Articles

Passive Integrated Transponder Tags: Review of Studies on Warmwater Fishes With Notes on Additional Species

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Abstract

Although numerous studies have assessed retention and survival of passive integrated transponder (PIT) tags, data are scattered and information gaps remain for many diminutive fishes. Our study objectives were to 1) systematically review PIT tag studies and summarize retention, growth, and survival data for warmwater fishes; and 2) conduct a laboratory study to evaluate the retention, survival, and growth effects of intracoelomic-placed, half duplex PIT tags on six small-bodied species common to warmwater streams. Our systematic review suggested small sample sizes were common within PIT tag retention and survival studies (39% with $n \leq 20$) and that many experiments (15%, 14 of 97) failed to use control fish as part of their evaluations. Studies focused primarily on short-term changes (15 d to 2 y) in tag retention and survival. Tag retention was equal to or greater than 90% in 85% of the experiments reviewed and median survival was 92%. Growth was reported by fishes in the majority of reviewed studies. We found similar results after PIT tagging (peritoneum tagging using 12- or 23-mm half duplex tags) adult Cardinal Shiner *Luxilus cardinalis*, Central Stoneroller *Campostoma annomalum*, Greenside Darter *Etheostoma blennioides*, Orangethroat Darter *Etheostoma spectabile*, Slender Madtom *Noturus exilis*, and juvenile Smallmouth Bass *Micropterus dolomieu*. Tag retention for all species was high, with only one tag loss recorded after 60 d. Survival was also high ($\geq$88%) for all of our species with the exception of Orangethroat Darter (56% survival). No significant difference in mean growth between treatment and control groups was found. Both our results and the findings of the literature review suggested generally high tag retention and low mortality in tagged fishes (across 31 species reviewed). However, within our study (e.g., Orangethroat Darter) and from the literature, examples of negative effects of PIT tagging on fishes were apparent, suggesting methodological testing is prudent before using PIT tags in field studies. We suggest future studies would benefit from addressing the behavioral implications that may be associated with tagging and examination of longer-term tag retention. Furthermore, standard reporting (i.e., sample sizes) in PIT tag studies would be beneficial, and use of control subjects or groups for statistical comparisons is needed.

Keywords: survival; tagging; retention

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Introduction

As smaller passive integrated transponder (PIT) tags have become available with technological advances, their use has increased in many studies in which individual identification is needed. Passive integrated transponder tags are glass-encapsulated microchips with unique identification, long operating time, and passive detection—characteristics that have increased the accuracy of mark–recapture estimates (Gibbons and Andrews 2004; Hewitt et al. 2010) and their application to an array of study objectives. Recaptures of PIT-tagged fishes have been used to estimate population size (Pine et al. 2003), growth (Walters et al. 2012), survival (Hewitt et al. 2010), movement (Skalski and Gilliam 2000), habitat use (Teixeira and Cortes 2007), predation (Ryan et al. 2003), behavior (McCormick and Smith 2004), and sampling efficiency (Price and Peterson 2010).

Small tags (9–12 mm) implanted into the body cavity (intracoelomic) have made PIT tags an effective option for studying small-bodied fishes (e.g., Dixon and Mesa 2011), but fish size remains a limiting factor (Prentice et al. 1990a; Lucas and Baras 2000; Skalski et al. 2009). Below a certain size, individuals may have slower growth and higher mortality after intracoelomic PIT tag injection (Prentice et al. 1990a). In addition, PIT tag retention is size dependent (Acolas et al. 2007), and the size threshold is associated with loss of fitness (i.e., reduced growth and survival), and unacceptable levels of tag retention are species specific (McCormick and Smith 2004; Jepsen et al. 2005). Although these relationships have been generally well established in the literature for salmonids (Skalski et al. 2009; Cooke et al. 2011), information is lacking for many warmwater fishes (Cooke et al. 2011).

Tag loss and tagging effects on growth and survival violate mark–recapture assumptions and bias parameter estimates that can handicap attempts to effectively manage populations (Burnham et al. 1987). Bolland et al. (2009) recommended retention and survival be evaluated for each species before field studies. This is especially important for juveniles and other small-bodied fishes where the risk of negative tag effects are increased (Prentice et al. 1990a). Although numerous studies have assessed PIT tag retention and survival, data are scattered and information gaps remain for fishes in certain ecosystems (e.g., warmwater streams; Cooke et al. 2011). Therefore, the study objectives were to 1) systematically review PIT tag studies and summarize retention and growth and survival data for nonsalmonid fishes; and 2) conduct a laboratory study to evaluate the retention, survival, and growth effects of intracoelomic PIT tags on six small-bodied species common to warmwater streams. Our laboratory study was conducted to ensure retention and survival were appropriate to follow up with a field-based study evaluating movement of select small-bodied fishes. Because our laboratory experiment was limited by sample size, we placed our experiments into context by comparing them with data from the literature to see whether the patterns observed in our study were consistent across other warmwater fishes. We also report patterns across studies to provide recommendations for future PIT tag studies.

Methods

Literature review

To provide an indication of the state of knowledge in relation to survival and retention of PIT tags in nonsalmonid fishes, we conducted a literature search by using ISI Web of Science in 2015. Four search strings were used, which were formed using the combinations of the following keywords: 'fish' AND 'passive-integrated-transponder' OR 'PIT Tag' AND 'retention' OR 'survival'. Within Web of Science, search results were screened based on the titles and abstracts and studies on salmonids, marine, and estuarine species and non-fish species (e.g., crayfish, salamanders) were omitted. The resulting literature was accessed and further filtered to remove studies that provided no information on survival or retention or were focused on anguilliform species.

