gray Whales Shift Distribution to Avoid RLs > 140 dB



Context Dependence of Behavior:

50% avoidance at 138 dB for inshore source.

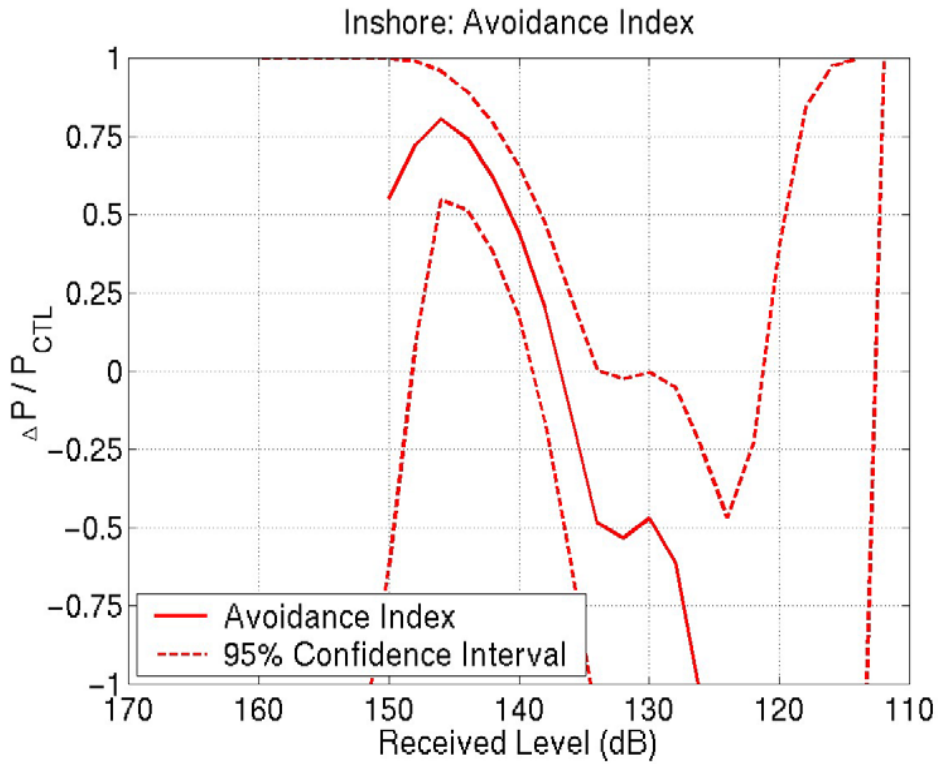
Inshore

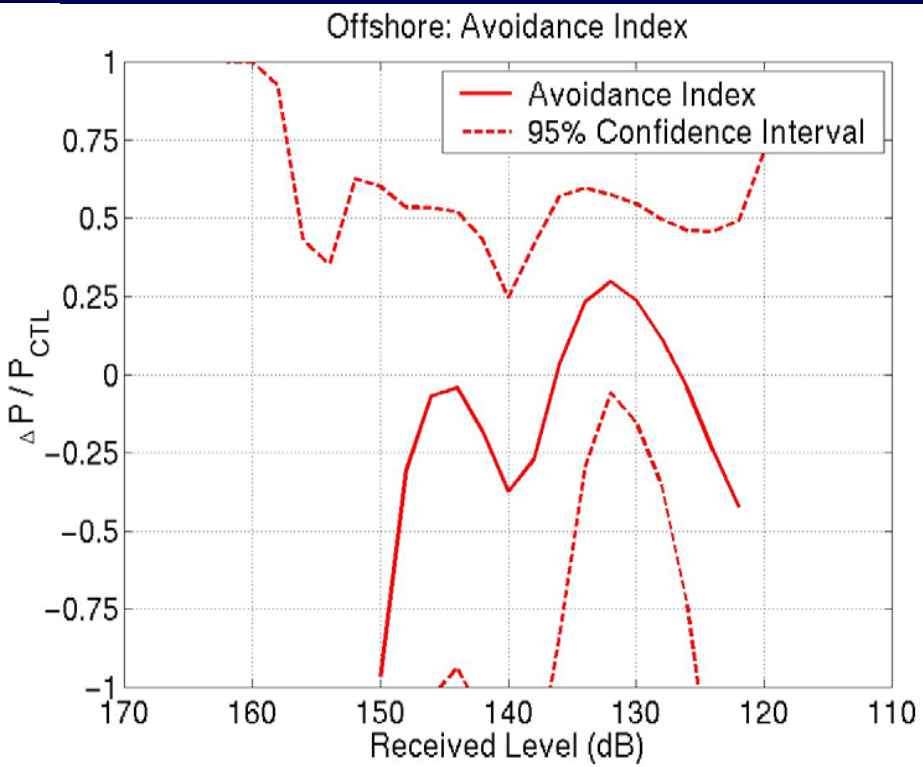


Context Dependence of Behavior:

50% avoidance at 138 dB for inshore source.
Avoidance never reaches 50% for offshore source

