FEATURE

How small can they go? Microelectronic tags for movement ecology of small aquatic organisms

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Atlantic Salmon *Salmo salar* parr were tagged with microacoustic transmitters (Juvenile Salmon Acoustic Telemetry System) in Prince Edward Island, Canada, to examine fine-scale habitat use. Photo credit: Morgan Piczak

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ABSTRACT

Miniaturization and optimization of batteries and electric components, as well as new technological innovations, are driving increased use of microelectronic tags to study animals in the wild that are smaller than ever before. Here, we provide an overview of the different alternatives to common electronic tagging and tracking tools used for aquatic research and discuss the research opportunities afforded by these micro tags and the challenges for investigators. We are optimistic that the miniaturization of tags will create opportunities for novel ecological inquiry. A key advance will be to allow investigators to address broader questions at an ecosystem scale about aquatic environments that span small-bodied adult fishes and life stages (i.e., juveniles). However, even the new developments have limitations in what can be tagged, how long tags will last, and their detection distance. Moreover, investigators will need to better understand how to effectively instrument the smallest animals with surgical implants or attachments of tags to maintain fish welfare and minimize alterations of behavior or survival. Collaboration with engineers will be important to assess where the field can go next for miniaturization, which will help to further advance the understanding of small species and early life stages in rivers, lakes, estuaries, and oceans.

INTRODUCTION

A majority of aquatic tracking studies has focused on megafaunal species such as large sharks, tunas, sturgeon, marine turtles, and seals (Matley et al., 2022). This is a common trend within biology where larger, more charismatic species receive the bulk of research funding and are the subject of disproportionate scientific literature (Sitas et al., 2009). Indeed, within trackdAT, a database of acoustic telemetry studies (currently up until 2022), the majority of publications included animals where the minimum length tagged was greater than 10 cm (Matley et al., 2024). A key limitation of developing more holistic knowledge provided by tracking small animals has been the size of the batteries used in electronic tags and the memory demands of archival tags, and therefore the weight and size of the devices. Much of our growing knowledge about aquatic organismal movement consequently comes from species and life stages that are large enough to be instrumented with tags without undue burden placed on the animal. Larger animals can carry larger tags that have longer battery life and the potential to be equipped with more sensors, therefore providing more information to the investigator. Larger animals are also less impacted by the effects of the tag, such that results are more reliable. Still, investigators have continued to try to push the limits and gain more knowledge about smaller animals given their importance to population and ecosystem dynamics for fisheries management and habitat protection.

Developments in electronics and technology have facilitated size reductions in tags and a novel subdomain of aquatic animal tracking is emerging with microelectronic tags, which includes micro passive integrated transponder (PIT) tags, micro logging tags, and micro transmitters (i.e., radio and acoustic). Miniaturization of tracking tools yields novel logistical and methodological challenges associated with instrumenting small fishes with these micro tags. However, there are exciting opportunities for intrepid investigators seeking to answer questions about animals that have previously evaded understanding due to their small body size. In this paper, we review the status of the field at the small end of the tag spectrum, discussing the micro tags currently being used by investigators. We conclude with a horizon scan for how this technology may change aquatic tracking efforts in the coming decade.

REVIEW OF MICROELECTRONIC TAGS

We start this review with a note about defining micro tags. The use of micro, nano, pico and other terms to describe sensors and batteries is not consistent in the literature, and Wu et al. (2023) specifically noted this when reviewing the miniaturization of sensors. We do not aim to provide a definition of what a micro tag is because it is relative to the existing technology, the state of the art, and cannot easily be harmonised across tag types. Because we cover passive tags with no battery, archival tags and transmitters that are battery powered, and, also, pop-up tags that need to float and transmit data to satellites, the state of the art for each device is quite different and what constitutes miniaturization varies. As such, we consider micro tags to be those tags that have reduced size compared to the average, often coinciding with advances in engineering that have allowed these size reductions (Table 1). Not all micro tags are completely new technologies, but they merit consideration of how these tools can be applied and what considerations investigators need to have to make the best use of these tools in aquatic movement ecology research.

Passive tags

Passive integrated transponders are small tags without a battery that send a unique ID when charged. The lack of a battery means the read range (potentially leading to false detections) is short. Scientists have used PIT tags extensively for tracking small-bodied fishes and generally are used for the smallest size-classes of fishes. Standard PIT tags have been either 12 or 23 mm, but smaller units are now commercially available. Referred to as micro or pico PIT tags by manufacturers, the smallest measures 8.4 mm and weighs 0.03 g and has been tested in several, mostly laboratory, studies (Figure 1A; Delcourt et al., 2018). Watson et al. (2019) tagged 10 species, including as small as Pacific Blue-eye *Pseudomugil signifer* weighing 0.4–0.7 g. Although 100% of the Pacific Blue-eye died, there was variably better success with other small species, including four species that had no mortality. Bangs et al. (2013) found a significant difference in survival of Oregon Chub *Oregonichthys crameri* tagged with pico PIT tags and a slightly larger comparator tag, which measured 9.0 mm long, 2.1 mm wide, and 0.07 g (about double the weight of the pico PIT). Although systematic evaluations of pico PIT tags are lacking, Burnett et al. (2013) demonstrated the reduced detectability of 12-mm compared to 23-mm PIT tags in field settings; further effort should be allocated to understanding how likely false negatives are when using pico PIT tags for tracking small fish in the wild.

