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The effect of rapid and sustained decompression on barotrauma in juvenile brook lamprey and Pacific lamprey: Implications for passage at hydroelectric facilities

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ABSTRACT

Fish passing downstream through hydroelectric facilities may pass through turbines where they experience a rapid decrease in pressure, which can lead to barotraumas including swim bladder rupture, exopthalmia, emboli, and hemorrhaging. In juvenile Chinook salmon, the main mechanism for injury is thought to be expansion of existing gases (particularly those present in the swim bladder) and the rupture of the swim bladder ultimately leading to exopthalmia, emboli and hemorrhaging. In fish lacking a swim bladder, such as lamprey, barotraumas due to rapid decompression may be reduced, however this has yet to be extensively studied. Another mechanism for barotrauma can be gases coming out of solution and the rate of this occurrence may vary among species. In this study, juvenile brook and Pacific lamprey acclimated to 146.2 kPa (equivalent to a depth of 4.6 m) were subjected to rapid (<1 s) or sustained decompression (17 min) to a very low pressure (13.8 kPa) using a protocol previously applied to juvenile salmon. No mortality or evidence of barotraumas was observed following rapid decompression, nor up to 120 h after sustained decompression. In contrast, mortality or injury would be expected for 97.5% of juvenile Chinook salmon exposed to a similar rapid decompression to these very low pressures. Additionally, juvenile Chinook salmon experiencing sustained decompression died within 7 min. Thus, juvenile lamprey may not be susceptible to barotraumas associated with turbine passage to the same degree as juvenile salmonids.

1. Introduction

The development of hydropower facilities has influenced fish worldwide. The presence of hydroelectric dams can result in habitat destruction, fragmentation of populations and hinder migration (Kareiva et al., 2000). Passage through turbines has been of particular concern. During turbine passage, there are several potential sources of injury and mortality including blade strike, shear forces, and rapid decreases in pressure (Čada et al., 1997). Mortality associated with blade strike, turbulence and shear forces is generally low among turbine passed fish (Neitzel et al., 2004). However, all fish passing turbines experience a rapid decrease in pressure which can result in barotraumas, most notably rupture of the swim bladder, exopthalmia, emboli and hemorrhaging (Brown et al., 2009, 2012a; Carlson et al., 2012). The ratio of pressure change from acclimation pressure (the depth at which gasses in the body are at equilibrium with their surrounding environment and neutral buoyancy has been attained) to exposure pressure (the lowest pressure fish experience, also called the nadir) is most predictive of mortality and injury for juvenile Chinook salmon exposed to simulated turbine passage (STP; Brown et al., 2012a).

Decompression induced damage can arise from two mechanisms: the expansion of existing bubbles, dictated by Boyle's Law, and gases coming out of solution and forming bubbles in the blood and tissues, dictated by Henry's Law. Among juvenile Chinook salmon, Brown et al. (2012b) determined that the former was responsible for most of the barotrauma observed following STP. As fish experience a decrease in pressure during turbine passage, the volume of the swim bladder will increase proportionally, which can result in the rupture of the swim bladder, and exopthalmia, hemorrhaging or emboli in the tissues and fins (Brown et al., 2012b).

Gases coming out of solution in the blood and tissues and forming bubbles can also lead to barotraumas, especially if decompression is maintained longer than is observed in STP. Henry's Law states that the amount of gas that can be dissolved in a fluid is directly proportional to the partial pressure of the gases to which it is equilibrated. As the surrounding pressure is reduced, such as

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during turbine passage, the solubility of gases is reduced and blood becomes temporarily supersaturated. The dissolved gas may come out of solution into a gas phase, resulting in emboli. To explore this source of barotrauma, Brown et al. (2012b) slowly (over 3 min) decompressed juvenile Chinook salmon to avoid swim bladder rupture by allowing fish to release gas through their pneumatic duct, and then held fish at a sustained low pressure (13.8 kPa). After a median of 3 min (range = 2.2–7) at this pressure, juvenile Chinook salmon lost equilibrium and died, many with emboli in the fins, heart, caudal vein, gills or kidney but no swim bladder rupture. Thus, mortality was likely associated with gases coming out of solution at this low sustained pressure. Exposure to low pressures for 7 min is a much greater duration than fish would experience during rapid decompression (<1 s) associated with turbine passage; thus most barotraumas observed in juvenile salmon exposed to turbine passage likely result from the expansion and rupture of the swim bladder. However, it is not known if barotraumas of this nature can also occur through this route in fish that lack a swim bladder, such as lamprey, during migration through hydro facilities.

