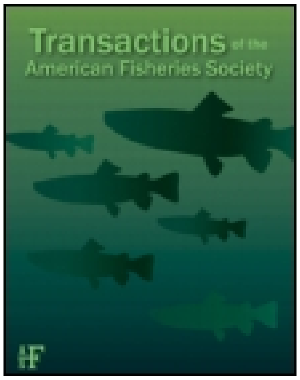

Transactions of the American Fisheries Society
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/utaf20

The Effects of Neutrally Buoyant, Externally Attached Transmitters on Swimming Performance and Predator Avoidance of Juvenile Chinook Salmon

Jill M. Janak [a], Richard S. Brown [a], Alison H. Colotelo [a], Brett D. Pflugrath [a], John R. Stephenson [a], Z. Daniel Deng [b], Thomas J. Carlson [c] & Adam G. Seaburg [d]

[a] Pacific Northwest National Laboratory, Ecology Group, Post Office Box 999, Richland, Washington, 99352, USA

[b] Pacific Northwest National Laboratory, Hydrology Group, Post Office Box 999, Richland, Washington, 99352, USA

[c] Pacific Northwest National Laboratory, Marine Sciences Laboratory, 1520 West Sequim Bay Road, Sequim, Washington, 98382, USA

[d] Columbia Basin Research, School of Aquatic and Fishery Sciences, University of Washington, 1325 Fourth Avenue, Suite 1820, Seattle, Washington, 98101-2509, USA

Version of record first published: 27 Aug 2012

To cite this article: Jill M. Janak, Richard S. Brown, Alison H. Colotelo, Brett D. Pflugrath, John R. Stephenson, Z. Daniel Deng, Thomas J. Carlson & Adam G. Seaburg (2012): The Effects of Neutrally Buoyant, Externally Attached Transmitters on Swimming Performance and Predator Avoidance of Juvenile Chinook Salmon, Transactions of the American Fisheries Society, 141:5, 1424-1432

To link to this article: http://dx.doi.org/10.1080/00028487.2012.688915

Transactions of the American Fisheries Society 141:1424–1432, 2012

ISSN: 0002-8487 print / 1548-8659 online
DOI: 10.1080/00028487.2012.688915

ARTICLE

The Effects of Neutrally Buoyant, Externally Attached Transmitters on Swimming Performance and Predator Avoidance of Juvenile Chinook Salmon

Jill M. Janak, Richard S. Brown,* Alison H. Colotelo, Brett D. Pflugrath, and John R. Stephenson
Pacific Northwest National Laboratory, Ecology Group, Post Office Box 999, Richland, Washington 99352, USA

Z. Daniel Deng
Pacific Northwest National Laboratory, Hydrology Group, Post Office Box 999, Richland, Washington 99352, USA

Thomas J. Carlson
Pacific Northwest National Laboratory, Marine Sciences Laboratory, 1520 West Sequim Bay Road, Sequim, Washington 98382, USA

Adam G. Seaburg
Columbia Basin Research, School of Aquatic and Fishery Sciences, University of Washington, 1325 Fourth Avenue, Suite 1820, Seattle, Washington 98101-2509, USA

Abstract
Migrating juvenile salmonids experience rapid decompression that could result in injury or mortality due to barotrauma as they pass turbines at hydropower facilities. Recent research indicates that the risk of injury or mortality due to barotrauma is higher in fish bearing surgically implanted transmitters. Since tagged fish are used to represent the entire population, this tag effect potentially leads to inaccuracies in survival estimates for fish passing turbines. This problem led to development of a novel transmitter, the use of which may eliminate bias associated with the passage of transmitter-bearing fish through turbines. Juvenile Chinook salmon *Oncorhynchus tshawytscha* were tagged with two different neutrally buoyant, externally attached transmitters (types A and B). The effects of transmitter presence on swimming performance were examined by comparing critical swimming speeds (U_{crit}; an index of prolonged swimming performance) of externally tagged fish, untagged individuals, and fish that received surgically implanted Juvenile Salmon Acoustic Telemetry System acoustic transmitters. Fish tagged with external transmitters had lower U_{crit} than untagged individuals. However, there was no difference in U_{crit} between fish with external transmitter type A or B and fish with surgically implanted transmitters. Testing was conducted to determine whether predator avoidance was affected by the presence of type A transmitters compared with untagged fish. No difference in predation mortality was detected between tagged and untagged fish. Although results suggest that U_{crit} was affected by externally attached transmitters in comparison with untagged fish, the overall impact as reflected by survival was similar; field-based survival studies involving juvenile salmonids passing through hydroturbines are recommended. The absence of swimming performance effects in fish with external tags relative to fish with internally

*Corresponding author: rich.brown@pnnl.gov
Received November 5, 2011; accepted April 20, 2012

implanted transmitters and the lack of an increased predation risk relative to untagged fish suggest that an externally attached, neutrally buoyant transmitter is a viable option for telemetry studies in estimating survival of juvenile salmonids passing through hydroturbines.

Juvenile salmonids that migrate through hydropower facilities can be exposed to rapid changes in pressure, leading to swim bladder expansion and associated barotrauma that is characterized by swim bladder rupture, hemorrhaging, emboli in the gills, and exopthalmia (Brown et al. 2009, 2012a, 2012c). Recent research indicates that juvenile salmon bearing an internally implanted tag or transmitter are more likely to suffer injury or mortality than untagged fish (Carlson et al. 2012). This could be due to (1) an increased air volume in the swim bladder as the fish compensates for the additional excess mass of the transmitter or (2) the area for swim bladder expansion being limited by the transmitter's presence in the body cavity.

Carlson et al. (2012) surgically implanted acoustic transmitters into juvenile Chinook salmon *Oncorhynchus tshawytscha* and subjected the fish to simulated turbine passage. Tag burden (i.e., weight of the transmitter expressed as a percentage of fish body weight) ranged from 0.0% to 6.6%. The rate of mortality and injury in fish increased not only with the magnitude of pressure change but also with tag burden, indicating that the the likelihood of injury or mortality during rapid decompression was increased by the additional mass of the transmitter, the volume of the transmitter inside the body cavity, or both factors. Carlson et al. (2012) suggested that this tag bias likely leads to inaccuracies in estimating the survival of fish as they pass through turbines. These results led to the investigation of whether a neutrally buoyant (tag burden in water = 0.0%), externally attached transmitter could provide more accurate estimates of survival during turbine passage (Brown et al. 2012b; Deng et al. 2012).

