NOISE EXPOSURE CRITERIA: EMERGENT CONCLUSIONS FROM AUDITORY THRESHOLDS TO BROADER ISSUES

Brandon L Southall

Southall Environmental Associates

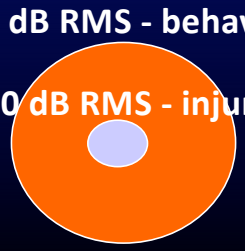
University of California, Santa Cruz

Duke University Marine Laboratory

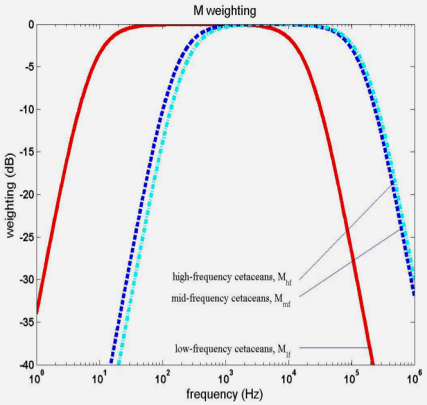
Historical U.S. regulatory view

Single sound source

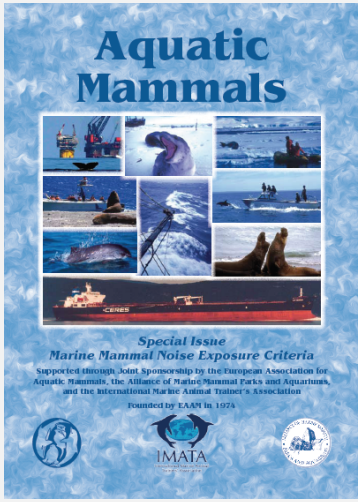
2-D sound “isopleths” with impacts based solely on broadband (all frequencies) exposure level “thresholds”



Key components of Southall et al. (2007)



- Segregation of species into 'functional hearing groups'
- Distinction of 'pulses' and 'non-pulses'
- Creation of auditory 'M-weighting' filters
- TTS/PTS onset thresholds using dual-metric approach for both in-air and underwater exposures

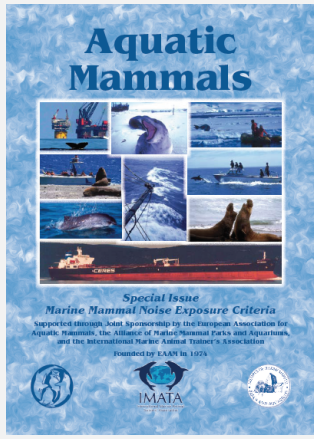


- Novel behavioral response 'severity scale' and evaluation of group-specific exposure:response probability

Received Exposure Level (dB_{RMS} re: 1µPa)

Response Score	80 to <90	90 to <100	100 to <110	110 to <120	120 to <130	130 to <140	140 to <150	150 to <160	160 to <170	170 to <180	180 to <190	190 to <200
9												
8												
7										1 (6)		
6				9.5 (3.7)	47.4 (3.7)	2.2 (3.7)	1.4 (4)	2 (1.2)	5.5 (1.2,6.8)	9.3 (1.2,6.8)		
5					1 (3.7)		1 (4)	1 (1.2)				
4												
3									1 (1.2)	1 (1.2)		
2												
1				5 (3.7)	6 (3.7)	1 (3.7)	2 (1.2)	3 (8)				
0				59.8 (3.7)	17.7 (3.7)	1.1 (3.7,8)	0.1 (8)	0.1 (8)	6.8 (1.2,8)	6.3 (1.2,8)		

Limitations of Southall et al. (2007)



- Major gaps in key data areas – requisite extrapolation and precaution
- Did not include all marine mammals (U.S. and NMFS-centric)
- Conservative approach to distinction of ‘pulses’
- Conservative approach to energy (SEL) accumulation that was based on BOTH auditory and behavioral perspectives (‘24-h rule’)
- Did not propose explicit behavioral response threshold criteria
- Was scientifically outdated as soon as it was written

Revised Auditory Exposure Criteria: Hearing, weighting functions, TTS/PTS onset Thresholds Finneran (2016) published in Southall et al. (2019)

CHALLENGES

- Evaluate all marine mammal species in water and air (amphibious species)
- Update hearing groups, weighting functions, and TTS/PTS onset criteria
- Learn from scientific and analytical progress to provide clear, fair guidance

Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects

Brandon L. Southall,[1,2] James J. Finneran,[3] Colleen Reichmuth,[2] Paul E. Nachtigall,[4] Darlene R. Ketten,[5,6] Ann E. Bowles,[7] William T. Ellison,[8] Douglas P. Nowacek,[9,10] and Peter L. Tyack[5,11]

Revised Auditory Exposure Criteria: Hearing, weighting functions, TTS/PTS onset Thresholds (Southall et al., 2019)

APPROACHES AND OUTCOMES

(1) Segregate all marine mammals into hearing groups

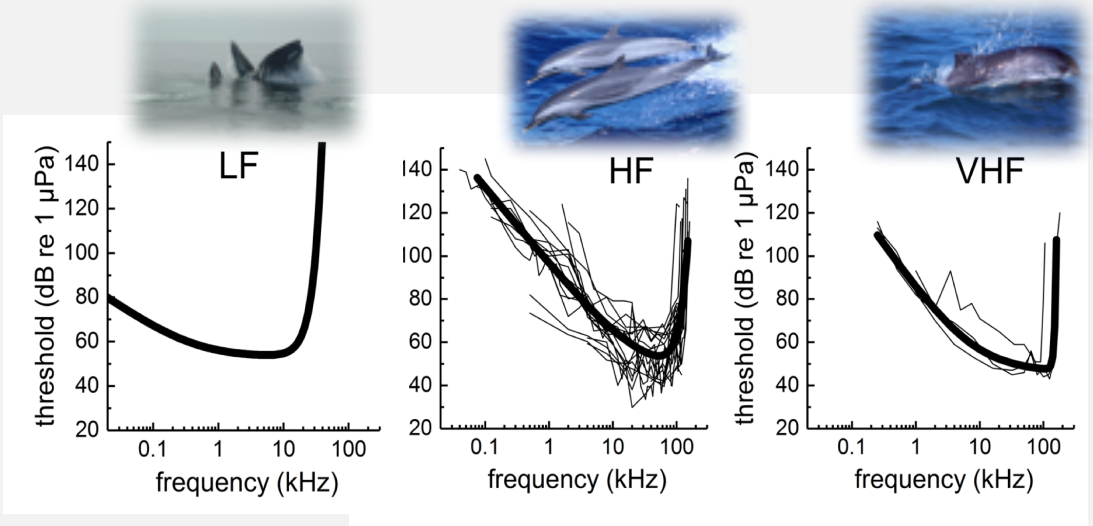
Taxon	Audiometry	Ear Type	Auditory modeling	Sound Production	Click type	References
Physeter macrocephalus Sperm whale	-	physeteroid middle ear, type I cochlea	-	SOC: 0.4 (squeal) to 9 kHz (coda) ECH: 3 to 26 kHz*	MP	Audiometry: No data Anatomical models: No data Acoustic: (Backus & Schevill, 1966; Levenson, 1974; Watkins & Schevill, 1977, 1980; Watkins, 1980; Weilgart & Whitehead, 1988; Goold & Jones, 1995; Madsen, Wahlberg, et al., 2002, Madsen, Payne, et al., 2002; Møhl et al., 2003; Weir et al., 2007)
Ziphius cavirostris Cuvier's beaked whale goose-beaked whale	-	physeteroid middle ear	-	ECH: 28 to 47 kHz*	FM	Audiometry: No data Anatomical models: No data Acoustic: (Frantzis et al., 2002; Zimmer et al., 2005; Baumann-Pickering, McDonald, et al., 2013)
Delphinapterus leucas Beluga	BEH: 0.04 to 130 kHz AEP: < 4 to 150 kHz	odontocete middle ear	-	SOC: 0.1 (whistle, pulsed calls) to 21 kHz (whistle, pulsed calls) ECH: 40 to 120 kHz* click type: BBHF	BBHF	Audiometry: BEH: (White et al., 1978; Awbrey, 1988; Johnson et al., 1989; Ridgway et al., 2001; Finneran, Carder, Dear, et al., 2005, Finneran et al.)(n=8); exclude (Finneran et al., 2005, individual "*Turner*"); AEP: (Popov & Supin, 1990; Klishin et al., 2000; Mooney et al., 2008; Popov et al., 2013; Castellote et al., 2014)(n=12) Anatomical models: No data Acoustic: (Kamminga & Wiersma, 1981; Sjare & Smith, 1986; Au et al., 1987; Turl et al., 1991; Belikov & Bel'kovich, 2001, 2005, 2006, 2007; Karlsen et al., 2001; Rutenko & Vishnyakov, 2006; Lammers & Castellote, 2009; Chmelnitsky & Ferguson, 2012)