In the Columbia River Basin (CRB) Pacific lamprey, *Entosphenus tridentatus*, are of concern as populations are in decline (Close et al., 1995; Kareiva et al., 2000). While there are many factors influencing lamprey, the effect of rapid decompression associated with turbine passage is largely unknown. Lamprey lack a swim bladder and consequently may respond differently to pressure changes than salmonids. Juvenile lamprey may also have a higher potential for turbine entrainment because they migrate lower in the water column (Long, 1968). The objective of this study was to gain a better understanding of how juvenile lamprey are affected by exposure to low pressures. Since they lack a swim bladder, we hypothesized that they would be less susceptible to barotrauma than fish with a swim bladder. We also hypothesized that if they did suffer from barotrauma that they may be more associated with Henry's Law (gas coming out of solution) rather than Boyle's Law (expansion of existing gas). This study used the methods previously applied by Brown et al. (2012b) to determine the pathways of barotraumas in juvenile Chinook salmon.

2. Methods

2.1. Fish acquisition and handling

Juvenile western brook lamprey ammocoetes, *Lampetra richardonii*, (n = 15; median length = 111 mm, range = 80–124 mm; median weight = 2.4 g, range = 0.8–3.3 g) were collected from the Little Klickitat River, Washington (March, 2011). They were held in 37 L aquaria supplied with Columbia River water with a sediment layer to provide natural conditions at the Pacific Northwest National Laboratory Aquatic Research Laboratory. Approximately 1 week prior to testing, lamprey were acclimated to 17 °C well water.

Juvenile Pacific lamprey, *E. tridentatus*, (n = 20; median length = 138 mm, range = 127–183 mm; median weight = 3.3 g, range = 2.7–7.9 g) were obtained from the John Day Dam juvenile bypass system (July, 2011). They were held in 17 °C well water in aquaria at the Pacific Northwest National Laboratory – Aquatics Research Laboratory during the study.

2.2. System description

All testing was conducted in the hyper/hypobaric chambers of the Mobile Aquatic Barotrauma Laboratory, described by Stephenson et al. (2010). Throughout the study, 17.0 °C well water was supplied to chambers and total dissolved gas levels were ~102%. All pressures reported are absolute pressures, with surface pressure at 101.3 kPa.

2.3. Barotraumas due to rapid decompression

Three brook lamprey were loaded into a hyper/hypobaric chamber and acclimated for 16–24 h to pressures equivalent to 4.6 m depth (146.2 kPa) in June 2011. They were exposed to pressures representative of passage of Kaplan turbine units typical of Columbia River hydropower projects (see Fig. 2 in Stephenson et al., 2010). As fish pass between the turbine blades, they are exposed to a sudden pressure decrease (lasting <1 s) before returning to surface pressure downstream of the dam (Deng et al., 2010). Nadir (the lowest) pressures lower than 50 kPa are likely less common than those greater than 50 kPa in the CRB. The lowest pressure the fish were exposed to was 13.8 kPa (a ratio of pressure change = 10.6) representing a pressure that would be lower and more damaging than most fish experience when passing turbines.

Immediately following exposure to the pressure profile, brook lamprey were euthanized. X-rays of one lamprey were taken. Necropsies were performed within 15 min of exposure on the remaining lamprey to establish the presence of barotraumas.

2.4. Barotraumas due to sustained decompression

Juvenile brook (n = 12) and Pacific lamprey (n = 20) were placed in hyper/hypobaric chambers and acclimated for 16–24 h to pressures equivalent to a depth of 4.6 m (146.2 kPa) in August 2011. For tests with brook lamprey, three individuals were placed in each chamber per trial. For tests with Pacific lamprey, each individual was placed in a plexiglass cylinder (length = 19.0 cm; diameter = 5.1 cm) for better viewing, and then placed in a chamber. The cylinder ends were covered with perforated screen.

Following acclimation, the pressure was slowly decreased from 146.2 to 13.8 kPa over ~3 min (median = 2.1 min for brook lamprey; median = 3.0 for Pacific lamprey) similar to Brown et al. (2012b). Pressure was maintained at 13.8 kPa for ~17 min (median = 17.9 min [range = 13.0–20.0 for brook lamprey]; median = 17.0 min [range = 17.0–17.5] for Pacific lamprey).

Following exposures, seven Pacific lamprey were euthanized, and necropsied. X-rays were taken of two Pacific lamprey prior to necropsy. All other lamprey were held in aquaria for up to 120 h (brook lamprey: 48 h [n = 3] or 72 h [n = 9]; Pacific lamprey: 24 h [n = 3], 48 h [n = 3], 72 h [n = 2], 96 h [n = 3] or 120 h [n = 2]) to monitor for delayed effects, then euthanized and necropsied.

3. Results

3.1. Barotraumas due to rapid decompression

None of the brook lamprey exposed to rapid decompression died as a result of the exposure. Also, no barotraumas were observed during necropsy or in X-rays (Table 1).