Once the final set of literature was gathered, each paper was examined for general information: the year of publication, journal, taxonomic group studied, and objectives. For each paper, the number and identity of the species studied and the taxonomic family were recorded. The study objectives in relation to the use of PIT tags were categorized into seven groups, with studies sometimes belonging to multiple categories: 1) tag retention, 2) fish survival, 3) fish growth, 4) behavioral responses, 5) different PIT tagging methodologies, 6) different anatomical tagging locations, and 7) comparisons with other fish-marking procedures.

Within each individual study, more than one experiment was often identified, and was eventually used to summarize retention and survival for each species. For our analysis, we split studies into experiments if they used different species, different methodologies (e.g., tag size, tagging location, tagging method, PIT tags combined with other types of tags), different sizes of fish, different times, or different study locations (e.g., laboratory, fish pond, or field). If PIT tags were implanted in multiple locations on the same fish, each anatomical location was deemed an experiment. For each experiment, data were recorded on the study duration, location type, source of the fish (wild or hatchery), and sample size. The tag size (length and width), tagging method, and tagging location were also recorded. Where available, statistics on percentage of tag retention, fish survival and growth (positive or negative), and whether it was statistically different from a control group were collated. If a study had multiple experiments using a single species, we recorded these separately. If retention, survival, or growth statistics were reported at multiple time steps through an experiment, information from the last time step was used.

Table 1. Characteristics of six warmwater fish species that were collected from Flint Creek, OK in 2012 to determine passive integrated transponder (PIT) tag retention in the laboratory. All fish were tagged in the peritoneum with 12- or 23-mm (tag size) half duplex PIT tags. The number of individuals (*N*) varied by each species due to availability at sample locations. The mean initial total length (TL) and mean initial weight (WT) are provided for each study species. Variance was reported as SD.

Common name	Scientific name	*N*	TL ± SD (mm)	WT ± SD (g)	Tag size (mm)
Cardinal Shiner	*Luxilus cardinalis*	24	91.1 ± 9.6	6.8 ± 2.3	12.0 × 2.12
Central Stoneroller	*Campostoma annomalum*	16	94.3 ± 18.2	7.3 ± 4.5	12.0 × 2.12
Slender Madtom	*Noturus exilis*	26	76.8 ± 10.0	3.4 ± 1.4	12.0 × 2.12
Orangethroat Darter	*Etheostoma spectabile*	18	60.2 ± 5.7	2.1 ± 0.7	12.0 × 2.12
Greenside Darter	*Etheostoma blennioides*	6	94.8 ± 9.3	6.5 ± 1.7	12.0 × 2.12
Smallmouth Bass	*Micropterus dolomieu*	50	148.0 ± 10.8	31.0 ± 7.2	23.0 × 3.65

Laboratory trials

Laboratory experiments were conducted on six warmwater fishes in 2012 to assess tag retention and the effects on fish growth by intracoelomic PIT tagging. Wild fishes included in the laboratory study were Cardinal Shiner *Luxilus cardinalis* ($n = 24$), Central Stoneroller *Campostoma annomalum* ($n = 16$), Greenside Darter *Etheostoma blennioides* ($n = 6$), Orangethroat Darter *Etheostoma spectabile* ($n = 18$), and Slender Madtom *Noturus exilis* ($n = 26$; Table 1). Wild fishes were collected from Flint Creek, a third-order tributary of the Illinois River located in northeast Oklahoma by using standard seining methods (Bonar et al. 2009). Water temperatures at the time of fish collections ranged from 21 to 24°C. Juvenile Smallmouth Bass *Micropterus dolomieu* ($n = 50$), acquired from the Kansas Department of Wildlife and Parks (Pratt Fish Hatchery, Pratt, KS), were also included in the study (Table 1). All fishes were acclimated to laboratory conditions for a minimum of 2 wk and placed on a twice-daily feeding schedule with weekly water changes and daily water-quality monitoring (i.e., pH, dissolved oxygen, ammonia, and temperature). Water temperatures in the laboratory were 23–25°C during the study. Dissolved oxygen and ammonia were maintained at acceptable levels and the pH was 6.8–8.2. All fishes were fed a dense-culture feed or freeze-dried krill (Aquatic Ecosystems, Apopka, FL).

Fish were haphazardly assigned to a treatment or control group. Before handling, all fish were anesthetized using tricaine methanesulfonate (MS-222; approximately 2.5 mL/L stock solution of 20 g of MS-222 and 50 g of $NaHCO_3$/L, Hauer and Lamberti 2006). Upon loss of equilibrium, fish were measured to the nearest 1.0 mm (total length) and weighed to the nearest 0.1 g. All treatment fishes, except Smallmouth Bass, were tagged with a 12-mm half duplex PIT tag (Oregon RFID, Portland, OR). Half duplex tags were chosen over full duplex tags because they are less susceptible to noise (i.e., interference), and 12 mm is the smallest tag size currently produced. Because of their larger size, Smallmouth Bass were tagged with a 23-mm half duplex PIT tag (Oregon RFID). Larger tag size is associated with greater read range and is advantageous in field studies (see description at https://www.oregonrfid.com/index.php?main_page=page&id=31&zenid=bk2kfb9p1c1mev066aappu07h5). Control fishes were subject to the same handling as treatment fishes (i.e., anesthetized, measured, weighed), but were not tagged. The same person (W.C.M.) conducted all tagging.

Tags were injected using a 12-gauge hypodermic needle (12-mm tag) or surgically implanted using a scalpel and manual insertion (23-mm tag) into the peritoneum from underneath the pectoral fin following methods of Prentice et al. (1990b). Smaller species (e.g., minnows, darters, and madtoms) were placed in an individual 38-L aquarium with a control fish of the same species. Smallmouth Bass were placed into three replicate 2,400-L tanks in groups of ten (control $n = 5$, treatment $n = 5$). These holding densities were within the range found under field conditions (S.K. Brewer, unpublished data).

