Fisheries Research 176 (2016) 48–54

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Effects of a novel acoustic transmitter on swimming performance and predator avoidance of juvenile Chinook Salmon: Determination of a size threshold

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ARTICLE INFO

Article history:
Received 11 September 2015
Received in revised form
15 December 2015
Accepted 18 December 2015

Keywords:
Behavior
Dam passage
Juvenile Salmon Acoustic Telemetry System
Migration
Telemetry

ABSTRACT

The miniaturization of acoustic transmitters enables researchers to tag smaller fish for telemetry studies, thus representing a greater proportion of the population of interest. Fish having a smaller transmitter burden (e.g., the weight of the transmitter relative to the weight of the fish) may also have fewer potential adverse transmitter effects. The development of an injectable acoustic transmitter has led to research that determined the least invasive and quickest method of implantation. Following that research, the objectives of this study were to determine the effects of transmitter implantation on swimming performance and predator avoidance, and to find a minimum size threshold of fish that can be tagged without adversely affecting those responses. To assess critical swimming speed (U_{crit}; an index of prolonged swimming performance) and predator avoidance for juvenile Chinook Salmon (*Oncorhynchus tshawytscha*), fish were split into three treatments: (1) implantation with a dummy injectable acoustic transmitter (IAT treatment), (2) implantation with a dummy injectable acoustic transmitter and passive integrated transponder tag (IAT + PIT treatment), and (3) an untagged control. IAT treatment fish had lower U_{crit} values than untagged controls among individuals below 79 mm fork length (transmitter burden 3.4–4.0%). U_{crit} values for the IAT + PIT treatment were not significantly different from untagged controls and no size threshold was found. There was no significant difference in predator avoidance between fish implanted with the IAT or IAT + PIT compared to untagged controls. These guidelines could provide researchers and managers with a powerful tool to examine behavior and survival of small salmonids.

1. Introduction

Telemetry studies are used worldwide to investigate the behavior and survival of fishes. Chinook Salmon (*Oncorhynchus tshawytscha*) species are commonly studied in the Pacific Northwest (USA) to evaluate fish survival as they pass large hydroelectric projects. Therefore much of the technology advancements in acoustic telemetry, and more specifically the Juvenile Salmon Acoustic Telemetry System (JSATS; McMichael et al., 2010), has been driven by the study of juvenile Chinook Salmon in this region. A basic assumption in telemetry work is that tagged fish are representative of the overall population of interest (Peven et al., 2005). However, the tagging process (i.e., fish collection, handling, anesthesia, and surgical implantation of transmitters) can adversely affect swimming performance, survival, growth, and predator avoidance of fish (Adams et al., 1998; Brown et al., 2006, 2010, 2013a; Welch et al., 2007). To avoid potential adverse effects of a large transmitter burden (e.g., describing the percent weight of the transmitter relative to the weight of the fish), researchers often implant transmitters in larger individuals within a cohort. This approach potentially introduces biases for estimates of survival and behavior because smaller fish are not represented (Skalski et al., 2006). However, contin-

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http://dx.doi.org/10.1016/j.fishres.2015.12.007
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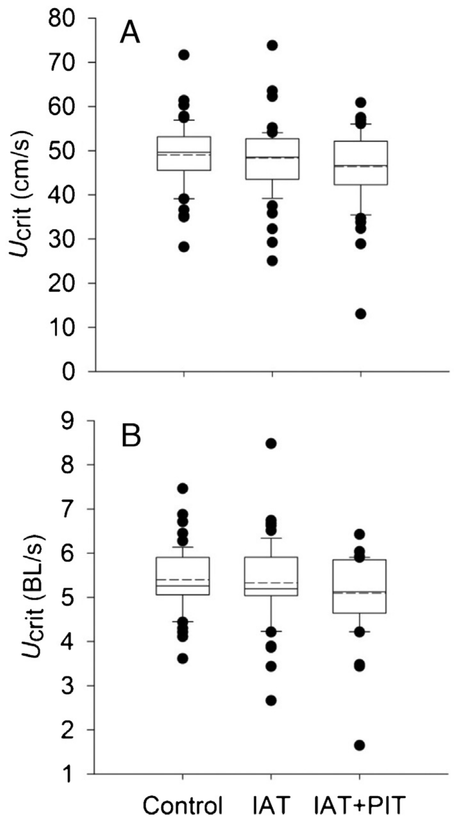

