

# PHYSIOLOGICAL EFFECTS OF NOISE ON FISHES

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**Introduction** While the effects of noise on humans and other mammals have received considerable attention, only a few studies have examined the effects of noise on fishes. There is a growing concern, however, that human-generated (anthropogenic) noise in the marine environment may potentially have a significant impact on marine organisms (National Research Council 1994, 2000, 2003; Richardson *et al.*, 1995). Indeed the findings of three recent studies summarized here, give evidence to a variety of physiological and physical effects resulting from the interaction between anthropogenic noise and fishes.

Unlike terrestrial mammals, fish are acoustically coupled to the surrounding water. Thus they do not require an outer ear or middle ear for reception of sound. The structure of their inner ears, however, is similar to that of other vertebrates. Each ear has three semicircular canals and three otolithic organs, the utricle, saccule and lagena, which are interconnected and filled with endolymphatic fluid. Fishes do not have a cochlea, but one or more of the otolithic organs is involved in audition. Each of these consists of a sac containing a calcium carbonate stone, the otolith, which is loosely connected to a sensory epithelium, the macula, on the inside wall of the sac through a gelatinous otolithic membrane. The epithelia contain sensory hair cells, which are also found in the basilar membrane in the cochlea of mammalian ears. Figure 1 (right) shows a scanning electron microscope (SEM) picture of the saccular epithelium removed from the inner ear of a goldfish (*Carassius auratus*). Its surface is covered with the ciliary bundles of the underlying hair cells. (Magnification is 2000 $\times$ .)



Figure 1

Dijkgraaf (1960) first proposed that hearing occurs when the more dense otoliths lag behind the fish's body, which moves with the surrounding water in the presence of sound. This relative motion imparts a shearing force on the apical ciliary bundles of the hair cells, which bend and cause the hair cells to generate neural signals. In many fishes the swimbladder, a gas-filled chamber inside the body that enables a fish to maintain neutral buoyancy, acts as an eardrum by responding to the acoustic pressure wave and radiating a secondary stimulus to the inner ear. This additional path for acoustic energy enhances hearing sensitivity in some species.

The auditory system and hearing capabilities of fishes vary depending on the species. Generally fish hear sounds at frequencies between 50 and 2000 Hz with best sensitivity from 200 to 800 Hz (Popper and Fay, 1993); however some species in the teleost taxonomic order Clupeiformes detect sounds at frequencies up to 200 kHz (Mann *et al.*, 1997, 1998, 2001). The lateral line system also contains sensory hair cells. It consists of tissue found free on the body and head surfaces, and in canals on the head and trunk. This system detects nearfield hydrodynamic disturbances usually at frequencies below 100 Hz. The literature, albeit very

small, has no reports of damage to the lateral line system caused by underwater sound (Hastings *et al.*, 1996).

**Threshold Shifts** It has been well documented in the mammalian literature that temporary threshold shifts (TTS) reach an asymptote after a specific duration of noise exposure (Clark, 1991). These asymptotic threshold shifts increase linearly with sound pressure level (SPL) on a dB scale. Recent work by the authors at the University of Maryland indicates that noise-induced threshold shifts in fish increase linearly with increasing SPL above baseline thresholds (the linear threshold shift or LINTS hypothesis). To test this hypothesis, the effect of white noise on hearing loss was determined for goldfish (*Carassius auratus*).

Goldfish were exposed to white noise from 0.1 to 4 kHz with an overall SPL ranging from 164 to 170 dB (re: 1  $\mu$ Pa) for either 0 (control), 7, or 21 days in 600-L aquaria. The sound was presented via an underwater speaker placed centrally on the bottom of the aquaria. Auditory thresholds were measured using the auditory brainstem response (ABR). This technique is a noninvasive method of measuring the whole brain response to auditory stimuli and is commonly used for measuring hearing in fishes and other vertebrates. Each fish was restrained in a mesh sling and suspended in a 19-L plastic bucket filled with water so that the top of the head was approximately 2 cm below the surface of the water and 25 cm above the underwater speaker. A reference electrode was placed on the dorsal surface of the fish's head along the midline between the anterior portion of the eyes, while a recording electrode was placed on the dorsal midline surface of the fish approximately halfway between the anterior insertion of the dorsal fin and the posterior edge of the operculae. A ground electrode was placed in the water near the body of the fish to reduce background noise. Sound stimuli were presented and ABR waveforms collected using a Tucker-Davis Technology physiology apparatus with SigGen and BioSig software.