Archival and pop-up satellite archival tags

Micro data archival tags are now available for tagging small-bodied fish. Because archival tags typically do not send data

Table 1. Micro tags for animal tracking. Abbreviations are as follows: PNNL = Pacific Northwest National Laboratory.

Tag type	Description	Minimum size	Other manufacturers
PIT	Passive tags charged by a wire to send a unique ID according to ISO standards. No battery and no memory on board	Biomark Pico PIT tags are 0.03 g, 8.4 mm (length), 1.4 mm (diameter)	Oregon RFID
Archival	Tags that store temperature, depth, acceleration, or light data on board	Archival: Star Oddi Micro DST tag are 2.5 g, 25.4 mm (length), 8.3 mm (diameter)	CEFAS
Radio	Radio transmitters send very high-frequency signals (>100 mHz) to a receiver station	Lotek Freshwater Nano tags are 0.24 g, 9.6 mm (length), 5 mm (width), 3 mm (height), 18-cm antenna length Advanced Telemetry Systems' T15 tags are 0.15 g,11 mm (length), 3.4 mm (diameter)	Sigma8
Acoustic	High-frequency (180, 307, 417 kHz) transmitters typically <1g	PNNL has produced the ELAT (eel and lamprey tag) at 0.08 g, 11.4 mm (length), 2 mm (diameter) Innovasea V3 tag is 15 mm long, 4 mm wide and 0.3 g Lotek PinTag is 15 mm long, 3.4 mm wide, and 0.22 g	Advanced Telemetry Systems

but rather store it in memory (unless they do both, like pop-up satellite archival tags; Table 1), these devices need to have sufficient space allocated to store data, which is a key limitation of miniaturization. Archival tags are also limited by the potting of electronic components needed to withstand depths and may also require space for floatation necessary for tags to return to the surface. Archival tags use sensors predominantly for measuring and storing depth, temperature, acceleration, and light levels for light-based geolocation on board the tag, along with novel options like oxygen sensors (da Costa et al., 2024). Compared to transmitters that do not need to store any data onboard, logging tags tend to be larger in size, mass, and volume and have less scope for reduction unless the memory needs can be compromised. Smaller tags are also possible when working with animals in shallows that will not dive to depths that require a housing to protect from increased pressures. Micro archival tags have been used to study depth and temperature during the full ocean migration of Atlantic Salmon *Salmo salar* smolts moving out of Icelandic rivers (Figure 1B; Guðjónsson et al., 2015). A micro archival tag with real-time biotelemetric capability (Yang et al., 2022) was also developed by the Pacific Northwest National Laboratory (PNNL). It combines edge computing with wireless sensing of in vivo physiology (electrocardiogram, electromyogram), behavior (activity level, tail beat frequency), and ambient environment (temperature, pressure, and magnetic field). Some small temperature loggers that are widely used (i.e., Maxim Integrated iButtons) have been deconstructed by researchers such that the bulky external case can be replaced by waterproofing, such as Plasti-Dip, to reduce size (Lovegrove, 2009).

Transmitters

Radio

Major advancements have been made in radio transmitter size since their first use on fish in 1968 (Murchie et al., 2004). At that time, the transmitter weighed 38 g in air and was mounted to the dorsal side of White Suckers *Catostomus commersonii* and Brown Trout *S. trutta* (Lonsdale & Baxter, 1968). Currently available commercial tags are much smaller: Advanced Telemetry System's T15 are only 0.15 g. Lotek's Freshwater Nano Series transmitters start at 0.24 g (NTF1-1) and can last up to 120 d (Figure 1C). The heaviest model within this series (NTF6-2) weighs only 4 g and can last up to over 6 years. Lu et al. (2021) have also designed a smaller radio transmitter to be used in fish telemetry weighing 0.16 g and a larger option that can last up to 205 d; however, this model is not widely available yet.

Acoustic

For aquatic telemetry, standard acoustic transmitters have been programmed on 69 kHz, a trade-off between power consumption of the tag and transmission strength in different environments (i.e., conductivity, salinity). We have seemingly reached the size limits for transmitters in the 69-kHz space given the power demands of such tags, and the smallest 69-kHz transmitters are generally ∼1.0–2.5 g, a size that still excludes many of the smallest species and life stages. However, higher frequency tags have started to come to market that have allowed further miniaturization.