Inshore **Offshore**

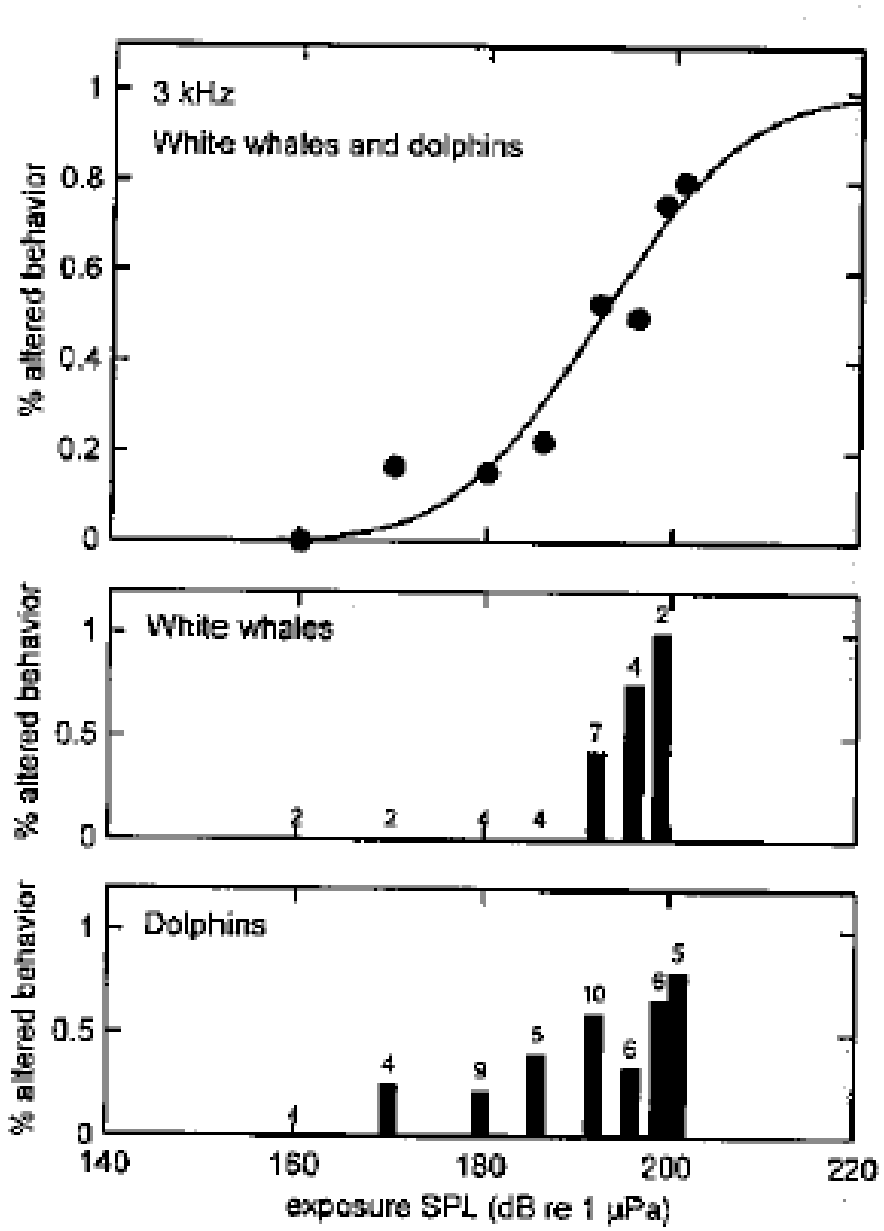




Pool results from different studies to create a dose response function for each cell in matrix?

Include all contexts?

Use data from captive animals?



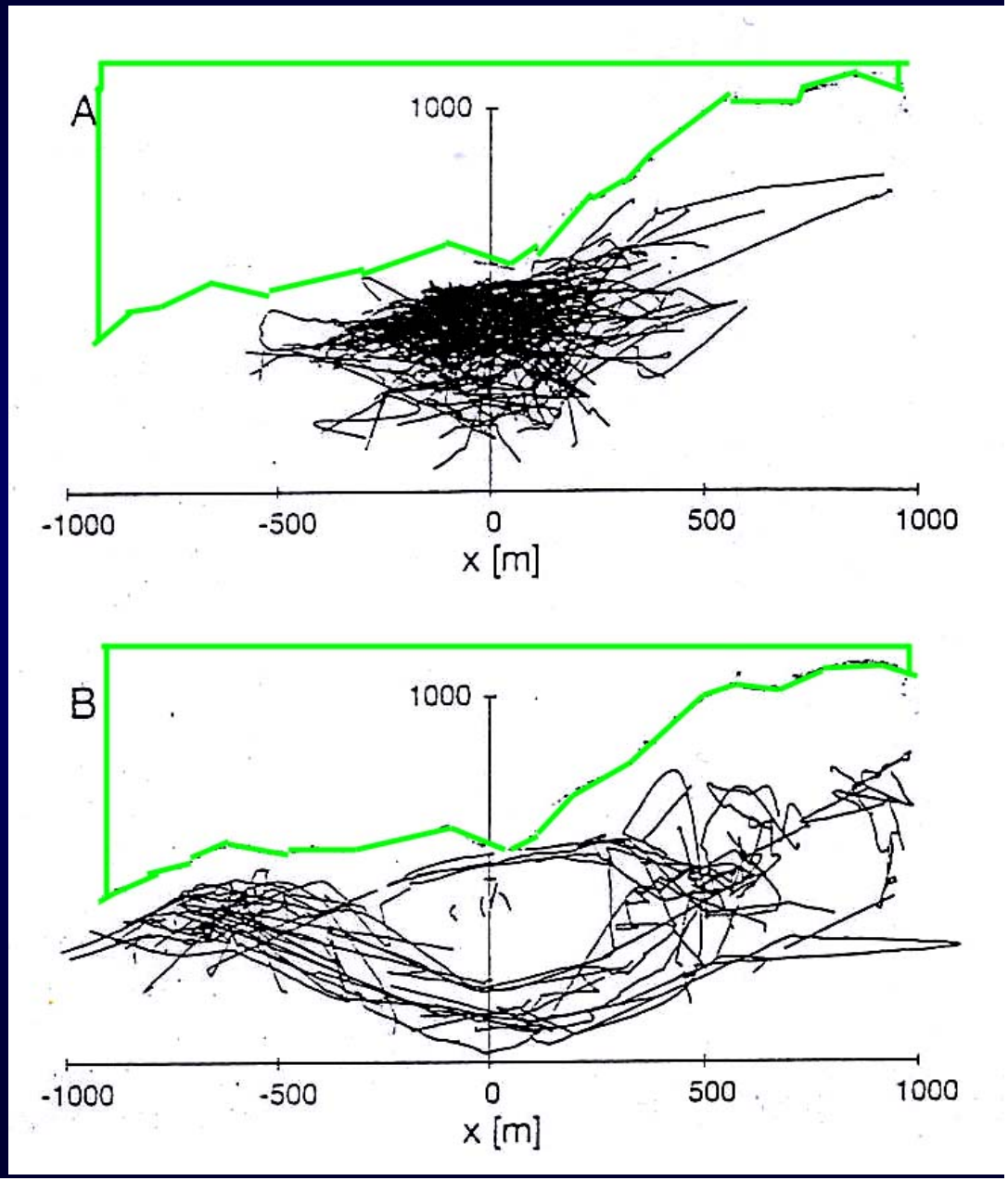
Finneran and Schlundt 2004

Responses of *Phocoena* to 145 dB pinger

Control

50% avoidance of RL=100 dB assuming 15 log r Spreading Loss

Transmit



Culik et al 2001 Mar Ecol Prog Ser 211:255-260

Example of 24 hour rule for *Phocoena* and pingers
(where habituation has been studied)

- Effect reduced by 50% after 3 days of transmission.
- If user plans to keep source where individual *Phocoena* may be exposed for > 1day, evaluate impact of exclusion from zone of avoidance (10% avoidance?).