Experiments lasted a minimum of 30 d. Fish were then removed from the tanks, anesthetized, measured (total length), weighed, and scanned with a hand-held PIT tag reader (DataTracer, Oregon RFID) for the presence of the tag. Treatment fishes that retained tags after 30 d were held for an additional 30 d, but they were placed in larger 2,400-L tanks. Treatment Smallmouth Bass were still kept in separate 2,400-L tanks to avoid predation on smaller study species. At the end of the experiments, fish were euthanized using a lethal dose of MS-222, measured, weighed, and then preserved in 10% formalin.

Growth rates (final weight − initial weight), survival (percentage alive after the trial), and tag retention (percentage retaining tags after the trial) were calculated at the conclusion of the experiment. Significant differences ($\alpha = 0.05$) in mean growth for treatment vs. control fish by species were assessed using a Welch's *t*-test in R (R Core Team 2012). Welch's *t*-test does not make the assumption of homogeneity of variance and uses a correction to adjust degrees of freedom (Field et al. 2012). Normality of growth data by species and treatment were evaluated using a Shapiro–Wilk test.

Results

Literature review

The literature search returned 167 individual articles of which 29 met the review criteria (e.g., retention and survival) of PIT tag studies on non-salmonid fishes. Publication dates ranged from 1989 to 2015, with a general increase in publications since 2009. There was a clear bias in the journals where studies were published, with only nine outlets represented. More than half (15 of 29) of the studies were published in the *North American Journal of Fisheries Management*. Additional journals represented were the *Journal of Applied Ichthyology* ($n = 3$), *Ecology of Freshwater Fish* ($n = 2$), *Transactions of the American Fisheries Society* ($n = 2$), *North American Journal of Aquaculture* ($n = 2$), *Progressive Fish-Culturist* ($n = 2$), and three other journals with one publication each.

Studies were biased toward those carried out in the United States (72%; including one field study in Lake Erie, United States and Canada). Three studies were conducted in the UK; two in Belgium; and one each in Canada, Germany, and Japan. The majority of studies focused on a single species ($n = 25$), with one study containing information on two species and three studies comparing three species. Information was reviewed on 31 species with Muskellunge *Esox masquinongy* ($n = 4$), Largemouth Bass *Micropterus salmoides* ($n = 2$), and Burbot *Lota lota* ($n = 2$) represented in multiple studies. The 31 species represented 15 families, with most species belonging to five families: Cyprindae (26%), Cottidae (10%), Ictaluridae (10%), and Lepisosteidae (10%).

The papers covered multiple objectives, but those objectives were not equally represented. As expected given the search terms, after tag retention, fish survival was the most common study area (83% of studies; Table 2). Information on fish growth in relation to tagging was reported in almost half the studies ($n = 12$), whereas studies comparing PIT tags to other tagging methods were also well represented (41% of studies). Nine studies compared different anatomical tagging locations, whereas different insertion methods (e.g., injecting vs. incisions) were the subject of four papers. Studies reporting information on fish behavior focused on swimming performance ($n = 2$), feeding ($n = 2$), and net avoidance ($n = 1$).

Studies also varied in the location where they were conducted, the study duration, and the sample size. A majority of the 29 studies was conducted in the laboratory ($n = 15$), but field ($n = 4$) and aquaculture pond ($n = 9$) setups were also used. There was also one paper that included both lab and pond setups. Study duration was highly variable, ranging from 15 d to more than 2 y. Wild fish ($n = 16$) were more commonly used in studies compared to hatchery-raised fish ($n = 13$). The number of fish tagged per experiment ranged from 4 to 930 individuals (median = 32).

Tagging methodology was mainly split between tags implanted into the peritoneal or dorsal musculature by using injection, or into the peritoneal by incision. The most common methods and locations reported were PIT tags inserted via incision into the peritoneal cavity and injected into the dorsal musculature (41% of studies each). Other well-represented methods were injection into the peritoneal cavity ($n = 11$). Injection into the cheek musculature and operculum were reported in two papers each. The least common methods reported were injection into the isthmus and esophageal implants, with one paper each.

We identified several experiments, which were used to summarize tag retention and fish survival by species. Statistics on tag retention and fish survival were available from the majority of the experiments (Table 2). Across all experiments, retention ranged from 13 to 100%. Tag retention was equal to or greater than 90% in 85% of experiments. Fish survival was more variable, although survival was equal to or greater than 90% in 57% of experiments, ranging between 0 and 100% (median = 92%). Control groups were used in 83 of 97 experiments, allowing significant differences in survival to be calculated for some studies (Table 2). Twenty-six of the control-paired experiments did not report statistics relating survival between treatment groups. For the remaining experiments, there was no difference in survival for the majority ($n = 41$); however, significantly lower survival was reported for the treatment group on sixteen occasions. Of the 47 experiments where growth data were available, growth was reported in all but one instance. Lastly, sample sizes varied greatly across experiments with 39% (38 of 97) of studies using 20 or fewer individuals.

Laboratory trials

The mean total length of the experimental fishes (Table 3; Tables S1 and S2, *Supplemental Material*) ranged from 60 mm for Orangethroat Darter to 148 mm for juvenile Smallmouth Bass. All species growth data fit the assumption of normality. Survival 24 h post tagging was 100% for all species and remained high for the study duration (Table S3, *Supplemental Material*). After 30 days, treatment survival was 100% for Cardinal Shiner, Central Stoneroller, Greenside Darter, and Slender Madtom, with a single mortality for each of Smallmouth Bass and Orangethroat Darter (Table 3). After 60 d, there was a single Central Stoneroller mortality and three additional Orangethroat Darter mortalities. Survival remained constant for all other species (Table 3). Tag retention after 60 d was 100% for all species except Orangethroat Darter. Orangethroat Darter lost a single tag in the first 30 d, reducing retention to 88%, but the overall retention percentage dropped further at 60 d due to mortalities (e.g., four of five fish retained tags; Table 3). There were no significant differences in mean growth between treatment and control groups for all species (Figure 1).

