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The effect of an externally attached neutrally buoyant transmitter on mortal injury during simulated hydroturbine passage

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On their seaward migration, juvenile salmonids commonly pass hydroelectric dams. Fish passing through hydroturbines experience a rapid decrease in pressure as they pass by the turbine blade. The severity of this decompression can be highly variable but can result in injuries such as swim bladder rupture, exophthalmia, and emboli and hemorrhaging in the fins and tissues. Recent research indicates that the presence of a telemetry tag (acoustic, radio, inductive) implanted inside the coelom of a juvenile salmon increases the likelihood that the fish will be injured or die during turbine passage. Thus, previous turbine passage survival research conducted using telemetry tags implanted into the coelom of fish may have been inaccurate. Therefore, a new technique is needed to provide unbiased estimates of survival through turbines. This study evaluated the effectiveness of a neutrally buoyant externally attached acoustic transmitter on decompression-stressed juvenile Chinook salmon. Both nontagged fish and fish tagged with a neutrally buoyant external transmitter were exposed to a range of rapid decompressions simulating turbine passage. Juvenile Chinook salmon tagged with a neutrally buoyant externally attached acoustic transmitter did not experience a higher degree of barotrauma-induced injuries than their nontagged counterparts. We suggest that future research include field-based comparisons of survival and behavior among fish tagged with a neutrally buoyant external transmitter and those internally implanted with transmitters. © *2012 American Institute of Physics*. [doi:10.1063/1.3682062]

I. INTRODUCTION

Survival of juvenile salmonids passing through hydroturbines can vary depending on several factors. The stresses experienced by fish when passing through turbines vary depending on the type of turbine, the ways in which turbines are operated, the route the fish take when passing through the turbine, the discharge rate, and the head differential (forebay and tailrace elevation differential).[1–3] Rapid decreases in pressure during turbine passage can result in injuries such as swim bladder rupture, exophthalmia, and emboli and hemorrhaging in the fins and tissues.[4,5] Researchers typically use telemetry tags (acoustic or radio) as a tool to track movements of fish following turbine passage and to evaluate how these factors influence survival of turbine-passed fish. However, recent research indicates that the presence of a telemetry tag (acoustic, radio, inductive) implanted inside the coelom of a juvenile salmon increases the likelihood that the fish will be injured or die when exposed to rapid decompression that is

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characteristic of turbine passage.[6] Carlson *et al.*[6] found that the variability in injury and mortality sustained due to changes in pressure (experimental barotrauma that simulated turbine passage) varied with the fish's tag burden and the amount by which pressures changed. Fish implanted with larger transmitters or having a higher tag burden (i.e., the weight of a transmitter relative to the weight of a fish) had higher levels of injury and mortality. Thus, previous turbine passage injury and mortality estimates that were conducted using telemetry tags implanted into the coelom of fish may have been inaccurate.

Accurate and precise assessments of turbine survival are critical for evaluating turbine operations and for turbine assessment prior to and after their replacement to determine if different operations or turbine designs improve survival. This is especially important because a large proportion of the existing turbines in North America is nearing the end of their functional lifespan and need replacement. Thus, a new technique is needed to provide unbiased estimates of survival through existing and advanced replacement turbines.

This research provides an evaluation of the effectiveness of a neutrally buoyant externally attached acoustic transmitter (based on JSATS or the Juvenile Salmon Acoustic Telemetry System[7]) developed by Deng *et al.*[8] Images of the transmitter and a fish tagged with a transmitter are available in Ref. 8. We hypothesized that a neutrally buoyant externally attached acoustic transmitter would reduce bias in survival studies because it will not add excess mass (the weight in water of an object) to the fish or take up space within the coelom. Previous research has indicated that fish bearing acoustic transmitters that have an excess mass lead fish to increase the volume of their swim bladder; that is, they increase their displacement to balance the increased excess mass.[9,10] This increased volume of gas in the swim bladder leads to a higher likelihood that fish will be injured during the rapid decompression associated with turbine passage.[11] In addition, the volume of the transmitter present in the coelom would also likely lead to a higher incidence of barotrauma when fish are exposed to rapid decompression. The swim bladder may be more likely to rupture, and there may be a higher likelihood of compression-related injuries (injuries cause by the increased size of the swim bladder such as damage to internal organs or vasculature).

