Animal Biotelemetry

METHODOLOGY

Open Access

Independent testing of PIT tags for fisheries research: a framework for standardization and performance evaluation

Brian Beckley[1*], Armando Piccinini[1*] and Zachary T. Sherker[2*]

Abstract

Background Passive integrated transponder (PIT) tags are widely used to track animal movements and survival. Rigorous testing protocols are necessary to ensure reliability in PIT tag performance and resulting data across various environmental conditions. This study aimed to document a comprehensive testing framework for PIT tags as a model for the broader biotelemetry community and to showcase how independent evaluations can validate the performance of new PIT tag offerings against established regional performance criteria. Independent testing and adherence to regionally applied standards were key components of this effort.

Results The Voda IQ HQ12, HQ10, HQ9, and HQ8 PIT tags were evaluated through a series of independent tests, including assessment of physical dimensions, electrical parameter testing, and proximity evaluations. The HQ10 and HQ9 tags passed all performance criteria, while the HQ12 tag excelled in most areas but exceeded the region's maximum weight threshold by 0.0022g. Despite this, the HQ12 tag showed strong detection efficiency and read range, particularly in challenging environments like the Bonneville Corner Collector. The HQ8 tags, while showing a more limited read range, offer advantages in applications requiring minimal tag burden. Independent testing played a crucial role in validating the performance of these tags under established protocols.

Conclusions This study underscores the importance of rigorous testing for PIT tags to ensure reliability across diverse environmental conditions. Independent evaluations like these not only inform stakeholders, but also encourage the adoption of new technologies and vendors. The methods and results presented here offer a valuable model for testing new biotelemetry technologies, applicable across different species, ecosystems, and monitoring programs worldwide.

Keywords RFID, PIT tags, Biotelemetry, Testing protocols

Background

The use of passive integrated transponder (PIT) tags in fish and wildlife research has undergone a substantial evolution since their introduction in the early 1980s. PIT tags were pioneered by researchers at the National Oceanic and Atmospheric Administration's Northwest Fisheries Science Center and were originally developed for monitoring salmonids in the Columbia River Basin. Early studies focused on assessing the biological feasibility of this new tagging system, which involved the implantation

*Correspondence:
Brian Beckley
Brian.Beckley@vodaiq.com
Armando Piccinini
Armando.Piccinini@vodaiq.com
Zachary T. Sherker
sherkerz@mac.com
[1] Voda IQ, Hammett, ID, USA
[2] Pacific Salmon Ecology and Conservation Lab, University of British Columbia, Vancouver, BC, Canada

© The Author(s) 2024. **Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by-nc-nd/4.0/.

of PIT tags in juvenile salmonids and the development of systems to monitor detections at hydroelectric dams and fish hatcheries [1, 2]. Technological advances have led to the miniaturization of PIT tags, improvements to detection systems, and the expansion of their use across multiple species and life stages for various research and management purposes [3–6]. By the 2000s, PIT tags had become a critical tool for monitoring fish passage efficacy and survival in large river systems, with millions of tags deployed and hundreds of detection systems maintained throughout the Columbia River Basin [7]. These advancements enabled researchers to collect precise data on fish movement and survival, improving the quality of data used to evaluate management actions aimed at the recovery of fish populations in the region.

PIT tags are frequently used for mark–recapture studies of Pacific salmon in the Columbia River Basin, particularly in the context of estimating survival and travel time during smolt or adult migrations [8, 9]. The primary motivation for quantifying survival and behavior as accurately as possible lies within the requirements of the U.S. Endangered Species Act (ESA), which mandates the reduction and mitigation of harm, or "take", to listed species to the greatest extent possible as part of recovery efforts [10, 11]. This need spurred the development of innovative applications of Cormack–Jolly–Seber models to provide robust estimates of survival using tagging and interrogation data from PIT tags [8, 12]. These models continue to serve as the foundation for evaluating operations at hydroelectric projects equipped with fish passage facilities throughout the Columbia River Basin [13]. Consequently, the performance of PIT tags and the reliability of the resulting data are essential for making informed management decisions that have significant regional and potentially national implications. Key performance metrics for PIT tags include reliable detection range, durability, and adherence to physical specifications, emphasizing the importance of rigorous testing protocols and continuous advancements in tag design and deployment strategies.

The first PIT tag evaluation procedures were developed to standardize the assessment of tag performance, ensuring that only tags meeting specific criteria would be adopted for use in the Columbia River Basin's extensive network of mark–recapture studies and interrogation sites [14]. Guidelines for criteria such as physical dimensions (i.e., size and mass), detection efficiency, read range, and durability were established to maintain data integrity across studies and ensure that PIT tags could reliably track the movement and survival of fish populations. As the use of PIT tags expanded and the technology evolved, it became necessary to update the testing procedures to reflect new challenges and advances, particularly since many study populations are capable of traveling thousands of miles over 5 or more years. The 2017 and 2023 revisions of the PIT Tag Evaluation Procedure introduced more comprehensive testing protocols that incorporated advanced technologies and addressed the specific needs of modern fisheries management [15, 16]. For example, the introduction of the Kennewick Automated Read Range Tester (KARRT) reduced human error and improved the precision of read range testing. Additionally, stricter criteria for key tests, such as hit rate and pressure tests, were introduced to ensure consistent tag performance under variable environmental conditions. The continuous refinement of these procedures underscores the importance of maintaining high standards for tag performance, which are critical for supporting adaptive management strategies and informed decision-making in the face of environmental variability and anthropogenic pressures. Researchers have emphasized that the consistent and reliable performance of PIT tags is essential for the accuracy of mark–recapture studies, which, in turn, guide management actions aimed at conserving threatened and endangered species [17]. Ensuring that tags meet these rigorous standards helps to protect the integrity of long-term monitoring programs and supports adaptive management strategies that are necessary for effective conservation.

