Chapter 107
Effects of Seismic Air Guns on Pallid Sturgeon and Paddlefish

Arthur N. Popper, Thomas J. Carlson, Jackson A. Gross, Anthony D. Hawkins, David Zeddies, Lynwood Powell, and John Young

Abstract Pallid sturgeon and paddlefish were placed at different distances from a seismic air gun array to determine the potential effects on mortality and nonauditory body tissues from the sound from a single shot. Fish were held 7 days postexposure and then necropsied. No fish died immediately after sound exposure or over the postexposure period. Statistical analysis of injuries showed no differences between the experimental and control animals in either type or severity of injuries. There was also no difference in injuries between fish exposed closest to the source compared with those exposed furthest from the source.

Keywords Fish • Anthropogenic • Noise • Damage • Lake Sakakawea

---

A.N. Popper (✉)
Department of Biology, University of Maryland, College Park, MD 20742, USA
e-mail: apopper@umd.edu

T.J. Carlson
ProBioSound, Holmes Beach, FL 34218, USA
e-mail: tj3carlson@gmail.com

J.A. Gross
Smith-Root, Inc., Vancouver, WA 98686, USA
e-mail: jgross@smith-root.com

A.D. Hawkins
Loughine Limited, Kincraig, Blairs, Aberdeen AB12 5YT, UK
e-mail: a.hawkins@btconnect.com

D. Zeddies
JASCO Applied Sciences, Silver Spring, MD 20902, USA
e-mail: David.Zeddies@jasco.com

L. Powell
CSA Ocean Sciences, Inc, Stuart, FL 34997, USA
e-mail: lpowell@conshelf.com

J. Young
CSA Ocean Sciences, Inc., Houston, TX 77079, USA
e-mail: JYoung@conshelf.com

A.N. Popper, A. Hawkins (eds.), *The Effects of Noise on Aquatic Life II*, Advances in Experimental Medicine and Biology 875,
DOI 10.1007/978-1-4939-2981-8_107

1 Background

Very little is known about the effects of seismic air guns on the physiology of fishes. Moreover, all earlier studies on the effects of intense impulsive sounds on fishes (e.g., McCauley et al. 2003; Popper et al. 2005; Hastings et al. 2008), with the exception of recent pile-driving work (e.g., Halvorsen et al. 2012a, b; see Chapter 15 by Casper et al.), have focused on the effects on inner ear tissues and/or changes in hearing and have not systematically examined other nonauditory tissues. Because there is the potential that exposure to seismic air guns could affect mortality and nonauditory tissues, the current study assessed the effects of exposure to seismic air gun sounds on pallid sturgeon (*Scaphirhynchus albus*) and paddlefish (*Polyodon spathula*). In particular, the study was designed to provide quantified and statistically reliable data to evaluate the risk of immediate and/or delayed mortality as a result of exposure to impulsive sound produced by an air gun array of the same size that could potentially be used in a seismic survey of a lake.

The experiment was conducted in Lake Sakakawea, North Dakota, and involved placing fish in cages at different distances from the air guns and exposing them to different sound levels. Control animals were subjected to the identical treatment as the experimental animals but without exposure to sound.

2 Methods

The study used 3-years-old pallid sturgeon (41.4 ± 2.5 cm standard length; 224 ± 63 g) and 2-years-old paddlefish (46.8 ± 1.7 cm standard length; 352 ± 44 g) that were hatched and reared at the Garrison Dam National Fish Hatchery (GDNFH), Riverdale, ND. The fish were passive integrated transponder (PIT) tagged to enable individual identification, and care was taken to keep track of the exposure conditions and necropsy for each animal. For exposure, the fish were transported by truck to Lake Sakakawea, transferred to a boat, and then taken to the study site where they were placed in exposure cages that were constructed of 2.54-cm^2 braided knotless mesh mounted in a frame constructed of 2.54-cm PVC pipe. After exposure to the seismic source, the fish were retrieved from the cage and transported back to the hatchery where they were held for 7 days and then examined (see Section 2.5).

2.1 Fish Cage Location

Five cages were positioned at various distances from the array in Lake Sakakawea (Fig. 107.1). In addition, a sixth control cage was placed about 150 m south of the array. Control animals were treated identically to the fish in the sound-exposure cages except that the air gun array was not fired when control fish were in the water.