Few Experiments have studied habituation over times > 1 day

- Longer term correlational studies can be used to test for habituation
- If effect lasts for long time, safe to discount habituation

Current view of Noise Exposure Group on Behavioral Criteria
(other than single “pulse”)

- We have made progress in discussing the principles that should be used in establishing criteria for behavioral harassment.
- However, data are limited and highly variable, and data that are available are not always presented in ways that are directly comparable.
- Even after existing data are fully taken into account, additional studies will be needed to characterize the criteria for some combinations of sound type and mammal type.

“Behavioral Criteria”

Committee Questions for Panel

Noise Exposure Criteria:
“Concluding Remarks”

Roger Gentry

NOAA Fisheries Acoustics Program

General Discussion and Committee Questions

Reserve Slides

NRC Definition of the Precautionary Principle

"If the burden of proof were to show that an action would not harm a species rather than that it would harm a species, increased protection would result. The importance of shifting the burden of proof this way …is known as the "precautionary principle"

National Research Council. 2001. Science and the Endangered Species Act (p 169).

NOAA Fisheries Acoustic Exposure Guidelines: Extrapolation Procedures

PTS Rule: Permanent threshold shift (PTS) onset estimated using PTS data from other mammals in combination with marine mammal temporary threshold shift (TTS) data.

Dolphin Injury Rule: Injury criteria (PTS onset) for all cetaceans are based on data from mid frequency animals (dolphins and beluga).

NOAA Fisheries Acoustic Exposure Guidelines: Extrapolation Procedures

Impulse Rule: Data from TTS experiments with non-pulsed sounds are used to estimate TTS onset for pulses where no data exist.

Multiple Exposure Rules*: To determine the cumulative effect of multiple exposures, summing procedures depend on the interval between pulses or the duty cycle of non-pulses

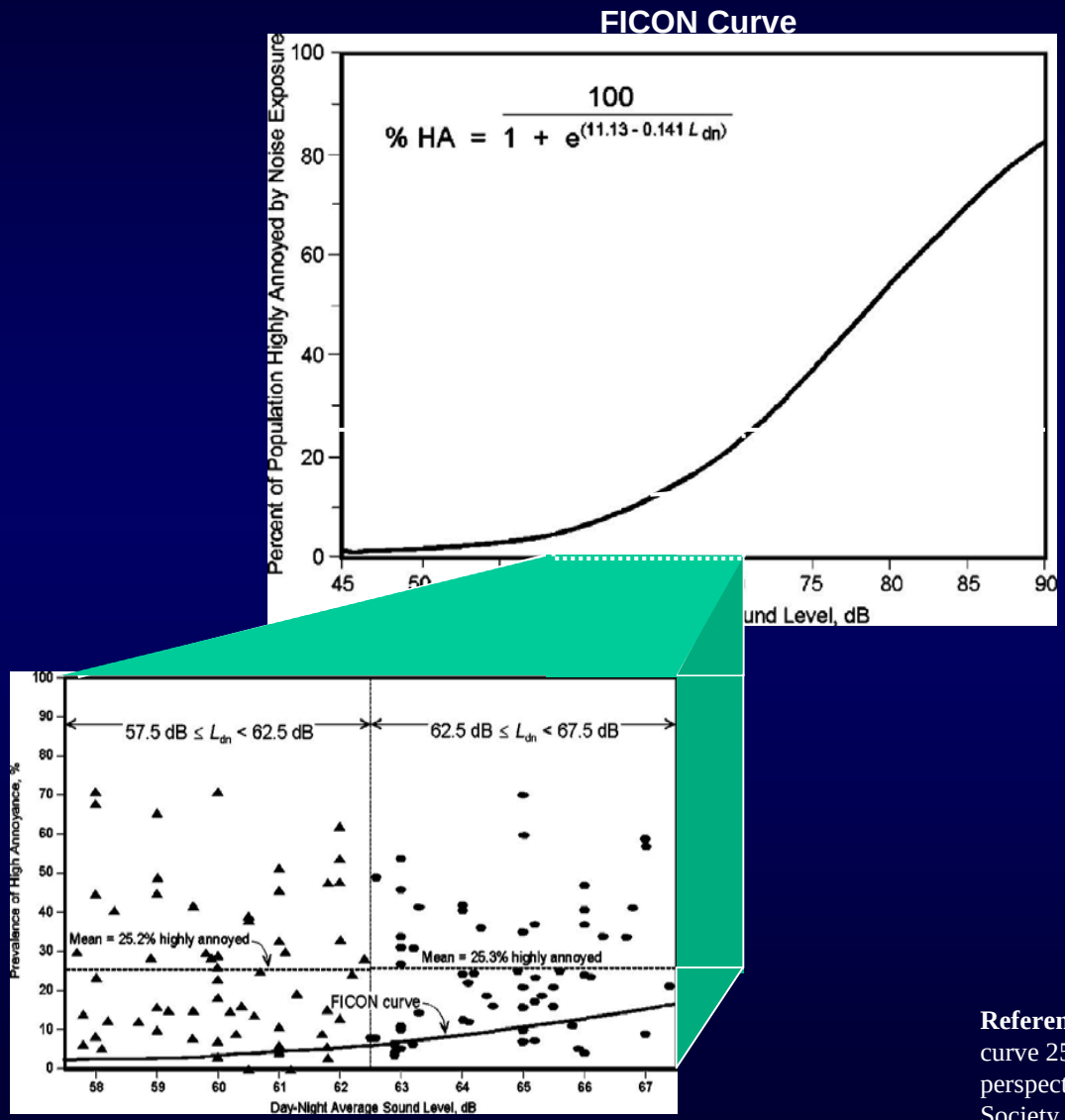
(* go to examples)

NOAA Fisheries Acoustic Exposure Guidelines: Extrapolation Procedures

Behavioral Disturbance Rule: The more conservative of empirical data on behavioral responses of animals to noise or TTS data are used to establish disturbance criteria.