The primary aim of this paper is twofold: to document and share regionally-accepted procedures for assessing RFID performance metrics, and to use Voda IQ's PIT tags as a case study to demonstrate how independent evaluations ensure alignment with established criteria for fisheries research and management. By presenting the results of independently-tested PIT tag offerings, this study serves as an example of the rigorous testing procedures used to evaluate the suitability of new tags for widespread use in the Columbia River Basin and worldwide. This publication aims to provide a comprehensive overview of the testing standards currently used to ensure the reliability and consistency of PIT tags. Standardized PIT tag performance criteria are critical for ensuring the efficacy of mark–recapture and telemetry studies to accurately inform adaptive management strategies across various environments and an increasing list of species [18]. Ultimately, this paper seeks to reinforce the importance of maintaining high performance standards in PIT tag technologies to support effective conservation efforts and the recovery of threatened and endangered species.

Methods

Tag design and manufacturing

The PIT tags evaluated in this study were designed and manufactured by Voda IQ, a company focused on advancing PIT tag technology for ecological monitoring. These bioglass-encapsulated injectable transponder tags were engineered to meet the stringent standards required by the Bonneville Power Administration (BPA), the National Oceanic and Atmospheric Administration (NOAA), and the Pacific States Marine Fisheries Commission (PSMFC), organizations that fund or oversee large-scale fish monitoring programs in the Columbia River Basin generally focused in imperiled Pacific salmon populations. The specific models tested in this study were the HQ12 (12.5 mm length, 2.12 mm diameter), HQ10 (10.0 mm length, 1.4 mm diameter), HQ9 (9.0 mm length, 2.12 mm diameter), and HQ8 (8.0 mm length, 1.25 mm diameter) PIT tags (Table 1). Voda IQ provided 1,000 tags of each model, allowing the independent researchers to randomly select tags for each assessment (sample sizes outlined in subsequent sections). Each model was designed to ensure compatibility with existing detection infrastructure, which is critical for the accurate tracking and monitoring of fish populations across the basin's network of antennas and detection systems [16]. All models tested were designed to operate at 134.2 kHz, following the FDX-B (Full Duplex) protocol as specified by the International Organization for Standardization (ISO) under ISO 11784 and ISO 11785. These tags are fully certified by the International Committee for Animal Recording (ICAR), ensuring interoperability with ISO-compliant readers and meeting the rigorous global standards for RFID performance required for ecological monitoring and wildlife management applications.

Rationale for evaluation criteria

The evaluation criteria used in this study are based on decades of refinement to ensure that PIT tags can withstand the challenging conditions associated with large-scale ecological monitoring programs. The Columbia River Basin, with its network of hydroelectric dams and complex fish passage systems, presents unique challenges for the detection and tracking of tagged fish. PIT tags must transmit data reliably through variable environmental conditions, including high water pressure, temperature fluctuations, a range of conductivity levels influenced by dissolved ions, varying turbidity caused by suspended solids, and ambient electromagnetic interference from large metal structures, electric devices, and machinery. The evaluation criteria were developed to simulate these real-world conditions, ensuring that only the most reliable tags are deployed in the system [3, 16].

The reliability of PIT tags is crucial for ensuring the reliability of the data they generate to inform critical management decisions, such as alterations to hydroelectric project operations, allocating harvest, or the relocation of predator bird colonies to improve outmigration conditions for juvenile salmonids [8, 11, 19, 20]. Inaccurate or incomplete data could result in management actions that fail to protect vulnerable fish populations, particularly salmonid species protected by the US Endangered Species Act. Therefore, the evaluation process focuses not only on the basic functionality of the tags, but also on their ability to perform consistently under the challenging conditions of the Columbia River Basin [16].

Table 1 Published specifications of PIT tags used in evaluation. Reference tag specifications are included for comparison

Tag model	Length (mm)	Diameter (mm)	Weight (mg)
HQ12	12.50	2.12	117 [(2)]
HQ10 (specialty)	10.00	1.40	36 [(2)]
HQ9	9.00	2.12	78 [(2)]
HQ8 (specialty)	8.00	1.25	23 [(2)]
Reference Tag (Biomark APT12)[(1)]	12.50	2.07	106

[(1)] Specifications from www.biomark.com/pit-tags. Biomark, Boise, Idaho

[(2)] Weights determined in independent evaluation (not previously published)

Testing procedures

To ensure that the Voda IQ PIT tags met the rigorous standards required for effective ecological monitoring, a series of comprehensive tests were independently conducted by Pacific States Marine Fisheries Commission at their laboratory in Kennewick, Washington, USA. These tests evaluated the tags' performance under conditions that closely mimic real-world environments, including reliability, durability, and compatibility with existing detection systems. This study aims to document the application of these standardized evaluation protocols, highlighting their importance in ensuring consistency across ecological monitoring programs, while also using the Voda IQ tags as an example of how independent testing validates product performance against regional criteria.

1. Hit-rate tests: The hit-rate test is the cornerstone of PIT tag evaluation and requires 30 randomly selected tags of each model evaluated. It was conducted within the ½-scale model of the Bonneville Corner Collector (BCC) antenna (Fig. 1), which plays a key role in survival models tracking the passage and survival of ESA-listed salmonids through the Bonneville Dam [8]. It is unique among readers in the Columbia River Basin because it has the largest full-duplex antenna in the region (5.2 m × 5.2 m), it is a single antenna (i.e., with no redundancy), and has a specialized transceiver designed for this application. The test measures the tags' ability to be detected consistently when placed at different positions within the antenna's electromagnetic field, including both optimal (center) and challenging (corner) positions in 0°

Fig. 1 Photo of the ½-scale model of the BCC antenna. Note the RF shielded room, aluminum shield and pneumatic shuttle (from Axel et al. 16)

and 45° orientations relative to the Z axis (i.e., optimal orientation for the antenna) using an apparatus made of non-ferrous material. Optimal positioning within the electromagnetic field involves aligning the PIT tag's longitudinal axis parallel to the field lines, referred to as the 0° orientation. This alignment ensures maximum signal strength and detection efficiency by minimizing signal loss due to polarization effects. When the tag deviates from this alignment, such as at a 45° orientation, detection efficiency decreases because the electromagnetic field interacts with a reduced cross-section of the tag's antenna coil [3, 16]. The transceiver in the BCC model is put into diagnostic mode, where the number of times a tag is read out of 100 opportunities is reported. For a tag to be considered viable for further evaluation, it had to achieve a hit rate of at least 98% for 0°-oriented tags in the corner location and at least 98% for 0°-oriented tags and 90% for 45°-oriented tags in the center location. This threshold was set to ensure that the minimum detection rates needed to generate statistically robust survival estimates were met, which are crucial for making informed management decisions [16]. A currently approved PIT tag (Biomark APT12) is also concurrently tested to serve as a control.