The five treatment cages were at 6 m depth for the pallid sturgeon and 2 m for the paddlefish (normal swimming depths for each species).

2.2 Experimental Design

During testing, three or four fish of one species were placed in each cage. The cage was then immediately lowered to the specified depth, exposed to one shot from the air gun array, and returned to the surface. By exposing only one cage at a time, it was possible to ensure that all fish were treated consistently and that all spent the same amount of time at depth before being exposed to air gun sounds. It should be noted that the physiological condition of the fish at the time of exposure, including whether the swim bladder was full at depth, was unknown other than that the fish were active and appeared healthy before being lowered to depth.

2.3 Air Guns

The air gun barge was outfitted with four Bolt Technologies Corporation (Norwalk, CT) Long Life Air Guns. Three air guns were 2,294 cm^3 and one was 3,277 cm^3, totaling 10,160 cm^3. The barge was placed at one end of the line of exposure cages (Fig. 107.1). The air guns were at 3 m depth during the experiments.

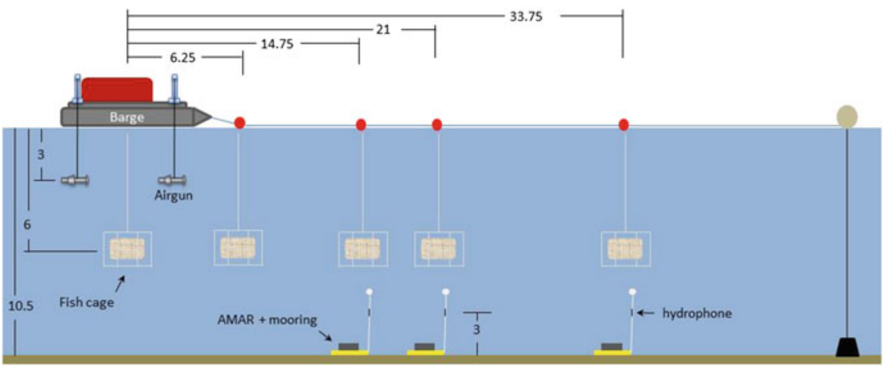

Fig. 107.1 Location of the five exposure cages relative to the air gun barge (*upper left*) and the air guns (just below the barge). Distances are in meters. The *red circles* represent the floats for the cages. The exposure cages were at a depth of 6 m for pallid sturgeon and 2 m for paddlefish. The black object at the far right represents the location of the control cage, which was at a depth of 3 m. The autonomous multichannel acoustic recorders (AMARs) and hydrophones were used to record all of the exposure signals for immediate and then later analysis

2.4 Acoustic Methodology

A comprehensive set of sound-exposure data was obtained using a combination of real-time and autonomous recording systems to measure sounds at the air gun barge and at the cages before and during the complete study (Fig. 107.1). This was necessary so that the effects on the fish (e.g., immediate or delayed mortality) could be correlated with the dose (sound) received by the fish. The sounds from each shot were monitored (via hydrophone) and the results were reviewed immediately after the shot to ensure that each was an acceptable replicate.

The maximum absolute peak sound pressure levels (SPLs) in the cages ranged from 231 dB re 1 μPa in Cage 1, which was located immediately below the barge, to 206 dB re 1 μPa at the furthest experimental cage (Cage 5), which was 33.75 m from the array. Respective values for root-mean-square (rms) SPL were 225 dB re 1 μPa at Cage 1–199 dB re 1 μPa at Cage 5, whereas the single-shot sound exposure level (SEL) for each air gun shot was 205 dB re 1 $\mu Pa^2 \cdot s$ at Cage 1 and 187 dB re 1 $\mu Pa^2 \cdot s$ at Cage 5. The rms SPL at the control site (without any seismic sound) was 105 ± 4.3 dB re 1 μPa, which represents the ambient noise level in the lake during the study.

2.5 Necropsy

Fish returned to the hatchery were kept in large tanks with flowing water. The animals were monitored every 12 h for 7 days postexposure. They were then euthanized, refrigerated for ~15 h, and necropsied. No animals died before euthanasia. Investigators doing the necropsies were not told the exposure of any individual fish.

Once a fish was removed from the refrigerator, the investigators made measurements of weight and size and recorded the tag number to correlate with exposure information. Necropsy procedures followed those developed by Halvorsen et al. (2012a, b).