24 Hour Rule: The guidelines differentiate between significant behavioral responses to human noise and brief, trivial responses.

FICON Curve



Reference: Fidell, S. 2003. The Schulz curve 25 years later: A research perspective. Journal of the Acoustical Society of America 114(6): 3007 – 3015.

Noise Exposure Guidelines: Limitations of Current Approach

- Number of data gaps require extrapolation procedures (*e.g.*, all injury criteria)
- Degree of within-group variability in hearing and behavioral sensitivities may be considerable
- Some of the behavioral criteria supported by science are untenable in terms of mitigation (*e.g.*, high frequency cetaceans)
- Criteria consider the effects of individual sound exposures on individual animals

MARINE MAMMAL DIVISIONS

18 families - 61 genera - 119 species
1 m. to 40 m. length
45 kg. to 95,000 kg. mass

Order Cetacea	(Whales, Dolphins, Porpoise)	78 species
Mysticetes	(baleen whales, rorquals)	11 species
Odontocetes	(toothed whales)	67 species
Order Pinnipedia	(Seals, Sea Lions, Walrus)	34 species
Phocids	(true, earless seals)	19 species
Otariids	(eared seals, sea lions)	14 species
Odobenids	(walrus)	1 species
Order Sirenia	(Manatees, Dugongs)	4 species
Order Carnivora	(Polar Bears, Sea Otters)	3 species

ABNORMAL FINDINGS - 25/42

TRAUMA (7)

Globicephala melaena	concussion/fracture	1/3	profound/bi
Megaptera novaeangliae	fracture	2/6	profound/bi
Phocoena phocoena	fracture	3/9	severe/uni
Tursiops truncatus	concussion/fracture	1/7	profound/bi

DISEASE (15)

Eubalaena glacilis	mesenchymal web	2/5	low/bi
Lagenorhynchus acutus	parasitism	2/4	low/bi
Phocoena phocoena	parasitism	6/9	low/bi
Tursiops truncatus	labyrinthitis	1/7	profound/bi
Phocoena phocoena	mycosis	1/9	low/bi
Tursiops truncatus	mycosis	1/7	profound/bi
Phoca vitulina	otitis externa	4/8	low/mod/u
Phoca vitulina	otitis media	4/8	low/mod/u

AGING - NOISE (3)

Tursiops truncatus	presbycusis	3/7	severe/bi

NIHL SUMMARY

Dolphins

- >20 kHz notch in odontocetes
- Profound, progressive ultrasonic hearing loss
- LF response characteristics unaffected
- Support cell and neural hypertrophy

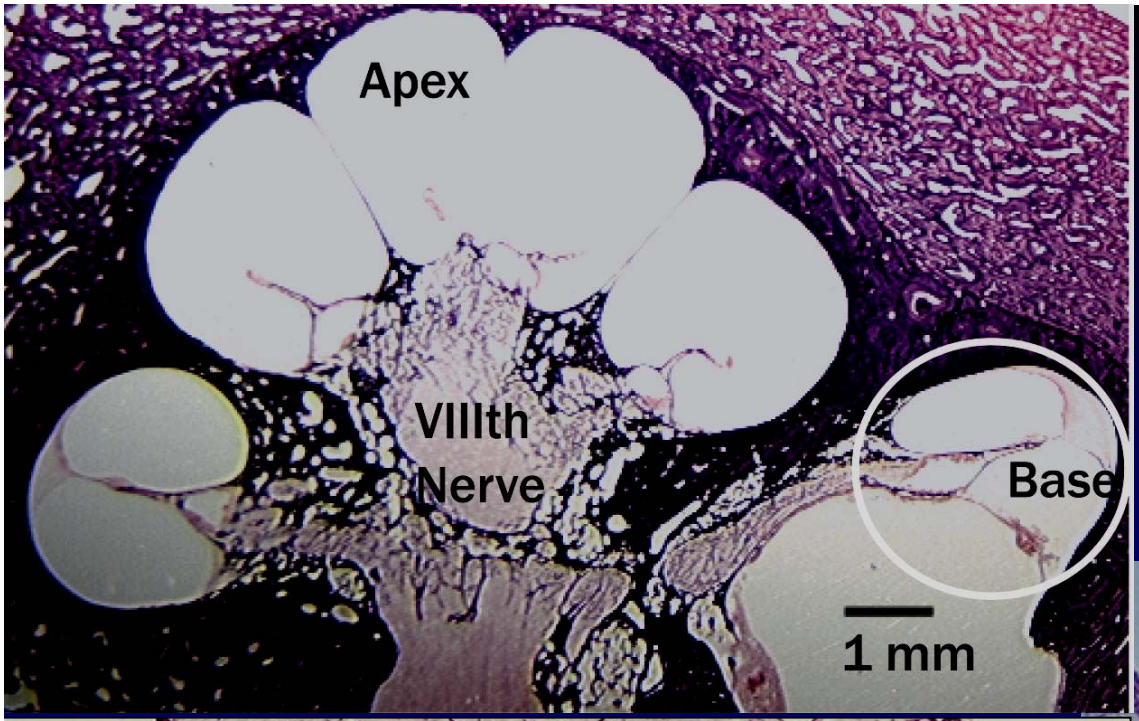
Seals and Sea Lions

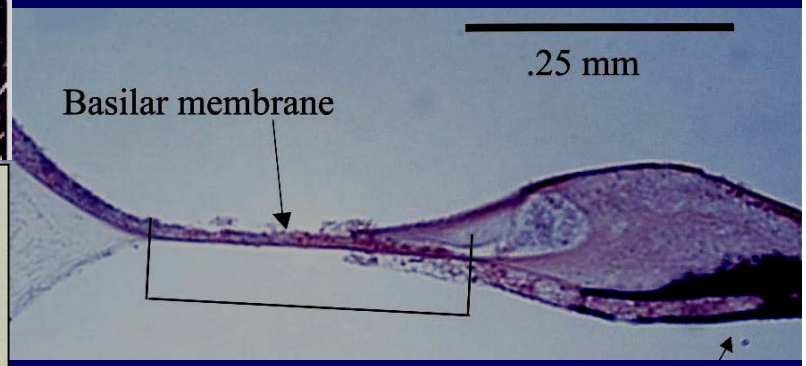
- 4-8 kHz notch
- No inner ear structural specializations
- More acute LF hearing