We hypothesized that juvenile Chinook salmon tagged with a neutrally buoyant externally attached acoustic transmitter would not experience a higher degree of barotrauma than their nontagged counterparts. To test this hypothesis, both nontagged fish and fish tagged with a neutrally buoyant external transmitter were exposed to a range of rapid decompressions simulating turbine passage.

II. METHODS

Hatchery-reared juvenile Chinook salmon *Oncorhynchus tshawytscha* ($n = 368$; mean length = 123.4 mm, range 95 to 137 mm; mean weight = 21.2 g, range 7.9 to 33.7 g) were exposed to simulated turbine passage (STP) treatments between January 8 and 27, 2011 (Table I). The fish were either acquired as fry or hatched and reared from eggs at the PNNL Aquatic Research Laboratory (ARL).

Testing of juvenile salmon was conducted in the hyper/hypobaric chambers described by Stephenson *et al.*[11] During testing, ambient well water (median temperature = 16.9 °C; range 16.6 to 17.4 °C) was pumped to the chambers. Total dissolved gas (TDG) levels were a median of 102.4% (range 101.8 to 102.9). Total dissolved gas was monitored with sensors installed

TABLE I. Sample sizes and mean length and weight of juvenile Chinook salmon examined for each treatment.

		Fork length (mm)	Mass (g)
Transmitter treatment	*n*	Mean ± SD (range)	Mean ± SD (range)
Nontagged	184	124 ± 8 (97–137)	21.2 ± 4.8 (9.6–32.1)
Externally tagged	184	123 ± 8 (95–137)	21.1 ± 4.9 (7.9–33.7)

within each chamber (Model T507, In-Situ, Inc., Fort Collins, Colorado; ± 1.5 mmHg accuracy). Levels of TDG were recorded on a data logger (Campbell Scientific, Logan, Utah) controlled by a program written in CRBASIC and implemented via LOGGERNET. Water was supplied to all chambers at a continuous rate of 7.6 l/min with a flow control accuracy of ±0.95 l/min (see Ref. 11 for a description of water treatment).

A. Acclimation prior to pressure exposure and simulated turbine passage

Juvenile Chinook salmon were marked and loaded into chambers as described in Ref. 11. Acclimated pressures were equivalent to the absolute pressures that would exist at a depth of 4.6 m (146.1 kPa; all pressures presented are in absolute pressure) in fresh water. Fish were held at acclimation pressure for 16–24 h prior to testing to allow ample time to attain neutral buoyancy and equilibration of gas tensions in bodily fluids and tissues. The determination of buoyancy, exposure to STP, and necropsy procedures were conducted using observations and video equipment described in Refs. 11 and 12. Although we tested 368 fish, a small proportion (7.3%) of fish were negatively buoyant (15 nontagged fish and 12 externally tagged fish; none of the fish were positively buoyant) and never gained neutral buoyancy following 16 h of acclimation. Given the results from Ref. 11 and the assumption that in-river fish are neutrally buoyant when approaching hydroelectric facilities (due to energy conservation in wild systems), we included only neutrally buoyant fish in statistical analyses.