Fish were immediately evaluated to assess bruising, hemorrhaging, and swim bladder condition. After the internal organs and body wall were evaluated, these organs were carefully removed or shifted to complete a more thorough examination of the swim bladder. Digital photographs were taken of all tissue as it was dissected and the internal condition of tissues of interest was recorded.

After evaluation of the swim bladder, the condition of the kidney was determined. The quantity of fat around the internal tissues was quite high in pallid sturgeon and so care was taken to not disturb the renal cavity and interconnecting vascularity while removing the fat. Removal of the fat allowed visualization of the kidney and swim bladder. Visualization of the swim bladder in paddlefish also required the removal of a layer of fat. This allowed the entire kidney to be seen.

2.6 Statistical Analysis

The experimental units in the study were individual cages, each with several fish inside. Each cage represents a binomial sample of n_i fish, of which xidied or had mortal injury. There were five sound-level classes (represented by Cages 1–5), with the level of sound decreasing with distance from the sound source. Each cage of fish received the sound generated by a single shot of the seismic array so that each cage of fish had a separate measure of sound exposure. Two sound covariates were used as independent variables to assess the relationship between sound level (exposure) and death/mortal injury (response). These were negative peak pressure (i.e., PEAK−) and SEL. There were also controls where fish received the same handling as the exposed fish except for exposure to sound. There were observations of death/mortal injury among the control fish so an Abbot's adjustment (Finney 1971) to the exposed fish was necessary.

3 Results

No animals died as an immediate result of exposure nor were there any mortalities for either species over the 7 days that the fish were held before being sacrificed. There were no significant differences in the level of tissue damage between exposed and control animals for either species or between specimens of the same species that were at different distances from the source.

4 Discussion

The single-shot exposure paradigm used in this study was selected because it was determined to be the best simulation of the probable exposure of individual fish during conduct of the proposed seismic survey strategy. In such a study, the seismic vessel carrying the air guns would move along preplanned transects where a single shot would be generated by the air gun array at each shot point. After a shot was completed, the vessel would move some distance to the next location where another shot would be fired. The distance traveled by the air gun vessel would, most likely, ensure that if a fish were exposed to two shots, one shot would usually be much higher in energy than the other so that any observed effect could be assumed to be a consequence primarily of the higher energy exposure. Thus, in the present experiment, it was concluded that only a single shot would be necessary to simulate the effective sound level to which fish would likely be exposed during an actual survey.

4.1 Overview of Findings

The initial goal in the experimental design was to develop a dose–response function whereby the levels of sound at fishes at different distances from the source could be quantitatively related to the response of the fishes to the sound exposure in terms of mortality during or within 7 days of exposure. However, a dose–response function could not be derived because no significant response of the test fish to seismic sound was detected and there were no differences in the observed effects between specimens at different distances from the source. Even at the highest sound levels, there was no mortality in fish suspended at the center of the air gun array where the greatest energy was found.

The results were contrary to the expectation that there would be mortality of fish exposed to the impulsive air gun sound, at least to sturgeon and paddlefish exposed at the highest sound levels (~224 dB re 1 μPa PEAK−, ~205 dB re 1 $\mu Pa^2 \cdot s$ SEL). The evaluation of mortality and mortal injury occurred over 7 days postexposure. At the completion of the study on day 7, the extent of swim bladder or kidney rupture or hemorrhaging did not differ significantly between exposed and control fish. Thus, it may be concluded that the sound levels from the seismic air guns used in this study, which is likely typical of many seismic surveys in lakes, were not sufficiently intense in terms of negative overpressure magnitude to cause mortality or mortal injury that could be associated with sound exposure within 7 days in sturgeon and paddlefish.

It is possible that under actual survey conditions the air guns would be fired repeatedly, possibly as frequently as once every few minutes, and so an alternative exposure scenario would have been to use multiple air gun shots. However, even if a fish were exposed to multiple air gun shots, the likelihood is that the sequence of exposures for freely swimming fish during the seismic survey would be a single high-level exposure followed by one or more exposures at much lower levels. The number of possible combinations of multiple exposures is very large when considering the uncertainties about the distribution of fish, their normal movement patters, and any possible response to sound. However, it is clear that because of the high rate of loss of sound energy (25log[r] transmission loss) with distance in shallow water, the total energy of exposure would almost certainly be dominated by the initial exposure.

