Aquat. Living Resour. 20, 197-203 (2007)

DOI: 10.1051/alr:2007032
www.alr-journal.org

Aquatic Living Resources

Note

A new microcontrolled fish tag for accurately estimating life span and survey life of spawning salmon

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Received 18 January 2007; Accepted 3 May 2007

Abstract – A microcontrolled fish tag which records post-tagging life span, was developed and tested as a prototype. The method of making the tag and the results of tank test trials on chinook salmon (*Oncorhynchus tshawytscha)* and field trials on chum salmon (*Oncorhynchus keta*) are presented. This tag was specifically designed to measure survey life (SL) but may have other applications. Survey life is an essential component for area-under-the-curve (AUC) estimation of Pacific salmon (*Oncorhynchus* spp.) spawning escapements. Accurate escapement estimates are critically important for salmon fisheries management and science. However, AUC spawner estimates must often employ average SL values from historic rather than year-specific studies because direct estimates of SL can require extensive and costly tag-recapture programs. Using assumed SL values can introduce serious bias in population estimates, therefore alternative methods of determining annual SL are important. In this study, the new tag estimated SL by measuring the elapsed time from tagging until the fish came to rest permanently on its lateral or dorsal surface. Details on how to construct the tag are provided so that researchers will be able to make their own.

Key words: Survey life / Salmon / Escapement / Tag / Life span / Stream residency

1 Introduction

Estimating life span can be important in the assessment and management of fish populations. In the case of Pacific salmon, life span, or more specifically, survey life (*SL*) is sometimes an essential component in the estimation of spawner populations (S) and therefore can play a central role in salmon management (Hilborn and Walters 1992). When using area-under-the-curve (*AUC*) estimates of escapement (English et al. 1992) *SL* is defined as the average number of days a live spawner resides in the area surveyed for the *AUC* estimate as in the relationship:

$$\hat{S} = AUC/SL \quad [1]$$

with $\hat{S}$: number of spawners, *AUC*: area under the curve in spawner-days, *SL*: survey life in days.

However, because determining *SL* is time consuming and expensive, annual *AUC* spawner surveys often rely on a constant *SL* derived from past years or other studies. Using a constant introduces serious bias because *SL* varies within each season, between years and between streams for each species (Perrin and Irvine 1990; Bue et al. 1998).

Past survey life studies for salmon have been conducted in several ways. Shardlow (2004) used time lapsed video while Johnston et al. (1987) and Parken et al. (1993) used *AUC* divided by total escapement to estimate *SL*. However, most past studies used tag-recovery methods, where tags were applied downstream of the survey area and later recovered on carcasses (Perrin and Irvine 1990). The average number of days between the application and recovery of tags was taken as the *SL* estimate. Other techniques using tags involve the development of a tag depletion curve from the number of tags recovered on dead fish plotted against time (Bocking et al. 1988). In both of these approaches and in other methods of estimating *SL*, extensive tag-recovery programs involving daily stream surveys were required to obtain reliable estimates of *SL* (Fukushima and Smoker 1996; Lady and Skalski 1998; Manske and Schwarz 2000; Korman et al. 2002; Parken et al. 2003). Moreover, one source of uncontrolled error in *SL* estimates based on tag and recovery methods is the unknown period of time between the death and recovery of the tagged spawner. Conventional tag studies are unable to determine

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Article published by EDP Sciences and available at http://www.alr-journal.org or http://dx.doi.org/10.1051/alr:2007032

this time period because the exact time of death is unknown. Biotelemetry methods using radio-tags, which do not need to rely on daily carcass recoveries, have been used to measure stream life (Koski et al. 1996). The radio-tag signals, recorded remotely, were used to fix the position of the tagged fish. The duration of a constant geographic position of the tag on the spawning ground was taken as the *SL* for chinook salmon *Oncorhynchus tshawytscha*. However, it was not always possible to determine if a stationary signal was from a live or a dead spawner. A review of biotelemetry methods in general (Cooke et al. 2004) found no existing technology that could easily be adapted for determining survey life. Methods involving archival data loggers and accelerometers have been used to record swimming activity in whales (Nowacek et al. 2001) and flatfish (Kawabe et al. 2003) and tuna (Block et al. 2005) for example. However, these devices could not easily be adapted for use on populations of spawning salmon where tens to hundreds of tags are needed because the vast majority of the tags in survey life studies would remain un-recovered.