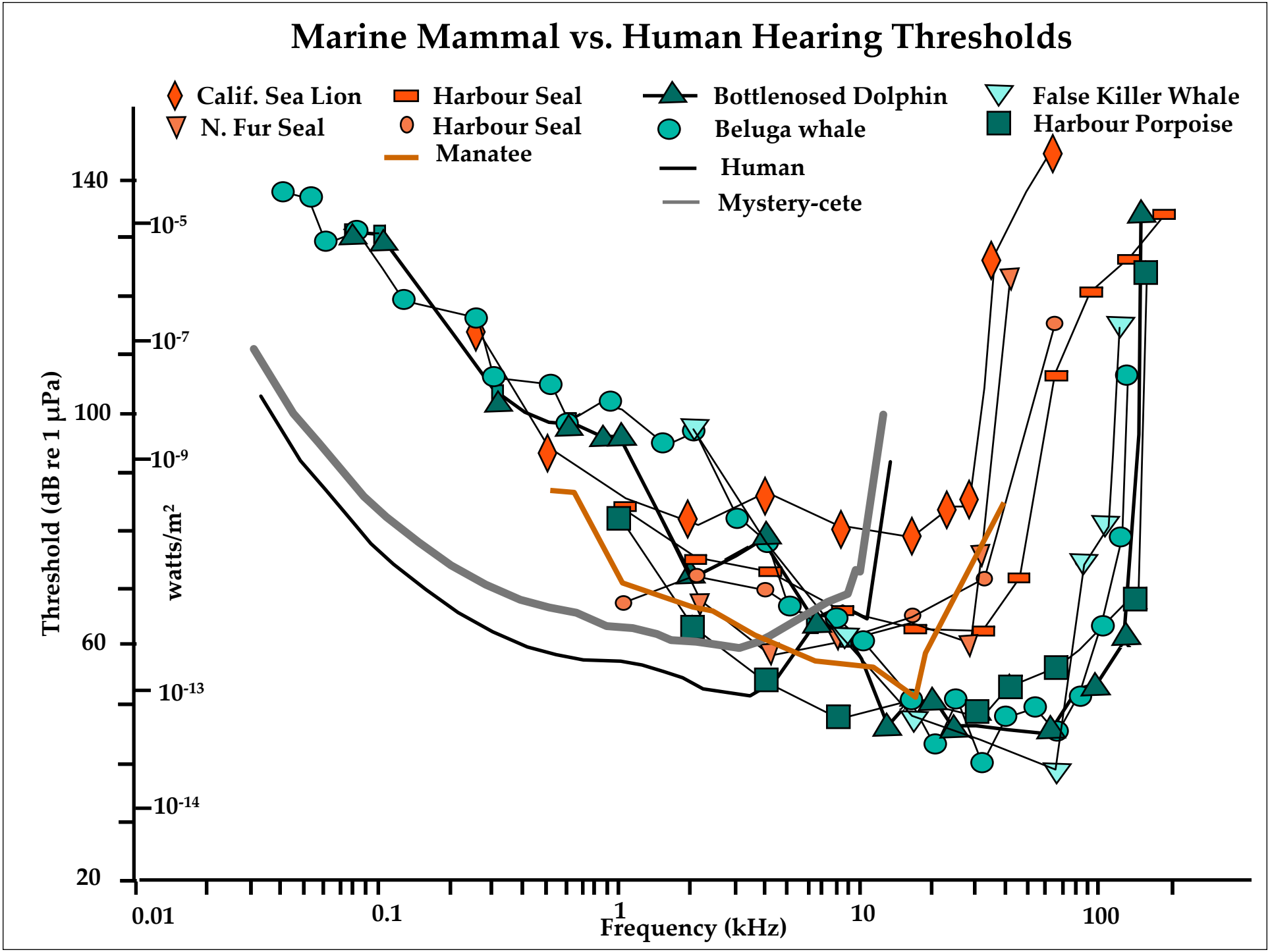
Same NIHL mechanisms as land mammals

Whales and dolphins have delayed TTS onsets

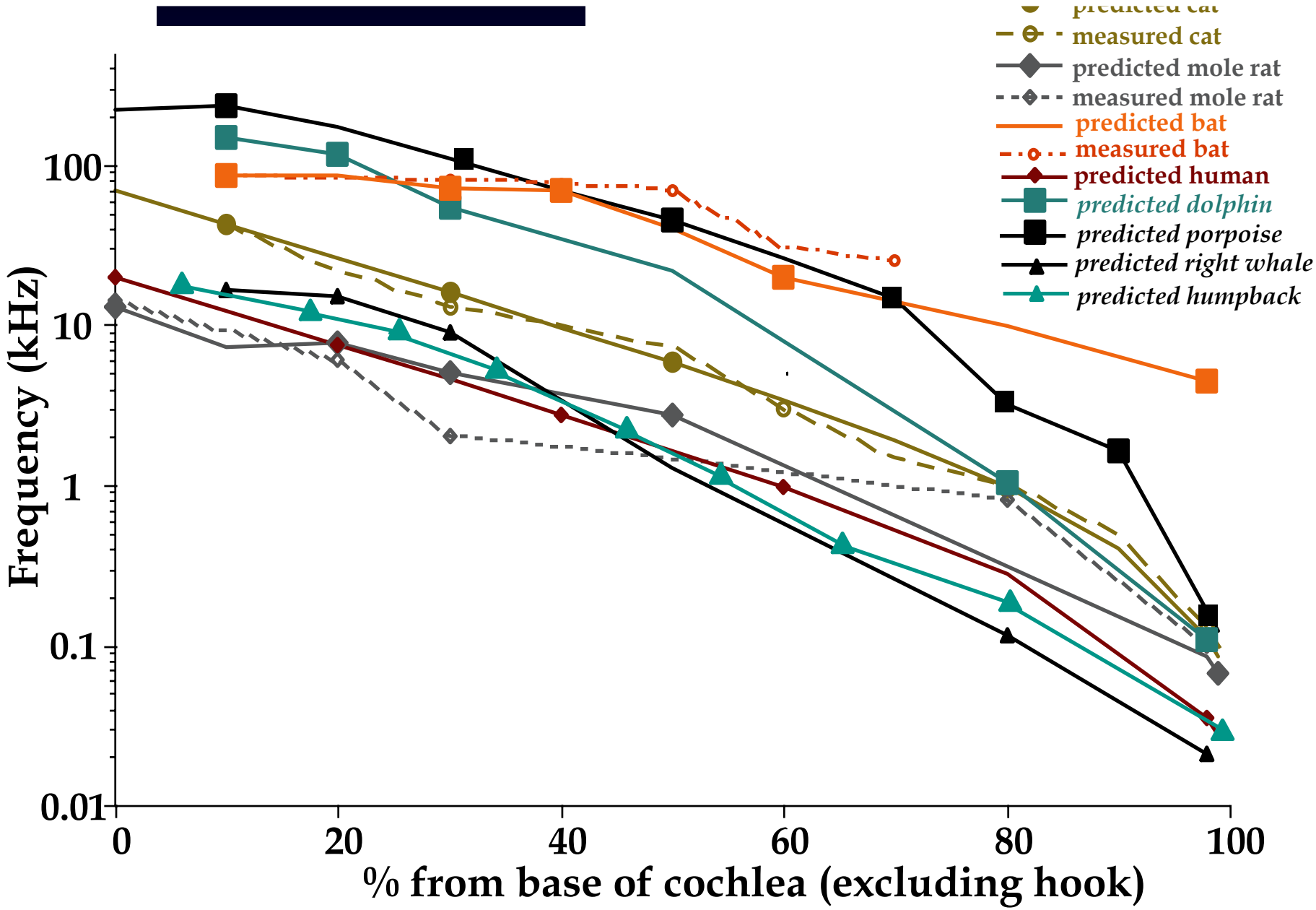
Pinnipeds are more fragile acoustically<10 kHz


Apex
VIIIth
Nerve
Base
1 mm

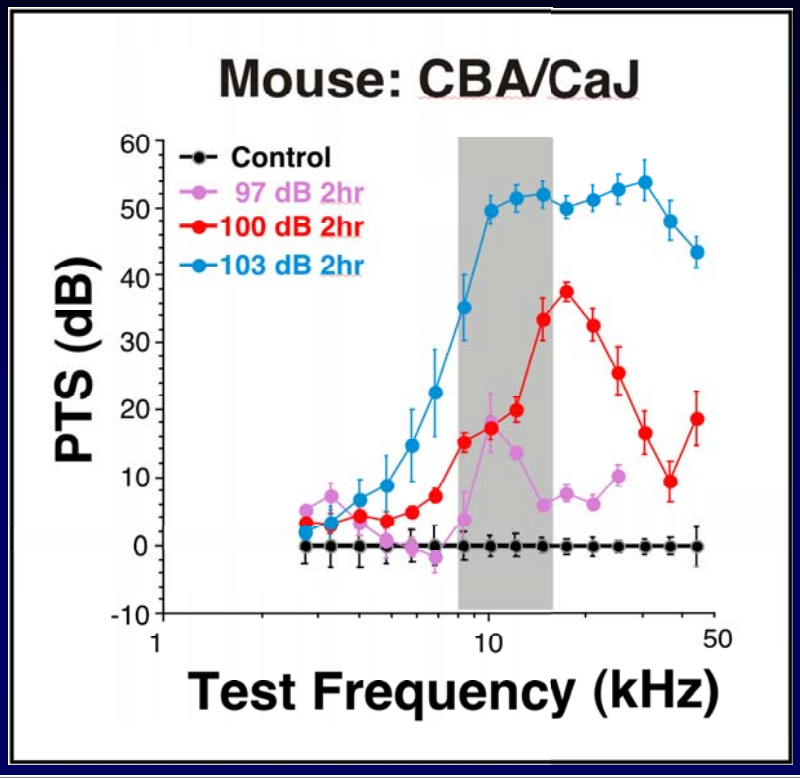

.25 mm
Basilar membrane