Fig. 1. Box plots of critical swimming speed (U_{crit}) in (A) centimeters per second (cm/s), and (B) body lengths per second (BL/s) for juvenile Chinook Salmon across treatments (untagged control, IAT, and IAT + PIT). The solid line inside the boxes represents the median value, the dashed line inside the boxes represents the mean value, the bottom and top of the boxes represent the 25th and 75th percentiles respectively, and the whiskers are the 10th and 90th percentiles. The black circles depict outlying points.

ual technological advances have reduced the size of transmitters, making it possible to implant transmitters into smaller fish. This miniaturization of transmitter size may change the implantation method (e.g., size of incision, number of sutures required to close the incision) leading to the need for new tagging methods and guidelines for telemetry research (Cook et al., 2014; Deng et al., 2015).

Researchers have examined several variables to provide guidelines for telemetry research. Variables may include species, life stage, body cavity length, incision location, study duration, and environmental conditions (Brown et al., 1999; Zale et al., 2005; Panther et al., 2011; Økland and Thorstad, 2013). Other important variables to consider are the weight of the transmitter in water, the volume of the transmitter, and the length of the antenna (for fish implanted with a radio transmitter; Brown et al., 1999). Recent development of a cylindrical micro-battery for the JSATS transmitter (McMichael et al., 2010) has reduced the weight of acoustic transmitters. For example, the weight of a JSATS injectable acoustic transmitter (IAT) has been reduced to 0.22 g (Chen et al., 2014). This could enable tagging of very small fish (~70 mm FL; 5–7% transmitter burden) or could result in lower transmitter burdens for bigger fish (Deng et al., 2015). During a recent laboratory based study, Cook et al. (2014) implanted juvenile Chinook Salmon with the new JSATS IAT and determined that implantation via an unsutured incision was a viable method for small fish (66–108 mm FL; 1.5%–7.3% transmitter burden). However, the authors suggested further research on the effects of the IAT on swimming performance and predator avoidance.

Implantation or attachment of acoustic transmitters to fish can adversely affect their swimming performance (Counihan and Frost, 1999; Cote et al., 1999). Yet, few studies (Zale et al., 2005; Perry et al., 2013) have measured swimming performance along a wide range of salmonid fish sizes to determine the minimum fish size or transmitter burden that is affected. Swimming performance may also influence the vulnerability of salmonids to predation (Bams 1967; Adams et al., 1998). Predator avoidance experiments may help determine if behavior (e.g., shoaling and schooling) is compromised and may provide insight into whether different types of swimming abilities (e.g., burst acceleration and rapid changes in direction) are negatively influenced by transmitter implantation. Because of this, it is critical to understand potential effects of a new transmitter on these metrics.

The objectives of this study were to: (1) determine if implantation with a novel, IAT would negatively influence swimming performance of juvenile Chinook Salmon (2) identify potential size-dependent swimming performance effects (e.g., at what length is the fish's swimming performance impaired because of the transmitter), and (3) determine potential size-dependent predator avoidance effects (e.g., at what length is the ability of a Chinook Salmon to avoid predation impaired).

2. Methods

2.1. Fish acquisition and holding for swimminig performance trials

Spring Chinook Salmon eyed eggs were obtained from the Washington Department of Fish and Wildlife, Leavenworth Hatchery (Leavenworth, Washington). The eggs were hatched and juvenile salmon were reared indoors at the Pacific Northwest National Laboratory's Aquatic Research Laboratory (ARL; Richland, Washington) in rectangular rearing troughs (197-L raceways; 300 cm length × 30 cm width × 30 cm depth) until ~2–3 g. All fish were reared in 650-L circular tanks (122 cm diameter × 91 cm depth) supplied with flow-through (set to 22 L/min) Columbia River water (UV-treated and sand-filtered) at ambient river temperature (3.5–6.0 °C). Dissolved oxygen levels maintained between 8 and 10 mg/L. Fish experienced a natural photoperiod simulated with fluorescent lighting. The juveniles were fed an ad libitum daily ration of commercial salmon feed (crumble–1.2 mm pellet; Bio Vita Fry, Bio-Oregon, Longview, Washington), except 24 h before surgical implantation when fish were unfed. Two weeks prior to the study, fish were graded to size and stocked into five 650-L circular tanks, with the same environmental conditions as rearing. The water temperature was increased 2.0 °C per day (to minimize stress) from rearing temperatures to 17.0 ± 2 °C prior to swimming performance trials. The size distribution of fish tagged was 75–104 mm fork length (FL) and 4.6–14.5 g in weight.