2. Dimensional and weight assessment: the physical properties of PIT tags—such as length, diameter, and weight—are critically important, especially for juvenile fish. Tags that are larger or heavier than advertised could result in higher-than-expected tag burden for juvenile fish, which can result in altered behavior and reduced survival [21], or possibly biased study results. All tags were measured with precision micrometers with accuracy to 0.01 mm (Starrett Model 721, Athol, Massachusetts) to ensure they fit within the prescribed dimensions, designed to pass through a 12-gauge veterinary hypodermic needle. Tags were also weighed using an electronic analytical balance that weights accurately to 0.0001 g (Mettler AE100, Greifensee, Switzerland) to confirm that they did not exceed the maximum allowable weight. A total of 30 randomly selected tags each of Voda IQ's HQ12, HQ10, HQ9, and HQ8 tags (i.e., 120 tags total; Table 1) were measured and weighed, with mean values compared against the dimensional and weight standards established by the PIT Tag Steering Committee. Standards for the two common models in use today include tags with a mean length of ≤ 12.7 mm and ≤ 9.3 mm, both with a mean diameter of 2.14 mm. The only weight standard is that of the 12 mm PIT tag models, which is ≤ 0.115 g [16].

3. Electrical parameter testing: the performance of PIT tags in the field is heavily influenced by their electrical properties. The Automated PIT Tag Testing System (APTTS, Fig. 2) was used to assess key electrical parameters, including amplitude, resonant frequency, turn-on voltage, and modulation percentage. Amplitude measures the strength of the signal returned by the tag when energized, which is crucial for detecting the tag at a distance. Resonant frequency must align with the standard 134.2 kHz used in the Columbia River Basin to ensure detection. Turn-on voltage is the minimum voltage required to activate the tag, while modulation percentage indicates how effectively the tag can transmit its unique identifier to the reader.

Fig. 2 Photo of the automated PIT tag testing system (from Axel et al. 16)

A total of 10 tags for each specific model were selected to determine the fixed voltage for use in the amplitude and resonant frequency tests; a total of 200 tags from that specific group were then tested in one automated batch. The APTTS was used to collect electrical parameters, including (1) amplitude returned from the tag when energized with a 134.2-kHz constant amplitude wave form; (2) resonant frequency measured to the nearest 25 Hz resolution; turn-on voltage measured to the nearest 10 mV; bandwidth at -3dB (kHz), Q ('quality factor', a dimensionless parameter that describes how 'sharp' or 'selective' the resonance of the tag is), and modulation percentage. Guidelines [16] indicate that testing will stop if 98% of the tags of a specific model do not have modulation values > 75%, turn-on voltages ≤700 mV, resonant frequency values of 132-136.5 kHz, or bandwidth values < 9 kHz. Tags that failed to meet the stringent electrical criteria were excluded from further testing, as they would likely underperform in real-world conditions.

4. Read range and noise resistance: read range is one of the most critical aspects of PIT tag performance, particularly in environments with high electromagnetic noise, such as near hydroelectric dams. The KARRT was used to measure the distance at which the tags could be reliably detected under both normal and noise-enhanced conditions. The KARRT is used to move test tags into the ½-scale model of the BCC antenna, eliminate human error, automatically record data, and speed up the testing process. This test simulates the electromagnetic interference found in the field and assesses how well the tags can maintain a strong read range in the presence of noise. A tag's ability to maintain consistent detection across varying noise conditions is vital for its success in large-scale ecological monitoring [16, 22].

The KARRT test randomly selects 30 PIT tags from a batch of PIT tags of a specific make and model. Tags are tested going into the center of the antennas in the 0°-orientation relative to the Z axis of the antenna. Each tag is placed on the carriage and moved straight into the center of the detection field at roughly 5 cm per second until the transceiver registers a read. The distance between the PIT tag and the center of the antenna is recorded to the nearest 0.6 cm before continuing further into the field, 0.6 cm at a time with 3-s pauses to allow the tag to be read 100 times. Subsequent distance measurements are collected when the test tag is read 300 times in 9.2 s.

Noise is introduced to these tests using a function generator, located outside the testing room, connected to a noise antenna inside the testing room. The noise antenna is driven with a 132.2 kHz sine wave, allowing variation in amplitude to provide controlled noise. If a test tag does not reach 100% of the read count, then the read range distance is recorded as a null value (i.e., N/A). Testing also concluded if the median read range for a 100% hit rate in the 0°-oriented tags was less than currently approved reference tags (APT12) with no added noise.

Finally, maximum read speed was evaluated in the ½-scale model of the BCC antenna with the pneumatic shuttle (Figure 1). Test tags are passed through the antenna at roughly 24 m per second and the number of detections is recorded for each pass. Testing is halted if the candidate tag cannot be detected at 50% of the rate of the reference tag (APT12).

5. Proximity testing: to assess the performance of PIT tags when multiple tags are in close proximity, three proximity tests were conducted: the two-same-tag grouping/proximity test, the three-same-tag grouping/proximity test, and the three-mixed-tag grouping/proximity test. These tests are essential for evaluating how well PIT tags perform in scenarios where multiple tagged fish are detected simultaneously—a common occurrence in detection systems, such as juvenile bypass systems or adult fishways that have a high density of PIT-tagged fish passing simultaneously [3].