In this current study, microcontrolled tags using a simple tilt switch and a timer system were developed and tested. The new tag records the elapsed time between application of the tags and the death of the fish, to estimate *SL*. Because the exact time of death is stored electronically, the tagged carcasses do not need to be recovered daily, thus reducing survey costs. The methods of construction of the tag are outlined to guide researchers in having their own tags made.

2 Materials and methods

2.1 Tag construction

The microcontrolled tag records the elapsed time from the time of tag application to the time the fish dies. This duration is determined by sensing the angle or attitude of the fish. An upright position, or 0°, indicates the fish is alive. A tilt beyond a specified angle laterally for more than a specified amount of time, indicates the fish is dead. The angle and required time duration, or lag time, of the tilt can be varied. These parameters were set to assure that the fish is dead by requiring a set maximum tilt angle to last for the specified lag time before the timer stops. Below is a list of expected durations and angles about a vertical axis assumed in this study for various behavioural events in spawning salmon.

Behavioural event	Expected duration	Angles assumed
Swimming	continuous	315° to 45°
Fighting	< 20 s	0° to 360°
Jumping	< 5 s	0° to 360°
Digging	< 10 s	90° to 270°
Dead	> 3 min	45° to 315°

Thus, any spawner in the 315° to 45° arc would be considered alive, while a spawner continuously in the 45° to 315° arc for more than 3 min was assumed to be dead. All other behaviours, even though they can occur at the angles assumed by dead fish, will fall far short of the lag time of 3 min required to stop the timer.

The tag is comprised of four basic components: tilt switches, battery, timer system, and platform (Fig. 1).

2.1.1 Tilt sensor switch and battery

Numerous tilt sensor technologies are commercially available. In this application, a non-mercury, environmentally benign, mechanical switch that detects tilt angles of 90° or greater was used. This type of switch contains a metal ball encased in a closed metal tube. When the ball falls to one end of the tube a contact is made. If that contact lasts longer than the lag time, the fish was determined to be dead. Two sizes were used; a small size measuring 3.5 mm × 6 mm and a large size measuring 5 mm × 10.5 mm. Each tag contained two tilt switches, one each for a right or a left rotation of the fish. The tag was powered from coin-type lithium manganese dioxide cell (CR) batteries that can range from 220 mAh (CR2032) to 1000 mAh (CR2477). Battery life is expected to be several years allowing for re-use of recovered tags.

2.1.2 Timer system

The timer system consists of a microcontroller, 3-wire serial communication port, a reed switch and a light emitting diode (LED). The timer system is controlled by a 20-pin 16-bit reduced instruction set computer (RISC) microcontroller from Texas Instruments. This device was chosen due to its low power consumption, small size, available peripherals, and low cost. The 6 mm × 6 mm footprint and multiple low-power modes make this microcontroller capable of long deployments, and standby currents as low as 0.1 μA allow the device to be encased in epoxy and stored with the battery installed for months before use. The device has the following on-board hardware peripherals required for this application: 4 kb of program space, 256-bit of data space, a watchdog timer, a general-purpose timer, an interrupt controller, and two Input/Output ports.

Thin 30-gauge wires protrude from the tags housing to provide a 3-wire serial communication link consisting of a ground, transmit, and receive signal. Stripping the ends allowed for a mechanical connection to each wire. Removing and sealing the exposed ends of the wires prepared the tags for redeployment. The 30-gauge wire is malleable and requires only a few inches for multiple deployments, reducing the possible stress to the fish caused by these protrusions.

A magnetic sensor, called a reed switch, monitored for the presence of a magnetic field. The tag's controls such as "deploy" and "upload data" were activated by moving a magnet close to the switch. Both the tilt switches and reed switch are inherently digital and do not require analog-to-digital conversion. These components do not consume power when disabled.