B. Exposure pressures and rate of pressure change

Lowest exposure pressures (i.e., the nadir) during STP ranged from 11 to 80 kPa, with a median of 32 kPa. The rate of pressure change (i.e., rate of decompression) during STP ranged from 889 to 2654 kPa/s (median = 1648 kPa/s). The pressure exposure profiles used represent passage through Kaplan turbine units typical of the hydropower projects on the lower Snake and Columbia rivers (see Ref. 11, Fig. 2, and Ref. 4). The exposure profile simulated the pressure of flow passing through the turbines, which may increase to nearly 400 kPa over approximately a 20-s period, as fish enter the turbine intake and approach the turbine runner. As fish pass between the turbine runner blades, they are exposed to a sudden pressure decrease (lasting < 1 s) before returning to near surface pressure as they enter the downstream channel. The overall pressure change will increase with increased project head. Pressures are higher on the upstream side of the turbine blades (pressure side) and lower on the downstream side (suction side). The magnitude of the pressure drop during turbine passage is dependent upon the turbine runner design, the operation of the turbine, the rate of flow through the turbine, the submergence of the turbine runner (i.e., elevation of the turbine runner relative to the downstream water surface elevation; at a constant forebay height, nadirs will be lower if the submergence is more shallow), the total project head, and the flow path.[1–3] The pressure changes are not uniform across the cross-section of the turbine; locally higher pressures occur near the leading edges of the blades on the upstream side, and lower pressures occur near the blade tips on the downstream side. However, all fish that pass through a turbine runner experience decompression.[13] For any given turbine, the nadir pressure will decrease with increased turbine flow. The lowest pressure a fish may experience during turbine passage can vary from approximately 200 to -2 kPa,[2] depending on turbine design, operation, head, and passage route.

C. Mortal injury

After they were exposed to STP, many fish died within a few minutes or received pressure related injuries (barotrauma) sufficient to cause eventual mortality. It is not always feasible to hold fish following rapid decompression testing, and the conditions in which fish could be held could be highly variable (pressure, temperature, total dissolved gas, or other conditions may vary). Consequently, a metric that predicted mortal injury[14] was used as the response variable in this study instead of mortality and a multitude of different injury types. The mortal injury metric was derived by analysis of a large data set of juvenile Chinook salmon (similar in size to those in this study) exposed to rapid decompression in a series of earlier research.[5] The metric associated the fish that died within minutes of rapid decompression with the injuries that were observed during subsequent necropsy. The injuries seen most often in fish that died were included in the metric.[14] The first step in building this metric was to make odds ratios from 2×2 contingency tables that associated mortality with the presence or absence of each injury type. Using Fisher's exact test, it was determined if an injury was significantly associated with mortality. The 28 injuries that were significantly associated with mortality were entered into a stepwise logistic model under step two of the analysis. Model building is the process of selecting a best subset of predictor variables in a stepwise regression model from a larger set, based on the value of the Akaike information criterion (AIC).[15,16] The AIC is a goodness-of-fit measure of an estimated statistical model that trades off the goodness of fit and the number of variables included in the model. The injuries retained by this model included exopthalmia (eye-pop); hemorrhaging in the pericardium, liver, or kidney; ruptured swim bladder; blood or bile secretions from the vent; and emboli in the gills or pelvic fins. The third step of this analysis was to fit these 8 injuries into another logistic regression model and test the significance of individually adding all 28 possible two-way interaction terms. No two-way interaction terms were found to be significant. Therefore, mortal injury served as the endpoint and response variable for these analyses, and fish with any one of these eight injuries present, or fish that were dead shortly following testing (within ~10 min), were classified as mortally injured. Although other injuries were noted which could lead to delayed mortality or increased chance of predation, they were not highly associated with mortality shortly after STP and therefore were not included in this analysis. This metric may not be useful in research involving other species due to anatomical differences among species.

D. Statistical models

An analysis of deviance table was constructed to examine the differences in mortal injury between tagged and nontagged fishes. Analysis of deviance based on a binomial error structure and log-link was used in modeling the data and testing the hypotheses. The independent variables included nadir as a continuous variable and tag type as a categorical variable (tagged or nontagged). A confidence interval was also constructed on the proportion difference in mortality from nontagged to externally tagged and fitted regression lines using a log-link. A plot of nadir versus proportion of mortal injury shows that fish with a nadir higher than 51 kPa did not experience mortal injury. These fish were removed from the analysis because they may obscure an effect of tag type.

III. RESULTS

The relationship between the probability of mortal injury and nadir was not significantly ($P = 0.38$) different between externally tagged and nontagged juvenile Chinook salmon (Table II). An overall significant ($P < 0.001$) decrease in mortal injury was seen as the nadir to which fish were exposed decreased (Table III; Fig. 1). The equation for predicting mortal injury at a given logged ratio of pressure (LRP) change (the acclimation pressure divided by the exposure pressure; logged using natural log) for nontagged fish is

TABLE II. Analysis of deviance of the factors associated with the mortal injury of juvenile Chinook salmon with respect to simulated turbine passage.