2.2. Surgical procedures for swimming performance and predator avoidance trials

Three treatments were evaluated in this study: (1) fish implanted with a dummy IAT (3.4 mm diameter × 15 mm long and weighing 0.22 g in air [0.11 g in water]; IAT treatment), (2) fish implanted with a dummy IAT (size presented above) and a passive integrated transponder (PIT) tag (2.1 mm diameter × 12.5 mm long and weighing 0.10 g; Destron Technologies, St. Paul, Minnesota; IAT + PIT treatment), and (3) an untagged control. Sham controls were not used because a tag cannot be implanted without an incision; therefore the data gained would not be applicable to field studies. In the Pacific Northwest, PIT tags are coupled with acoustic transmitters to ensure fish tagged for use in many field studies are

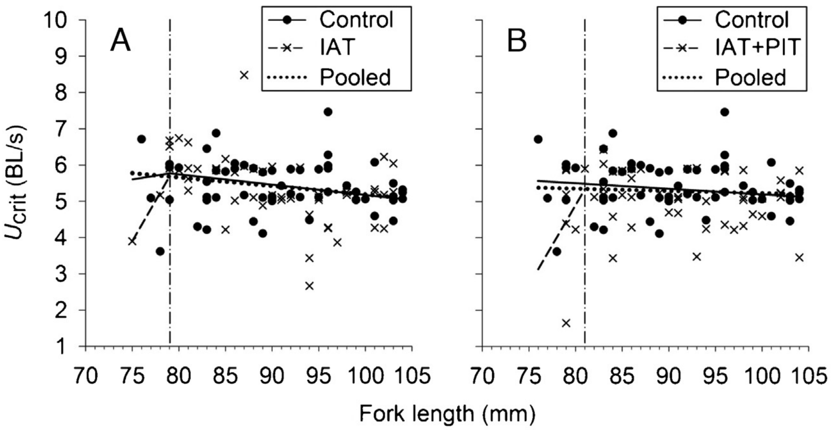

Fig. 2. Spline regression analyses of fork length (FL) and critical swimming speed (U_{crit}) for juvenile Chinook Salmon exposed to three treatments: an untagged control treatment (A & B), IAT implants (A), and IAT + PIT implants (B). Fish size thresholds (FLs) are identified by a spline break (also known as a knot). Spline regression lines are shown for the IAT treatment or IAT + PIT treatments (dashed lines, panels A and B respectively), the untagged control treatment (solid line), and pooled treatments (dotted line). A significant ($P = 0.02$) spline break (black vertical dashed and dotted line) was detected at 79 mm FL for the IAT treatment, but the spline break (81 mm FL) for the IAT + PIT treatment was nonsignificant ($P = 0.61$).

Table 1
Swimming performance experimental design for one block of juvenile Chinook Salmon implanted with an injectable acoustic transmitter (IAT), an IAT + passive integrated transponder (IAT + PIT), or untagged control over a range of sizes, separated by size bins. There were 10 total blocks used for this study ($n = 180$).

		Size bins FL (mm)					
Treatment	*n*	75–79	80–84	85–89	90–94	95–99	100–104
IAT	6	1	1	1	1	1	1
IAT + PIT	6	1	1	1	1	1	1
Untagged control	6	1	1	1	1	1	1