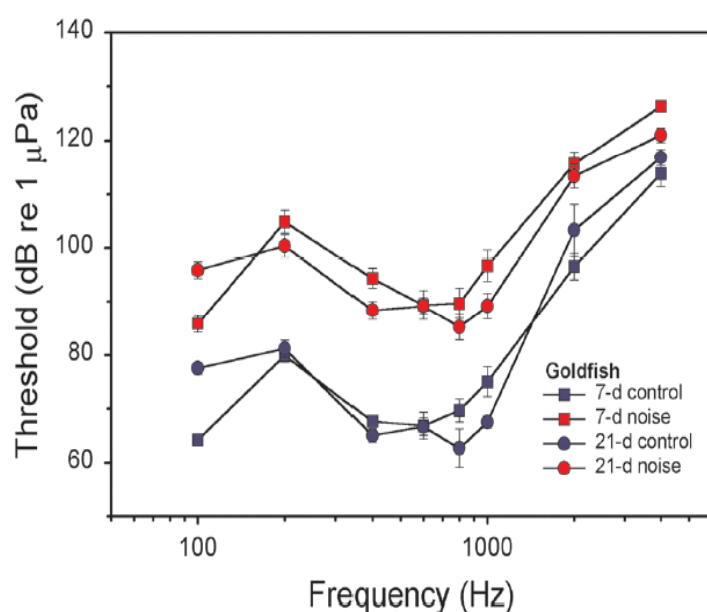


Figure 2

Figure 2 (left) compares auditory thresholds of goldfish after 7 and 21 days of white noise exposure. ABRs were detectable up to 4 kHz. Goldfish had significant threshold shifts at all frequencies after only 7 days of noise exposure. After 7 days, further noise exposure did not produce greater threshold shifts, suggesting an asymptote had been reached. Thresholds returned to baseline levels after 14 days.

The LINTS relationship is statistically robust and is predictive on many different levels. On the level of an individual animal it predicts that when stimulated with white

noise, the threshold shift will be greatest at frequencies where the animal's baseline hearing threshold is the lowest. On the next higher level of prediction, the LINTS hypothesis predicts that, for a given sound pressure level, more sensitive species will be more prone to TTS than less sensitive species. This was the case in comparing fish with mammals and birds.

Figure 3 (right) shows the relationship between TTS and SPL above baseline levels in fish, birds, and mammals (Smith *et al.*, 2003). Regression relationships were significant for all taxa, with slopes increasing from fish to birds to mammals. Data sources are summarized in Smith *et al.*, 2003. Even though different researchers utilized different species and methodologies, and stimulated with sounds of various characteristics, subtracting the species' baseline hearing threshold from the noise exposure SPL for each experiment standardizes the LINTS relationship and allows easy comparison between species.

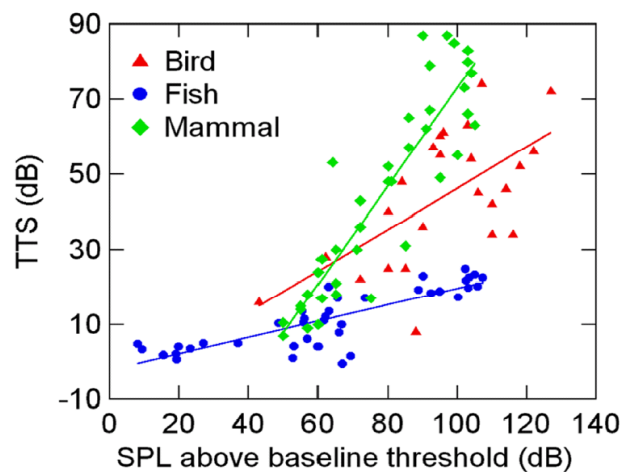


Figure 3

**Repetitive Impulsive Noise** While exposure to elevated white noise for extended periods can cause temporary threshold shift, exposure to relatively intense impulsive sounds may not only cause changes in behavior (Engås *et al.*, 1996) and hearing capabilities, but also damage auditory sensory cells or other tissue and organs in fishes. Several types of high-energy anthropogenic noise sources produce repetitive, impulsive low-frequency sounds in the water. These sources include air-guns, water-guns, acoustic harassment devices, explosives, and hydraulic hammers used in off-shore construction (Richardson *et al.*, 1995).