An intermediate miniaturization of acoustic tags includes transmitters at 180 kHz. Yet, challenges exist in the detection range of higher frequency tags because signals are more quickly attenuated in water; 69-kHz tags having detection ranges >300–400 m, and 180-kHz tags having only 80–100 m (Rechisky et al., 2020). High-frequency tags can, however, have effective range depending on the source level, and Li et al. (2023) measured a 330-m range for transmitters in a high conductivity environment. Where range is of concern, high-frequency tags may require a more strategic receiver array design, or adjusting tag programming (Stevenson et al., 2019).

Very high-frequency acoustic tags are now on the market, including micro tags <0.5 g. Innovasea series of 307 kHz tags are ∼0.3 g in air and can include predation sensors (Shorgan et al., 2024). Small, high-frequency tags developed for use at 417 kHz are also commercially available from Lotek and Advanced Telemetry Systems. The U.S. Army Corps of Engineers and the PNNL first developed the 417-kHz Juvenile Salmon Acoustic Telemetry System (JSATS) tags that are as small as 0.2 g and last more than 100 d at 3-s ping rate intervals (Figure 1D; Deng et al., 2015) and can include depth sensors. Both the 307-kHz and 417-kHz JSTATS have become increasingly

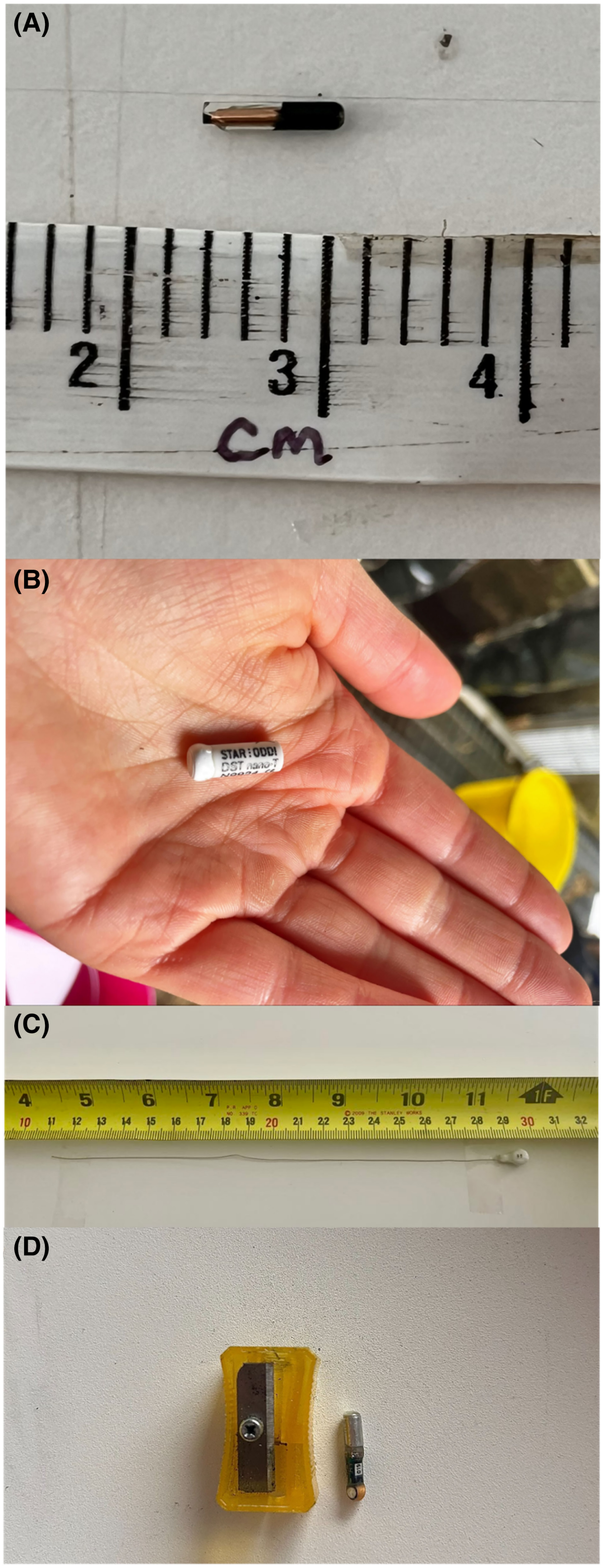

Figure 1. Examples of micro transmitters including, (A) micro passive integrated transponder (PIT) tag. Photo credit: Craig Franklin, University of Queensland. (B) A micro logger that stores temperature and depth. Photo credit: Lene Klubben Sortland, Danish Technical University. C) A micro radio tag. Photo credit: Kara Scott, Carleton University. (D) A micro acoustic tag. Photo credit: Paris Mastrodimitropoulos, Dalhousie University.

used for tracking subyearling Chinook Salmon *Oncorhynchus tshawytscha* (Lingard et al., 2023; McMichael et al., 2010). New developments and further miniaturizations include a new ELAT (eel and lamprey tag; Deng et al., 2021), weighing only 0.08 g, a remarkably small tag for tracking juvenile eel (Jepsen et al., 2022) and ammocoete larvae of Sea Lamprey *Petromyzon marinus* (Haas et al., 2024 ; Liedtke et al., 2022).

