STUDY TITLE: Effects of Pile Driving Sounds on Non-Auditory Tissues of Fish

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BACKGROUND: There is a growing concern in the United States and throughout the world that sounds produced during in-water pile driving that is used in construction of wind farms, bridges, and other projects has the potential to affect the health and survival of fishes. These sounds may be sufficiently intense to potentially produced damage to tissues. This occurs due to the rapid pressure changes resulting from intense impulsive sounds. Such damage is called barotrauma. Earlier field studies attempted to examine the impacts on fishes at actual pile driving construction sites. These studies suffered, however, from the inability of the investigators to control the pile driving activities and the immense difficulties of working in the field. As a consequence, this study described here was designed to provide pile-driving exposure within the confines of a controlled laboratory setting. This allowed for complete control of the sounds to which fish were exposed and the quantitative assessment of tissue damage in fish. The data and analyses determined, for the first time, the sound levels at which onset of tissue damage would occur in several fish species.

OBJECTIVES: The primary objectives of the study were to: (1) determine the barotrauma effects of realistic pile driving signals on different species of fish; and (2) suggest safe levels of sound that would not harm fish.

DESCRIPTION: In order to expose fish to realistic pile driving signals, a High Intensity Controlled Impedance Fluid-filled wave Tube (HICI-FT) was developed that enabled laboratory simulation of high-energy impulsive sounds that were characteristic of aquatic far-field, plane-wave acoustic conditions. The HICI-FT was used to expose fish to controlled pile driving signals. The number of strikes was held constant at 1920 or 960 while the energy of the single strike was varied. Altering these variables provided a controlled total energy level to which fish were exposed and provided a three dimensional exploration of typical exposure space as would be experienced in the field. The barotrauma response of the fish tissues was quantitatively assessed at each sound exposure level for Chinook salmon, striped bass, Nile tilapia, lake sturgeon, and hogchoker. Comparisons of the barotrauma effects were made at the different sound levels and on each species. Measurements of post-exposure recovery were determined for several of the tested species.

SIGNIFICANT CONCLUSIONS: The results from these studies are the first to quantify the effects of impulsive sounds on fishes. These are also the first scientific data useful for developing criteria relevant to impulsive sources. The results defined an onset of injury in Chinook salmon at an SEL_{cum} of 210 dB re 1µPa^2·s derived from 960 strikes and SEL_{ss} of 180 dB re 1µPa^2·s. Onset of physiological effects occurred at around SEL_{cum} was 207 re 1µPa^2·s derived from 960 strikes and SEL_{ss} of 177 dB re 1µPa^2·s. Results suggested that other species may be slightly more sensitive and might have a lower injury threshold. It is important to note the metrics used to define threshold include the number of strikes and the SEL_{ss} levels that yield the SEL_{cum} values.

Major conclusions of this study were that: (a) for all species studied, onset of barotrauma effects did not occur until the SEL_{cum} was substantially above the current interim regulations; (b) barotrauma injuries were not observed in a species without a swim bladder (hogchoker); (c) there were differences in the sound exposure level at which barotrauma appeared in fish. In the most sensitive tested species barotrauma was seen at an SEL_{cum} of 207 dB re 1 µPa^2·s yielded from SEL_{ss} 177 dB re 1 µPa^2·s and 960 strikes. (d) The important metrics used to define the impulsive exposure incorporate how the energy accumulated. Three recommended metrics are: SEL_{cum}, SEL_{ss}, and the number of strikes. (e) Effects from exposure to pile driving sounds appear to be consistent across species, even when there are substantial differences in fish morphology, including in both physostomous and physoclistous fishes.

RESULTS: In the first study juvenile Chinook salmon (*Oncorhynchus tshawytscha)*, a species with a physostomous swim bladder, were exposed to impulsive sounds and subsequently evaluated for physical barotrauma injuries. Observed injuries ranged from mild hematomas at the lowest sound exposure levels to organ hemorrhage at the highest sound exposure levels. Frequencies of observed injuries were used to compute a biological response weighted index (RWI) to evaluate the physiological impact of injuries at the different exposure levels. As single strike and cumulative sound exposure levels (SEL_{ss}, SEL_{cum} respectively) increased, RWI values increased. Based on the results, tissue damage associated with adverse physiological costs occurred when the RWI was greater than 2. In terms of sound exposure levels, an RWI of 2 was achieved for 1920 strikes by 177 dB re 1 µPa^2·s SEL_{ss} yielding a SEL_{cum} of 210 dB re 1 µPa^2·s, and for 960 strikes by 180 dB re 1 µPa^2·s SEL_{ss} yielding a SEL_{cum} of 210 dB re 1 µPa^2·s. These metrics define thresholds for onset of injury in juvenile Chinook salmon.

The question then arose as to whether fish show increased injuries post exposure, and/or whether they could recover from injuries. To explore this, juvenile Chinook salmon were exposed to simulated high intensity pile driving signals to evaluate their ability to recover from barotrauma injuries. Fish were exposed to one of two cumulative sound exposure levels for 960 pile strikes (217 or 210 dB re 1 µPa^2·s SEL_{cum}; single strike sound exposure levels of 187 or 180 dB re 1 µPa^2·s SEL_{ss} respectively). This was followed by an assessment of injuries immediately (day 0), 2, 5, or 10 days post-exposure. There were no observed mortalities from the pile driving sound exposure. Fish exposed to 217 dB re 1 µPa^2·s SEL_{cum} displayed evidence of healing from injuries as post-exposure time increased. Fish exposed to 210 dB re 1 µPa^2·s SEL_{cum} sustained minimal injuries that were not significantly different from control fish at days 0, 2, and 10. The exposure to 210 dB re 1 µPa^2·s SEL_{cum} replicated the findings in the previous study that defined this level as the threshold for onset of injury. Furthermore, these data support the hypothesis that one or two *Mild* injuries resulting from pile driving exposure are unlikely to affect the survival of the exposed animals, at least in a laboratory environment.

Another issue was to determine if the effects of pile driving found in juvenile Chinook salmon apply to other species. This phase of the study was a comparative analysis of responses to pile driving stimuli. Three other species were used, the lake sturgeon (*Acipenser fulvecens*, Acipenseridae), a species with a physostomous swim bladder; the Nile tilapia (*Oreochromis niloticus*, Cichlidae), a species with a physoclistous swim bladder; and the hogchoker (*Trinectes maculates*, Achiridae) a flatfish without a swim bladder, and these species were also compared to the Chinook salmon.

Results for the hogchoker demonstrated no observable barotrauma at the maximum sound exposure used (the same level that resulted in mortal injuries in the other tested species). At the maximum sound exposure, Nile tilapia had the highest number and most severe injuries overall as compared to the lake sturgeon. Decreases in the exposure levels were correlated with a decrease in the number and severity of injuries for each species. Moreover, as exposure levels came nearer to the onset of injury threshold found in juvenile Chinook salmon, Nile tilapia, lake sturgeon, and Chinook salmon showed similar injury responses, yet the tilapia and sturgeon showed similar RWI value at an SEL_{cum} of 207 dB re 1 $\mu Pa^2 \cdot s$ yielded from SEL_{ss} 177 dB re 1 $\mu Pa^2 \cdot s$ and 960 strikes . These results imply that the presence and type of swim bladder correspond with barotrauma injuries at the higher sound exposure levels. Therefore, physoclistous fish may be more sensitive to the higher sound exposure levels than physostomous fish.

STUDY PRODUCTS:

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