In addition to the reduction in barotrauma during turbine passage, externally attached transmitters are commonly used in fisheries research and have many other possible advantages over internal implantation, including reduced time for attachment and handling, the potential for being less invasive, and the ability to be easily shed from the fish once the study has concluded (Lucas et al. 1993; Bégout Anras et al. 1998; Jepsen et al. 2002; Cooke et al. 2003; Deng et al. 2012). However, the presence of an externally attached transmitter is often associated with the possibility of impaired swimming performance (i.e., snags and drag) as well as increased susceptibility to predation, especially for smaller fish.

Many studies have examined the swimming performance of fish with surgically implanted transmitters (Adams et al. 1998; Anglea et al. 2004; Brown et al. 2006), but few have examined the influence of externally attached transmitters (Table 1). Thorstad et al. (2000) found no differences in swimming performance among groups of adult Atlantic salmon that received externally attached radio transmitters, surgically implanted transmitters, or no transmitters (controls). Peake et al. (1997) compared swimming performance of wild and hatchery-reared Atlantic salmon smolts with externally attached, internally implanted, and gastrically implanted radio tags. Those authors found no difference between externally and internally tagged fish; however, swimming performance was lower for externally and internally tagged fish than for untagged controls.

Increased rates of predation on tagged fish can be attributed to trauma from the tagging procedure, tag visibility to predators, and impaired swimming performance due to drag associated with the transmitter or antenna (Ross and McCormick 1981). Several studies of tagging effects on juvenile salmonids' ability to avoid predators (Jepsen et al. 1998; Anglea et al. 2004; Table 2) have found no difference in predation rates between tagged and untagged fish. However, Adams et al. (1998) reported increased rates of predation on juvenile Chinook salmon into which radio transmitters were surgically and gastrically implanted relative to untagged controls.

Although previous studies have found that external attachment of transmitters can alter the swimming performance and behavior of fish, there is a paucity of research on the effects of externally attached acoustic transmitters on juvenile salmonids. Recent technological advances have led to a reduction in the size of acoustic transmitters, making it possible to study smaller fish. With the decrease in transmitter size resulting in lower tag burdens, external attachment of acoustic transmitters to juvenile salmonids has become a more plausible option for biotelemetry studies. The objective of this research was to determine whether the swimming performance and predator avoidance ability of juvenile Chinook salmon would be compromised by the external attachment of a neutrally buoyant acoustic transmitter that was developed for monitoring the survival of juvenile salmonids passing through hydroturbines.

METHODS

Fish acquisition and holding.—Juvenile fall Chinook salmon were originally obtained as eyed eggs from Priest Rapids Hatchery (Washington Department of Fish and Wildlife) in December 2009. Fish were reared at the Aquatic Research Laboratory (ARL), Pacific Northwest National Laboratory, Richland, Washington. During the study period, all test fish were held inside the ARL in 650-L circular tanks. All holding and test tanks were supplied with 15.0–17.8°C well water. Fish within the rearing and test population were fed an ad libitum ration of Bio Vita Starter (Bio-Oregon, Longview, Washington). Fish that were selected for testing were unfed for 24 h prior to

TABLE 1. Summary of studies examining the effects of transmitters on swimming performance of salmonids (CS = Chinook salmon; RT = rainbow trout *Oncorhynchus mykiss*; SS = sockeye salmon *O. nerka*; AS = Atlantic salmon *Salmo salar*; GI = gastric implantation; SI = surgical implantation; EX = external attachment). Values for length, mass, and tag burden are means or ranges of means (values in parentheses are full ranges of values). Tag burden is the transmitter weight in air expressed as a percentage of fish weight in air. Externally attached transmitters used in the present study were neutrally buoyant, thus applying no tag burden to the fish when in water. Data presented are for all fish tested, including controls and shams.

Reference	Species	*n*	Tag type	Method of attachment	Length (mm)	Mass (g)	Tag mass in air (g)	Tag burden (%)
Adams et al. (1998)	CS	128	Radio	GI, SI	(95–160)		1.0	(2.2–10.4)
Brown et al. (1999)	RT	38	Radio	SI	88–89	(5.0–10.0)	0.6	(6.0–12.0)
Anglea et al. (2004)	CS	156	Acoustic	SI	(122–198)	(22.2–99.0)	1.5	(1.4–6.7)
Brown et al. (2006)	CS	150	Acoustic	SI	108–110 (94–125)	13.1–13.8 (6.7–23.1)	0.7	(3.1–10.7)
Brown et al. (2006)	SS	150	Acoustic	SI	113–114 (101–133)	11.2–11.5 (7.0–16.0)	0.7	(4.5–10.3)
Thorstad et al. (2000)	AS	168	Radio	EX, SI	(450–590)	(1,021–2,338)	15.1, 25.0	<1.0 (in water)
Peake et al. (1997)	AS	126	Radio	SI, GI, EX	185–208	54.0–112.5	2.6	(1.8–6.0)
Robertson et al. (2003)	AS	80	Radio	SI	143–144	29.2–31.9	0.75	2.4–2.5
Present study	CS	102	Acoustic	EX, SI	124 (98–135)	22.0 (9.0–30.7)	0.53[a]	2.3 (1.9–2.6)[a]

[a]Relates only to SI.

TABLE 2. Summary of studies examining predator avoidance by salmonids (CS = Chinook salmon; AS = Atlantic salmon; BT = brown trout *Salmo trutta*; GI = gastric implantation; SI = surgical implantation; EX = external attachment). Values for length, mass, and tag burden are means or ranges of means (values in parentheses are full ranges of values). Tag burden is the transmitter weight in air expressed as a percentage of fish weight in air. Externally attached transmitters used in the present study were neutrally buoyant, thus applying no tag burden to the fish when in water. Data presented are for all fish tested, including controls and shams.

Reference	Species	*n*	Tag type	Method of attachment	Length (mm)	mass (g)	Tag mass in air (g)	Tag burden (%)
Adams et al. (1998)	CS	384	Radio	GI, SI	(95–160)		1.0	(2.2–10.4)
Anglea et al. (2004)	CS	160	Acoustic	SI	(122–198)	(22.2–99.0)	1.5	(1.4–6.7)
Jepsen et al. (1998)	AS	50	Radio	SI	(160–180)		1.4, 1.7	
Jepsen et al. (1998)	BT	24	Radio	SI	(160–240)		1.4, 1.7	
Present study	CS	113	Acoustic	EX, SI	125–143 (105–155)	24.0–33.3 (13.2–40.4)	NA	NA

tagging or testing. Fish in both test groups (swimming performance and predator avoidance) ranged from 98 to 155 mm in fork length (FL) and from 9.0 to 40.4 g in weight (Tables 3, 4).