Discussion

The use of PIT tags in the conservation and management of fish species is a valuable tool; however, understanding tagging limitations (i.e., changes to fish fitness and the likelihood of tag retention) is critical. For all our study species, we observed high PIT tag retention, with only a single Orangethroat Darter losing a tag. This is consistent with the findings of the review in which reported retention across the experiments was high. Our

Table 2. Summary of reviewed passive integrated transponder (PIT) tag studies on warmwater fishes resulting from a literature search by using ISI Web of Science in 2015. Four search strings were used: 'fish' AND 'passive-integrated-transport' OR 'PIT Tag' AND 'retention' OR 'survival'. Within Web of Science, search results were screened based on the titles and abstract and studies on salmonids, marine and estuarine species and nonfish species (e.g., crayfish and salamanders) were omitted. The resulting literature summarized included percentage of tags retained (R) by fish at the study endpoint, survival (S), and growth (G). Stage of each species is reported as indicated by the reviewed manuscript (source) as J = juvenile or A = adult. "Other" refers to criteria unique to specific experiments: weight classes, size classes in fork length (FL) or total length (TL), different tagging locations, temporal differences, and additional tag differences. *N* refers to the number of fish used in the trials and length indicates the study duration. When possible, we calculated percentage of retention of fish holding tags. In some cases, investigators estimated retention (%) and we report that below. We report growth direction as positive (+) or negative (–) as studies used different approaches to estimate growth. "Method" refers to tagging method: 1 = insertion or 2 = injection. Locations of tag are as follows: 1 = peritoneal cavity; 2 = dorsal musculature; 3 = cheek musculature; 4 = opercular; 5 = esophageal implant; 6 = isthmus. Type refers to the environment where the study took place: 1 = lab; 2 = pond; 3 = field. Species included in the review were Alewife *Alosa pseudoharengus*, Alligator Gar *Atractosteus spatula*, White Sucker *Catostomus commersonii*, Mottled Sculpin *Cottus bairdii*, Shorthead Sculpin *C. confusus*, Bullhead *Cottus gobio*, Moapa White River Springfish *Crenichthys baileyi moapae*, Lost River Sucker *Deltistes luxatus*, Northern Pike *Esox Lucius*, Muskellunge *Esox masquinongy*, Humpback Chub *Gila cypha*, Rio Grande Silvery Minnow *Hybognathus amarus*, Blue Catfish *Ictalurus furcatus*, Channel Catfish *Ictalurus punctatus*, Spotted Gar *Lepisosteus oculatus*, Longnose Gar *Lepisosteus*, Pumpkinseed *Lepomis gibbosus*, European Chub *Leuciscus cephalus*, Common Dace *Leuciscus leuciscus*, Burbot *Lota lota*, Largemouth Bass *Micropterus salmoides*, Oriental Weather Loach *Misgurnus anguillicaudatus*, Nile Tilapia *Oreochromis niloticus*, Flathead Chub *Platygobio gracilis*, Topmouth Gudgeon *Pseudorasbora parva*, Flathead Catfish *Pylodictis olivaris*, Common Roach *Rutilus rutilus*, Walleye *Sander vitreus*, Pallid Sturgeon *Scaphirhyncus albus*, Creek Chub *Semotilus atromaculatus*, European Catfish *Silurus glanis*.

Species	Tag size (mm)	Stage	Other	*N*	Length (d)	R (%)	G	S (%)	Method	Location	Type	Source
Alosa pseudoharengus	23 × 3.8	A		49	38	100		57	1	1	1	Castro-Santos and Vono 2013
A. pseudoharengus	23 × 3.8	A		49	38	95		41	1	5	1	Castro-Santos and Vono 2013
Atractosteus spatula[e]				10	800–876	100			2	2	2	Buckmeier and Reeves 2012
Catostomus commersonii[b]	12.5			19	30	100		32	1	1	1	Ficke et al. 2012
C. commersonii[b]	23			18	30	100		44	1	1	1	Ficke et al. 2012
Cottus bairdii	12 × 2.1			26	28	96	+	96	2	1	1	Ruetz et al. 2006
Cottus confusus	12.5 × 2		<80 mm TL	20	29	100		100	2	1	1	Zaroban and Anglea 2010
C. confusus	12.5 × 2		<80 mm TL	20	29	12.5		80	2	2	1	Zaroban and Anglea 2010
C. confusus	12.5 × 2		≥80 mm TL	20	29	90		100	2	1	1	Zaroban and Anglea 2010
C. confusus	12.5 × 2		≥80 mm TL	20	29	35		100	2	2	1	Zaroban and Anglea 2010
Cottus gobio	12 × 2.1	A	50–64 mm	13	49	100	+	100	1	1	1	Knaepkens et al. 2007
C. gobio	12 × 2.1	A	65–79 mm	21	49	90	+	100	1	1	1	Knaepkens et al. 2007
C. gobio	12 × 2.1	A	80–94 mm	10	49	100	+	90	1	1	1	Knaepkens et al. 2007
Crenichthys baileyi moapae	9 × 2			90	41	100		96	1	1	3	Dixon and Mesa 2011
Deltistes luxatus	12.45 × 2.02	J		51	34	98		90	2	1	1	Burdick 2011
Esox lucius[a,b]	12 × 2.15	J		71	520	94	+	25	2	2	2	Hühn et al. 2014
E. lucius[a,c]	12 × 2.15	J	Also tagged with T-bar anchor tag	72	520	100	+	28	2	2	2	Hühn et al. 2014
E. lucius[a,b]	12 × 2.15	J	Also tagged with opercular tag	70	520	100	+	31	2	2	2	Hühn et al. 2014
E. lucius[a,b]	12 × 2.15	J	Also tagged with streamer tag	71	520	100	+	07	2	2	2	Hühn et al. 2014
Esox masquinongy	12.45	A	Spider Lake Chain	49	365	88			2	3	3	Jennings et al. 2009
E. masquinongy	12.45	A	Mud-Callahan Lake	24	365	95.8			2	3	3	Jennings et al. 2009
E. masquinongy[a]	12 × 2.1	A		841	3,652	>99			2	2	3	Rude et al. 2011
E. masquinongy	12 × 2.1	J	Illinois	100	153	100	+	84	2	1	2	Wagner et al. 2007
E. masquinongy	12 × 2.1	J	Illinois	100	153	100	+	87	2	2	2	Wagner et al. 2007
E. masquinongy	12 × 2.1	J	Wisconsin	200	210	100	+	92	2	1	2	Wagner et al. 2007
E. masquinongy	12 × 2.1	J	Wisconsin	200	210	99	+	93	2	2	2	Wagner et al. 2007
E. masquinongy	11.5 × 2.1	J		150	176	100		91	2	2	1	Younk et al. 2010
E. masquinongy	11.5 × 2.1	J		150	176	92		89	2	3	1	Younk et al. 2010
Gila cypha	8.4	J	40–49 mm TL	40	60	100	+	88	2	1	1	Ward et al. 2015