4.2 Acclimation to Depth

Fish use their swim bladder to manage their buoyancy at different depths. To do this, they add gas to or remove gas from the swim bladder as they change depth. Fish add gas to the swim bladder either by gulping air at the surface of the water before they descend (physostomous species) or by using a special gland that they have as part of the swim bladder to pump air from the blood into the chamber (physoclistous species; see Stephenson et al. 2010). In either case, if the swim bladder is not properly inflated at the depth of the animal, the swim bladder does not help the fish maintain its position in the water column, thereby making it expend energy not otherwise required.

More important for this study, if the swim bladder is not fully inflated, the walls of the organ are not properly located with respect to the surrounding tissues. As a consequence, when the animal is exposed to an impulsive source, the walls do not move with the same amplitude or speed as they do in a fish with a normally inflated swim bladder. Thus, a fish that does not have proper swim bladder inflation for the depth at which it is exposed is less likely to show injuries than would a fish in which the swim bladder is properly inflated.

It is not clear whether the fish used in the study were physiologically acclimated to the exposure depth or not. The fish were lowered to depth as soon as they were placed in the cages and then exposed to sound within about a minute of reaching depth. As a consequence, the physostomous pallid sturgeon and paddlefish may not have had sufficient time at the surface to gulp the air they would need to have a properly filled swim bladder at 2 m depth (~120.9 kPa absolute pressure) in the case of the paddlefish and 6 m (~160.2 kPa absolute pressure) for the pallid sturgeon.

4.3 Implications of Results to Other Seismic Studies

It is concluded that although each seismic survey differs in the size of the air gun array, operational water depths, and the species potentially affected, the results from the present study suggest levels of impulsive seismic air gun sound to which adult fish can be exposed without immediate mortality. Pallid sturgeon and paddlefish with a body mass on the order of 200–400 g exposed to a received single-impulse SEL of 205 dB re 1 $\mu Pa^2 \cdot s$ did not die immediately or within 7 days of exposure and that the probability of mortal injury did not differ between exposed and control fish.

Acknowledgments We are grateful to the very large number of people who provided support for this project. Although there is insufficient room here to mention all the people, we express particular thanks to Al Hart (Continental Shelf Associates) for his strong logistical support; Dr. Brandon Casper (University of Maryland) for training personnel in necropsy and animal handling procedures; Tristany Wagner, Carl Schilt, and Alicia Stewart for their conduct of the necropsy; and Laura Burckhardt (SWCA Environmental Consultants) for her help in many aspects of this study including data management. We are grateful to Helen Popper for careful editing of the final manuscript.

References

Finney DJ (1971) Probit analysis, 3rd edn. Cambridge University Press, Cambridge

Halvorsen MB, Casper BM, Matthews F, Carlson TJ, Popper AN (2012a) Effects of exposure to pile driving sounds on the lake sturgeon, Nile tilapia, and hogchoker. Proc Biol Sci 279: 4705–4714

Halvorsen MB, Casper BM, Woodley CM, Carlson TJ, Popper AN (2012b) Threshold for onset of injury in Chinook salmon from exposure to impulsive pile driving sounds. PLoS ONE 7, e38968. doi:10.1371/journal.pone.0038968

Hastings MC, Reid CA, Grebe CC, Hearn RL, Colman JG (2008) The effects of seismic airgun noise on the hearing sensitivity of tropical reef fishes at Scott Reef, Western Australia. In: Conference on underwater noise measurement, impact and mitigation, Southampton, 14–15 October 2008, Proceedings of the Institute of Acoustics, vol 30, part 5

McCauley RD, Fewtrell J, Popper AN (2003) High intensity anthropogenic sound damages fish ears. J Acoust Soc Am 113:638–642

Popper AN, Smith ME, Cott PA, Hanna BW, MacGillivray AO, Austin ME, Mann DA (2005) Effects of exposure to seismic airgun use on hearing of three fish species. J Acoust Soc Am 117:3958–3971

Stephenson JR, Gingerich AJ, Brown RS, Pflugrath BD, Deng Z, Carlson TJ, Langeslay MJ, Ahmann ML, Johnson RL, Seaburg AG (2010) Assessing barotrauma in neutrally and negatively buoyant juvenile salmonids exposed to simulated hydro-turbine passage using a mobile aquatic barotrauma laboratory. Fish Res 106:271–278