There were two major software components for the system: an inexpensive toolchain, and an easily comprehensible codebase. MSPGCC, a port of the GNU C compiler is available free of charge from Texas Instruments. In addition to the GNU Public Licence (GPL) compiler, the microcontroller code can be debugged in-situ using free debug tools. The GNU Project Debugger (GDB), combined with front-end integrated

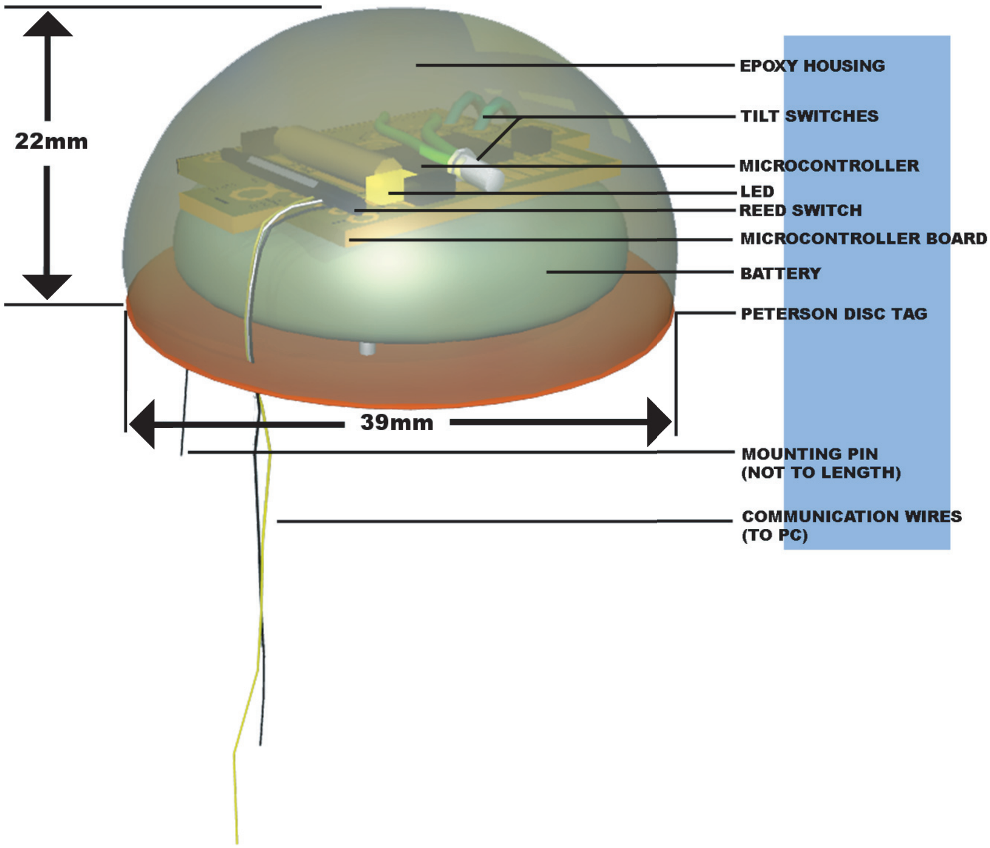

Fig. 1. Diagrammatic view of the microcontrolled tag and its components. (illustration credit: Matt Wooding, mwooding@gmail.com).

drive electronics (IDEs) such as the data display debugger (DDD) and Eclipse, creates a fully functional, free toolchain. Writing code in the C programming language instead of in assembly language increases the readability of the program. The C code is fully documented using inline javadoc style comments that are extractable using the GPL tool Doxygen. This tool allows access to information about constants, variables, structures, and file dependencies in hyperlinked HTML documentation. The codebase is simple, maintainable, and modifiable because of an adherence to object-oriented design and proper software engineering practices.

The tag operates in 4 different modes: command mode, deployment mode, sleep mode, and ultra-low power mode. In command mode, a PC configures and retrieves data from the tag via a 3-wire serial connection. Deployment mode monitors the fish's attitude and records elapsed time. Sleep mode conserves battery power during normal operation. Between received requests in command mode and between orientation checks in deployment mode, the device sleeps; the clocks and interrupt timer still function, but the attitude of the fish cannot be monitored. In this study the attitude was sampled once every 8 seconds, however this period is selectable in firmware. Power consumption is a maximum of 300 μA when the tag is activated, although the time spent actively running is only a few milliseconds per 8-second sample period. Consumption of the microcontroller is a maximum of 2.7 μA in Sleep mode. Ultra-low power, or off mode, is used when storing the tag and when pending retrieval after a fish dies. The current consumption of the microcontroller in this mode is a maximum of 0.5 μA. The newly released MSP430F2xx series microcontroller are a drop-in replacement with a one-half reduction in the active mode current, which will allow the construction of even longer lasting tags.