Table 2. Continued.

Species	Tag size (mm)	Stage	Other	*N*	Length (d)	R (%)	G	S (%)	Method	Location	Type	Source
G. cypha	12.5	J	40–49 mm TL	40	60	88	+	80	2	1	1	Ward et al. 2015
G. cypha	8.4	J	50–59 mm TL	40	60	81	+	93	2	1	1	Ward et al. 2015
G. cypha	12.5	J	50–59 mm TL	40	60	97	+	80	2	1	1	Ward et al. 2015
G. cypha	8.4	J	60–69 mm TL	40	60	100	+	100	2	1	1	Ward et al. 2015
G. cypha	12.5	J	60–69 mm TL	40	60	92	+	95	2	1	1	Ward et al. 2015
G. cypha	8.4	J	70–79 mm TL	40	60	98	+	100	2	1	1	Ward et al. 2015
G. cypha	12.5	J	70–79 mm TL	40	60	95	+	100	2	1	1	Ward et al. 2015
Hybognathus amarus	12.5 × 2.07	A		80	32	90	+	87	1	1	1	Archdeacon et al. 2009
H. amarus	12.5 × 2.07	A		80	32	89	+	50	2	1	1	Archdeacon et al. 2009
H. amarus	12.5 × 2.07			280	49	90		90	1	1	1	Archdeacon et al. 2009
Ictalurus furcatus[a]	8.5 × 2.1			81	182	100		96	2	2	2	Bodine and Fleming 2014
Ictalurus punctatus	10 × 2.1	A		75	365	97			2	2	2	Moore 1992
I. punctatus	10 × 2.1	A		126	730	97			2	2	2	Moore 1992
Lepisosteus oculatus[a]				4	800–876	100			2	2	2	Buckmeier and Reeves 2012
Lepisosteus osseus[a]				16	500–599	100			2	2	2	Buckmeier and Reeves 2012
Lepomis gibbosus[b,c]	12 × 2			20	21	100	+	90	1	1	1	Stakenas et al. 2009
Leuciscus cephalus	12 × 2.1	J	87–167 mm FL	80	182	100		98	1	1	1	Bolland et al. 2009
L. cephalus	23 × 3.4	J	114–210 mm FL	101	182	100		98	1	1	1	Bolland et al. 2009
L. cephalus[b]	23 × 3.4	J	87–167 mm FL	80	182	100		96	1	1	1	Bolland et al. 2009
L. cephalus[b]	23 × 3.4	J	114–210 mm FL	100	182	100		100	1	1	1	Bolland et al. 2009
Leuciscus leuciscus	12 × 2.1	J		80	182	100		96	1	1	1	Bolland et al. 2009
L. leuciscus[b]	23 × 3.4	J		80	182	97		73	1	1	1	Bolland et al. 2009
Lota lota	9.0 × 2.03	J		50	365	100	+	94	2	2	1	Ashton et al. 2014
L. lota	9.0 × 2.03	J		50	365	100	+	98	2	1	1	Ashton et al. 2014
L. lota	9.0 × 2.03	J		50	365	98	+	92	1	1	1	Ashton et al. 2014
L. lota	23	A		101	60	100	−	92	1	1	1	Gardunio and Myrick 2012
Micropterus salmoides	21 × 10	A		22	730	100		91	2	1	3	Harvey and Campbell 1989
M. salmoides	12.34 × 2.04		March	18	365	95	+	89	2	1	2	Siepker et al. 2012
M. salmoides	12.34 × 2.04		March	20	365	100	+	85	2	2	2	Siepker et al. 2012
M. salmoides[d]	11 × 2.86		March	15	365	100	+	93	2	1	2	Siepker et al. 2012
M. salmoides[d]	11 × 2.86		March	13	365	100	+	100	2	2	2	Siepker et al. 2012
M. salmoides	12.34 × 2.04		April	32	365	100	+	97	2	1	2	Siepker et al. 2012
M. salmoides	12.34 × 2.04		April	32	365	100	+	97	2	2	2	Siepker et al. 2012
M. salmoides[d]	11 × 2.86		April	26	365	100	+	100	2	1	2	Siepker et al. 2012
M. salmoides[d]	11 × 2.86		April	32	365	100	+	100	2	2	2	Siepker et al. 2012
Misgurnus anguillicaudatus	12.05 × 2.07	J		32	30	97	+	94	2	1	1	Kano et al. 2013
M. anguillicaudatus	12.05 × 2.07	J		32	30	97	+	97	1	1	1	Kano et al. 2013
Oreochromis niloticus[b]	10.3	J	<3 g	8	49	100	+	75	1	1	1	Baras et al. 1999
O. niloticus[b]	10.3	J	3–4 g	11	49	100	+	73	1	1	1	Baras et al. 1999
O. niloticus[b]	10.3	J	4–7 g	12	49	100	+	92	1	1	1	Baras et al. 1999
O. niloticus[b]	10.3	J	7–15 g	24	49	100	+	100	1	1	1	Baras et al. 1999
O. niloticus	10.3	J	<3 g	12	49	90	+	83	1	1	1	Baras et al. 1999
O. niloticus	10.3	J	3–4 g	14	49	90	+	71	1	1	1	Baras et al. 1999
O. niloticus	10.3	J	4–7 g	7	49	86	+	100	1	1	1	Baras et al. 1999
O. niloticus	10.3	J	7–15 g	7	49	100	+	100	1	1	1	Baras et al. 1999
O. niloticus	10.3	J	<3 g	10	49			0	2	1	1	Baras et al. 1999