not diverted into fish transport barges or trucks (used to bypass hydroelectric projects). These facilities can identify study fish by reading the PIT tags and route them back to the river. As such, PIT tags were incorporated into this study. Prior to surgery, fish were anesthetized in 80 mg/L of tricaine methanesulfonate (MS-222) buffered with equal parts sodium bicarbonate to stage four anesthesia (Summerfelt and Smith, 1990) and measured for FL and weight. Implantations were performed by three surgeons over the study duration; however, only one person performed surgeries for a particular test block (e.g., one person performed surgeries on 18 fish per test block [6 fish per treatment]; Table 1). During surgeries, fish were placed on a foam-rubber board covered in Fish Protector® (formerly called PolyAqua; Kordon LLC, Hayward, California; Harnish et al., 2011). Continuous anesthesia during surgery was unnecessary due to the speed of the procedure (~30 s). Following methods from Cook et al. (2014), the IAT and IAT + PIT tags were implanted into the coelom of juveniles through a 3–4 mm incision made with a number 11 scalpel blade (Becton, Dickinson and Company, Franklin Lakes, New Jersey). The incision was located immediately posterior to the tip of the pectoral fin and offset 2–3 mm from the linea alba. Following the most current recommendation for surgical implantation of IATs, the incision was not closed by suture after transmitter insertion (Cook et al., 2014). Throughout the tagging process, untagged control fish experienced the same level of handling and anesthesia as fish in IAT and IAT + PIT treatments to minimize bias, although no incisions were made. After the tagging process (or similar handling for untagged controls), the fish were individually isolated in 15-L buckets supplied with an air stone until they reached equilibrium and then returned to their 650-L holding tank. Fish were held for 16–24 h prior to swimming performance trials and prior to predator avoidance trials.

2.3. Swimming performance trials

Swimming performance trials were conducted at temperatures (15.4–18.0 °C) similar to pre- and post-tagging conditions for holding, because yearling Chinook Salmon in the Columbia River Basin (Washington, USA) make seaward migrations during times of similar river temperature conditions. Ten test blocks of fish were evaluated in trials of swimming performance at the ARL between December 26, 2013 and January 29, 2014. Each block consisted of three randomized treatments (i.e., IAT, IAT + PIT, and untagged) with six fish or replicates per treatment (e.g., a total of 180 fish; Table 1). Six size categories of 5-mm increments in FL (e.g., 75–79, 80–84, . . . 100–104 mm; transmitter burden ranging from 1.5–4.5% for IAT fish and 2.3–5.8% for IAT + PIT fish) were represented in each block (e.g., one replicate per category per block; Table 1). Two Blăzka-type respirometers (swimming area: 2736 cm^3 [inner diameter: 9 cm; chamber length: 43 cm]; overall respirometer length: 122 cm) with identical 560 W electric motors were used to conduct tests of critical swimming speed (U_{crit}; an index of prolonged swimming performance). Calculations of U_{crit} and trials of swimming performance were used with the following equation:

$$U_{crit} = u_1 + \left[\left(\frac{t_i}{t_{ii}}\right) \times u_{ii}\right],$$

similar to Janak et al. (2012). For the current study, the swimming velocity was increased by 0.8 BL/s every 15 min instead of 0.5 BL/s (Janak et al., 2012).

2.4. Fish acquisition and holding for predator avoidance trials

Predator avoidance experiments were conducted at the ARL between December 12, 2014 and January 15, 2015. Juvenile fall Chinook Salmon were chosen as prey and sourced from the Washington Department of Fish and Wildlife, Priest Rapids Hatchery (Mattawa, Washington) as eyed eggs. They were reared at the ARL with the same environmental conditions as the fish used for the swimming performance trials and held in 650-L tanks, again with the same environmental conditions as the fish reared for swimming performance trials. Rainbow Trout (*Oncorhynchus mykiss*) were selected as predators (see Anglea et al., 2004; Janak et al., 2012) and obtained from Troutlodge Inc. (Soap Lake, Washington). The trout were reared indoors in 2000-L (180 cm diameter × 89 cm depth) circular tanks. Ten trout were selected as predators (size range 395–520 mm FL; 0.91–1.77 kg) and relocated to an identical tank with the water flow set to 40 L/min and dissolved oxygen levels maintained between 8 and 10 mg/L and were acclimated to 16 °C. Live juvenile salmon (65–130 mm FL) were fed weekly as forage to the ten trout for several months prior to experimentation.

Prior to the start of predator experiments, a cylindrical frame of polyvinyl chloride plastic pipe was placed atop the tank and shade cloth was attached to it. This shade cloth maintained undisturbed visual field for the fish, so the fish could not see people walking by the holding tanks. A video camera (CCTV CSP-750IR24 infrared bullet Sony security camera, Cherry Hill, New Jersey) was also affixed to the frame for overhead monitoring (CCTV 960H digital video recorder, Cherry Hill, New Jersey) of predation trials. White mats (latex free and made from natural rubber; SlipX Solutions®, Traverse City, Michigan) lined the bottom of the tank and provided visual contrast for effective video monitoring of fish. At this time trout were fed a daily satiating ration of live juvenile Chinook Salmon which produced a tempered predatory response. Any forage fish that remained in the tank were removed immediately prior to starting each predation trial.