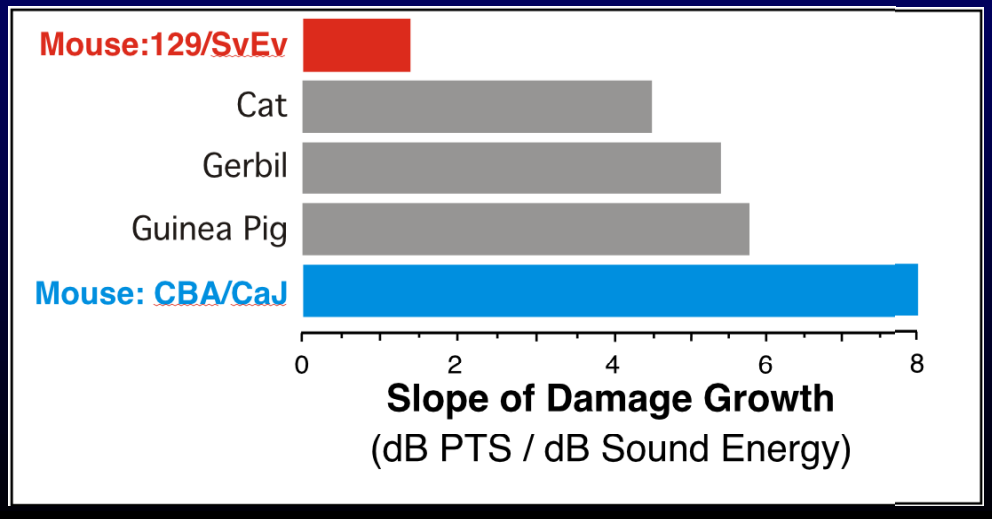

Marine Mammal vs. Human Hearing Thresholds
Calif. Sea Lion
N. Fur Seal
Harbour Seal
Harbour Seal
Manatee
Bottlenosed Dolphin
Beluga whale
Human
Mystery-cete
False Killer Whale
Harbour Porpoise
Threshold (dB re 1 µPa)
140
100
60
20
watts/m²
10-5
10-7
10-9
10-13
10-14
0.01
0.1
1
10
100
Frequency (kHz)