3.2. Barotraumas due to sustained decompression

No immediate or delayed mortalities or injuries were observed among either brook or Pacific lamprey exposed to slow decompression from surface pressure (101.3 kPa) to 13.8 kPa and then held at low pressure (13.8 kPa; Table 1). Neither X-rays nor necropsies revealed barotraumas (Fig. 1). Juvenile lamprey remained on the bottom of the chamber throughout the exposure, seemingly undisturbed.

Table 1
Summary of mortality and injuries observed in juvenile Chinook salmon, brook lamprey and Pacific lamprey exposed to rapid and sustained decompression. Results for juvenile salmon are from Brown et al. (2012b). "X" denotes the injury was observed.

Injury	Location	Juvenile Chinook salmon		Juvenile brook lamprey		Juvenile Pacific lamprey
		Rapid decompression	Sustained decompression	Rapid decompression	Sustained decompression	Sustained decompression
Mortality		97.5%[a]	100% ($n = 23$)	0% ($n = 3$)	0% ($n = 12$)	0% ($n = 20$)
Swim bladder rupture		X		n/a	n/a	n/a
Hemorrhaging						
	Heart	X	X			
	Kidney	X	X			
	Gills	X	X			
	Fin	X	X			
	Vent	X				
Emboli						
	Heart	X	X			
	Caudal vein	X	X			
	Kidney	X	X			
	Liver	X				
	Gills	X	X			
	Fins	X	X			
Exopthalmia		X				

[a] The number of juvenile Chinook salmon expected to be mortally injured (mortality or injuries leading to mortality) from rapid decompression is based on the relationship between the ratio of pressure change of Brown et al. (2012a).

4. Discussion

Results indicate that juvenile brook and Pacific lamprey have low susceptibility to mortality or injury resulting from rapid decompression during STP or during sustained decompression (up to 17 min). This was the case despite the fact that the lamprey were exposed to extremely low pressures that fish likely seldom experience when passing turbines. The lack of a swim bladder in lamprey, and the duration over which they could tolerate low pressures without ill effect demonstrates their resistance to the two possible mechanisms leading to barotrauma in juvenile salmonids.

Brown et al. (2012b) have shown that swim bladder rupture during rapid decompression is likely the main mechanism of barotrauma during STP in juvenile Chinook salmon, and several other injuries are also observed (Table 1). In the current study, brook lamprey acclimated to 4.6 m of depth (146.2 kPa) and exposed to rapid decompression with a nadir pressure of 13.8 kPa (ratio of pressure change = 10.6) did not exhibit mortality or injuries. Based on the equation for the probability of mortal injury (i.e., mortality or injury leading to mortality) presented in Brown et al. (2012a), 97.5% of juvenile Chinook salmon exposed to the same rapid pressure change would have exhibited mortal injuries. Clearly, juvenile Chinook salmon are much more susceptible to barotraumas resulting from rapid decompression than lamprey, likely due to the presence of the swim bladder.

Although juvenile lamprey appear to be relatively unaffected by sustained exposure to low pressures, both emboli and hemorrhaging were observed within 3 min among juvenile Chinook salmon exposed to similar conditions (Table 1; Brown et al., 2012b). While it is unlikely that either juvenile lamprey or salmonids would be exposed to low pressures for prolonged periods during passage of hydro facilities, this highlights the unique physiological differences between salmonids and lamprey, which may be useful for management of these populations.

The results of this study demonstrate that differences in fish morphology and physiology can result in dramatic differences in responses to decompression and more research is required to gain a broader understanding of the basis for these differences. For example, physoclistous fish (i.e., those lacking a connection between the swim bladder and gut) cannot rapidly expel gases from the swim bladder, which may predispose them to even greater risk of barotrauma (Hogan, 1941; Čada et al., 1997). Research should also be done on a range of life stages since younger fish may be more fragile and vulnerable to injury.

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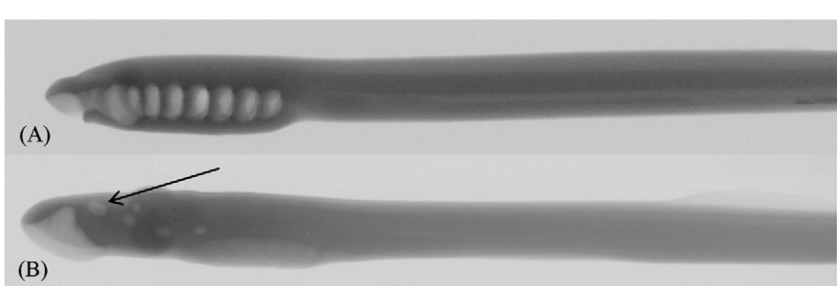

Fig. 1. X-ray images of a juvenile Brook lamprey (A) and a juvenile Pacific lamprey (B) slowly decompressed and held at 13.8 kPa for 17 min. These fish were previously acclimated to 146.2 kPa. Bubbles can be seen within the mouth on the X-ray of the Pacific lamprey (an arrow indicates one of these bubbles).

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