The adult rainbow trout that were used as predators were obtained from Trout Lodge Hatchery (Soap Lake, Washington) in November 2010. All predators were held outside the ARL in two 2,000-L circular tanks prior to the study period. Holding tanks were supplied with 15–16°C well water. Predators ranged from 300 to 460 mm FL and from 400 to 1,200 g in weight.

Tagging procedures.—Four treatment groups were used in the swimming performance tests: (1) fish that were tagged with an external transmitter anterior to the dorsal fin (type A; Figure 1a), (2) fish that were tagged with a two-part external transmitter beneath the dorsal fin (type B; Figure 1b), (3) fish

TABLE 3. Mean ± SD and range of fork length (FL) and weight for each treatment group of juvenile Chinook salmon evaluated for swimming performance (JSATS = Juvenile Salmon Acoustic Telemetry System; PIT = passive integrated transponder).

		FL (mm)		Mass (g)	
Treatment	*n*	Mean ± SD	Range	Mean ± SD	Range
External transmitter type A (anterior to dorsal fin)	30	123 ± 6.4	111–135	21.2 ± 4.2	14.2–30.4
External transmitter type B (two-part transmitter, beneath dorsal fin)	31	126 ± 7.3	102–135	22.6 ± 4.5	11.9–30.3
Internal transmitter (JSATS tag + PIT tag)	10	125 ± 4.4	119–132	23.1 ± 2.4	20.3–27.7
Control (untagged)	31	124 ± 8.6	98–135	21.8 ± 5.5	9.0–30.7
All treatments	102	124 ± 7.2	98–135	22.0 ± 4.6	9.0–30.7

TABLE 4. Mean ± SD (range in parentheses) fork length (FL) and weight of juvenile Chinook salmon used in predator avoidance trials. Several trials show results for fewer than 10 fish because some fish jumped out of the tank during testing.

	Tagged fish			Untagged fish		
Trial	*n*	FL (mm)	Mass (g)	*n*	FL (mm)	Mass (g)
1	7	136 ± 8 (117–145)	29.8 ± 5.0 (18.9–35.9)	10	137 ± 12 (106–152)	31.0 ± 6.9 (13.2–39.7)
2	7	140 ± 6 (127–149)	30.5 ± 4.2 (22.2–38.8)	10	143 ± 7 (128–155)	33.3 ± 4.4 (25.2–40.4)
3	10	125 ± 7 (113–135)	24.0 ± 4.2 (16.1–31.2)	10	129 ± 6 (114–135)	25.1 ± 3.8 (18.5–32.4)
4	10	129 ± 5 (120–134)	25.9 ± 3.1 (19.1–29.4)	9	128 ± 6 (120–135)	25.1 ± 4.7 (14.8–31.4)
5	10	130 ± 5 (115–135)	28.9 ± 3.3 (19.4–32.1)	10	130 ± 4 (125–135)	28.6 ± 2.6 (23.5–31.9)
6	10	128 ± 8 (105–135)	28.4 ± 5.5 (14.1–35.0)	10	130 ± 5 (118–134)	29.7 ± 3.4 (22.6–34.4)
Overall	54	131 ± 8 (105–149)	27.7 ± 4.7 (14.1–38.8)	59	133 ± 9 (106–155)	28.6 ± 5.2 (13.2–40.4)

that received an internally implanted Juvenile Salmon Acoustic Telemetry System (JSATS; McMichael et al. 2010) acoustic transmitter and a passive integrated transponder (PIT) tag (Destron Technologies, St. Paul, Minnesota), and (4) untagged controls (Table 3). Information on the dimensions and characteristics of the transmitters used in the present study is detailed by Deng et al. (2012).

Deng et al. (2012) found that fish receiving type A transmitters attached using Monocryl 5-0 absorbable monofilament sutures (Ethicon, Inc., Somerville, New Jersey) exhibited better growth than fish that were tagged with type B transmitters. Because of these differences, only two groups were used for predation trials: fish that received type A transmitters (attached with Monocryl 5-0 absorbable sutures) and untagged controls.

To eliminate tagging or handling bias, all tagging was performed by one person (Deters et al. 2010). The daily order in which tagging was performed (i.e., type A or type B transmitter) was randomized. An 80-mg/L solution of tricaine methanesulfonate (MS-222) buffered with an 80-mg/L solution of sodium bicarbonate was used to anesthetize the fish until they reached stage 4 anesthesia (as described by Summerfelt and Smith 1990). The FL (mm) and mass (g) of each fish were measured while the fish were anesthetized. Fish were placed on a foam rubber pad and were oriented dorsal side up for external attachment or ventral side up for internal implantation. A small tube was inserted into the fish's mouth during tagging to provide a constant maintenance flow of 40-mg/L MS-222 buffered with a 40-mg/L solution of sodium bicarbonate.

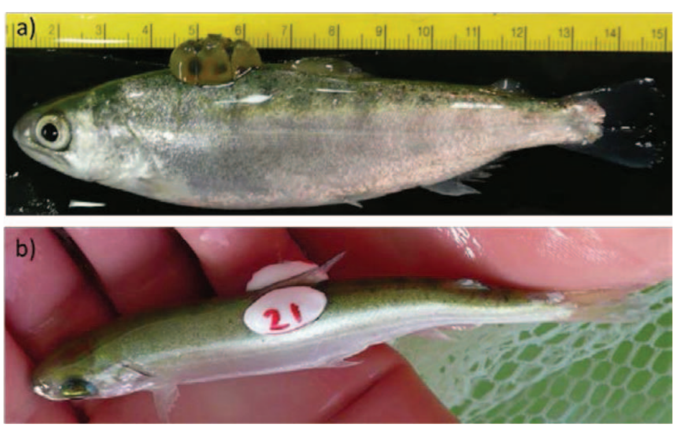

FIGURE 1. Juvenile Chinook salmon with external transmitters attached: (**a**) type A transmitter, painted with a green base coat and dark-green spots (used for predation trials and swimming performance tests); and (**b**) type B transmitter (used for swimming performance tests only). [Figure available online in color.]