OPPORTUNITIES

Smaller species

Miniaturization of tags will allow researchers to tag additional species (e.g., < 10 cm), leading to the study of movement in more diverse taxa (e.g., smaller fish or invertebrate species; Table 2). New examples include small invasive Round Goby *Neogobius melanostomus* tagged with JSATS to examine connectivity (Figure 2A; Bergman et al., 2022) and tagging of Japanese crayfish *Cambaroides japonicus* to study movement patterns (Makiguchi et al., 2024).

Additional sensors

Sensors are important components of many electronic tags that add context and resolution to observations made about animal movements. The addition of predation sensors to micro transmitters presents a particularly novel application allowing us to gain an understanding of food web interactions (e.g., tagging prey species; Figure 2B; Table 2). Shorgan et al. (2024) recently evaluated the Innovasea predation tag as a potentially novel tool for tracking predation in very small species.

Younger life stages

Micro tags will be increasingly relied upon in coming years to fill knowledge gaps about younger life stages of key species that has historically been limited to adult organisms due to tag burden (Figure 2C; Table 2; Shillinger et al., 2012). The majority of publications in acoustic telemetry have been on adults (Matley et al., 2024), although the number of studies on juveniles has increased since a review in 2012 (Hazen et al., 2012). Micro PIT tags are already suitable for some fish larva, young-of-the-year, or hatchlings. However, the smallest acoustic transmitters are now tractable for juvenile and even larval fishes. Subyearling (age-0) Cisco *Coregonus artedi* were tracked with JSATs (Koeberle et al., 2023), subyearling Chinook Salmon (age < 1) were tracked with V3 tags (0.3 g), and hatchling loggerhead sea turtles *Caretta caretta* have been outfitted with tags weighing 0.65 g (Scott et al., 2014). Novel ELAT tags weighing only 0.08 g are also being used for larval stages of species like lamprey (Table 2).

Lifetime tracking

Smaller tags mean that we may be able to track animals throughout their lifecycle, which will be a transformative development for some questions related to demography and fisheries (Table 2). Lifetime tracking has been possible for only a few applications, such as with PIT tags or once animals get large enough to carry a long-life tag (Lu et al., 2016). Logging tags tend to have shorter battery life than transmitters, so smaller transmitters will be important to tag younger animals. To do so, tags will require some effort to design duty cycles that allow the tag to turn on and off, preserving battery life. Developments

Table 2. Summary of opportunities and challenges for using micro transmitters to track aquatic animal movements. Abbreviations are as follows: JSATS = Juvenile Salmon Acoustic Telemetry System.

Attribute	Description	Examples	Reference
Opportunities			
Ability to tag smaller organisms	Tag more diverse taxa beyond megafauna including smaller species	• JSATS tagging of invasive Round Goby • PIT tagging of Japanese crayfish	Bergman et al., 2022; Makiguchi et al., 2024
Ability to use multiple sensors	Inclusion of additional sensors that were previously limited to larger tags including pressure, temperature, acceleration, or predation	• Lab testing of acoustic tags with predation sensors implanted into Rainbow Trout, with subsequent feeding to Largemouth Bass	Shorgan et al., 2024
Ability to tag younger life stages	Larger tags were typically limited to adult life stages, while micro tags permit tagging of younger life stages, as well as lifetime tracking	• JSATS tagging of juvenile bonefish *Albula* spp., Great Barracuda *Sphyraena barracuda*, Redfin Needlefish *Strongylura notata*, and Yellowfin Mojarra *Gerres cinereus* • JSATS tagging of juvenile Sea Lamprey • Innovasea tagging of juvenile Chinook Salmon • JSATS tagging of juvenile American Shad *Alosa sapidissima*	Deters et al., 2024; Haas et al., 2023; Lingard et al., 2023; Szekeres et al., 2023
Self-Powered Acoustic Tags (SPT)	Shrinks tag size with avoidance of battery constraints with piezoelectric self-powered unit, which harnesses energy from the animals movement	• Laboratory study examining performance and welfare of SPT on juvenile White Sturgeon *Acipenser transmontanus*	Liss et al., 2022
Challenges			
Attenuation of detections	Limitations associated with signal strength and beam pattern, impacting transmission	• Detection range and detection efficiency of micro acoustic transmitter	Li et al., 2023
Surgical implantation	Logistic challenges stemming from surgery or insertion of smaller animals	• Use of injectable PIT tags and micro acoustic transmitters in Chinook Salmon parr using a needle	Liss et al., 2016
Resilience to surgery	Welfare and survival of smaller animals after surgery	• Ability of surgeon influences speed of surgery, accuracy of incision, precision of suturing and mortality • Novice surgeons resulted in worse fate for juvenile Largemouth Bass compared to expert	Cooke and Wagner, 2004
Infrastructure compatibility	Most micro acoustic transmitters require higher frequency receivers than standard use, therefore limiting compatibility with larger tag infrastructure	• Not problematic for radio tracking • Lack of regional networks with capacity to detect micro transmitters	This paper