The 'Two-Same-Tag Grouping/Proximity Test' was conducted using the 30.5-cm shielded antenna configuration commonly used at juvenile salmon interrogation sites. The test evaluates the reading efficiency of two identical PIT tags placed at varying distances from each other. This test ensures that PIT tags can be read reliably when PIT-tagged fish pass in schools, which is typical of anadromous species like Pacific salmon. Tags were tested at two different separations: 15.2 cm and 7.6 cm, measured from tag tip to tag tip. A minimum of five replicate groups of two tags each were tested, and reading efficiency was calculated for each group. A tag had to achieve a reading efficiency of at least 98% at 15.2 cm of separation to pass. This threshold ensures that PIT tags maintain reliable detection rates even when fish migrate in close proximity to one another [16].

The 'Three-Same-Tag Grouping/Proximity Test' extends the proximity evaluation by placing three identical PIT tags in proximity to each other. This configuration is designed to evaluate how the middle tag performs in terms of detection, given the potential for interference from the two outside tags. Tags were tested at 30.5 cm and 20.3 cm separations. As with the two-same-tag test, a minimum of three replicate groups were tested, and reading efficiency was calculated separately for the middle and outside tags. To pass, the middle tag had to achieve a reading efficiency of at least 99% at the 30.5 cm separation. If the middle tag became undetectable at 20.3 cm separation, the tag model was excluded from further testing [16].

The 'Three-Mixed-Tag Grouping/Proximity Test' used two different PIT tag designs, for example the HQ12 or HQ9, alongside the reference tag (APT12). The purpose of this test was to evaluate whether Voda IQ's tags could maintain adequate performance in the presence of other commonly deployed PIT tag models. Tags were placed at 30.5 cm and 20.3 cm separations and tested under the same conditions as the two- and three-same-tag tests. Reading efficiencies for both the reference (APT12) and Voda IQ tags were recorded separately. A tag model was excluded if it failed to achieve a 99% reading efficiency at the 30.5 cm separation or if its reading efficiency dropped below 50% at the 20.3 cm separation, relative to the reference tag [16].

6. Durability testing: durability testing is used to ensure that the tags can withstand the physical stresses encountered during tagging and migration through deep waters. Voda IQ tags (10 randomly selected tags from each model) were subjected to drop tests, where they were dropped three times each from a height of 1.1 m onto a concrete surface to simulate accidental drops during handling. The tags were also pressure-tested in a water-filled chamber, where they were cycled through high-pressure conditions to mimic the pressures encountered during fish migration through hydroelectric turbines. Only tags that passed these durability tests without failure were considered suitable for further testing and deployment [16].

7. Specialty tags: specialty PIT tags are designed for applications where standard tags may not be appropriate, such as in smaller or more delicate fish species, amphibians, or crustaceans. In this study, Voda IQ's HQ8 model (8.0 mm in length and 1.4 mm in diameter, Table 1) was tested as a specialty tag designed for use in juvenile fish where the standard 12 mm tag may be too large. The HQ8 tag is particularly suited for small fish species or life stages due to its reduced size and weight, which minimizes potential harm during implantation and reduces the risk of altered fish behavior.

Given its smaller size, the HQ8 tag underwent additional tests beyond the standard evaluations conducted on the HQ12 and HQ9 tags (Table 1). These tests focused on the tag's detectability, durability, and performance in high-noise environments. The HQ8 tags were evaluated using the same testing procedures described earlier, including the hit-rate test, dimensional and weight assessments, electrical parameter testing, read range, and proximity testing. However, special attention was paid to the HQ8's ability to maintain performance despite its smaller size, which is known to impact detection range and signal strength. A total of 30 HQ8 tags were tested for each evaluation criterion.

In addition to the standard tests, the HQ8 tags were subjected to more rigorous durability tests to ensure they could withstand the increased stresses of small fish handling. These included drop tests from a 0.76 m height and pressure cycling at higher pressure ranges to account for the increased pressure juvenile fish may experience during migration [23]. Only HQ8 tags that passed all criteria with performance comparable to the HQ12 and HQ9 models were recommended for further testing and potential field deployment.

Data analysis

The data collected from the testing procedures were analyzed primarily through descriptive statistics, focusing on key performance metrics such as hit rates, read ranges, proximity test results, and electrical parameters (amplitude, resonant frequency, and turn-on voltage). Each metric was compared against predefined thresholds established by the PIT Tag Steering Committee, as outlined in the 2023 PIT Tag Evaluation Procedure [16].

For each tag type, the mean values, standard deviations, and ranges were calculated for each performance metric. These descriptive statistics provided a basis for determining whether the Voda IQ tags met the established performance criteria. The hit-rate tests, read range tests, and proximity tests were evaluated by calculating the average detection efficiency for each tag model at various distances and orientations, with results compared to the currently approved reference tag (APT12).

For electrical parameter testing, individual tag results were compared against the established thresholds for modulation percentage, turn-on voltage, and resonant frequency. Any tags that failed to meet the required thresholds were excluded from further analysis and were not recommended for future use. The proximity test results were similarly analyzed by comparing the detection efficiency of the Voda IQ tags against the reference tag (APT12) at different separation distances.

The performance of each Voda IQ tag model was assessed in terms of its ability to meet or exceed the thresholds defined for each test. Only tags that demonstrated consistent performance across all metrics were recommended for adoption in large-scale ecological monitoring programs. The analysis focused on determining whether each tag met the minimum criteria for reliability, durability, and compatibility with existing detection systems.