When not in the field, communication with the fish tag is conducted through a standard serial port using Hyperterminal. Communication is set to 2400 baud so that slower, more efficient microcontroller clock speeds can be used. The implementation of a reduced functionality, low cost alternative was necessary for field applications where the use of a computer or Personal Digital Assistant (PDA) is problematic. A reed switch allows the deployment of a tag using only a magnet. Bringing a magnet close to the tag wakes the tag up from the ultra-low power state. The tag provides confirmation of the deployment request by blinking a LED. When in deployment mode, the tag can be checked at any time for correct operation. Each time the magnet is brought close, the tag sends a series of LED pulses.

In command mode, the tag can interpret eight instructions: Help, Calibrate, Identification (ID) Set, Lag time set, Store tag, Deploy, Upload data, and Reset data. The Help command displays a list of available commands and a short description of each. If any unrecognised character is received, the operator is prompted to type H for assistance. Calibration mode continually refreshes the onboard LED with the current tilt switch state as on or off to allow correct positioning of the tilt switch sensors. The ID setting permits the assignment of a unique electronic serial number to each tag. Lag time is the elapsed

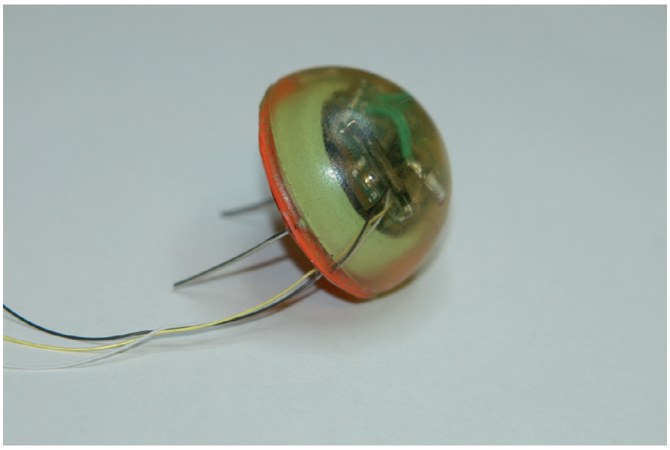

Fig. 2. Photograph of an assembled tag mounted on a Peterson disk and embedded in a hemispherical epoxy housing.

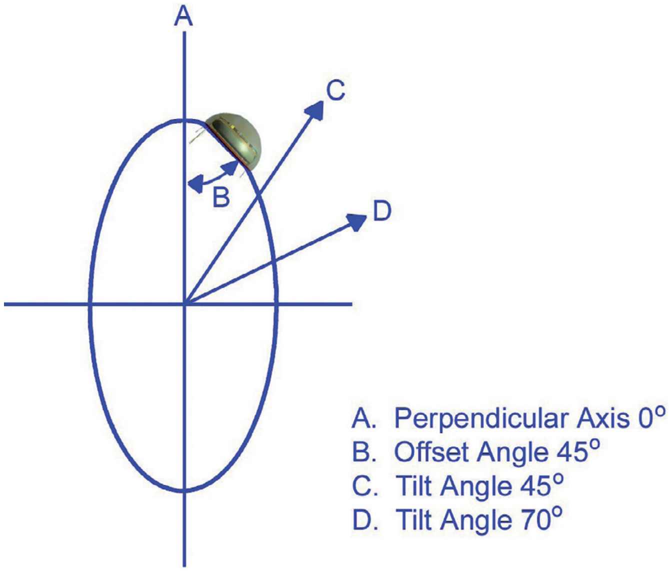

Fig. 3. Diagrammatic view of offset and tilt angles used when applying the tag to the dorsal surface of spawning chum salmon.

time the tilt sensors must be tilted beyond a predetermined angle before the timer is stopped. A lag time is required because the tags are susceptible to false positives. A single tilt event may not be indicative of a dead fish but perhaps only of a temporary lateral attitude taken, for instance, during the digging of a redd or when jumping over falls. The Deploy command immediately places the tag in deployment mode with the timer running. The Store tag command places the tag in an ultra-low power mode ready for field deployment with a magnet. Upload, requests a serial transmission of the time dead, tag ID, and elapsed time to the PC. The Reset command resets the clock to zero ready for a new deployment. Though the tag is reusable, the number of deployments is limited by the life of the battery.