2.5. Predator avoidance trials

Juvenile Chinook Salmon were acclimated to 16 °C, and were naïve to Rainbow Trout predators before starting each trial. The juveniles underwent the same surgical procedures as the swimming performance trials and were randomly assigned to the same tagging treatments as the swimming performance trials. Unlike the swimming performance trials, tagging sizes in the predation trials were different for IAT and IAT + PIT fish to maintain similar transmitter burdens across treatments. IAT treatments used prey that measured 75–85 mm FL (4.4–6.9 g; transmitter burdens of 3.1–4.8%), and were compared to untagged controls of the same length (75–85 mm FL; 3.8–7.1 g). Fish in the IAT + PIT treatment were 85–95 mm FL, 6.0–10.7 g, and had transmitter burdens ranging from 3.0–5.3%. The IAT + PIT treatment fish were compared to untagged controls that also ranged from 85 to 95 mm FL (6.9–10.5 g). After the implantation process, the fish were isolated in 15-L buckets and returned to the 650-L circular holding tanks for 24 h prior to predation trials. Each trial consisted of 10 IAT-implanted fish (either IAT only or IAT + PIT only) and 10 unimplanted fish. Total fish was 240 ($n = 120$ for IAT compared to untagged controls, and $n = 120$ for IAT + PIT compared to untagged controls). Fish from both treatments (either IAT or IAT + PIT and untagged controls) were introduced to the predator tank simultaneously. Trials were terminated when ~50% of the prey were consumed (similar to Anglea et al., 2004; Janak et al., 2012; Thompson et al., 2014). No artificial refuge or shelter was provided for prey. The surviving prey were netted, euthanized with an overdose (250 mg/L) of MS-222, and identified to treatment. If prey were seriously injured (e.g., open wound, loss of equilibrium, continuous erratic swimming, and or lying on the bottom of the tank) they were classified as “consumed”.

2.6. Statistical analysis

A generalized linear model (GLM; Gaussian link; normal error distribution) was used to estimate effects from blocks and covariates (i.e., FL, transmitter-type, assessor, surgeon, and test day) on U_{crit} values for swimming performance trials. A comparison of P-values from Analysis of Deviance (ANODEV) tests and Akaike’s Information Criterion (AIC; Akaike, 1974) values were used to select the best fitting model after stepwise addition of covariates and interactions to the blocked model. In the final model for swimming performance trials, Student’s t-values (generated by dividing the parameter estimate [i.e., coefficient] by its standard error) tested the null hypothesis that the coefficient (given the variables included in the model) from the tagged treatment was no different from the untagged control treatment. For the predator avoidance trials, a similar approach was used for selecting the best fitting predator avoidance model (GLM; logit link; binomial error distribution) which tested block (e.g., trial) and covariate (i.e., FL, weight, condition factor, and transmitter-type) effects on the probability of prey consumption.

For determining a minimum fish size threshold for transmitter implant effects on swimming performance, a spline regression model was used to compare the relationship between FL and U_{crit} for each transmitter-type against the untagged control treatment. A spline point or knot (e.g., the point at which U_{crit} values abruptly shift in relationship to FL) was selected within the range of measured FLs. The knot location that produced the highest R^2 value for the regression was deemed the best fit. Because a spline regression will always improve or be equal to the R^2 value against an ordinary linear regression, an F-test was used to determine if the spline point significantly improved model fit. Significance or Type I error (α) was defined at 0.05 for all statistical tests. All statistical analyses were performed with R software (R Core Team, 2014).

3. Results

3.1. Swimming performance

The mean U_{crit} was not significantly different ($P > 0.05$; ± standard deviation; S.D.) between IAT and untagged controls, or between IAT + PIT and untagged controls. Mean U_{crit} was 5.3 ± 0.9 for IAT, 5.1 ± 0.9 for IAT + PIT, and 5.4 ± 0.7 BL/s for untagged controls, (Fig. 1). Although a knot of 81 mm was identified between the IAT + PIT treatment and untagged fish, it was not significant ($P = 0.61$; Fig. 2). Conversely, when examining comparisons between untagged controls and IAT fish along their entire size range, spline regression modeling indicated a significant ($P = 0.02$; Fig. 2) knot at 79 mm FL (transmitter burden ranging from 3.42 to 4.04%).