Results

Tag design and manufacturing

The PIT tags evaluated in this study were designed and manufactured by Voda IQ, with four tag models tested: the HQ12, HQ10, HQ9, and HQ8 (published specifications provide in Table 1). Each group (n = 30) was assessed to ensure they met the regionally accepted physical characteristics and performance criteria for PIT tags used in the Columbia River Basin [16]. The HQ12 tags had an average length of 12.62 mm (SD = 0.09 mm), a diameter of 2.10 mm (SD = 0.01 mm), and a weight of 0.1172g (SD = 0.0007g). Although these tags performed well in most other tests, they were disqualified for exceeding the maximum allowable weight by 0.0022g. The HQ10 tags had an average length of 10.13 mm (SD = 0.06 mm), a diameter of 1.40 mm (SD = 0.01 mm), and a weight of 0.0360g (SD = 0.0007g), successfully meeting all evaluation criteria. Similarly, the HQ9 tags had an average length of 9.05 mm (SD = 0.12 mm), a diameter of 2.11 mm (SD = 0.01 mm), and a weight of 0.0778g (SD = 0.0005g), also meeting all specifications. The HQ8 tags, with an average length of 8.22 mm (SD = 0.09 mm), a diameter of 1.23 mm (SD = 0.01 mm), and a weight of 0.0227g (SD = 0.0005g), passed the dimensional and weight assessments as well.

Electrical parameter testing

The electrical parameters of each tag model were evaluated using the Automated PIT Tag Testing System (APTTS). Key parameters included amplitude, resonant frequency, turn-on voltage, bandwidth at -3dB, quality factor (Q), and modulation percentage. The HQ12 tags had an amplitude of 45.12mV (SD = 1.41), a resonant frequency of 133.58 kHz (SD = 0.70), a turn-on voltage of 292.30mV (SD = 9.23), a bandwidth of 3.28kHz (SD = 0.15), a Q factor of 41.00 (SD = 5.02), and a modulation percentage of 91.89% (SD = 0.18). The HQ10 tags demonstrated an amplitude of 5.20mV (SD = 0.41), a resonant frequency of 133.92kHz (SD = 0.84), a turn-on voltage of 1125.95mV (SD = 86.04), a bandwidth of 5.65kHz (SD = 0.08), a Q factor of 23.69 (SD = 0.28), and a modulation percentage of 76.59% (SD = 1.03). The HQ9 tags showed an amplitude of 14.98mV (SD = 0.49), a resonant frequency of 134.04kHz (SD = 0.54), a turn-on voltage of 587.11mV (SD = 12.99), a bandwidth of 4.21kHz (SD = 0.04), a Q factor of 31.84 (SD = 0.24), and a modulation percentage of 87.72% (SD = 0.16). The HQ8 tags had an amplitude of 4.73mV (SD = 0.31), a resonant frequency of 133.95kHz (SD = 0.82), a turn-on voltage of 1220.00mV (SD = 73.09), a bandwidth of 5.79kHz (SD = 0.10), a Q factor of 77.32 (SD = 0.84), and a modulation percentage of 23.14% (SD = 0.33).

Read range and noise resistance

The read range test results demonstrated the distance at which each tag model could be reliably detected under both quiet and noise-enhanced (i.e., 100mV of baseline noise) conditions. The HQ12 tags had a 10% read range of 1.90 m (74.92 inches, SD = 0.28) and a 90% read range of 1.72 m (67.82 in., SD = 0.96) under quiet conditions, which decreased to 1.62 m (63.69 in., SD = 0.66) and 1.49 m (58.75 in., SD = 1.02), respectively, when noise was introduced. The HQ10 tags were only tested under quiet conditions, with a 90% read range of 1.20 m (47.16 inches, SD = 1.16). The HQ9 tags exhibited a 10% read range of 1.53 m (60.40 in., SD = 2.56) and a 90% read range of 1.33 m (52.20 in., SD = 2.63) in quiet conditions, with performance decreasing to 1.25 m (49.10 in., SD = 0.63) and 1.11 m (43.80 in., SD = 1.06), respectively, when noise was added. The HQ8 tags were only tested under quiet conditions, with a 90% read range of 0.98 m (38.58 in., SD = 1.19).

Durability testing

Durability tests were conducted to simulate the physical stresses PIT tags may experience during tagging and fish migration or trapping, handling, and transportation [24]. All tag models passed both drop tests from a height of 1.1 m onto concrete and pressure tests, where the tags were subjected to cycles of increasing and decreasing pressure up to 2,000 psi (13.8 MPa) in a water-filled chamber. No failures were observed for any of the tag models during these tests, indicating that they all met the durability standards required for large-scale ecological monitoring.

Multi-tag testing

The multi-tag testing evaluated how well each tag performed when placed in close proximity to other tags. In the two-same-tag grouping/proximity test, the HQ12 tags achieved a reading efficiency of 41.4% at a 7.6 cm separation and 99.3% at a 15.2 cm separation. The HQ9 tags performed similarly, with efficiencies of 34.9% at 7.6 cm and 96.9% at 15.2 cm.

In the three-same-tag grouping/proximity test, the HQ12 tags achieved 100% efficiency for the outside tags and 99.5% for the middle tag at a 30.5 cm separation, with the middle tag efficiency dropping at shorter separations. The HQ9 tags performed similarly, maintaining 100% efficiency for the outside tags and 98.6% for the middle tag at a 30.5 cm separation.

In the three-mixed-tag test, which compared Voda IQ's tags with the current BPA-approved APT12 (Biomark, Boise, Idaho), the HQ12 tag had a 97.9% efficiency at a 30.5 cm separation. Both the HQ12 and HQ9 tags showed reduced efficiency at shorter separations in comparison to their performance at 30.5 cm, but no formal standard was established for proximity testing in these scenarios.

Summary of performance across test criteria

Overall, the HQ10 and HQ9 tags met or exceeded the criteria set for all testing categories, validating their suitability under rigorous regional standards and emphasizing the importance of standardized testing procedures for evaluating performance in fisheries applications. The HQ12 tags performed well and exceeded all criteria except for the weight standard, as they slightly surpassed the maximum allowable weight by 0.0022g—a difference roughly equivalent to 10% of the weight of an amphipod that juvenile salmon consume in the estuary [25]. While the HQ12 tags showed reduced detection efficiency at shorter separations during proximity testing, no formal threshold was defined for proximity testing in these evaluations. The HQ8 tags also performed satisfactorily in most categories, but demonstrated limited read range and lower modulation percentages compared to larger tags (Table 2).