2.1.3 Platform

The tilt switch, timer system and battery were mounted on a 32 mm Peterson disk tag (Fig. 2). The assembly was altered so that two mounting pins were placed at the sides of the disk instead of the usual placement of a single central pin. Using two pins helped to secure the tag and prevented rotation that would have interfered with the accurate operation of the tilt switches. Once mounted on the disk, the assembly was encased in a two-part epoxy encapsulating compound. The non-conductive and waterproof compound was moulded into a half sphere using a ping pong ball mould. The hemispherical shape was adopted to facilitate hydro-dynamic efficiency and thus reduce drag while the fish is swimming.

The tags when applied to the fish, were offset from a perpendicular position by the dorsal surface of the fish (Fig. 3). This angle, called the offset angle, needed to be accounted for when mounting the tilt switches into the tag housing. A predetermined offset angle of 45° was adopted as the standard setting although the actual angle after placement on a fish varies with species and sex. Once the offset angle was set, the tilt switches were aligned such that a tilt angle of either 45° or 70° (Figs. 3c and d) triggered a contact that stopped the timer. An assembled tag weighs approximately 25 g.

2.2 Tag Testing

2.2.1 Bench test trials

Fourteen tags were secured to a New Brunswick Scientific shaker. The tags were mounted at a 0° and 30° offset angle and vibrated at 250 rpm in a 40 cm circular pattern for 24 h. The elapsed time as indicated by the tag's timer was recorded. In addition, twenty tags were randomly rotated for 60 s while being shaken through 360° of rotation.

2.2.2 Holding tank trials

Six chinook salmon (*O. tshawytscha)* were held in oval hatchery stock tanks measuring 2.1 m by 2.7 m with a volume of 4000 L. Three salmon were anaesthetised with MS 222, tags were then applied taking about a minute each and the timers were activated. Three salmon remained untagged as controls. Swimming behaviour of the tagged and untagged fish was observed. After two to three days the tagged fish were netted, placed in a small tub, anaesthetised and allowed to assume the side-down to belly-up positions naturally taken by dead fish. The elapsed time between tag activation and simulated death was recorded at this time. After waiting for the 5 min ±8 s lag time to pass, the tags were interrogated through the 3-wire serial connection to a PC. The elapsed time on the tag was recorded without removing the tag from the fish. Following interrogation of the tags, the salmon were placed in a small holding tub to recover. The timers were restarted with the magnet, and the fish were returned to the main holding tank. This procedure was repeated every few days over a period of 22 days.

2.2.3 Spawning channel trials

In 2005, chum salmon were captured using a dip net at a fence on the Little Qualicum spawning channel located on

Fig. 4. Photograph of the a chum salmon with tag applied prior to release into the Little Qualicum spawning channel.

Table 1. Results of vibration tests on tags set at various angles while recording elapsed time as determined by the tag's timer.

Angle	Trial Duration	Number of Trials	Average([a]) Tag Recorded Time
0°	24 h	14	24.05 h, 0.03 h SD (*)
30°	24 h	14	24.08 h, 0.05 h SD
0° to 360°	60 s	20	60.8 s, 4.0 s SD

a. deviation from trial duration resulted from inherent accuracy of +/- 8 seconds of the timer plus handling time while downloading tag data. (*) 1.8 min Standard Deviation.

Vancouver Island, British Columbia. The chum were placed on a tagging board equipped with a holding cradle and fitted with individually colour coded tags without using anaesthetic. Once tagged, the fish were placed in an oxygenated holding tank and trucked to a 1 km section of the channel which was blocked off for this study. The first set of tags were released on November 2 (Fig. 4) followed by releases on November 8, 10 and 15. A total of 27 tagged chum were released. Daily foot surveys of the spawning channel noted the colour codes of tags on live fish. All dead fish were removed and the tags were recovered and interrogated for elapsed time. In 2004, 9 tags were released between November 9 and 12.

3 Results

3.1 Bench test trials

Table 1 shows the results of bench testing. All of the tags tested recorded the elapsed within acceptable limits of accuracy during the bench test trials. No tags recorded deaths prematurely.