in self-powered acoustic tags (SPT) to overcome battery constraints will generate longer life and more synoptic observations at the lifetime scale (Figure 2D; Li et al., 2016, 2022). Innovations in micro SPT archival tags or transmitters will provide more complete information through space and time, leading to much more thorough and comprehensive understanding of movement ecology throughout the entirety of life history phases (e.g., Liss et al., 2022).

CHALLENGES

Attenuation of transmitter signals detections

Besides its physical dimensions, a transmitter is characterized by its source level for signal strength and beam pattern for signal directivity (Table 2). For a given frequency, a higher source level leads to longer detection range, and a more uniform beam pattern provides a higher direction probability and flexibility for receiver deployment. Radio waves are strongly attenuated in water and cannot penetrate 10 m of freshwater, which is more pronounced in saltwater. Therefore, limiting this technology to shallow freshwater environments. For acoustic telemetry, the total transmission loss is a combination of the absorption loss by water and spreading loss as the sound wave propagates from the source towards a larger area. This attenuation can be described as: $TL = \alpha(R + C) \times \log_{10}(R)$, where TL is the total transmission loss in dB, α is the absorption coefficient, R is the distance from the transmitter, and C is the spreading coefficient. Absorption loss depends on carrier frequency, transmitter depth and distance, temperature, conductivity, and acidity of the water. The higher the carrier frequency and salinity, the greater the absorption. Ainslie and McColm (1998) developed a simplified equation for estimating the absorption coefficient: C depends on how the acoustic wave propagates from the transmitter toward the receiver. In deep water where there are no boundaries (such as physical structures or the water surface) that impede spreading, spherical spreading is assumed, and the spreading coefficient is 20. Conversely, in shallow water where boundaries affect uniform spreading, cylindrical spreading is assumed, and the spreading coefficient is 10. The values of 20 and 10 are estimates, and the actual spreading loss typically lies between these values, necessitating accurate estimation through acoustic modelling or comprehensive measurements.