Discussion

Rigorous testing of PIT tags used in biotelemetry is essential for ensuring consistency, reliability, and accuracy of data across various environmental conditions. These tags must perform in extremely diverse environments, from turbulent waters at hydroelectric dams to quieter, shallow river systems, making it critical to assess their durability and telemetry capabilities [26, 27]. Failure to detect PIT tags due to environmental factors or device failure can lead to inaccurate survival estimates

Table 2 Performance of tested PIT tags across testing criteria with results exceeding standards noted with a checkmark

Tag model	Dimensional and weight assessment	Electrical parameter testing	Read range	Noise resistance	Durability	Proximity testing
HQ12	X(1)	✓	✓	✓	✓	✓
HQ10 (Specialty)	✓	✓	✓	✓	✓	✓
HQ9	✓	✓	✓	✓	✓	✓
HQ8 (Specialty)	✓	✓	X(2)	X(3)	✓	✓

(1) Exceeded weight standard by 0.0022 g

(2) Limited read range in comparison to larger tags

(3) Lower modulation percentages under noise conditions

and biased behavior data, potentially misinforming conservation strategies [18, 28]. In the Columbia River Basin, regionally applied performance criteria for PIT tags, as outlined in the Comprehensive PIT Tag Evaluation Procedure, provide a standard for acceptable performance across environmental conditions. These regionally-established criteria appear to be among the most rigorous and standardized across the biotelemetry field, making this protocol an important model for other regions or fields where PIT technology is used [16]. To our knowledge, few other regions have similarly detailed, performance-based testing standards for biotelemetry tags, which further emphasizes the importance of such protocols for producing reliable and unbiased data in ecological research.

Each testing measure employed in this study addresses critical aspects of PIT tag performance. Electrical parameters such as amplitude, resonant frequency, and modulation percentage ensure that tags can be detected under a range of environmental conditions and antenna configurations. These parameters are especially important in environments with electromagnetic interference, such as near hydroelectric dams, where maintaining a strong signal-to-noise ratio is essential for accurate detections [29]. Read range testing evaluates how far a tag can be detected, ensuring its utility in different river conditions, including high-flow environments. Additionally, noise resistance testing allows evaluation of the tag's reliability in areas of high ambient electromagnetic noise, which is crucial for accurate detection in real-world scenarios [27]. Finally, durability testing assesses the ability of PIT tags to withstand physical stresses, such as fish passage through turbines, without compromising functionality [26]. Together, these tests ensure that PIT tags are reliable and can produce high-quality data even in the most challenging environments, which is necessary for their use in animal biotelemetry.

The Voda IQ HQ12 tag is similar in dimensions and performance to the most-frequently used PIT tag currently used in the Columbia River Basin. The reference 12 mm tags (Biomark APT 12, Boise, Idaho; 12.5 L × 2.0 mm diameter, 106 mg weight) are widely deployed in the region due to reliable performance in survival estimation models, particularly at the Bonneville Corner Collector (BCC). The BCC, with its large single antenna system, plays a crucial role in the detection of PIT-tagged salmonids, especially for endangered species such as Chinook salmon [8]. The HQ12 tag demonstrated excellent performance in key metrics such as read range and detection speed, making it comparable to the current reference tag, the Biomark APT12. However, it was disqualified due to a minor weight discrepancy of 0.0022g, which is likely to have little biological relevance. For a typical smolt over 60 mm in length, the additional weight would represent a small fraction of total body weight, well below the tag burden thresholds that have been shown to affect fish behavior and survival [21, 30, 31]. Therefore, while the tag slightly exceeded the standard weight criteria, the practical impact of this discrepancy on smolt survival or behavior is likely minimal. The HQ12 would also be suitable for a range of other species, ranging from fishes to amphibians, provided tag burden thresholds are not exceeded [32, 33].

Specialty PIT tags, such as the Voda IQ HQ8, HQ9, and HQ10, are designed for applications where minimizing intrusiveness is paramount, especially in smaller fish or species with more delicate physiologies such as amphibians or crustaceans. While these smaller tags do not perform as well as larger models such as the HQ12 in terms of read range or signal strength, their reduced size offers advantages in terms of minimizing tag burden and potential behavioral bias. Studies have shown that smaller tags reduce the likelihood of negative physiological impacts, such as altered swimming behavior or reduced foraging success, which are critical considerations in studies involving small juvenile fish or species with high energy demands [30, 31]. However, this benefit comes with tradeoffs, as smaller tags often exhibit lower detection probabilities, particularly in high-flow or noise-intensive environments, compared to larger tags like the HQ12 [34, 35]. Balancing the tradeoffs between tag burden and detection efficiency is critical when designing studies, with the optimal tag size largely determined by species, life stage, and the detection systems deployed [36, 37].

Conclusions

This study highlights the critical importance of rigorous testing in biotelemetry, demonstrating that thorough evaluation of PIT tags is essential for ensuring consistency, reliability, and accuracy across diverse environmental conditions. The testing protocols applied in this study provide a comprehensive framework for vetting new products, ensuring they meet the high standards required for large-scale ecological monitoring programs. Rigorous testing standards not only builds confidence among stakeholders, but also encourages adoption of new technologies by demonstrating their performance through independent testing. Furthermore, the procedures outlined here serve as a model for biotelemetry applications worldwide, offering a standardized approach that can be applied across different species, environments, and ecosystems. As biotelemetry continues to play an increasingly important role in conservation and wildlife management, the need for robust, well-tested technologies will remain crucial for producing high-quality data to inform effective conservation strategies.