3.2 Holding tank trials

The results of the holding tank trials are shown in Table 2. Tag numbers 1 and 2 showed that the timers were able to repeatedly record the elapsed time between activation and simulated death to within ±0.1 h. Tag number 3 worked well on the first trial but developed a pin hole in the epoxy housing on day 4 which allowed water to corrode the tilt switch. Tag 1 was kept in place for 22.8 d and for tag 2 for 20.6. No difference in swimming behaviour was observed between the tagged and untagged fish and all fish were alive at the end of the trial period.

Table 2. Comparison of elapsed hours versus hours recorded by the tag on chinook salmon in holding tank experiments at the Pacific Biological Station 2005.

Tag No.	Trial No.	Elapsed Hours (a)	Recorded Hours (b)	Recorded Days	Difference (a – b)
1	1	53.8	53.9	2.24	–0.1
	2	90.4	90.4	3.77	0
	3	166.4	166.4	6.93	0
	4	25.6	25.6	1.07	0
	5	50.1	50.2	2.09	0
	6	51.2	51.2	2.13	0
	7	44.9	45.0	1.87	–0.1
	8	66.4	66.5	2.77	–0.1
	Total			(22.85)	
2	1	90.3	90.4	3.76	–0.1
	2	166.7	166.8	6.95	0
	3	25.2	25.3	1.05	–0.1
	4	51.0	51.0	2.12	0
	5	51.0	51.0	2.12	0
	6	44.8	44.9	1.86	–0.1
	7	66.8	66.9	2.79	0
	Total			(20.63)	
3	1	90.6	90.8	3.78	–0.1

3.3 Spawning channel trials

Of the 27 tagged chum released in 2005, 5 tags erroneously recorded deaths while still in the tank-truck. This was attributed to the fish unnaturally orienting in vertical head-down position caused by overcrowding in the tank and a rheotactic response to the circulation pump. One tag suffered from a dead battery and 6 tags went missing and were never recovered leaving a total of 15 recovered tags. In 2004, a total of 9 tags were released, of these 2 suffered from dead batteries, 1 delaminated, and 1 had a faulty tilt switch angle leaving 5 operative tags recovered.

Foot surveys of the spawning channel were conducted once daily to recover dead spawners. Only 8 of the 16 tags recorded the time of death as less than 1 day before the time of carcass recovery (Table 3). The remaining tags recorded the time of death at between 1 d and 3.9 d prior to recovery. Table 3 shows that the elapsed time recorded on the tag never exceeded the time between release and dead recovery. However, in three cases the tags were known to record deaths prematurely because the fish was observed alive after the time of death recorded on the tag. On average it took 1.6 d to detect and recover a fish once it had died (Table 3).

Table 3. Elapsed time between tag application and dead recovery compared to time recorded on tags for chum salmon released in the Little Qualicum River spawning channel in 2004 and 2005.

Year	Tag no.	Elapsed hours to dead recovery	Elapsed hours on tag	Last seen alive (h)	Days to dead recovery	Recorded days tag	Days dead but unrecovered
2005	1	170	133.18	118	7.1	5.5	1.5
	2	147	4.17[a]	147	NA	NA	NA
	3	267	174.27	142	11.1	7.3	3.9
	4	195	168.06	142	8.1	7.0	1.1
	5	120	103.35	0	5.0	4.3	0.7
	6	118	61.80	46	4.9	2.6	2.3
	7	166	145.73	142	6.9	6.1	0.8
	8	192	130.46	0	8.0	5.4	2.6
	9	166	164.35	46	6.9	6.8	0.1
	10	120	26.52[a]	120	NA	NA	NA
	11	190	166.11	0	7.9	6.9	1.0
	12	214	189.48	0	8.9	7.9	1.0
	13	190	147.86	71	7.9	6.2	1.8
	14	190	158.49	0	7.9	6.6	1.3
	15	190	132.84	0	7.9	5.5	2.4
				Average	**7.6**	**6.0**	**1.6**
2004							
	1	96	79.42	46	4.0	3.3	0.7
	2	128	115.69	94	5.3	4.8	0.5
	3	129	125.70	70	5.4	5.2	0.1
	4	120	33.65[a]	96	5.0	1.4	NA
	5[b]	70	63.98	46	2.9	2.7	NA

a - Tags "died" prematurely.
b - Fish held in holding pond.