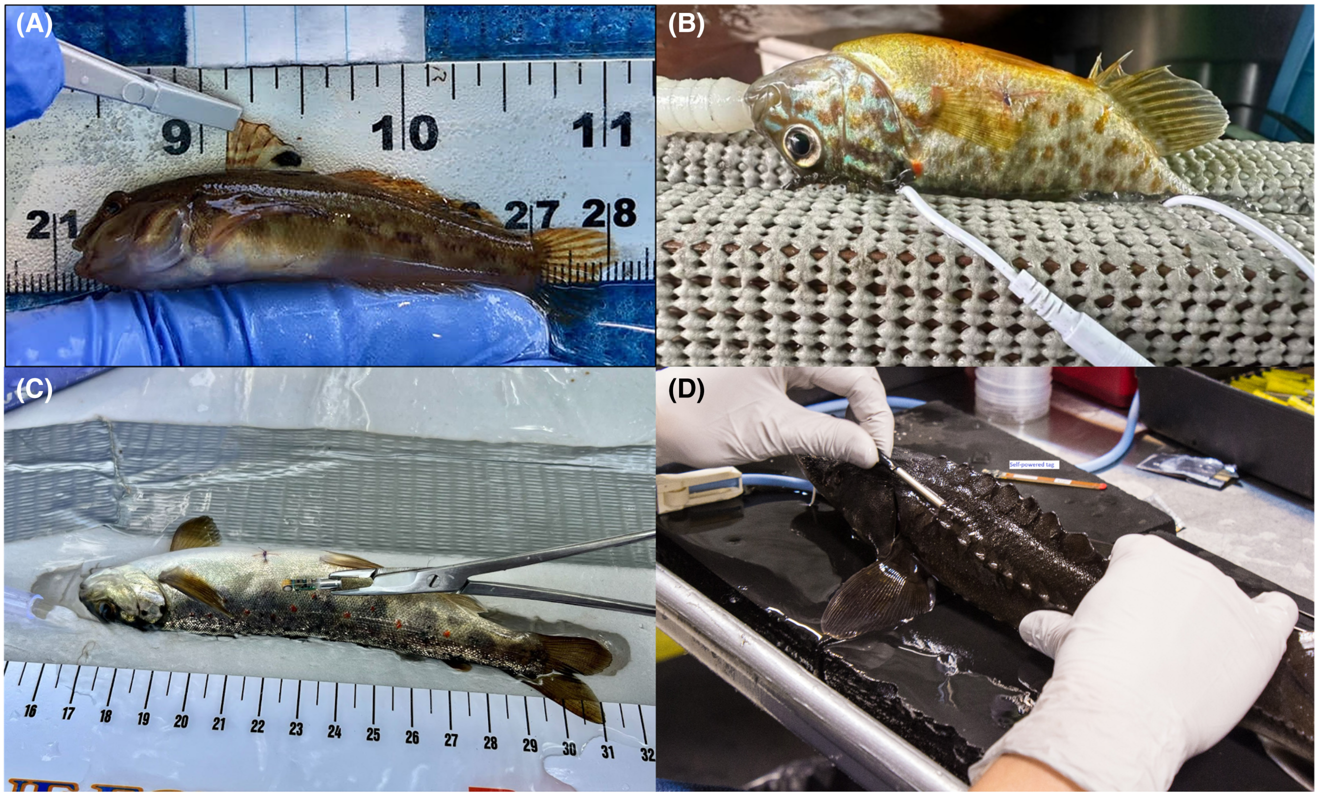

Figure 2. (A) Round Gobies inserted with micro acoustic transmitters to examine habitat connectivity in a canal system. Photo credit: Jordanna Bergman, Carleton University. (B) Pumpkinseed *Lepomis gibbosus* were implanted with micro acoustic transmitters equipped with predation sensors. Photo credit: Bradley Howell, Trent University. (C) Atlantic Salmon parr were inserted with micro acoustic transmitters to examine fine-scale habitat use in pools. Photo credit: Morgan Piczak, Dalhousie University. (D) Juvenile White Sturgeon had self-powered acoustic tags inserted with needles. Photo credit: Daniel Deng, Pacific Northwest National Laboratory.

For instance, in the Columbia River basin, an empirical spreading coefficient of 15 for JSATS has been found from direct measurements to provide a good estimate for spreading loss and corresponding detection range (Li et al., 2023). After estimating *TL*, signal-to-noise ratio of the signal received by the hydrophone can be calculated by subtracting the *TL* and the background noise level of the hydrophone from the source level. By considering the minimum signal-to-noise ratio required for valid detection and decoding of the acoustic telemetry system, one can determine the detection range of the transmitter.

Implanting micro tags

One of the most significant challenges of using microtags is the scaling of the surgical operation. As the size of the animal decreases, the margin for error for surgeons also decreases (Table 2). Small fish being implanted with micro transmitters or loggers require a small cradle or platform for tagging, and the hose used to ventilate must not exert enough water pressure to cause tissue damage or push the fish out of place; for fish that are 5–10 g, this is not trivial. Even routine handling of small fish may yield major injuries to their delicate dermis and muscles. Some very small tags may be injectable rather than requiring surgery. Liss et al. (2016) used an 8-gauge needle to inject PIT and micro acoustic transmitters into Chinook Salmon. For surgical operations using a scalpel and wound closure with sutures, surgeons must account for the extremely thin body wall and minimal musculature. A very small scalpel will be necessary (Figure 3A & 3B). The diminutive peritoneal cavity in small fish may mean that the organs are packed tightly and protrude when an incision is made or when a transmitter is inserted, resulting in displacement. Careful suturing using fine material, thin reverse-cutting suture needles, and often round tweezers to make way for the needle to pass will be necessary to effectively close the wound without damaging the viscera or risking tag ejection (Figure 3C & 3D). When implanting micro tags, a magnifying lens and light are both helpful tools.

Other considerations include overheating or drying of the animal because the large surface area to volume ratio of a small animal will result in a more rapid shift in temperature than a large animal when it is exposed to air. If air and water temperatures are extreme, special attention to keeping the animal's body temperature should be paid, including shading from the sun, partial immersion in water without covering the surgical site, and light spraying of the body with ambient water. Small animals may also be more sensitive to other stressors such as light (Boeuf & Le Bail, 1999).

Resilience of early life stages to surgery including post-release predation

A number of variables are known to affect the resilience of young fish after surgical implantation of a tag (Table 2). Resilience of young fish post-surgery has also been affected