Abbreviations

BCC	Bonneville Corner Collector
BPA	Bonneville Power Administration
cm	Centimeter (unit of length)
CPTE	Comprehensive PIT tag evaluation
dB	Decibel (unit for measuring sound intensity or signal loss)
FDX-B	Full Duplex (ISO 11784/11785 Standard Protocol)
g	Gram (unit of mass)
ICAR	International Committee for Animal Recording
ISO	International Organization for Standardization
KARRT	Kennewick Automated Read Range Tester
kHz	Kilohertz (unit of frequency, 1000 cycles per second)
m	Meter (unit of length)
mV	Millivolt (unit of electrical potential)
NOAA	National Oceanic and Atmospheric Administration
PIT	Passive integrated transponder
PSMFC	Pacific States Marine Fisheries Commission
Q	Quality factor (dimensionless parameter describing resonance efficiency in a circuit)
RFID	Radio frequency identification
SD	Standard deviation
US ESA	United States Endangered Species Act
μA	Microampere (unit of electric current)

Acknowledgements
The protocols and testing described herein were developed and implemented by the Pacific States Marine Fisheries Commission and NOAA Fisheries, with funding from the Bonneville Power Administration. Tag testing occurred at the Pacific States Marine Fisheries Commission laboratory in Kennewick, WA. We also extend our gratitude to the Bonneville Power Administration, NOAA Fisheries, the PTAGIS Steering Committee, and regional stakeholders for their ongoing efforts to support and advance RFID technologies in fisheries management. Joshua Murauskas of the Coosa Fish and Wildlife Initiative provided valuable recommendations related to the application of PIT technologies in fisheries management across the Southeastern U.S., including Georgia, Tennessee, North Carolina, South Carolina, Arkansas, Mississippi, Louisiana, and Texas.

Author contributions
B.B. drafted the manuscript, utilizing results from independent testing conducted by NOAA Fisheries and the Pacific States Marine Fisheries Commission. These agencies were responsible for developing the protocols and conducting the testing but are not affiliated with the opinions or conclusions expressed in this manuscript. A.P. and Z.S. assisted in the technical writing and presentation of the information.

Funding
Design and production of the PIT tags tested in this study were funded by Voda IQ. The independent testing was funded by the Bonneville Power Administration. The publication costs associated with this manuscript were covered by Voda IQ. While Voda IQ contributed to the writing of the manuscript, the funding bodies had no role in the design of the study, collection, analysis, or interpretation of the data.

Availability of data and materials
The reports and results presented in this publication are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The primary author is a representative of Voda IQ, the company that manufactures the PIT tags examined in this study. The testing was conducted independently and blind by NOAA and PSMFC, ensuring no influence from Voda IQ in the research process. The results are published to share rigorous testing methodologies and to illustrate a product that passed these independent evaluations. While there is a financial interest in the publication of positive results, the author affirms that the study was conducted with full scientific rigor and independence.

Received: 1 October 2024 Accepted: 5 December 2024
Published online: 20 December 2024

References

1. Prentice EF, Park DL. A study to determine the biological feasibility of a new fish tagging system. Annual report of research (1983–84). Bonneville Power Administration, Agreement DE-AI79-83BP11982, Project 83–19.
2. McCutcheon CS, Giorgi AE. An assessment of freeze-brand and PIT-tag recovery data for juvenile salmonids at McNary Dam, 1988. Annual report of research. Bonneville Power Administration, Project 87-130.
3. Prentice EF, Flagg TA, McCutcheon CS, Brastow DF. PIT-tag monitoring systems for hydroelectric dams and fish hatcheries. Am Fish Soc Symp. 1990;7:323–34.
4. Achord S, Matthews GM, Johnson OW, Marsh DM. Use of passive integrated transponder (PIT) tags to monitor migration timing of Snake river Chinook salmon smolts. North Am J Fish Manage. 1996;16(2):302–13.
5. Giorgi AE, Hillman TW, Stevenson JR, Hays SG, Peven CM. Factors that influence the downstream migration rates of juvenile salmon and steelhead through the hydroelectric system in the mid-Columbia River Basin. North Am J Fish Manage. 1997;17(2):268–82.
6. Marsh DM, Matthews GM, Achord S, Ruehle TE, Sandford BP. Diversion of salmonid smolts tagged with passive integrated transponders from an untagged population passing through a juvenile collection system. North Am J Fish Manage. 1999;19(4):1142–6.
7. Pacific States Marine Fisheries Commission. 2024. PTAGIS (PIT Tag Information System), advanced query tool. https://www.ptagis.org/.
8. Skalski JR, Smith SG, Iwamoto RN, Williams JG, Hoffmann A. Use of passive integrated transponder tags to estimate survival of migrant juvenile salmonids in the Snake and Columbia rivers. Can J Fish Aquat Sci. 1998;55:1484–93.
9. Matter AL, Sandford BP. A comparison of migration rates of radio- and PIT-tagged adult Snake river Chinook salmon through the Columbia River hydropower system. North Am J Fish Manage. 2003;23(3):967–73.
10. National Marine Fisheries Service (NMFS). Threatened status for Snake River spring/summer chinook salmon, threatened status for Snake River fall chinook salmon. Fed Reg. 1992; 57: 14653–63.
11. Muir WD, Smith SG, Williams JG, Hockersmith EE, Skalski JR. Survival estimates for migrant yearling Chinook salmon and steelhead tagged with passive integrated transponders in the Lower Snake and Lower Columbia rivers, 1993–1998. North Am J Fish Manage. 2001;21(2):269–82.
12. Perez-Comas JA, Skalski JR. Design and analysis of salmonid tagging studies in the Columbia Basin, Volume V: analysis of in-river growth for PIT-tagged spring Chinook smolt. Technical report, University of Washington, Seattle, Washington.
13. Widener DL, Faulkner JR, Smith SG, Marsh TM. Survival estimates for the passage of spring-migrating Juvenile Salmonids through snake and Columbia river dams and reservoirs, 2021; https://repository.library.noaa.gov/view/noaa/49078. Accessed 9 Sep 2024.
14. Downing S. Procedures for evaluating candidate PIT tags: description of tests that shall be conducted to determine if the candidate tags can be successfully adapted to the PIT tag systems installed throughout the Columbia River Basin. 2011. Technical report prepared for Bonneville Power Administration and PIT Tag Steering Committee.
15. Axel G, Brooks G, Brower A, Warf D. Comprehensive PIT tag evaluation procedure: outline of tests that shall be conducted to determine if candidate tags can be acceptably detected by the PIT-tag systems installed throughout the Columbia River Basin. Revision 1, March 2017. Technical report prepared for the Bonneville Power Administration, Project 200100300.
16. Axel G, Brooks G, Brower A, Warf D. Comprehensive PIT tag evaluation procedure: outline of tests that shall be conducted to determine if candidate tags can be acceptably detected by the PIT-tag systems installed