External transmitter attachment was performed as described in detail by Deng et al. (2012). Type A transmitters were attached anterior to the dorsal fin by using two sutures that were threaded through the dorsal musculature and secured by a 2 × 2 × 2 × 2 knot (as described by Deters et al. 2012) that rested in grooves on the top of the transmitter. Type B transmitters were attached using two 25-gauge, 2.22-cm (0.875-in) hypodermic needles (Becton, Dickinson, and Company, Franklin Lakes, New Jersey) to guide the wires (attached to the battery side of the transmitter) through the dorsal musculature. The needles were then removed, the wires were threaded through the transducer side of the transmitter, and the excess wire was trimmed.

Internal transmitters were surgically implanted by making a 6–7-mm incision on the linea alba, inserting a JSATS tag and a PIT tag, and closing the incision with two simple interrupted sutures (Monocryl 5-0 absorbable monofilament) using a 1 × 1 × 1 × 1 knot (similar to Panther et al. 2011; Deters et al. 2012).

After all tagging procedures (or handling for controls) were completed, fish were allowed to recover in a 20-L bucket containing oxygenated water. After recovery, fish were placed in a floating 20-L bucket (perforated to allow flow-through of water), which was placed in a 650-L circular tank inside the ARL; fish were held in the tank for approximately 24 h prior to testing. Lights inside the ARL were controlled automatically to follow the natural photoperiod.

Swimming performance tests.—A Blazka-type respirometer was used to conduct swimming performance tests. The relationship between water velocity in the swim chamber and motor speed was calibrated using a type S pitot tube (United Sensor Corp., Amherst, New Hampshire). Flow straighteners at the upstream end of the tube were used to achieve uniform water velocity within the swim chamber. The swim chamber had an electrified grid at the downstream end. A black shade was placed at the upstream end of the swim chamber during testing to provide shelter and orientation. Flow-through well water (16.8–17.8°C) was supplied to the swim chamber during the tests.

Swimming performance tests were conducted during November 8–December 17, 2010. For each trial, one fish was selected at random and placed inside the swim chamber. Fish were given a 30-min acclimation period during which the respirometer velocity was set at 1 body length (BL)/s. Thereafter, the velocity was increased by 0.5 BL/s every 15 min. When a fish stopped swimming and fell back to the downstream end of the swim chamber, the shocking grid was activated to emit a 6–12-V shock. The fish received a 1-s shock if it came in contact with the grid. If the fish did not swim away from the grid, the fish was shocked consecutively at 1-s intervals for 10 s. If the fish remained on the grid at the end of 10 s, the motor was stopped to allow the fish to swim away from the grid. The velocity was set back to the acclimation speed and was increased gradually to the last velocity setting. If the fish did not swim away from the grid, the fish was considered to be fatigued and received no further shocks. If the fish continued to swim, the procedure was continued until the fish became fatigued. When the fish was considered fatigued, it was removed from the swim chamber and euthanized with MS-222 (250 mg/L). Critical swimming speed (U_{crit}) was calculated based on the formula of Brett (1964):

$$U_{crit} = u_1 + [(t_i/t_{ii}) \times u_{ii}], \qquad (1)$$

where u_1 = the highest velocity (cm/s) maintained for the prescribed period, u_{ii} = the velocity increment (cm/s), t_i = time (min) for which the fish swam at the "fatigue" velocity, and t_{ii} = prescribed period of swimming (min).

Predator avoidance tests.—Juvenile fall Chinook salmon were randomly designated as treatment fish (tagged; type A external transmitter) or control fish (untagged) for the predation trials. Type A transmitters were air-brushed with a mixture of green, black, white, and blue paint (CS Coatings, Wausau, Wisconsin) before attachment. The paint camouflaged the transmitter by mimicking the coloring of Chinook salmon (Figure 1a). Sample size for both groups combined was between 17 and 20 fish/trial. Several trials had fewer fish because some fish jumped out of the tank during testing.

Rainbow trout were chosen as predators because of their performance as test predators in previous studies and the ease with which they acclimate to the test environment (Neitzel et al. 2000; Anglea et al. 2004). Ten rainbow trout were held in the 2,000-L circular test tank for an acclimation period of 8 weeks prior to the start of the predation trials. During the acclimation period, predators were conditioned to prey on live fish (as described by Anglea et al. 2004) by feeding them juvenile Chinook salmon (~130 mm FL; 30 g).

Predation trials lasted from December 7, 2010, to January 12, 2011. Trials were at least 7 d apart, and predators were not fed between trials. To begin the trial, 10 tagged fish and 10 untagged fish were placed in 20-L buckets and were introduced into the 2,000-L circular predation tank by emptying the buckets directly into the tank. Trials started approximately 24 h after the fish were tagged.

Video cameras were set up above the tank to remotely monitor the rates of predation and minimize outside disturbances. Observations from the live video feed were made at 15-min intervals, and observations at the tank were made every hour until the end of the trial. Trials ended when 50% of the prey were consumed or after 8 or 24 h if less than 50% of the prey were consumed. If injuries from predation attempts were serious (e.g., fish lying on the tank bottom), fish were categorized as "consumed" based on the assumption that those fish would not survive the trial. At the end of the trial, all remaining juvenile Chinook salmon were removed from the tank and euthanized with a 250-mg/L solution of MS-222. All fish were externally examined for injuries related to predation attempts.

Statistical analysis.—Differences in U_{crit} among transmitter treatment groups were tested using ANOVA. The first analysis included three groups (type A, type B, and control). The analysis was performed again with the addition of the fourth treatment group (fish with internally implanted transmitters). In addition to transmitter type, the influence of fish length on U_{crit} was examined. The ANOVA was also used to compare each pair of transmitter treatments. To control for the increased probability of a type I error, a Šidák correction was used to adjust the rejection region, depending on the number of pairwise tests:

$$\alpha_{family} = 1 - (1 - \alpha_{comparison})^{1/t}, \qquad (2)$$

where t = the number of pairwise tests, $\alpha_{comparison} = 0.05$, and α_{family} = the new familywise error rate.

For swimming performance, power curves were constructed to show the sample size needed for comparing any pair of tagging treatments. Assuming homogeneous variances, the mean square error from the overall ANOVA test was used as an estimate of variance in making calculations involving power. Assuming that the mean square error and sample mean difference between two treatments do not change with increased sample size, we calculated the estimated power and percentage of detectable difference for different levels of n. This was done for the observed sample mean differences.