Table 2. Continued.

Species	Tag size (mm)	Stage	Other	*N*	Length (d)	R (%)	G	S (%)	Method	Location	Type	Source
O. niloticus	10.3	J	3–4 g	10	49	50		20	2	1	1	Baras et al. 1999
O. niloticus	10.3	J	4–7 g	10	49	100		30	2	1	1	Baras et al. 1999
O. niloticus	10.3	J	7–15 g	10	49	100		50	2	1	1	Baras et al. 1999
O. niloticus	10.3	J	15–20 g	10	49	100		90	2	1	1	Baras et al. 1999
O. niloticus	10.3	J	20–25 g	10	49	100		100	2	1	1	Baras et al. 1999
Platygobio gracilis[b]	12.5			17	30	100		100	1	1	1	Ficke et al. 2012
P. gracilis[b]	23			17	30	100		100	1	1	1	Ficke et al. 2012
Pseudorasbora parva[c]	12 × 2			20	21	35	+	85	1	1	1	Stakenas et al. 2009
P. parva[c]	12 × 2			20	20			0	1	1	1	Stakenas et al. 2009
P. parva[c]	12 × 2			20	20	65	+	95	1	2	1	Stakenas et al. 2009
Pylodictis olivaris[e]	8.5 × 2.1			72	300	100		92	2	2	2	Daugherty and Buckmeier 2009
P. olivaris[e]	8.5 × 2.1			72	300	98		91.67	2	4	2	Daugherty and Buckmeier 2009
Rutilus rutilus	12 × 2.1	J		80	182	100		100	1	1	1	Bolland et al. 2009
R. rutilus[b]	23 × 3.4	J		80	182	99		98	1	1	1	Bolland et al. 2009
Sander vitreus	12			930	1,461	98			2	6	3	Vandergoot et al. 2012
Scaphirhyncus albus	12	J		40	189	85		100	2	2	1	Hamel et al. 2013
S. albus	12	J		40	189	83		100	2	4	1	Hamel et al. 2013
Semotilus atromaculatus[b]	12.5			19	30	95		68	1	1	1	Ficke et al. 2012
S. atromaculatus[b]	23			16	30	100		63	1	1	1	Ficke et al. 2012
Silurus glanis	12 × 2.2			5	15	100		100	1	1	1	Rees et al. 2014
S. glanis[a]	12 × 2.2			5	15	100		100	1	1	1	Rees et al. 2014
S. glanis	12 × 2.2			65	455	85			1	1	2	Rees et al. 2014

[a] Fish were also tagged with another type of tag (T-bar anchor, opercular, etc.).
[b] Sutures were used to close wounds.
[c] All mortalities could be attributed to an unrelated outbreak of fungal infection.
[d] Plastic infusion process PIT tags were used.
[e] Each Fish in this study had two PIT tags in different locations.

Table 3. Survival (S) and passive integrated transponder (PIT) tag retention (R) of six warmwater fish species that were collected from Flint Creek, Oklahoma, in 2012 to determine PIT tag retention in the laboratory. The six species included in the study were Cardinal Shiner *Luxilus cardinalis*, Central Stoneroller *Campostoma annomalum*, Slender Madtom *Noturus exilis*, Orangethroat Darter *Etheostoma spectabile*, Greenside Darter *Etheostoma blennioides*, and Smallmouth Bass *Micropterus dolomieu*. All fish were tagged in the peritoneum using 12- or 23-mm (tag size) half duplex PIT tags. Survival and PIT tag retention were reported after 30, 60, and 90 d. Survival was reported cumulatively across all time steps, whereas retention was reported as the number of living fish that retained their tags at each time step. We reported the number of fish (*N*) on occasions where survival or retention was not 100%. Growth (G, $weight_{final} - weight_{initial}$) was represented as positive (+) or negative (–) after 30 d. We reported the test statistic resulting from Welch's *t*-test where comparisons were made between growth of treatment and control groups (differences between groups).