Off-shore pile driving creates a repetitive series of impulsive sounds that can be very harmful to marine life. The peak pressure and width of the pulse depend on the size of the hammer, the physical structure of the pile, the boundary conditions defining the local ocean environment, water depth and quality, and the distance from the pile. Table 2 (first row) summarizes the characteristics of the impulses recorded at one-meter depth and 110 meters east of a pile driving activity using a Menke hydraulic hammer (MHU1700T) in the shallow waters of San Francisco Bay (California Department of Transportation, 2001a). The MHU1700T with a maximum capacity of 1700 kilojoules (kJ), was delivering approximately 1400 kJ to drive hollow steel pile sections, approximately 2.5 meters in diameter and 30 meters in length, into the bottom.

Table 2. Received Level (RL) Characteristics of Two Types of Underwater Impulsive Noise

Activity	Peak. SPL (rms) (dB re: 1 $\mu$ Pa)	Pulse Width (s)	Significant Spectral Bandwidth (Hz)	RL Depth (m)	Total Depth (m)
Pile driving*	178	0.071	80 – 2000	1	17
Air-Gun Firing <sup>^</sup>	180	--	20 – 1000	5	9

\*California Department of Transportation, 2001a; <sup>^</sup>McCauley *et al.*, 2003.

Wild schools of fish (anchovy, herring, sardine, pile surfperch, white surfperch, and shiner surfperch) within 100 meters of the pile were monitored for 20 minutes while the hammer was operated during nine one-minute periods. Each one-minute period of operation had 30 hammer strikes. Moribund fish were visible on the water surface after only two strikes and fish continued to float to the surface throughout the 20 minutes of pile driving (California Department of Transportation, 2001b).

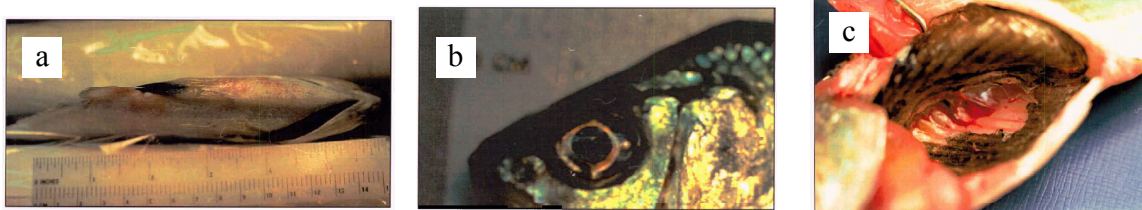


Figure 4 (adapted from California Department of Transportation, 2001b)

Figure 4 (above) shows various types of tissue damage inflicted on wild surfperch during just a few hammer impulses. Areas of redness indicate ruptured blood vessels on the ventral surface of the surfperch in Figure 4(a). The surfperch in 4(b) has broken blood vessels in the eye. The open abdomen of the surfperch in Figure 4(c) shows a ruptured swimbladder.

Air-guns are often used by the petroleum industry to locate oil reserves. Table 2 (row 2) summarizes the characteristics of a 0.33-L Bolt PAR 600B air-gun operating at 5-meters depth with a gas pressure of 10 MPa and a pulse every 10 seconds, as reported by McCauley, Fewtrell, and Popper (2003) in their recent paper about the effects of air-gun noise on the inner ears of pink snapper (*Pagrus auratus*). These fish were held in cages as an air-gun moved toward and away from the cages to simulate a passing survey vessel. Received SPL (rms) ranged from approximately 145 to 180 dB (re: 1  $\mu$ Pa) during periods of exposure which included four approaches and retreats during a 1:05 hour period, followed by a break of 1:12 hours and then three approaches and two retreats over 0:36 hours. After exposure fish were held either 18 hours or 58 days and then sacrificed. Sensory epithelia from the saccule were removed and examined using SEM. Destruction of sensory hair cells resulting from exposure to air-gun noise was apparent over time by the increased number of missing ciliary bundles and blebs on the epithelial surface. Blebs are herniations of the cell membrane that appear in hair cells in response to acoustic trauma or other insults. They are associated with cell death because of potential for eventual rupture, which also produces holes in the epithelial surface.