For the predator avoidance trials, ANOVA was used to test whether tagged (type A) and untagged groups differed in the proportion of fish surviving. All assumptions of parametric tests were met (i.e., independence, normality, and homogeneity of variance). A significance level of 0.05 was used.

RESULTS

Swimming Performance

Comparison between fish with external transmitters and control fish.—Mean U_{crit} for juvenile Chinook salmon ranged from

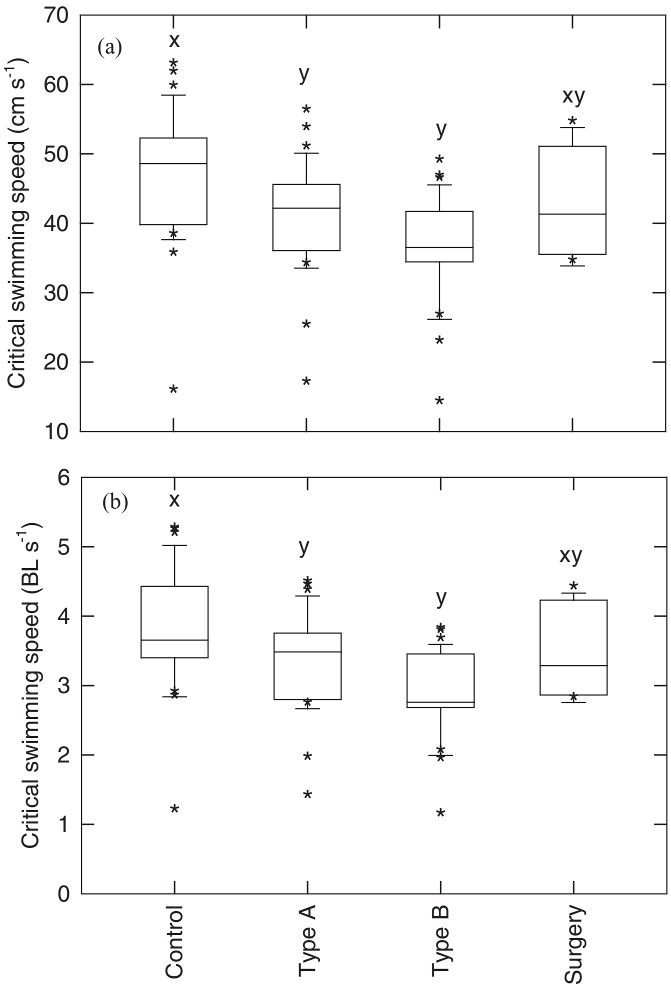

FIGURE 2. Box plots of critical swimming speed in (**a**) centimeters per second and (**b**) body lengths (BL) per second for juvenile Chinook salmon that received external transmitters of type A or type B, surgically implanted internal transmitters (Juvenile Salmon Acoustic Telemetry System tag and passive integrated transponder tag), or no tags (control fish). Significant differences ($P < 0.009$) between treatment groups are indicated by differing letters (line within each box = median; lower edge of box = 25th percentile; upper edge of box = 75th percentile; ends of whiskers = 1.5 × interquartile range; asterisks = outliers).

36.7 to 46.7 cm/s (Figure 2). The U_{crit} varied significantly with both fish size ($P < 0.0001$; decreasing with increasing fish size) and transmitter type ($P < 0.0001$). Control fish had significantly higher U_{crit} (mean $U_{crit} = 46.7$ cm/s) than fish with external transmitters of type A (mean $U_{crit} = 41.2$ cm/s; $P = 0.0087$) or type B (mean $U_{crit} = 36.7$ cm/s, $P < 0.0001$). The U_{crit} did not significantly differ between fish tagged with type A transmitters and those tagged with type B transmitters ($P = 0.038$).

The sample sizes from these experiments provided high overall power to determine differences among treatment groups. The sample data from experiments showed that the maximum difference in sample means between treatment groups was 0.07 BL/s (the maximum difference between fish with type B transmitters and control fish). The data obtained were sufficient to detect a 10% difference with a power of 75%, a 15% difference with a power of 97%, and a 20% difference with a power approaching 100%. The mean U_{crit} for control fish was 11.3% higher than the mean for fish tagged with type A transmitters. Data obtained from these experiments were sufficient to detect this difference with a power of 84%. The mean U_{crit} for controls was 22.5% higher than that of fish with type B transmitters; the power to detect this difference was 99.99%. The mean U_{crit} for fish with type A transmitters was 12.6% higher than that of fish with type B transmitters, and the power to detect this difference was 91%.

Comparison between externally tagged fish and control fish or fish with internally implanted transmitters.—When fish that received internally implanted transmitters were added as a pilot-scale comparison, there was also a significant difference in swimming performance related to fish length (decreasing with increasing FL; $P < 0.001$) and transmitter type ($P = 0.001$). Control fish still had significantly higher U_{crit} than fish with external transmitter type A ($P = 0.0087$; Table 5) or external transmitter type B ($P < 0.0001$). However, there was no significant difference between fish with internally implanted transmitters (mean $U_{crit} = 42.9$ cm/s) and control fish ($P = 0.2245$), fish with type A transmitters ($P = 0.512$), or fish with type B transmitters ($P = 0.0317$). The mean U_{crit} of control fish was 9.0% lower than that of fish with internally implanted transmitters; the power to detect this difference was 29%. The mean U_{crit} for fish that received internally implanted transmitters was 2.5% higher than the mean U_{crit} for fish that received type A external transmitters, with a power of 6% to detect this difference. The U_{crit} of fish with internally implanted transmitters was 15% higher than the U_{crit} of fish that received type B external tags, with a power of 55% to detect this difference.

Predator Avoidance

The percentage of juvenile Chinook salmon consumed by predators was not significantly different ($P = 0.2622$) between tagged (type A) and untagged groups. The percentage of fish consumed did not significantly differ ($P = 0.8263$) among the six predation trials conducted. The percentage consumed averaged 38.9% for untagged fish compared with 47.6% for tagged fish (Figure 3); the estimated difference in survival was 8.7% between the two groups.