Source	df	Deviance	Mean deviance	*F*	*P*
Null	61	115.36			
Nadir	1	47.988	47.988	42.581	<0.0001
Tag type	1	0.88	0.88	0.781	0.3804
Error	59	66.492	1.127		

TABLE III. Coefficients of the model describing the relationship between mortal injury and nadir. Tag type refers to fish being either nontagged or externally tagged with a neutrally buoyant acoustic transmitter.

Source	Estimate	SE	*T*	*P*
Intercept	0.336	0.197	1.701	0.089
Nadir	−0.382	0.064	−5.961	<0.001
Tag type	0.134	0.13	1.031	0.303

$$\text{Probability of mortal injury} = e^{-2.963+1.064*\text{LRP}}. \quad (1)$$

The equation for predicting mortal injury for juvenile Chinook salmon at a given logged ratio of pressure change (logged using natural log) for fish tagged with an externally attached neutrally buoyant transmitter is

$$\text{Probability of mortal injury} = e^{-2.837+1.061*\text{LRP}}. \quad (2)$$

Because there was no significant difference in mortal injury between nontagged and externally tagged fish, the data for these two groups were combined to provide the following equation for predicting mortal injury at a given ratio of pressure change:

$$\text{Probability of mortal injury} = e^{-2.922+1.075*\text{LRP}}. \quad (3)$$

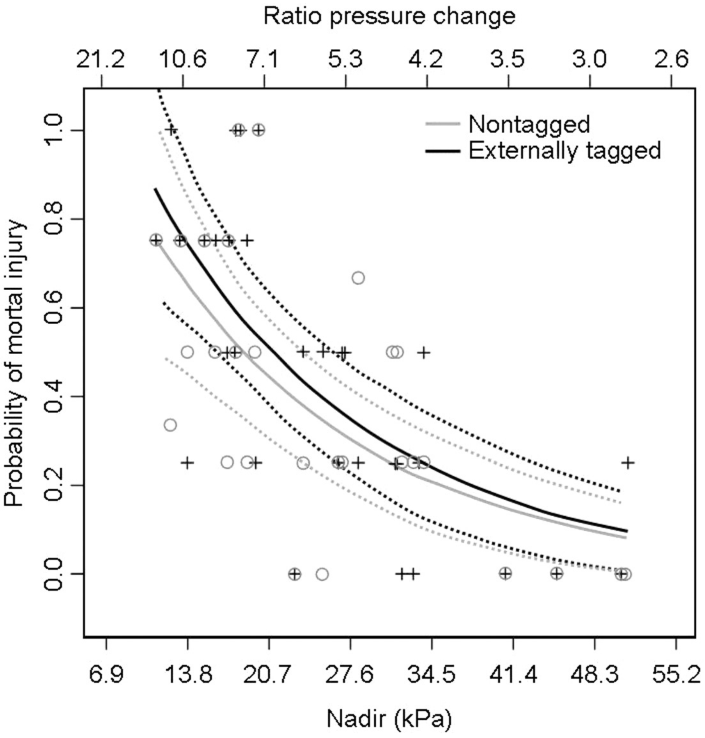

FIG. 1. The probability of mortal injury along a range of nadirs for juvenile Chinook salmon that were either untagged or tagged with a neutrally buoyant externally attached transmitter. The 95% confidence interval is shown on either side of the regression line (solid center line). Each dot on the graph indicates an individual fish exposed to simulated turbine passage. The bottom X axis depicts the nadir, or lowest pressure of the exposure. The upper X axis depicts the ratio of pressure change that fish were exposed to; the acclimation pressure divided by the nadir pressure.

IV. DISCUSSION

We hypothesized that juvenile Chinook salmon tagged with a neutrally buoyant externally attached acoustic transmitter[8] would not receive a higher degree of barotrauma than their non-tagged counterparts. Our hypothesis was confirmed because there was no difference in mortal injury between these two groups. Other research has indicated that having a negatively buoyant tag either implanted gastrically or inserted into the coelom of a fish by injection or via surgery can increase the likelihood that fish will be injured or killed during turbine passage.[4,6] However, the use of this neutrally buoyant externally attached transmitter did not cause increased injury or mortality. This is likely due to the lack of an implantation of a negatively buoyant tag into the coelom.