3.2. Predator avoidance

The percentage of prey consumed in six different trials for prey with IAT implants in comparison to untagged controls was not significantly ($P > 0.05$) different between the two treatments (Fig. 3). The same was the case for the percentage of prey consumed for trials comparing IAT + PIT to untagged controls ($P > 0.05$; Fig. 3).

4. Discussion

4.1. Swimming performance

Fish implanted with an IAT smaller than 79 mm FL (transmitter burden ranging from 3.42 to 4.04%) had lower critical swimming speeds (e.g., poorer swimming performance) than similar sized untagged control fish. This indicates that fish at 79 mm FL and smaller should not be implanted with an IAT because of the adverse impacts the transmitter has on swimming performance. However, no significant threshold was found among IAT + PIT and untagged control fish, despite fish in this treatment having a slightly higher transmitter burden range (2.3–5.8%) compared to IAT fish (1.5–4.5%). The handling of fish is recognized as a stressor and therefore the swimming ability of control fish in this study may potentially have slightly lower U_{crit} values than fish that were not handled at all. It appears that the knot found at 81 mm for IAT + PIT fish may have been due to the lack of fish at the smaller end of the size distribution (e.g., to the left of where the knot position was tested). This was likely due to a higher number of fish at the mid-

Table 2
A summary of critical swimming speeds (U_{crit}) of salmonids, reported as the range of sizes of individuals (CS = Chinook Salmon; SS = Sockeye Salmon; CT = Westslope Cutthroat Trout, CO = Coho Salmon, AS = Atlantic Salmon). Fork length, weight, and U_{crit} data incorporates tagged and untagged fish. Values in parenthesis are the range of sizes of means identified by researchers. While Zale et al. (2005) did examine swimming performance they identified a stamina threshold (discussed in the text above but not indicated in this table) instead of a critical swimming speed threshold.

References	Species	*n*	FL (mm)	Weight (g)	U_{crit} (BL/s)	U_{crit} (cm/s)	Tag burden (%)
Adams et al. (1998)	CS	128	95–160	10–46	2.2–5.3		2.2–10.4
Anglea et al. (2004)	CS	156	122–198	22–99	3.7–4.9		1.4–6.7
Brown et al. (2006)	CS	189	94–125	7–23	4.3–4.7	47.5–51.2	3.2–10.0
	SS	196	101–133	8–15	4.1–4.3	46.1–48.6	4.6–8.4
Chittenden et al. (2009)	CO	82	105–142	(15–30)	(3.1–7.8)	(34.7–109.1)	(6.0–10.0)
Janak et al. (2012)	CS	102	98–135	9–31		(36.7–46.7)	1.9–2.6
Morrison et al. (2013)	CO	59	(117.4)	(19)	(4.2–6.1)	(49.2–69.2)	
Perry et al. (2013)	CS	167	81–139	6–30	3.6–10.8	44.6–98.4	1.4–7.9
Robertson et al. (2003)	AS	80	(143–144)	(29–32)	(7.8–8.8)		(2.4–2.5)
Zale et al. (2005)	CT	104	210–280*	81–207			0.5–5.3
Present study	CS	166	75–104	5–15	1.7–8.5	13.0–73.8	1.5–5.8

* Total length.