DISCUSSION

Juvenile Chinook salmon (98–135 mm) that were tagged with external transmitter types A and B exhibited lower swimming performance than untagged fish. Similar results were reported by Peake et al. (1997) in examining the effects of external transmitters on the swimming performance of Atlantic salmon smolts (range of mean lengths, 185–208 mm; Table 1 provides fish size and tag burden details from the Peake et al. [1997] study and other studies).

Swimming performance of fish that received internally implanted acoustic transmitters was similar to the swimming

TABLE 5. Results of ANOVA comparing critical swimming speed (i.e., U_{crit}) scores (with fork length and tag type as covariates) for juvenile Chinook salmon in pairs of tagging treatment groups (fish with external transmitter types A and B; fish that received surgically implanted internal transmitters [Juvenile Salmon Acoustic Telemetry System tag and passive integrated transponder tag]; and control [untagged] fish). Significant *P*-values are shown in bold italics ($\alpha_{family} = 0.009$ after Šidák correction; see equation 2).

Comparison	Source	df	Sum of squares	Mean square error	*F*	*P*
Type A versus type B	Length	1	4.4522	4.4522	11.8299	***0.0011***
	Tag type	1	1.6902	1.6902	4.4909	0.0384
	Residuals	58	21.8284	0.3764		
Control versus type B	Length	1	7.7723	7.7723	17.568	***0.0001***
	Tag type	1	9.7116	9.7116	21.952	<***0.0001***
	Residuals	59	26.1017	0.4424		
Control versus type A	Length	1	7.2809	7.2809	15.5248	***0.0002***
	Tag type	1	3.4605	3.4605	7.3788	***0.0087***
	Residuals	58	27.201	0.469		
Control versus internal	Length	1	5.9544	5.9544	11.8974	***0.0014***
	Tag type	1	0.763	0.763	1.5246	0.2245
	Residuals	38	19.0182	0.5005		
Type A versus internal	Length	1	2.6528	2.6528	6.5527	0.0147
	Tag type	1	0.1775	0.1775	0.4384	0.512
	Residuals	37	14.979	0.4048		
Type B versus internal	Length	1	1.6785	1.6785	4.7378	0.0358
	Tag type	1	1.7626	1.7626	4.9751	0.0317
	Residuals	38	13.4625	0.3543		

performance of control fish. Other researchers have found similar results for the swimming performance of juvenile Chinook salmon with surgically implanted acoustic transmitters (122–198-mm fish: Anglea et al. 2004; 94–125-mm fish: Brown et al. 2006). However, Brown et al. (2006) found that juvenile sockeye salmon (101–133 mm) with surgically implanted acoustic transmitters had poorer swimming performance than their untagged counterparts.

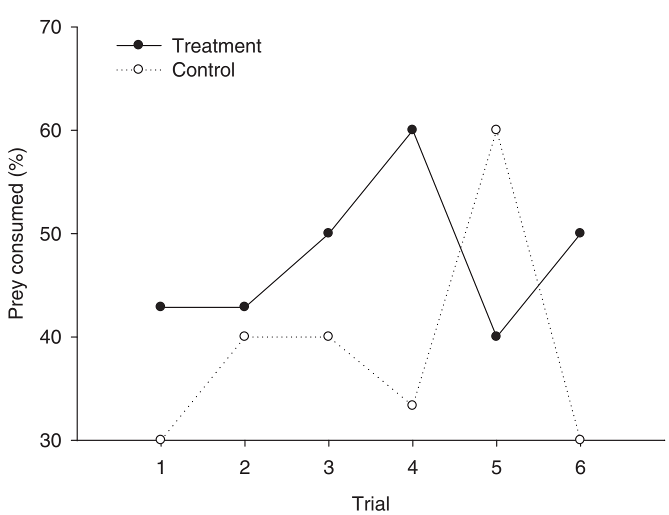

FIGURE 3. Percentages of juvenile Chinook salmon that were consumed by rainbow trout predators during each of six predation trials. Control fish were untagged; treatment fish were tagged with external transmitter type A (i.e., neutrally buoyant). See Table 4 for sample sizes.

Swimming performance of juvenile Chinook salmon with internally implanted acoustic tags was also similar to the swimming performance of fish that were externally tagged with type A and type B transmitters. Although the 10 fish in the internally tagged group were initially added on a pilot scale, the difference in U_{crit} was detected with a moderately high statistical power for the comparison of internally implanted transmitters with type B external transmitters (55% power to detect a difference of 15%). However, there was much lower statistical power to detect any potential difference between fish with internally implanted transmitters and fish with type A external transmitters (6% power to detect the 2.5% difference) or control fish (29% power to detect the 9.0% difference). When the two external transmitter types were compared, we found no difference in swimming performance between fish carrying type A external transmitters and fish with type B transmitters.

Swimming performance also decreased with increasing fish length. This trend was also noted in U_{crit} among the control fish tested by Adams et al. (1998). In addition, Brett (1964) stated that the swimming ability of fish decreases as size increases. However, Peake et al. (1997) found no correlation between U_{crit} and fish length for radio-tagged Atlantic salmon smolts (185–208 mm). The results reported by Peake et al. (1997) mirror those of Brown et al. (2006) for acoustic-tagged juvenile Chinook salmon.

Although the swimming performance of externally tagged fish in this study was lower than that of untagged fish, we found no detectable difference in predation rates between tagged and untagged fish. Very few studies have examined the effects of externally attached transmitters on the rates of predation on juvenile salmonids. Although external transmitters have been commonly used in fisheries research, their utility has been somewhat limited to larger fish. The larger size of the fish and the proportionately smaller size of the transmitter could explain why predation effects have not been closely examined. Many factors are involved in a fish's ability to avoid predation; swimming performance, prey conspicuousness, and ability to detect predators may lead to differential predation rates (Bams 1967; Mesa 1994). The presence of an external transmitter has the potential to impair some of these avoidance abilities by possibly creating drag and visible differences among prey. In smaller fish, such as juvenile salmonids, these effects can be magnified and the relative size of the transmitter is imperative. Multiple stressors associated with the tagging process itself may also lead to an increased risk of predation by eliciting physiological and behavioral stress responses, potentially resulting in substandard condition of the prey at the time of their interaction with predators (Temple 1987; Schreck 1990).

The additional mass of a transmitter can cause an increase in fish density, which potentially leads to increased energy expenditure (Lefrançois et al. 2001). This potential increase in energy expenditure could affect both swimming performance and the ability to avoid predation. Although the attachment of an external transmitter adds more surface area to the fish and thus may lead to drag forces, the transmitter used in this study was neutrally buoyant in water. Thus, there was no tag burden for fish bearing external transmitters in our study.