4 Discussion

4.1 Bench tests and holding tank trials

The bench tests showed the tags could sustain vigorous vibrations and record elapsed time accurately. Trials from the holding tank show that the tag placed on live fish was able to accurately record within 0.1 h the duration between tag activation and simulated death. No fish died during the trial period despite being repeatedly anaesthetised during the course of the trials. This result indicates that tag induced mortality will be low over the life span of spawning salmon. The failure of tag No. 3 was a result of a faulty placement while embedding the tag in the epoxy mould during construction. This type of failure is avoidable with proper construction technique.

4.2 Spawning channel trials

Results from the bench tests and tank trials showed the tags were capable of accurately recording the time of death to within 0.1 h (i.e. 6 min). Therefore, it was assumed that the time of death was accurately recorded in the spawning channel and these dead fish went undetected during the daily foot survey. Some tagged carcasses took as long as 3.9 days to detect. This was not unexpected given that even in good conditions the ability to detect and recover carcasses is rarely over 50% (Shardlow et al. 1987; Shardlow et al. 1985). On average dead fish went undetected for 1.6 d. The Little Qualicum spawning channel represents near ideal conditions for seeing and recovering carcasses. Spawning areas in natural streams would make detecting tagged carcasses more difficult than in a spawning channel. Therefore, the length of time which tagged fish are dead but undetected in natural streams is expected to be greater than the 1.6 d (t test, $p < 0.05$) found in this study.

The causes of the tags recording deaths prematurely can be threefold. First, the tilt angle may have been insufficient. In two cases, i.e. tag number 2 in 2005 and tag number 4 in 2004, the tilt angle and the offset angle were both set at 45°. In some spawners, particularly with males, the actual offset angle after application was less than 45° thus reducing the tilt angle required to trigger the timer. The lesser the tilt angle, the greater the likelihood of the tag recording a death prematurely. However, 2005 series tags numbered 10 to 15 were set at the 70° tilt angle, yet tag number 10 still recorded death prematurely. The second cause for the premature recording of death is insufficient lag time. Tag 10, along with 5 others from the 2005 study had a lag time set of 1.5 min instead of 3 min. A third possibility for premature deaths could have been failure of the tag's components. For example, the behaviour of fish in the holding tanks did not include fighting, jumping, or redd digging. These behaviours could potentially have taxed the tags ability to accurately record time of death. The expected duration and angle associated with behaviour of naturally spawning salmon are given in the materials and methods section. Bench testing, which subjected the tags to rigorous vibrations at various angles, was conducted to simulate conditions expected during spawning. Vibrations at the intensities tested simulated movements that would occur during fighting, redd digging, or burst swimming behaviours. These behaviours have durations typically lasting for seconds or at most minutes. The duration of the bench trials were, therefore, in excess of those expected from spawners in natural field conditions. The results indicate that failure of the tag's components was unlikely. No tags recorded deaths while being subjected to the tests shown in Table 1.

Future improvements to the tag could include several refinements. First, the offset angle could be preset such that offset is matched to species or sex of spawners. Second the lag time could be set for longer duration than the 3 min used in these field trials. A minimum lag time of 5 min is suggested for future applications. Thirdly, using one tilt switch instead of two will reduce the complexity of the tag and may be sufficient to accurately record the time of death. Using one tilt switch will require the carcass to assume a tilt angle of greater than 90° to record a death. Our sample observations at the Little Qualicum spawning channel found that almost all carcasses (7996 out of 8000) assumed an angle of greater than 90° and almost all of these were very close to the 180° or belly-up position. This ratio, however, will likely be lower in natural systems and will vary between spawning streams. Lastly, tags should use the largest capacity battery within size and budget constraints. Care must be taken to ensure that the battery has the required capacity for an application because all collected data will be lost if the battery dies before the data can be collected.

In closing, although the tag was designed for measuring survey life in spawning salmon, it could have broader applications. The tag is capable of measuring the post tagging life span of any fish that dies belly-up provided the fish are large enough to tag and that the tags can be recovered. There may also be applications for toxicity tests on fish or for studies beyond fisheries. For example, this tag or a modification of it, fitted to an animal collar could record intervals spent in horizontal versus vertical attitudes and therefore determine activities such as rest periods, sleep, or hibernation. Knowing this may be of use in studies of animal behaviour or energetics. This tag is currently not commercially available, but we hope to have provided sufficient details so that this tag or versions of it can be constructed by others.

Acknowledgements. Special acknowledgement is given in memory of Michal Urednicek who generously shared his ideas on microcontrollers during the conceptual stages of this study.

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