throughout the Columbia River Basin. Revision 2, April 2023. Technical report prepared for the Bonneville Power Administration, Project 200100300.
17. Fuller SA, Henne JP, Seals J, Mudrak VA. Performance of commercially available passive integrated transponder (PIT) tag systems used for fish identification and interjurisdictional fisheries management. N American J Fish Manag. 2008;28(2):386–93.
18. Gibbons JW, Andrews KM. PIT tagging: simple technology at its best. Bioscience. 2004;54:447–54.
19. Collis K, Roby DD, Craig DP, Ryan BA, Ledgerwood RD. Colonial waterbird predation on juvenile salmonids tagged with passive integrated transponders in the Columbia river estuary: vulnerability of different Salmonid species, stocks, and rearing types. Trans Am Fish Soc. 2001;130(3):385–96.
20. Bi R, Zhou C, Jiao Y. Detection of fish movement patterns across management unit boundaries using age-structured Bayesian hierarchical models with tag-recovery data. PLoS ONE. 2020;15(12):e0243423.
21. Brown RS, Harnish RA, Carter KM, Boyd JW, Deters KA, Eppard MB. An evaluation of the maximum tag burden for implantation of acoustic transmitters in juvenile Chinook salmon. North Am J Fish Manage. 2010;30(2):499–505.
22. Sherker ZT, Martin C, Zubick P, Straker D, Bass AL, Hinch SG. Novel application of two- and four-lobed noise-canceling passive integrated transponder antennas for tracking fish in areas of high ambient electromagnetic interference. J Fish Biol. 2024;105:1–5.
23. Trumbo BA, Ahmann ML, Renholds JF, Brown RS, Colotelo AH, Deng ZD. Improving hydroturbine pressures to enhance salmon passage survival and recovery. Rev Fish Biol Fish. 2014;24(3):955–65.
24. Murauskas JG, Fryer JK, Nordlund B, Miller JL. Trapping effects and fisheries research: a case study of Sockeye Salmon in the Wenatchee river. USA Fisheries. 2014;39(9):408–14.
25. Weitkamp LA, Claiborne AM, Rice CA, Fresh KL, Rust MB. Estuary fish data: juvenile salmon in migratory corridors of the lower Columbia River estuary. 2024. https://www.fisheries.noaa.gov/inport/item/30834.
26. Roussel JM, Haro A, Cunjak RA. Field test of a new method for tracking small fishes in shallow rivers using passive integrated transponder (PIT) technology. Can J Fish Aquat Sci. 2000;57:1326–33.
27. Cooke SJ, Midwood JD, Thiem JD, Klimley P, Lucas MC, Thorstad EB. Tracking animals in freshwater with electronic tags: past, present, and future. Anim Biotelemetry. 2013;1(1):1–19.
28. Schooley RL, Sharpe PB, Doak DF. Passive integrated transponders for marking free-ranging Townsend's ground squirrels. J Mammal. 1993;74(2):480–4.
29. Cucherousset J, Britton JR, Beaumont WRC, Nyqvist M, Sievers K, Gozlan RE. Determining the effects of species, environmental conditions, and tracking method on the detection efficiency of portable PIT telemetry. J Fish Biol. 2010;76(4):1039–45.
30. Jepsen N, Thorstad EB, Havn T, Lucas MC. The use of external electronic tags on fish: an evaluation of tag retention and tagging effects. Anim Biotelemetry. 2015;3(1):1–23.
31. Vollset KW, Lennox RJ, Thorstad EB, Auer S, Bär K, Larsen MH, Mahlum S, Näslund J, Stryhn H, Dohoo I. Systematic review and meta-analysis of PIT tagging effects on mortality and growth of juvenile salmonids. Rev Fish Biol Fish. 2020;30:553–68.
32. Závorka L, Aymes JC, Guiheneuf A, Mercier O, Huger F, Bejean M, et al. Effect of 12 mm PIT tags on the survival, growth, and ecologically significant behaviours of juvenile critically endangered endemic *Zingel asper*. Knowledge and management of aquatic ecosystems. 2024 Jan 1 [cited 2024 Nov 25]; https://www.scienceopen.com/document?vid=e19e0a0b-2856-4256-8b80-74be24ac06a3
33. Ousterhout BH, Semlitsch RD. Measuring terrestrial movement behavior using passive integrated transponder (PIT) tags: effects of tag size on detection, movement, survival, and growth. Behav Ecol Sociobiol. 2014;68(2):343–50.
34. Lennox RJ, Stöger E, Dahlmo LS, Helle T, Wiers T, Hanssen EM, et al. Effects of tag type and surgery on migration of Atlantic salmon (Salmo salar) smolts. J Fish Biol. 2022;101(3):515–21.
35. Lamb JJ, Sandford BP, Smith SG, Axel GA. Comparing standard- and reduced-size passive integrated transponder (PIT) tags for monitoring juvenile wild spring Chinook Salmon. Trans Am Fish Soc. 2024;153(4):505–21.
36. Tiffan KF, Perry RW, Connor WP, Mullins FL, Rabe CD, Nelson DD. Survival, growth, and tag retention in age-0 Chinook Salmon implanted with 8-, 9-, and 12-mm PIT Tags. North Am J Fish Manag. 2015;35(4):845–52.
37. Tiffan KF, Rhodes TN, Bickford BK, Lebeda DD, Connor WP, Mullins FL. Performance of subyearling fall Chinook salmon tagged with 8-, 9-, and 12-mm passive integrated transponder tags in the snake river. North Am J Fish Manag. 2021;41(1):176–86.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.