In considering externally attached transmitters, one of the major concerns of researchers is the long-term consequences for the fish. As a juvenile fish grows, a fixed transmitter could have detrimental effects on the fish's well-being, such as inhibited growth and tissue damage. In this study, absorbable monofilament sutures were used for the attachment of type A transmitters. Absorbable monofilament sutures used for surgical implantation of transmitters were expelled in as little as 28 d from juvenile Chinook salmon that were held at 12–17°C (Deters et al. 2012). The acoustic transmitters used in our study have a battery life of approximately 20–70 d. Once the battery has expired, the transmitter and the tagged fish are no longer of use to the researcher. The ability of the external transmitter to be shed after its utility has ended is a major advantage over internally implanted transmitters, which may never be expelled, and over type B transmitters, which were attached by wires and were not designed to be easily shed after conclusion of the research. Deng et al. (2012) found that fish tagged with type B transmitters had significantly lower growth rates after 14 d than fish tagged with type A transmitters and untagged controls. Our swimming performance tests were conducted before those results were available, and the predator avoidance trials were conducted after those results were obtained. After the growth analysis was completed, only type A transmitters were used for further testing.

Although this research indicates that the swimming performance of externally tagged juvenile Chinook salmon was lower than that of untagged fish, there was no difference in swimming performance between fish with type A or type B external transmitters and fish with internally implanted transmitters. In addition, no difference in predation rates was detected between externally tagged and untagged fish. These results, in combination with the potential advantages of externally attached transmitters (less invasive, transmitter shedding ability, and decreased risk of barotrauma) and the increasingly smaller size of transmitters as technology advances, provide a good indication that an externally attached, neutrally buoyant transmitter may be a viable option for telemetry studies to estimate survival of juvenile salmonids passing through hydroturbines. However, as suggested by Zale et al. (2005), Thorstad et al. (2000), and Brown et al. (2010), conclusive evidence of transmitter effects and the presence of bias resulting from these transmitters will require field studies that involve tagging a wide size range of juvenile salmonids with transmitters and measuring their rates of migration, growth, predation, and survival.

ACKNOWLEDGMENTS

Funding for this research was provided by the U.S. Army Corps of Engineers (USACE) Portland District. We thank USACE staff, including Robert Johnson, Martin Ahmann, Brad Eppard, Dennis Schwartz, and Mike Langeslay, and the USACE Turbine Survival Technical Team for their commitment, assistance, and oversight. We extend appreciation to Tom Hancock (Eastern Washington University) and John Skalski (University of Washington) for their technical insight and input. We also thank the Pacific Northwest National Laboratory staff members whose diverse professional expertise contributed to the success of this study and the overall project, including Tylor Abel, Duane Balvage, Andrea Currie, Kate Deters, Gayle Dirkes, Joanne Duncan, Curt Lavender, Andrea LeBarge, Jayson Martinez, Geoff McMichael, Mitchell Myjak, Kathy Neiderhiser, Cory Overman, Jes Smart, Noel Tavan, Tim Linley, Ricardo Walker, and Mark Weiland.

REFERENCES

Adams, N. S., D. W. Rondorf, S. D. Evans, J. E. Kelly, and R. W. Perry. 1998. Effects of surgically and gastrically implanted radio transmitters on swimming performance and predator avoidance of juvenile Chinook salmon (*Oncorhynchus tshawytscha*). Canadian Journal of Fisheries and Aquatic Sciences 55:781–787.

Anglea, S. M., D. R. Geist, R. S. Brown, K. A. Deters, and R. D. McDonald. 2004. Effects of acoustic transmitters on swimming performance and predator avoidance of juvenile Chinook salmon. North American Journal of Fisheries Management 24:162–170.

Bams, R. A. 1967. Differences in performance of naturally and artificially propagated sockeye salmon migrant fry, as measured with swimming and predation tests. Journal of the Fisheries Research Board of Canada 24:1117–1153.

Bégout Anras, M. L., R. A. Bodaly, and R. McNicol. 1998. Use of an acoustic beam actograph to assess the effects of external tagging procedure on lake whitefish swimming activity. Transactions of the American Fisheries Society 127:329–335.

Brett, J. R. 1964. The respiratory metabolism and swimming performance of young sockeye salmon. Journal of the Fisheries Research Board of Canada 21:1183–1226.

Brown, R. S., 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. 2012a. Quantifying mortal injury of juvenile Chinook salmon exposed to simulated hydro-turbine passage. Transactions of the American Fisheries Society 141:147–157. DOI: 10.1080/00028487.2011.650274.

Brown, R. S., 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. 2009. Assessment of barotrauma from rapid decompression of depth-acclimated juvenile Chinook salmon bearing radiotelemetry transmitters. Transactions of the American Fisheries Society 138:1285–1301. DOI: 10.1577/T08-122.1.

Brown, R. S., S. J. Cooke, W. G. Anderson, and R. S. McKinley. 1999. Evidence to challenge the "2% rule" for biotelemetry. North American Journal of Fisheries Management 19:867–871. DOI: 10.1577/1548-8675(1999)019>0867:ETCTRF<2.0.CO;2.

Brown, R. S., D. R. Geist, K. A. Deters, and A. Grassell. 2006. Effects of surgically implanted acoustic transmitters >2% of body mass on the swimming performance, survival and growth of juvenile sockeye and Chinook salmon. Journal of Fish Biology 69:1626–1638. DOI: 10.1111/j.1095-8649.2006.01227.x.

Brown, R. S., R. A. Harnish, K. M. Carter, J. W. Boyd, K. A. Deters, and M. B. Eppard. 2010. An evaluation of the maximum tag burden for implantation of acoustic transmitters in juvenile Chinook salmon. North American Journal of Fisheries Management 30:499–505. DOI: 10.1577/M09-038.1.

Brown, R. S., B. D. Pflugrath, T. J. Carlson, and Z. D. Deng. 2012b. The effect of an externally attached neutrally buoyant transmitter on mortal injury during simulated hydroturbine passage. Journal of Renewable and Sustainable Energy [online serial] 4(1):article 013107. DOI: 10.1063/1.3682062.