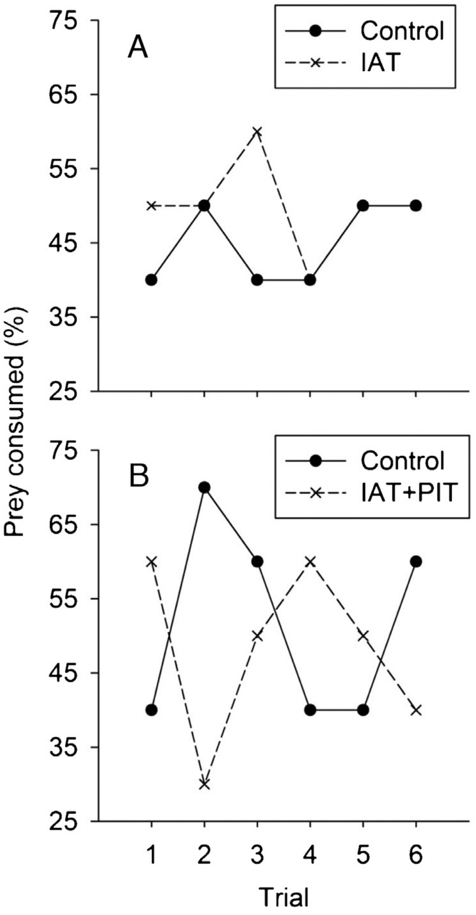

Fig. 3. Percentages of juvenile Chinook Salmon prey consumed by Rainbow Trout in six trials per tagging treatment (*n* = 10 prey per treatment [e.g., 10 untagged controls with 10 IAT fish, or 10 untagged controls with 10 IAT + PIT fish], per trial) comparing the untagged control treatment against the IAT (A) and IAT + PIT treatments (B).

dle and larger end of the size distribution, and transmitter burdens decreased as fish size increases (Brown et al., 2010); therefore the IAT + PIT fish may have had fewer adverse tagging related effects. The lack of a minimum size threshold for IAT + PIT fish is similar to Zale et al. (2005), as the authors did not identify a size-related threshold below which swimming performance of Westslope Cutthroat Trout (*Oncorhynchus clarkii*) was compromised (see Table 2 for details on all studies discussed here and the following paragraphs). However, Zale et al. (2005) examined fish fatigue time, unlike the current study where critical swimming speed was examined. In another study, Perry et al. (2013) examined the critical swimming speed of juvenile Chinook Salmon and did not find a size threshold between swimming performance and transmitter burdens. There have been many other swimming performance studies that compared tagging treatments to untagged control fish (such as Adams et al., 1998; Brown et al., 1999; Mesa et al., 2004; Brown et al., 2006). However, only Zale et al. (2005), Perry et al. (2013), and the current study had an objective of finding a size threshold, which was identified in the IAT treatment (at 79 mm FL) in this study.

Interestingly, studies investigating swimming performance of grouped fish (tested without specifically looking for a size threshold) have produced contradictory results. Adams et al. (1998) reported a lower swimming performance of some groups of juvenile Chinook Salmon surgically implanted with transmitters and compared to untagged control fish. However the size range in that study included larger fish and individuals had a greater transmitter burden range compared to this research (Table 2). Conversely, Brown et al. (2006) tested a similar size range of Chinook Salmon at an elevated transmitter burden range in small fish (Table 2), but did not find a significant difference in swimming performance among internally tagged, sham tagged, and untagged control fish. Some possible reasons why swimming performance results vary are outlined by Mesa et al. (2004). Those authors found it difficult to compare critical swimming speeds among investigations due to variances in swimming protocols, temperature, body size, fish training, and metabolic condition, all of which have been linked to U_{crit} results. Regardless, under the tested conditions from the current study, the swimming ability of fish greater than 80 mm FL tagged with an IAT (or 75 mm FL tagged with an IAT + PIT) was not impaired by the implantation of a transmitter.

4.2. Predator avoidance

Implantation of an IAT or IAT + PIT in juvenile Chinook Salmon did not influence their ability to avoid predators compared to untagged control individuals. This indicates that fish as small as 75 mm FL (IAT) or as small as 85 mm FL (IAT + PIT) can be implanted and it will not increase their risk of predation. The outcomes of other studies that used predator avoidance as a metric to evaluate tagging effects have had mixed results. Anglea et al. (2004) found no difference in the proportion of juvenile Chinook Salmon (mean length ~140 mm FL; transmitter burden up to 6.7%) implanted with an acoustic transmitter that were consumed by Rainbow Trout predators compared to untagged cohorts. Janak et al. (2012) evaluated how predator avoidance affected juvenile Chinook Salmon (98–135 mm FL) tagged with a neutrally buoyant external transmitter (i.e., 0% transmitter burden). They found no difference in predator avoidance between tagged and untagged fish. Conversely, Adams et al. (1998) determined that juvenile Chinook Salmon (95–120 mm FL) implanted with radio transmitters (4.6–10.4% transmitter burden) were consumed by Smallmouth Bass (*Micropterus dolomieu*) in higher proportions than control fish. They also observed that salmon implanted with a transmitter had difficulty swimming with a shoaling of control fish cohorts. Adams et al. (1998) also suggested that the trailing antennae of their implanted radio-transmitter could be a potential attractant for predators, although implanted acoustic transmitters do not have this potential drawback. The difference in results among studies conducted to date could be due to a multitude of factors such as using different transmitters, the species of predator, tagging techniques, the prey population source, and the laboratory setting. However, under the conditions tested in this study, no difference in predator avoidance was identified when comparing IAT and untagged controls, nor when comparing IAT + PIT and untagged controls.

