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REVIEW

The Use of Electronic Tags in Fish Research – An Overview of Fish Telemetry Methods

Eva B. Thorstad[1,2,*], Audun H. Rikardsen[2], Ahmet Alp[3], Finn Økland[1]

[1] Norwegian Institute for nature Research, P.O. Box 5685 Sluppen, NO-7485 Trondheim, Norway.
[2] University of Tromsø, Faculty of Biosciences, Fisheries and Economics, NO-9037 Tromsø.
[3] University of Kahramanmaraş Sütçü Imam, Department of Fisheries, Faculty of Agriculture, Kahramanmaraş, Turkey.

* Corresponding Author: Tel.: +47.91 661130 ; Fax: +47.91 661130;
E-mail: eva.thorstad@nina.no

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Abstract

An overview of electronic tags that can be used in fish research is given, including radio and acoustic transmitters, data storage tags (DST, also termed archival tags), pop-up satellite archival tags (PSAT) and passive integrated transponder tags (PIT-tag). Fish telemetry is a term used to describe the application of these methods. Typically, an electronic tag is attached to a free-swimming fish, and information on position, movements and/or measurements of environmental and physiological parameters can be recorded wirelessly by use of a mobile receiver or stationary loggers. For most methods, the fish need not to be recaptured to achieve data. However, DSTs record and store information on environmental and/or physiological parameters in the tag, and therefore need to be retrieved for downloading data. In the case of PSATs, stored data is transferred to satellites when the tag loosens from the fish and pops up to the surface, and in addition, the pop up position is recorded. The developments of telemetry methods have provided opportunities to reveal previously unknown information on fish behavior, habitat use and migrations in fresh water, estuaries, near-coastal areas and oceans, especially since extensive long-term data can be collected repeatedly from individual fish. Detailed information on fish behaviour and migrations is needed to better understand, protect and manage fishes in freshwater and marine systems. The development of successful management measures depends on knowledge of where fish reside and migrate during the day, season and year. There has been a tremendous increase in the use of electronic tagging methods, especially during the last 10-20 years. In addition to descriptive and ecological studies, the methods have been used to assess effects of for instance hydropower production, other river regulations, migration barriers, protected areas, fishing regulations, catch-and-release angling, hatchery-rearing, fish aggregating devices (FADs), water pollution and aquaculture. The main methods for attaching electronic tags to fish are 1) surgical implantation in the body cavity, 2) external attachment, and 3) gastric insertion via the mouth. Potential negative handling effects are inflammations, infections, tag expulsion, altered behavior, decreased swimming performance, reduced feeding, reduced growth and increased mortality. The catch, handling and tagging procedures should have minimal effects on the fish. If not, an anomalous behaviour caused by the tagging may be recorded instead of the natural behaviour, and the study is a failure from a scientific point of view. Furthermore, optimal anaesthetic and tagging methods are required to meet the ethical standards for use of experimental animals, and to ensure fish survival and welfare.

Keywords: Fish telemetry, electronic tags, tagging, fish migration, methods.

Introduction

Traditional catch methods like gillnetting, trawling, trapping and electrofishing have for centuries provided important information on fish species and stocks related to *e.g.* demography (age, growth, sex), parasites and diet. Data collected by use of these methods can indirectly provide information on behavior and life-history, which is important for a better understanding and management of fish species. These methods will continue to be useful tools in fish biology studies also in the future.

Studies based on tagging and recapture of individual fish with traditional mechanical fish tags such as anchor T-bar tags, dart tags and coded wire tags, can further increase the accuracy in estimates of growth, stock size and migrations. However, the disadvantages with both traditional catch methods and studies based on tagging and recapture of individual fish are that they usually provide only snapshot information, and less accurate information on the continuous long-term fish behavior, dispersal and habitat use. The traditional tag methods depend on recapture of the tagged fish to obtain data on movement behaviour, and the distribution of recaptures will therefore be highly influenced by the distribution and intensity of the fishing effort. No information is provided between the fish is tagged and recaptured, and no information is provided for the fish not being recaptured. Studies using traditional catch and tagging methods often need to be based on a large number of individuals to answer the questions asked, placing a potential extra burden on stocks or species that may be depleted and endangered.