Fish implanted with telemetry tags can compensate for the additional excess mass of the tag by increasing their displacement via increased swim bladder volume.[9,10] The presence of this additional gas in the swim bladder has been associated with higher mortality and swim bladder ruptures when fishes are exposed to rapid decompression. Stephenson *et al.*[11] noted higher rates of injury and mortality among fish that were neutrally buoyant (thus having more gas in their swim bladder) than fish that were negatively buoyant when exposed to rapid decompression.

The volume occupied by the tag may also be an important factor influencing barotrauma. When rapidly decompressed, the expansion of gases in the swim bladder and tissues may reduce the available volume of space within the coelom where the tag rests, which is finite. The presence of a tag may limit the volume to which the gases can expand before barotraumas such as compression-related injuries occur.

Bearing a tag that increases the mass of a fish could also influence the behavior of juvenile salmonids by changing the maximum depth at which the fish can become neutrally buoyant. As mentioned above, fish can compensate for the additional excess mass of a transmitter by increasing displacement by adding more gas to the swim bladder.[9,10] This compensation, however, could influence the behavior of the fish. Salmon are physostomous and are therefore required to gulp air at the water surface to fill the swim bladder. To become neutrally buoyant at depth, the fish has to fill its swim bladder at the surface and then dive to a depth where it becomes neutrally buoyant. A fish bearing a transmitter would not have the ability to attain neutral buoyancy at a depth as deep as that of a nontagged fish. If a fish compensates for the excess mass of the tag by filling its swim bladder to the capacity limited by available coelom volume, it will have less swim bladder capacity available to attain neutral buoyancy at a greater depth. Also, the space taken up in the coelom by the transmitter could limit the inflation of the swim bladder and thus the depth at which the fish can attain neutral buoyancy.

Reduction of the maximum depth at which a fish can attain neutral buoyancy due to the presence of a tag with excess mass may bias studies examining survival and behavior. This bias has several possible outcomes. The fish will have two options—remain neutrally buoyant at a shallower depth or become negatively buoyant at deeper depths. If a tagged fish remains neutrally buoyant at a shallower depth than its nontagged counterpart, it may be exposed to less than ideal surroundings, for a number of reasons. Fish that migrate at shallower depths are likely more prone to bird and other predation. In addition, in rivers where increased TDG levels are an issue, fish with transmitters may not be able to protect themselves from gas bubble disease by hydrostatic compensation.[17] Conversely, if tagged fish occupy deeper depths, they would be negatively buoyant, likely leading to greater energy expenditures.

Reducing the maximum depth where a fish can become neutrally buoyant may also bias studies designed to determine the routes that fish use to pass hydroelectric facilities. Surface-oriented fish may be more likely to pass through the spillway than passage routes like turbines or juvenile bypass systems. Survival of juvenile salmonids that pass through hydroelectric dams is generally greatest through the spillway.[18] A change in behavior due to carrying a transmitter may skew results of studies that rely on accurate information about passage routes. A neutrally buoyant transmitter alleviates the need for the fish to compensate for the excess mass through inflation of the swim bladder. Therefore, a fish with a neutrally buoyant tag can become neutrally buoyant at the same depth as a nontagged fish with the same amount of gas in the swim bladder, reducing behavioral biases.

This research, combined with results from Ref. 8 (examining tissue reaction and shear injuries associated with the tag), indicates that this neutrally buoyant, externally attached transmitter could be a useful tool for assessing survival of juvenile salmonids passing through turbines or for survival studies in general. The use of this transmitter eliminated the bias observed among juvenile Chinook salmon tagged with negatively buoyant transmitters and exposed to simulated turbine passage.[6] We suggest that future research include field-based comparisons of survival and behavior among fish tagged with a neutrally buoyant external transmitter and those implanted internally with JSATS transmitters.