Marine Mammal Hearing Group	Auditory Weighting Function	Genera (or species) Included	Group-Specific Appendix
Very Low-Frequency & Low-Frequency Cetaceans	LF	***Balaenidae*** *(Eubalaenidae spp.; Balaena mysticetus;)* ***Balaenopteridae*** *(Balaenoptera musculus, B. physalus)*	1
		Balaenopteridae *(Balaenoptera acutorostrata, B. bonaerensis, B. omurai, B. edeni, B. borealis; Megaptera novaeangliae);* ***Neobalenidae*** *(Caperea);****Eschrichtiidae*** *(Eschrichtius)*	
Mid-Frequency & High-Frequency Cetaceans	HF	***Physeteridae*** *(Physeter);* ***Ziphiidae*** *(Berardius spp., Hyperoodon spp., Indopacetus, Mesoplodon spp., Tasmacetus, Ziphius);* ***Delphinidae*** *(Orcinus)*	2
		Delphinidae *(Steno, Sousa spp., Sotalia spp., Tursiops spp., Stenella spp., Delphinus, Lagenodelphis, Lissodelphis spp., Grampus, Peponocephala, Feresa, Pseudorca, Globicephala spp., Orcaella spp., Lagenorhynchus acutus, L. albirostris, L. obliquidens, L. obscurus);* ***Montodontidae*** *(Delphinapterus, Monodon);* ***Plantanistidae*** *(Plantanista)*	
Very High-Frequency Cetaceans	VHF	***Phocoenidae*** *(Phocoena spp., Neophocaena spp., Phocoenoides);* ***Iniidae*** *(Inia);* ***Kogiidae*** *(Kogia);* ***Lipotidae*** *(Lipotes);* ***Pontoporiidae*** *(Pontoporia);* ***Delphinidae*** *(Cephalorhynchus spp.; Lagenorhynchus cruciger, L. australis)*	3
Sirenians (**SI**)	SI	***Trichechidae*** *(Trichechus spp.);* ***Dugongidae*** *(Dugong)*	4
Phocid Carnivores in Water (**PCW**)	PCW	***Phocidae*** *(Cystophora, Erignathus, Halichoerus, Histriophoca, Hydrurga, Leptonychotes, Lobodon, Mirounga spp., Monachus, Neomonachus, Ommatophoca, Pagophilus, Phoca spp., Pusa spp.)*	5
Phocid Carnivores in Air (**PCA**)	PCA		
Other Marine Carnivores in Water (**OCW**)	OCW	***Odobenidae*** *(Odobenus);* ***Otariidae*** *(Arctocephalus spp., Callorhinus, Eumetopias, Neophoca, Otaria, Phocarctos, Zalophus spp.);* ***Ursidae*** *(Ursus maritimus);* ***Mustelidae*** *(Enhydra, Lontra feline)*	6
Other Marine Carnivores in Air (**OCA**)	OCA		

Revised Auditory Exposure Criteria: Hearing, weighting functions, TTS/PTS onset Thresholds (Southall et al., 2019)

APPROACHES AND OUTCOMES

(2) Derive representative 'audiograms' for hearing groups



Cetaceans:

Very Low (VLF) (no function)

Low Frequency (LF) (estimated)

Mid Frequency (MF) (no function)

High Frequency (HF)

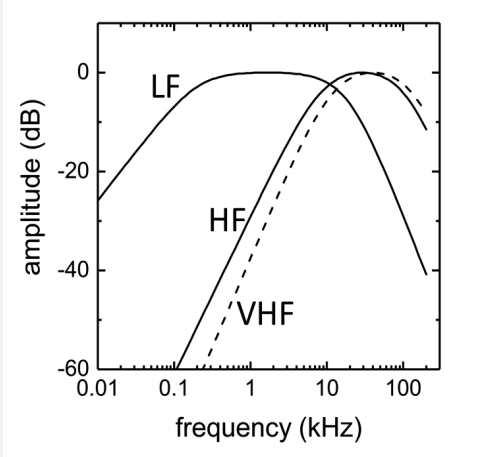
Very High Frequency (VHF)