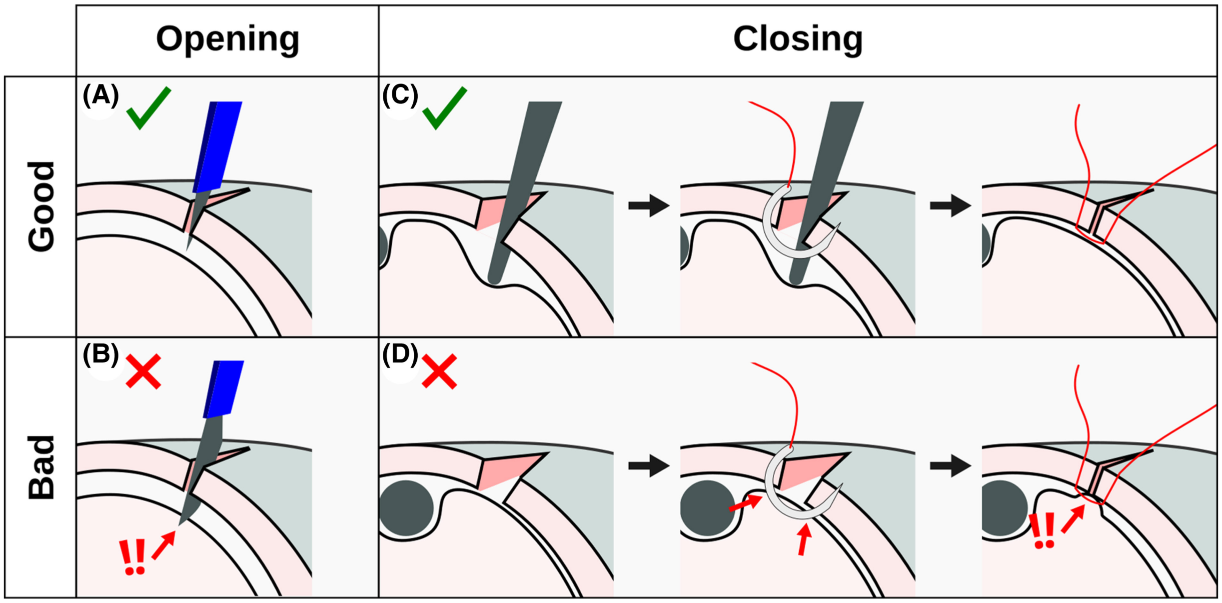

Figure 3. Surgical operations on small aquatic organisms using a scalpel and sutures present specific challenges for surgeons. (A) Small scalpel blades allow for better precision when opening the incision. (B) Larger scalpel blades increase the chance of accidentally injuring the internal organs of the organism. (C) Using a rounded tool (e.g., tweezers) to move the tag away from the incision and create an open space for the needle to pass will prevent injury to internal organs. (D) If care is not taken, the needle will puncture the internal organs, sewing them to the body wall.

by antenna length when using radio transmitters. Adams et al. (1998) noted that during their 21-d holding period, three Chinook Salmon < 120 mm had their antenna (310 mm) tangled around the standpipe of their holding tank, resulting in expulsion and physical trauma. Murchie et al. (2004) noted the same phenomenon and found that antennas > 300 mm caused a significant decrease in swimming performance compared to shorter antenna lengths (30, 75, 150, and 225 mm) among Rainbow Trout *O. mykiss* (~143 mm). Although both experiments were performed in an artificial setting, these incidents showcase the dangers of increased antenna length in the wild, because natural habitats can be extremely complex, increasing the chances of entanglement, injury, and predator attraction (Murchie et al., 2004). A trade-off is, therefore, needed to balance the requirements for antenna length and output power of the transmitter with the risks associated with a longer antenna (Beeman et al., 2007).

Adams et al. (1998) found that Chinook Salmon less than 120 mm in length displayed decreased swimming performance in comparison to those over 120 mm. Smallmouth Bass *Micropterus dolomieu* were added to their tanks to artificially simulate how surgery may affect predation risk, and individuals under 120 mm had decreased ability to school and were consequently eaten (Adams et al., 1998). However, tags in this study accounted for 4.6–10.4% of the fish's total body weight, up to five times heavier than the recommended 2% or less (Winter, 1983). Moore et al. (1990) performed a similar study to test the effect of surgically implanted acoustic tags (1.3 g) in Atlantic Salmon parr (127–172 mm) and smolts (122–189 mm) and found that there was no influence on survival, growth, feeding behavior, swimming performance, or smoltification (Moore et al., 1990). These studies highlight the importance of size restrictions adhering to the tag–body weight ratio (i.e., transmitter should be 2% or less of the fish's body weight) and therefore miniaturization.

Other factors that can affect resilience after surgery include experience of the surgeon, water temperature (Rub et al., 2014), and anaesthetic dosage (Wagner et al., 2014). The ability of the surgeon has been known to affect the speed of surgery, accuracy of the cut, precision of the suturing, and overall mortality of the fish (see Cooke & Wagner, 2004). An experiment on juvenile Largemouth Bass *M. nigricans* used two surgeons, one novice (5 h of training), and one expert (6 years of experience) to determine the impact that individual surgeons have on the success of the surgery (Cooke et al., 2003). They found that a novice surgeon caused more damage to the gastrointestinal tract, took longer to perform the surgeries, and had more difficulty with suture placement, all of which resulted in increased mortality (Cooke et al., 2003). Additionally, warmer temperatures have been associated with higher infection and mortality rates, and rates of tag expulsion (Robinson et al., 2021). Finally, there are very few studies on the appropriate dosage and exposure time of anaesthetics for smaller organisms, which could substantially impact post-release resilience. For example, juvenile Chinook Salmon undergoing surgery resulted in higher cortisol concentrations with longer exposure to MS-222 (80 mg/L; Wagner et al., 2014). Further research is required to determine appropriate dosage, exposure time, and anaesthetic type (including electroanesthesia), across various species of small organisms to maximise welfare and resilience post-release.