		30 d		60 d		90 d			
Common name	***N***	**S (%)**	**R (%)**	**S (%)**	**R (%)**	**S (%)**	**R (%)**	**G**	**Differences between groups**
Cardinal Shiner	12	100	100	100	100	100	100	+	$t_{18.60} = -0.35$, $P = 0.73$, $r = 0.08$
Central Stoneroller	8	100	100	88 (7/8)	100	88 (7/8)	100	+	$t_{9.96} = 0.29$, $P = 0.78$, $r = 0.09$
Slender Madtom	13	100	100	100	100	NA[a]	NA	–	$t_{21.87} = 1.21$, $P = 0.24$, $r = 0.25$
Orangethroat Darter	9	89 (8/9)	88	56	80 (4/5)	NA	NA	–	$t_{13.42} = 1.41$, $P = 0.18$, $r = 0.36$
Greenside Darter	3	100	100	100	100	NA	NA	–	$t_{2.33} = 0.18$, $P = 0.87$, $r = 0.12$
Smallmouth Bass	25	96	100	96	100	NA	NA	+	$t_{4.26} = -0.41$, $P = 0.70$, $r = 0.20$

[a] NA = not applicable.

analysis suggests that for studies that last up to 60 d, the use of intracoelomic PIT tags to monitor the population of our six species is a viable approach. Above that 60-d window, PIT tag retention in other species has shown to consistently be greater than 90% (e.g., Alligator Gar *Atractosteus spatula*, Longnose Gar *Lepisosteus osseus*, Spotted Gar *Lepisosteus oculatus*, Largemouth Bass; Buckmeier and Reeves 2012; Siepker et al. 2012), suggesting use in long-term experiments may be appropriate. A field-based study of adult Muskellunge *Esox masquinongy* using a combination PIT and T-bar anchor tags found that even up to 10 y post tagging, the probability of PIT tag loss was less than 1% (Rude et al. 2011). For our study, injection (implantation via incision in the Smallmouth Bass) into the peritoneal resulted in high tag retention; however, anatomical location and implantation method can highly influence that parameter. For example, for Topmouth Gudgeon *Pseudorasbora parva* tag loss was much lower in individuals tagged in the flank (35%) compared to those implanted in the ventral area (65%; Stakenas et al. 2009). Conversely, a laboratory study of Shorthead Sculpin *Cottus confusus* found significantly higher retention in tags implanted in the body cavity (95 ± 5.06%) compared to those located in base of the spinous dorsal fin (23.75 ± 11.39%; Zaroban and Anglea 2010). Tagging method can also partly determine retention. Baras et al. (1999) found use of sutures reduced short-term tag expulsion (and protrusion of viscera) in Nile Tilapia *Oreochromis niloticus*.

With the exception of Orangethroat Darter, we found survival to 60 d was high (≥88%). Our finding agrees with the results of the review where median survival of the 97 experiments was 92%. Lower survival in Orangethroat Darter may have been due to diet as weight loss was observed in both treatment and control fish. This is in line with the finding of other studies where higher mortalities of PIT tagged fish were potentially driven by external factors rather than the procedure itself (e.g., disease, Castro-Santos and Vono 2013; overwinter mortality, Rees et al. 2014). Significant differences in survival between tagged and control fish were uncommon in our review, with the vast majority showing no difference. Whereas we did not explicitly test different methods of implanting the PIT tag, the use of a hypodermic needle did not affect our study species. This is in contrast to Baras et al. (1999) who found higher mortality in Nile Tilapia injected with PIT tags and suggested that this was attributable to their difficulty controlling penetration of the syringe. Given the high survival and retention rate, placing the PIT tag in the peritoneal cavity seems appropriate for the species we studied. Other tagging locations or tag designs may need to be considered for applications where concerns exist about the tags being potentially consumed by humans (e.g., Daugherty and Buckmeier 2009; Siepker et al. 2012).

We found no reduction in growth related to the tagging procedure across any of our study species. However, weight loss was apparent in both control and treatment groups for three of our species: Slender Madtom, Orangethroat Darter, and Greenside Darter. Similarly, our review suggested weight loss in treatment fish was generally matched by growth rates of control fish (e.g., Gardunio and Myrick 2012). Several studies, however, have highlighted an immediate post tagging reduction in growth, which is later compensated by an increased growth rate (e.g., Baras et al. 1999; Ruetz et al. 2006). This initial growth slowdown has been linked to potential "compression of the digestive system" (Navarro et al. 2006). It is also possible that growth reductions may relate to a response by some wild fish to being held in captivity.

The results of our retention and survival trials were largely consistent with data obtained from the literature review. Whereas the studies included in our review are by no means exhaustive (i.e., there are numerous available databases), by undertaking the literature search in a systematic manner, we aimed to reduce bias in study selection. Despite the limitations in the literature pool (e.g., specificity of search terms and absence of gray literature; see Pullin and Stewart 2006), we believe the review highlights some important overall trends. First,