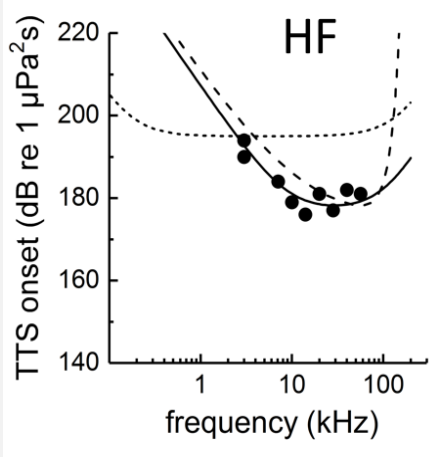
Revised Auditory Exposure Criteria: Hearing, weighting functions, TTS/PTS onset Thresholds (Southall et al., 2019)

APPROACHES AND OUTCOMES

(3) Derive auditory weighting and noise exposure functions

(4) Predict TTS and PTS onset thresholds for each hearing group





”Impulsive” exposures

Marine Mammal Hearing Group	TTS-onset: SEL (weighted)	TTS-onset: peak SPL (unweighted)	PTS-onset: SEL (weighted)	PTS onset: peak SPL (unweighted)
LF	168	213	183	219
HF	170	224	185	230
VHF	140	196	155	202
SI	175	220	190	226
PCW	170	212	185	218
OCW	188	226	203	232
PCA	123	138	138	144
OCA	146	161	161	167

”Non-Impulsive” exposures

Marine Mammal Hearing Group	TTS-onset: SEL (weighted)	PTS-onset: SEL (weighted)
LF	179	199
HF	178	198
VHF	153	173
SI	186	206
PCW	181	201
OCW	199	219
PCA	134	154
OCA	157	177

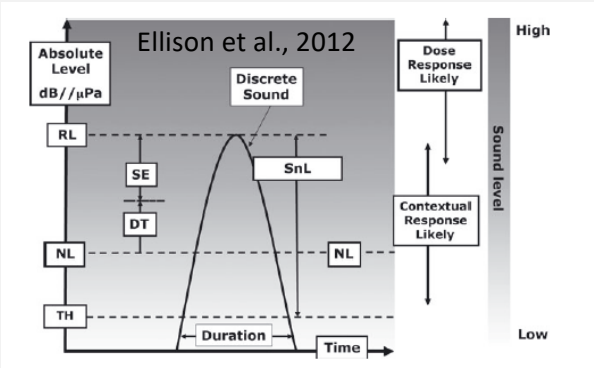
Emergent (BLS) conclusions on noise exposure criteria from several decades of research and deliberation

- Has been and will remain an adaptive, self-correcting process, benefiting from multiple perspectives
- Broadly applicable, quantitative criteria are desirable – major progress has been made in a short time
  - Major limitations in underlying knowledge exist (and will persist) – extrapolation required
  - Individual and species differences are likely to exist (direct evidence should supersede broader criteria)
- Uncertainty has and should lead to more precautionary approaches (e.g., mysticetes)
- Extensive evidence that porpoises are particularly sensitive – extrapolation to other VHF
- For most species even TTS and certainly PTS is quite unlikely in most realistic exposure scenarios
  - Thresholds are generally quite high
  - Propagation effects mean impulsive noise becomes less impulsive (and arguably addressed with other criteria)
  - Many instances of what are very likely cSEL accumulation overestimates (recall nature of 24-h ‘rule’ and recovery data)
  - Animal/source movement and behavioral avoidance means that animals

Emergent (BLS) conclusions on noise exposure criteria from several decades of research and deliberation

While there are major knowledge gaps and some particularly sensitive groups, the predominant (especially conservation) concerns and focus, at least in terms of mitigation strategies, regarding noise impacts relate to behavioral disturbance, masking, and physiological effects

- Focus on potential injury can work ***against*** conservation goals



Paradigm shift in evaluation of behavioral responses to noise in marine mammals: *Exposure context*

Examples:	*Blue whale BRS results*
Behavioral state	Goldbogen et al., 2013 DeRuiter et al., 2017
Prey environment	Friedlaender et al., 2016
Source-animal range	Southall et al., 2019