Compatibility with existing infrastructure

Micro radio and PIT tags can, in some cases, be made fully compatible with existing infrastructure for tracking, but the smallest micro acoustic tags require higher-frequency receivers to decode them and, therefore, specialised receivers from those that are commonly used for fish tracking (Table 2). The smallest PIT tags are full duplex and not half duplex, so these small tags will not be compatible with some of the infrastructure that is typically used for fish tracking (e.g., acoustic telemetry; Bass et al., 2012). Radio tags can be tuned to specific frequencies and receivers are generally broadband to detect the tag and record the ID. It is up to the user to specify the radio frequency for their micro radio tags that fits with their existing tracking infrastructure. Micro acoustic tags are more challenging; most of the global tracking infrastructure in the ocean consists of 69-kHz pulse position modulation (PPM) receivers, which perform well in fresh and marine waters. The 180-kHz tags tend to have lower detectability in the ocean and are less commonly used; 307- and 417-kHz tags are usually binary phase-shift keying-based (Ingraham et al., 2014) instead of PPM-based systems and are mostly limited to freshwater applications with few, if any, receivers in the ocean that can detect them. Differences in detection range for PPM and other systems (e.g., code division multiple access, InnovaseaHR) dictate which tags and receivers are deployed (Sanderson et al., 2023). Micro acoustic tags, therefore, tend to require dedicated study designs that are spatially limited, with specific receivers that are designed to decode tags on these frequencies.

Upgrading infrastructure for added capacity to detect smaller tags on different frequencies is an expensive undertaking. Although adding capacity for detecting small tags is exciting and the potential for unlocking the capacity to answer novel questions is valuable, networks and individual investigators will need to carefully consider costs and benefits of these upgrades. Ultimately, it is likely a question of prioritization to build capacity in key areas for species of interest.

FUTURE DIRECTIONS

Most of the available technologies for tracking fish have undergone some miniaturization but there are limits to sizes, as long as tags have to carry a battery. There is an unavoidable trade-off among tag size, sampling capacity, and battery life, such that smaller tags could be possible if they have shorter battery life or less frequent sampling rates. There may be increased use of SPT in the future, which reduces battery sizes and allows smaller tags; this has been discussed elsewhere (e.g., Lennox et al., 2017), but there has been recent progress in demonstrating feasibility (Liss et al., 2022).

What constitutes a “micro” tag is relative to the baseline of the current technology. How the products are marketed (e.g., the “microPAT” tag or “pico” PIT tag) should not necessarily define the tag. Large tags like pop-up satellite archival tags are a common tag used for large fish, predominantly in marine environments and these can come in various sizes, the smallest being the miniPAT (Wildlife Computers, 61 g, 730-d battery life). There is now a new microPAT (Wildlife Computers, 46 g, 365-d battery life) but this is still larger than a very large acoustic transmitter. These pop-up satellite tags are challenging to further miniaturize because of components needed for battery, memory, flotation, and satellite connection, but further reductions potentially enabled by energy harvesting (e.g., powering a battery from the animal’s movement) would be a great advance for tag size reductions.

We foresee one of the most significant challenges of increased use of micro tags being the scaling of impacts in smaller fishes. The fine motor skills required to tag especially small animals may challenge some investigators and more validation studies will be necessary to understand the impacts of tagging small fish on their physiology and survival. For fish, transmitters are often recommended not to exceed 2% of body weight as a general rule (Winter, 1983), but these thresholds may not scale effectively to the smallest body size-classes and may require some re-evaluation for small animals. Increased availability of micro tags, once validated, will offer new avenues for multitrophic studies, particularly if sensors like predation sensors can be integrated (e.g., Shorgan et al., 2024).

With PIT tags down to 0.03 g and acoustic tags as small as 0.08 g, have we reached the end of miniaturization of aquatic tracking devices? Miniaturization of tags is a key part of developing the tools and capacity to better understand the movement and distribution of aquatic animals and efforts to improve technology, availability, and affordability of micro tags in support of tracking. Collaboration with engineers has the potential to help facilitate innovations that can continue to make advances in batteries, sensors, and components of tags that will support further miniaturization, establishment of micro tags of different kinds, and potentially a next wave towards a generation of tags beyond micro, to “nano,” which opens further novel opportunities for tracking larval stages.

DATA AVAILABILITY

There are no new data associated with this article.

ETHICS STATEMENT

No people or other animals were implicated in the generation of this content.

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CONFLICTS OF INTEREST

None declared.

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