Brown, R. S., B. D. Pflugrath, A. H. Colotelo, C. J. Brauner, T. J. Carlson, Z. D. Deng, and A. G. Seaburg. 2012c. Pathways of barotrauma in juvenile salmonids exposed to simulated hydroturbine passage: Boyle's law vs. Henry's law. Fisheries Research 121–122:43–50. DOI: 10.1016/j.fishres.2012.01.006.

Carlson, T. J., R. S. Brown, J. R. Stephenson, B. D. Pflugrath, A. H. Colotelo, A. J. Gingerich, P. L. Benjamin, M. J. Langeslay, M. L. Ahmann, R. L. Johnson, J. R. Skalski, A. G. Seaburg, and R. L. Townsend. 2012. 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. North American Journal of Fisheries Management 32:249–261.

Cooke, S. J., B. D. S. Graeb, C. D. Suski, and K. G. Ostrand. 2003. Effects of suture material on incision healing, growth and survival of juvenile largemouth bass implanted with miniature radio transmitters: case study of a novice and experienced fish surgeon. Journal of Fish Biology 62:1366–1380.

Deng, Z. D., 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. G. Seaburg, R. L. Johnson, and M. L. Ahmann. 2012. Development of external and neutrally buoyant acoustic transmitters for juvenile salmon turbine passage evaluation. Fisheries Research 113:94–105.

Deters, K. A., R. S. Brown, J. W. Boyd, M. B. Eppard, and A. G. Seaburg. 2012. Optimal suturing technique and number of sutures for surgical implantation of acoustic transmitters in juvenile salmonids. Transactions of the American Fisheries Society 141:1–10. DOI: 10.1080/00028487.2011.638594.

Deters, K. A., R. S. Brown, K. M. Carter, J. W. Boyd, M. B. Eppard, and A. G. Seaburg. 2010. Performance assessment of suture type, water temperature, and surgeon skill in juvenile Chinook salmon surgically implanted with acoustic transmitters. Transactions of the American Fisheries Society 139:888–899. DOI: 10.1577/T09-043.1.

Jepsen, N., K. Aarestrup, F. Økland, and G. Rasmussen. 1998. Survival of radio-tagged Atlantic salmon (*Salmo salar* L.) and trout (*Salmo trutta* L.) smolts passing a reservoir during seaward migration. Hydrobiologia 371–372:347–353. DOI: 10.1023/A:1017047527478.

Jepsen, N., A. Koed, E. B. Thorstad, and E. Baras. 2002. Surgical implantation of telemetry transmitters in fish: how much have we learned? Hydrobiologia 483:239–248.

Lefrançois, C., M. Odion, and G. Claireaux. 2001. An experimental and theoretical analysis of the effect of added weight on the energetics and hydrostatic function of the swimbladder of European sea bass (*Dicentrarchus labrax*). Marine Biology 139:13–37. DOI: 10.1007/s002270100562.

Lucas, M. C., A. D. F. Johnstone, and I. G. Priede. 1993. Use of physiological telemetry as a method of estimating metabolism of fish in the natural environment. Transactions of the American Fisheries Society 122: 822–833.

McMichael, G. A., M. B. Eppard, T. J. Carlson, J. A. Carter, B. D. Ebberts, R. S. Brown, M. Weiland, G. R. Ploskey, R. A. Harnish, and Z. D. Deng. 2010. The juvenile salmon acoustic telemetry system: a new tool. Fisheries 35:9–22.

Mesa, M. G. 1994. Effects of multiple acute stressors on the predator avoidance ability and physiology of juvenile Chinook salmon. Transactions of the American Fisheries Society 123:786–793. DOI: 10.1577/1548-8659(1994)123>0786:EOMASO<2.3.CO;2.

Neitzel, D. A., M. C. Richmond, D. D. Dauble, R. P. Mueller, R. A. Moursund, C. S. Abernethy, and G. R. Guensch. 2000. Laboratory studies on the effects of shear on fish. Pacific Northwest National Laboratory, Report PNNL-13323, Richland, Washington. Available: www.pnl.gov/main/publications/external/technical_reports/PNNL-13323.pdf. (August 2011).

Panther, J. L., R. S. Brown, G. L. Gaulke, K. A. Deters, C. M. Woodley, and M. B. Eppard. 2011. Influence of incision location on transmitter loss, healing, survival, growth, and suture retention of juvenile Chinook salmon. Transactions of the American Fisheries Society 140:1492–1503. DOI: 10.1080/00028487.2011.637003.

Peake, S., R. S. McKinley, D. A. Scruton, and R. Moccia. 1997. Influence of transmitter attachment procedures on swimming performance of wild and hatchery-reared Atlantic salmon smolts. Transactions of the American Fisheries Society 126:707–714. DOI: 10.1577/1548-8659(1997)126>0707:IOTAPO<2.3.CO;2.

Robertson, M. J., D. A. Scruton, and J. A. Brown. 2003. Effects of surgically implanted transmitters on swimming performance, food consumption and growth of wild Atlantic salmon parr. Journal of Fish Biology 62:673–678. DOI: 10.1046/j.1095-8649.2003.00055.x.

Ross, M. J., and J. H. McCormick. 1981. Effects of external radio transmitters on fish. Progressive Fish-Culturist 43:67–72. DOI: 10.1577/1548-8659(1981)43[67:EOERTO]2.0.CO;2.

Schreck, C. B. 1990. Physiological, behavioral, and performance indicators of stress. Pages 29–37 *in* S. M. Adams, editor. Biological indicators of stress in fish. American Fisheries Society, Symposium 8, Bethesda, Maryland.

Summerfelt, R. C., and L. S. Smith. 1990. Anesthesia, surgery, and related techniques. Pages 213–272 *in* C. B. Schreck and P. B. Moyle, editors. Methods for fish biology. American Fisheries Society, Bethesda, Maryland.

Temple, S. A. 1987. Do predators always capture substandard individuals disproportionately from prey populations? Ecology 68:669–674.

Thorstad, E. B., F. Økland, and B. Finstad. 2000. Effects of telemetry transmitters on swimming performance of adult Atlantic salmon. Journal of Fish Biology 57:531–535. DOI: 10.1111/j.1095-8649.2000.tb02192.x.

Zale, A. V., C. Brooke, and W. C. Fraser. 2005. Effects of surgically implanted transmitter weights on growth and swimming stamina of small adult westslope cutthroat trout. Transactions of the American Fisheries Society 134:653–660. DOI: 10.1577/T04-050.1.