MORPH I. Inner Ear Frequency Response Maps
(Thickness/Width Gradient Based)



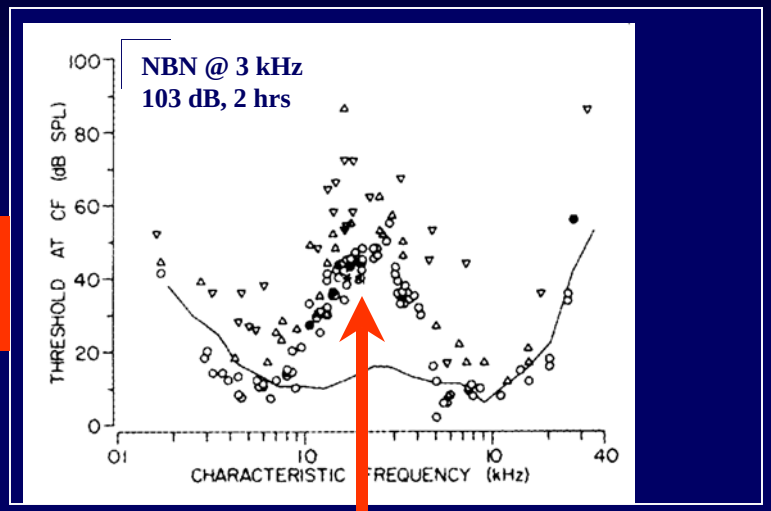
PTS: Rapid Growth above Critical Intensity