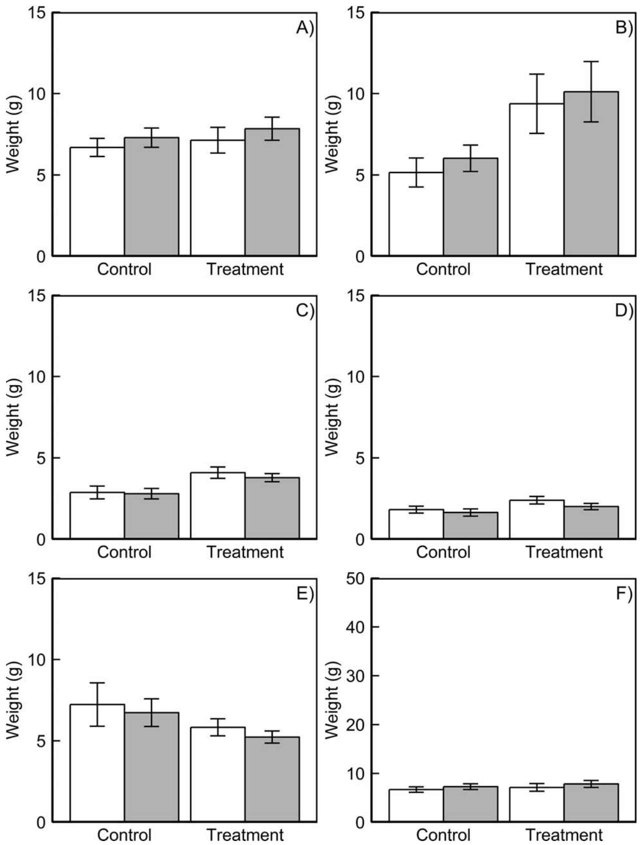

Figure 1. Initial mean weight (white bar, ±95% confidence limits) and weight after 30 d (gray bars, ±95% confidence limits) of six warmwater fish species that were collected from Flint Creek, Oklahoma, in 2012 to determine passive integrated transponder (PIT) tag retention in the laboratory. All treatment fish were tagged in the peritoneum with 12- or 23-mm (tag size) half duplex PIT tags. Control fish were handled in the same manner as treatment fish, but no tagging occurred. Weight was not significantly different between PIT tag treatment and control groups for all species (a = Cardinal Shiner *Luxilus cardinalis*; b = Central Stoneroller *Campostoma annomalum*; c = Slender Madtom *Noturus exilis*; d = Orangethroat Darter *Etheostoma spectabile*; e = Greenside Darter *Etheostoma blennioides*; f = Smallmouth Bass *Micropterus dolomieu*).

PIT tag retention and survival of tagged fishes were generally high; however, examples of high tag loss (e.g., Stakenas et al. 2009; Zaroban and Anglea 2010) and elevated mortality (e.g., Orangethroat Darter, this study; Ficke et al. 2012) were apparent. This is consistent with Rees et al. (2014) who suggested the "tagging efficiency is largely context-dependent" and therefore comparison across species and methods should be treated with caution (Archdeacon et al. 2009). Survival and retention seem to be a function of a multitude of variables including species (e.g., Stakenas et al. 2009; Ficke et al. 2012), tagging location (e.g., Zaroban and Anglea 2010), and tagging methodology (e.g., Archdeacon et al. 2009). Therefore, it would seem prudent to examine the effect of PIT tag use under controlled conditions before applying alternative tagging methodologies or to new species in situations where the assumptions cannot be tested. Second, although most studies determined the effect of PIT tag use on a combination of tag retention, fish survival or growth, fewer studies have assessed the effect of tag use on fish behavior (but see Knaepkens et al. 2007; Ficke et al. 2012). Third, there is a dearth of information from outside North America and Europe, a phenomenon that has been identified in other areas of ecology (e.g., Wilson et al. 2007; Pyšek et al. 2008; Archer et al. 2014). Given the applications of PIT tags to the conservation and management of fish species, information on a broader range of species from across a wider range of geographic locations would be beneficial. It is also important to recognize that the skill level of persons tagging fish could also affect tag retention and survival and thus warrants consideration. Lastly, examining possible behavioral changes associated with tagging could broaden the use of PIT tagging, especially in small-bodied fishes. Overall, the specific attributes of tagging studies are related to tagging objectives (e.g., survival, growth, and behavior), but reporting information on study duration, weight and length of tagged fish, handling and injection procedures, and use of control fish would benefit a more comprehensive examination of tag effects.

Supplemental Material

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Table S1. Spreadsheet containing three tables. Table 1 is a description of field headings used in Tables 2 and 3. Data described are from a laboratory study of passive integrated transponder (PIT) tag retention and survival of six warmwater fish species (scientific names provided in parentheses) that were collected from Flint Creek, Oklahoma, in 2012. All fishes were tagged in the peritoneum with 12- or 23-mm (tag size) half duplex PIT tags. Table 2 provides data on the total length (mm) and relative growth (g, difference in weight from the beginning to end of trials) of treatment (trt) and control (c) fishes (OTD = Orangethroat Darter *Etheostoma spectabile*; GRN = Greenside Darter *Etheostoma blennioides*; SLND = Slender Madtom *Noturus exilis*; CARD = Cardinal Shiner *Luxilus cardinalis*; CSTN = Central Stoneroller *Campostoma annomalum*; and SMB = Smallmouth Bass *Micropterus dolomieu*). The treatment group was subjected to intracoelomic-placed 12- or 23-mm (tag size) half duplex passive integrated transponder tags. The 23-mm tags were only used to tag Smallmouth Bass due to their larger size at tagging. Control fishes were subject to the same handling as treatment fishes (i.e., anesthetized, measured, and weighed), but they were not tagged. The same person (W.C.M.) conducted all tagging in the laboratory in 2012. Table 3 provides data on the total length (mm) and survival (30, 60, and 90 d) of treatment (trt) and control (c) fishes (OTD = Orangethroat Darter *Etheostoma spectabile*; GRN = Greenside Darter *Etheostoma blennioides*; SLND = Slender Madtom

Noturus exilis; CARD = Cardinal Shiner *Luxilus cardinalis*; CSTN = Central Stoneroller *Campostoma annomalum*; and SMB = Smallmouth Bass *Micropterus dolomieu*). The treatment group was subjected to intracoelomic-placed 12- or 23-mm (tag size) half duplex passive integrated transponder tags. The 23-mm tags were only used to tag Smallmouth Bass due to their larger size at tagging. Control fishes were subject to the same handling as treatment fishes (i.e., anesthetized, measured, and weighed), but they were not tagged. The number of fishes surviving is provided if less than 100%.

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