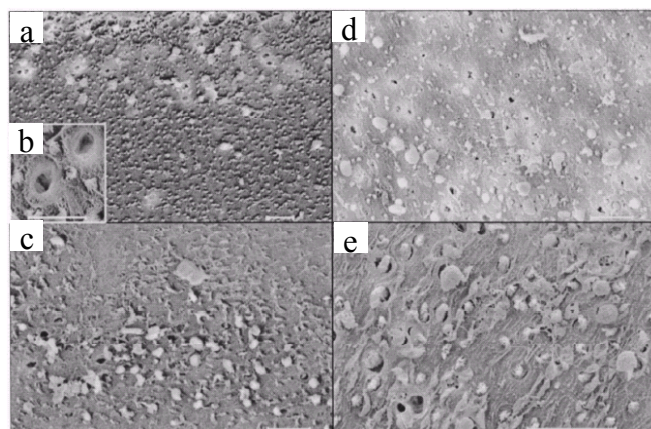


Figure 5 (adapted from McCauley *et al.*, 2003)

Figure 5 (left) shows the destruction of hair cells over time in the saccules of pink snapper exposed to the air-gun noise. Epithelia from fish sacrificed 18 hours after exposure are shown in panes a, b, and c. The holes may result from immediate mechanical damage to the hair cells or appear after membrane rupture and cell death. An increase in the number of blebs and holes is apparent in the epithelia from fish held for 58 days as pictured in panes d and e. (Scale bars are 20  $\mu$ m in a, c, d, and e, and 2  $\mu$ m in b.)

**Discussion** The pathologies associated with exposure to drastic changes in pressure are collectively known as barotraumas. These include hemorrhage and rupture of internal organs, including the swim bladder and kidneys in fish. Death can be instantaneous, occur within minutes after exposure, or several days later. Bubble expansion in blood vessels can cause a rupture resulting in hemorrhage. Other tissues with gas-filled voids, such as bowel and

swimbladder, can perforate and hemorrhage when exposed to high-energy impulse noise underwater. Bubble growth by rectified diffusion is the likely mechanism responsible for the barotraumas experienced by surfperch exposed to pile driving noise. Rectified diffusion (or stable cavitation) creates bubble growth during acoustic oscillations in regions of large sound pressure levels. In one cycle of pulsation during this process, more gas diffuses inward from the liquid to the bubble during its expansion than is squeezed out during contraction, primarily because the surface area of the bubble while expanded is much greater than the area while contracted (Crum and Mao, 1996). Small bubbles grow by rectified diffusion until they reach a critical radius, called the Blake threshold, at which they expand explosively if the sound pressure swing is constant. Growth of bubbles in tissue by rectified diffusion can cause inflammation and cellular damage because of increased stress and strain (Stroetz *et al.*, 2001), and blockage or rupture of capillaries, arteries and veins.

Noise that induces temporary threshold shifts or causes permanent damage to the inner ear also has detrimental effects on fish by causing stress, increasing risk of mortality by reducing predator avoidance capabilities, and interfering with communication necessary for navigation and reproduction. Even if threshold shifts do not occur, loud sounds can mask the ability of aquatic animals to hear in their environment. Noise-induced stress can be manifest in reduced growth rates, increased aggressive behavior, startle responses, and tighter schooling. Banner and Hyatt (1973) reported reduced growth rates for sheepshead minnows (*Cyprinodon variegatus*) and killfish (*Fundulus similis*) in tanks with noise levels 20 to 30 dB above ambient, and Terhune *et al.* (1990) noted a 5-8% reduction in smolting rates of Atlantic salmon (*Salmo salar* L.) in tanks with ambient noise levels 4-16 dB higher than other tanks. Pearson *et al.* (1992) observed tighter schooling and movement to the bottom of the water column by rockfish in response to onset of impulsive air-gun noise.

New data indicate that the linear threshold shift (LINTS) hypothesis, which states that asymptotic temporary threshold shifts increase linearly with SPL on a dB scale, may hold for fish as well as birds and mammals. Although this hypothesis must be tested with more fish species and a broader range of noise SPLs, it may become a useful tool for environmental planners in providing noise exposure safety criteria that minimize the risk of permanent damage to fishes.