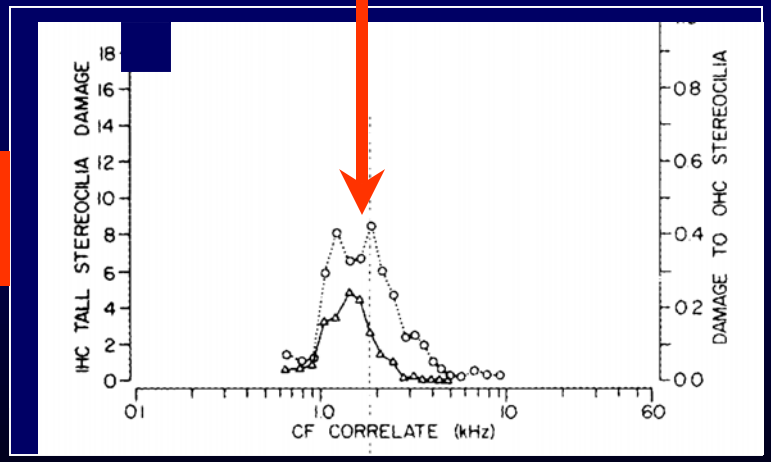


Correlating PTS and Stereocilia Damage

Auditory Nerve Thresholds

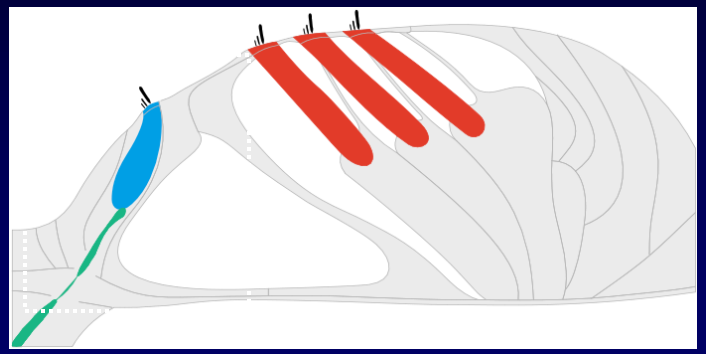


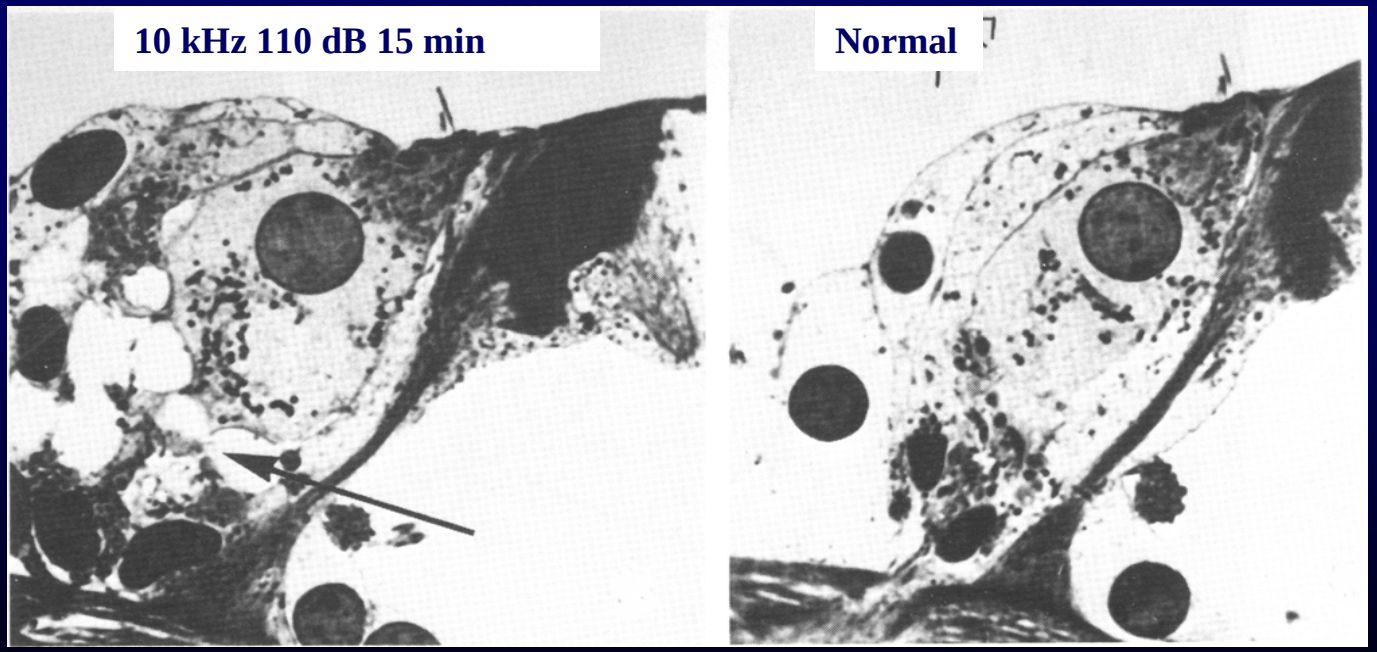
Stereocilia Damage



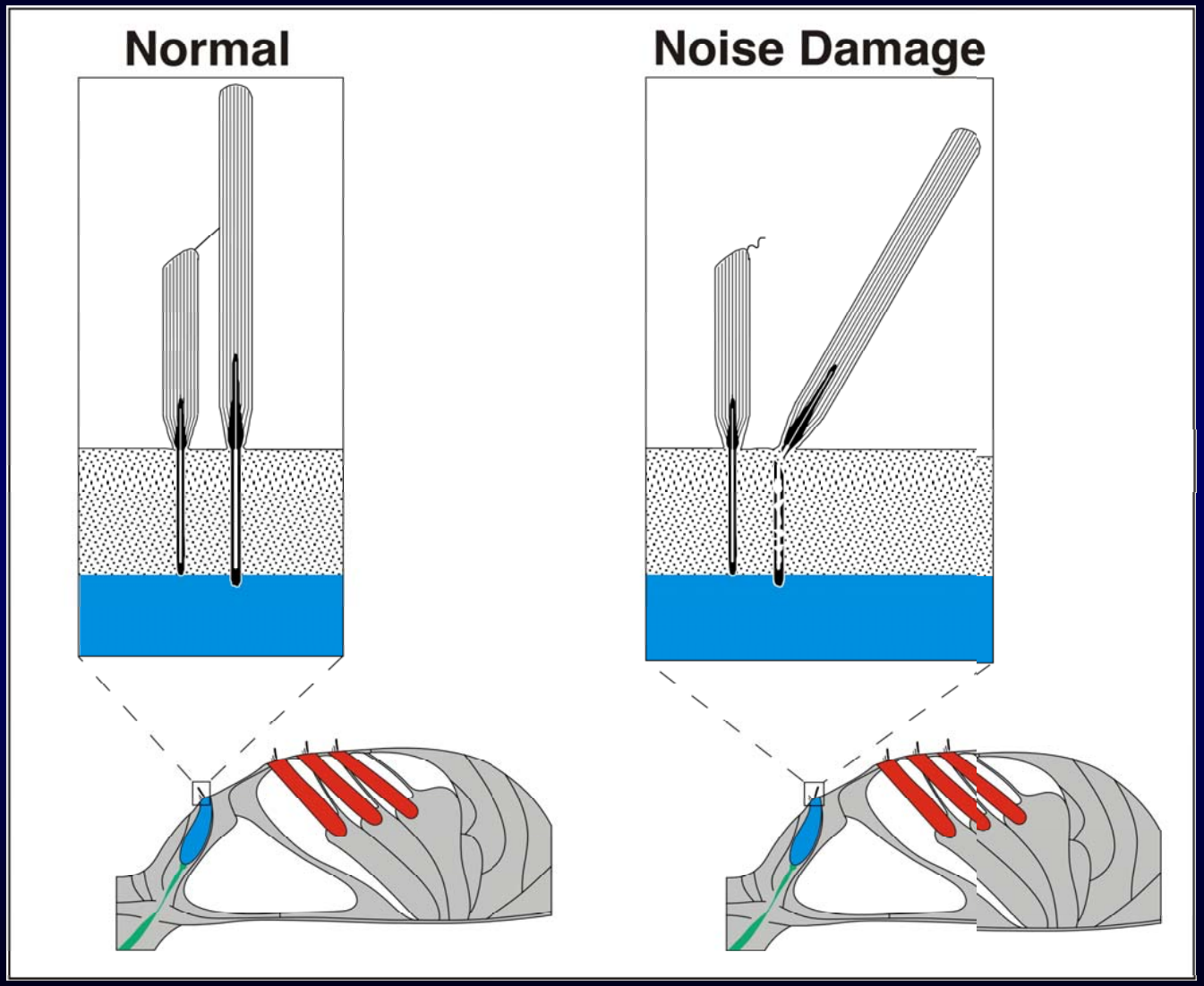
Stereocilia damage raises thresholds

TTS: Transitional Excitotoxic Effects on Sensory Cells





PTS: Stereocilia Damage disables Transduction



Energy Budget per Year

	SPL dBuPa	T sec	#	OP Day	Ping/min	Energy Joules
Bottlenose dolphin	**226**	**1xE-4**	**1,000,000**	**365**	**1.5xE4**	**6xE14**
ASW Sonar	**235**	**2**	**100**	**10**	**3**	**4xE13**
Wind (sea state 3)	**90**	**CW**	**N/A**	**365**	**CW**	**2xE13**
Heavy rain	**123**	**0.05%**	**N/A**	**365**	**N/A**	**1xE13**
Airguns	**250**	**.02**	**50**	**100**	**3**	**1xE13**
Supertanker	**185**	**CW**	**11,000**	**300**	**CW**	**7xE12**
Humpbacks	**185**	**0.025%**	**200,000**	**365**	**N/A**	**4xE12**
LFA Sonar	**235**	**6**	**1**	**100**	**1**	**4xE12**
Container Ship	**165**	**CW**	**40,000**	**300**	**CW**	**3xE11**
Research Exper	**195**	**1**	**10**	**360**	**1**	**2xE9**