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[1] G. F. Čada, N. Am. J. Fish. Manage. **10**(4), 418 (1990).
[2] Z. Deng, T. J. Carlson, J. P. Duncan, and M. C. Richmond, Sensors **7**, 3399 (2007).
[3] Z. Deng, T. J. Carlson, J. P. Duncan, M. C. Richmond, and D. D. Dauble, J. Renewable Sustainable Energy **2**, 053104 (2010).
[4] R. S. Brown, T. J. Carlson, A. E. Welch, J. R. Stephenson, C. S. Abernethy, B. D. Ebberts, M. J. Langeslay, M. L. Ahmann, D. H. Feil, J. R. Skalski, and R. L. Townsend, Trans. Am. Fish. Soc. **138**, 1285 (2009).
[5] R. S. Brown, T. J. Carlson, A. J. Gingerich, J. R. Stephenson, B. D. Pflugrath, A. E. Welch, M. J. Langeslay, M. L. Ahmann, R. L. Johnson, J. R. Skalski, A. G. Seaburg, and R. L. Townsend, "Quantifying mortal injury of juvenile Chinook salmon exposed to simulated hydro-turbine passage," Trans. Am. Fish. Soc. (in press).
[6] T. J. Carlson, R. S. Brown, J. R. Stephenson, B. D. Pflugrath, A. H. Colotelo, A. J. Gingerich, P. L. Benjamin, M. Langeslay, M. Ahmann, R. Johnson, J. R. Skalski, A. G. Seaburg, and R. L. Townsend, "The influence of tag presence on the mortality of juvenile Chinook salmon exposed to simulated hydroturbine passage: Implications for survival estimates and management of hydroelectric facilities," N. Am. J. Fish. Manage. (in press).
[7] G. A. McMichael, M. B. Eppard, T. J. Carlson, J. A. Carter, B. D. Ebberts, R. S. Brown, M. A. Weiland, G. R. Ploskey, R. A. Harnish, and Z. Deng, Fisheries **35**(1), 9 (2010).
[8] Z. Deng, J. J. Martinez, A. H. Colotelo, T. K. Abel, A. P. LeBarge, R. S. Brown, B. D. Pflugrath, R. P. Mueller, T. J. Carlson, A. Seaburg, R. L. Johnson, and M. L. Ahmann, Fish. Res. **113**, 94 (2012).
[9] G. W. Gallepp and J. J. Magnuson, Trans. Am. Fish. Soc. **101**, 507 (1972).
[10] R. W. Perry, N. S. Adams, and D. W. Rondorf, Trans. Am. Fish. Soc. **130**, 46 (2001).
[11] J. R. Stephenson, A. J. Gingerich, R. S. Brown, B. D. Pflugrath, Z. Deng, T. J. Carlson, M. J. Langeslay, M. L. Ahmann, and R. L. Johnson, Fish. Res. **106**, 271 (2010).
[12] B. D. Pflugrath, R. S. Brown, and T. J. Carlson, "Maximum neutral buoyancy depth of juvenile Chinook salmon: Implications for survival during hydroturbine passage," Trans. Am. Fish. Soc. (in press).
[13] ENSR, *Computational Fluid Dynamics Modeling of the John Day Dam Kaplan Turbine* (ENSR International Corporation, Westford, Massachusetts, 2008).
[14] C. A. McKinstry, T. J. Carlson, and R. S. Brown, "Derivation of mortal injury metric for studies of rapid decompression of depth-acclimated physostomous fish," Technical Report No. PNNL-17080, Pacific Northwest National Laboratory, Richland, Washington, 2007.
[15] D. W. Hosmer and S. Lemeshow, *Probability and Statistics* (Wiley, New York, 2000).
[16] W. N. Venables and B. D. Ripley, *Modern Applied Statistics with S-Plus*, 3rd ed. (Springer-Verlag, New York, 2000).
[17] J. W. Beeman and A. Maule, Trans. Am. Fish. Soc. **135**, 584 (2006).
[18] W. D. Muir, S. G. Smith, J. G. Williams, and B. J. Sandford, N. Am. J. Fish. Manage. **21**, 135 (2001).