**Keywords** fish hearing, temporary threshold shift, hair cell damage, barotrauma

## References:

- Banner, A. and Hyatt, M. (1973). Effects of noise on eggs and larvae of two estuarine fish, *Trans. Am. Fisheries Soc.*, 102, 134-136.
- California Department of Transportation (2001a). *Noise and Vibration Measurements Associated with the Pile Installation Demonstration Project*, Final Data Report submitted by Illingworth & Rodkin, Petaluma, CA.
- California Department of Transportation (2001b). *Pile Installation Demonstration Project Fisheries Impact Assessment*, Report PIDP 04-ALA-80-0.0/0.5, Sacramento, CA.
- Clark, W. W. (1991). Recent studies of temporary threshold shift (TTS) and permanent threshold shift (PTS) in animals, *J. Acoust. Soc. Am.*, 90, 155-163.
- Crum, L. A. and Mao, Y. (1996). Acoustically enhanced bubble growth at low frequencies and its implications for human diver and marine mammal safety, *J. Acoust. Soc. Am.*, 99, 2898-2907.
- Dijkgraaf, S. (1960). Hearing in bony fishes, *Proc. Roy. Soc. Lon. Ser. B*, 157, 51-54.
- Engås, A., Løkkeborg, S., Ona, E., Soldal, A. V. (1996). Effects of seismic shooting on local abundance and catch rates of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*), *Can. J. Fish. Aquat. Sci.*, 53, 2238-2249.

- Hastings, M. C., Popper, A. N., Finneran, J. J., and Lanford, P. J. (1996). Effect of low-frequency underwater sound on hair cells of the inner ear and lateral line of the teleost fish *Astronotus ocellatus*, *J. Acoust. Soc. Am.*, 99, 1759-1766.
- Mann, D. A., Lu, Z., and Popper, A. N. (1997). Ultrasound detection by a teleost fish, *Nature*, 389, 341.
- Mann, D. A., Lu, Z., Hastings, M. C. and Popper, A. N. (1998). Detection of ultrasonic tones and simulated dolphin echolocation clicks by a teleost fish, the American shad (*Alosa sapidissima*), *J. Acoust. Soc. Am.*, 104, 562-568.
- Mann, D. A., Higgs, D. M., Tavalga, W. N., Souza, M. J., and Popper, A. N. (2001). Ultrasound detection by clupeiform fishes, *J. Acoust. Soc. Am.*, 109, 3048-3054.
- McCauley, R. D., Fewtrell, J., and Popper, A. N. (2003). High intensity anthropogenic sound damages fish ears, *J. Acoust. Soc. Am.*, 113, 2003, 638-642.
- National Research Council (1994). *Low-Frequency Sound and Marine Mammals: Current Knowledge and Research Needs* (National Academy, Washington, DC, USA).
- National Research Council (2000). *Marine Mammals and Low Frequency Sound: Progress Since 1994* (National Academy, Washington, DC, USA).
- National Research Council (2003). *Ocean Noise and Marine Mammals* (National Academy, Washington, DC, USA).
- Pearson, W. H., Skalski, J. R., and Malme, C. I. (1992). Effects of sounds from a geophysical survey device on behavior of captive rockfish (*Sebastes spp.*), *Can. J. Fish. Aquat. Sci.*, 49, 1343-1356.
- Popper, A. N. and Fay, R. R. (1993). Sound detection and processing by fish: critical review and major research questions, *Brain Behav. Evol.*, 41, 14-38.
- Richardson, W. J., Greene, C. R., Malme, C. I. and Thomson, D. H. (1995). *Marine Mammals and Noise*, Academic Press, New York, 576 pp.
- Smith, M. E., Kane, A. S., and Popper, A. N. (2003). Relationship between acoustical stress and hearing sensitivity in fishes, *Abstracts of the 26<sup>th</sup> Annual Midwinter Research Meeting of the Association for Research in Otolaryngology*, Daytona Beach, FL, 164.
- Stroetz, R. W., Vlahakis, N. E., Walters, B. J., Schroeder, M. A. and Hubmayr, R. D. (2001). Validation of a new live cell strain system: Characterization of plasma membrane stress failure, *J. Appl. Physiol.*, 90, 2361-2370.
- Terhune, J. M., Friars, G. W., Bailey, J. K. and O'Flynn, F. M. (1990). Noise levels may influence Atlantic salmon smolting rates in tanks, *J. Fish Biol.*, 37, 185-187.