5. Conclusions

This research is the first to evaluate swimming performance of juvenile salmonids implanted with a novel, very small (0.22 g), injectable acoustic transmitter. This research found no negative transmitter effects associated with swimming performance or predator avoidance among IAT + PIT implanted fish over the entire size range that was examined (79–104 mm FL for swimming performance, 85–95 mm for predator avoidance). For IAT implanted fish, there were negative transmitter effects associated with swimming performance for IAT implanted fish at 79 mm FL and smaller (3.4–4.0%. transmitter burden). However, ther were no negative effects associated with predator avoidance over the tested size range (75–85 mm FL) for IAT fish. The absense of negative effects for IAT + PIT implanted fish for both swimming performance and predator avoidance experiments adds confidence that implanting small fish or fish with a smaller transmitter burden could be successfully conducted in field studies. Regardless, the results found in this study can be used to provide researchers and managers with a powerful tool to examine behavior and survival for fish in field research.

While this study examined the transmitter effects on swimming performance and predator avoidance in small juvenile Chinook Salmon, there are several other factors that could contribute to transmitter effects among fish implanted in the wild. Future laboratory studies should investigate the use of IAT and IAT + PIT implant treatments on a greater number of smaller fish (<79 mm FL), or examine the effects of this transmitter on swimming performance and predator avoidance in other species. It is also suggested that similar investigations should be done over a longer time frame (similar to Adams et al., 1998) to determine if transmitter effects arise or become worse over the lifespan of the transmitter (e.g., with a battery life of up to 100 days; Deng et al., 2015). This would not only improve the understanding of the effects of transmitter implantation on fish behavior, but could also help researchers better understand how metrics such as swimming performance and predator avoidance may change over the lifetime of the transmitter. Post-implantion transmitter effect variables such as growth, transmitter retention, survival, exposure to shear forces, and rapid pressure changes should also be considered prior to the use of fish implanted with an IAT or IAT + PIT transmitter in field telemetry studies associated with passing hydropower or other types of structures. When combined these factors relate to fish movement, survival, and behavior, however temperature may also influence transmitter effects.

Other research should be conducted in a range of ecologically relevant water temperatures. In turn, examining transmitter effects in different water temperatures could relate to a variety of habitats for different species of fish, as well as reflect typical riverine fluctuations. The ability to insert transmitters with a very small incision (~3–4 mm) and without using a suture could vastly reduce transmitter effects in tropical rivers or other water bodies with high water temperatures, where incisions, particularly incisions utilizing sutures, could be more prone to infection. Finally, comparative field studies should be performed to evaluate rates of migration, growth, predation, and survival of tagged fish along a wide size range, similar to Brown et al. (2013). While more research would be beneficial to increase confidence for using this transmitter in field studies, the current study provides critical information about swimming performance and predator avoidance for identifying broad guidelines for use of transmitters that are surgically implanted into juvenile salmonids.

Acknowledgments

We would like to the thank the Army Corps of Engineers, Portland District, for providing the funding for this research. We would also like to thank the Washington Department of Fish and Wildlife Leavenworth and Priest Rapids Hatcheries for providing the salmon used in this study. We also thank John Skalski from the University of Washington for statistical advice and Thomas Hancock from Portland State University for providing assistance with the swimming chambers. We appreciate the assistance from the following PNNL staff Zach Booth, Nikki Fuller, David Geist, Jill Janak, Brian Jeide, Bryan Jones, Ki Won Jung, Tim Linley, Jun Lu, Jayson Martinez, Brett Pflugrath, Jason Reynolds, and John Stephenson.

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