The recent development of animal electronic tracking technology (telemetry) has provided unique tools to reveal novel information on animal behavior both in terrestrial and aquatic habitats, which is knowledge that few decades ago was impossible to achieve based on traditional methods (Lucas and Baras, 2000; Adams *et al.*, 2012). With use of electronic tracking technology, extensive long-term data on fish movements, physiology and/or environmental parameters can be collected from each individual. This possibility to collect detailed data from individuals also often reduces the number of study animals needed to answer the research and management questions.

Detailed information on fish behaviour and migrations are needed to be better able to understand, protect and manage fishes in freshwater and marine systems. The development of successful mitigation and protection measures depends on knowledge of where fish reside and migrate during the day, season and year: When and where are they available to fisheries? Will they reside within the boundaries of planned or established protected areas during key life-history events and during periods of peak fishing activity? When do they perform migrations and have to pass man-made migration barriers? How do environmental and physiological variables influence their habitat use and movements? - And how do these behaviours vary among species, sizes, sexes and life stages? Knowledge on spatiotemporal behaviour of fishes is also a key to understand basic biological and ecological questions.

Use of electronic tags has proven to be a powerful and effective technology for studying movements, migrations and habitat use of individual free swimming fish and other aquatic animals in fresh water, estuaries, near coastal areas and the oceans (Lucas and Baras, 2000; Heupel *et al.*, 2006, Cooke *et al.*, 2013). The methods can also be used to monitor fish behaviour in aquaculture cages, and in experimental ponds and tanks. Electronic tags usually provide repeated information from the same individuals, and for most methods the fish do not need to be recaptured to achieve data. Typically, an electronic tag (Figure 1) is attached to the fish, and information on its position and/or measurements of environmental or physiological parameters are sent wirelessly from the tag to a receiver at some distance away. However, some tags only record and store information, and needs to be retrieved for downloading the data to the computer.

Here, we aim to give an overview of different electronic tags and tagging methods that can be used in fish research. Fish telemetry is a term often used to describe these methods, and first we discuss the definition of fish telemetry. Then we describe the main groups of electronic tags, which are radio transmitters, acoustic transmitters, data storage tags (DST, also termed archival tags), pop-up satellite archival tags (PSAT) and passive integrated transponder tags (PIT-tag). Case studies to illustrate use of these methods are referred to. Finally, different methods to attach tags to fish are described, and potential handling and tagging effects discussed. Similar telemetry methods can be used for other aquatic animals such as mammals, crustaceans and reptiles (Dervo *et al.*, 2010; Türkecan and Yerli, 2011), but the emphasis of this paper is on fishes. This overview is based on a combination of the authors own experiences with fish telemetry studies and other studies published in scientific journals.

Fish Telemetry Defined

Telemetry is derived from *tele*, which means remote, and *metron*, which means measure. Telemetry is a technology that allows data measurements to be made at a distance, and includes widely used technologies such as telephony, radio and computer networks. Fish telemetry in the broadest definition involves all methods used to obtain information on free-ranging fish, such as use of echo sounders, visual observation, animal vocalization, video and electronic tags (Priede, 1988). However, often when the term fish telemetry is used (also termed biotelemetry, or biologging), it refers only to the use of electronic tags such as radio and acoustic transmitters, data storage tags, pop-up satellite archival tags and PIT-tags (see for instance Klimley, 2013). 'Use of electronic tags' would be a more precise description of these methods than fish telemetry or biotelemetry, but the term telemetry to refer to these technologies has become commonly used in the scientific literature.

Main Types of Electronic Tags

Radio Transmitters

A radio transmitter is attached to the fish and can via its antenna transmit radio signals to a radio receiver at a distance of between tens of metres to a few kilometres away (for more details on signal range, see below) (Figure 2). Radio signals propagate both trough water and air, and tagged fish are usually located by using an aerial antenna connected to the receiver. Radio signals propagate omni-directionally in water, but only wave vectors less than 6° from the vertical to the air-water interface emerge into the air and can be detected by an aerial receiving antenna (Kuechle and Kuechle, 2012). Thus, it is this location at the surface, and not the location of the fish, that is the position tracked when using an aerial antenna. It is also possible to for instance use a stripped coaxial cable attached to the receiver as an underwater

Figure 1. Examples of main types of active electronic tags. The standard individual tags may be used for external recognition and information to fishers to increase the return rate of internal electronic tags from recaptured fish. Photo: Audun H. Rikardsen / Finn Økland.

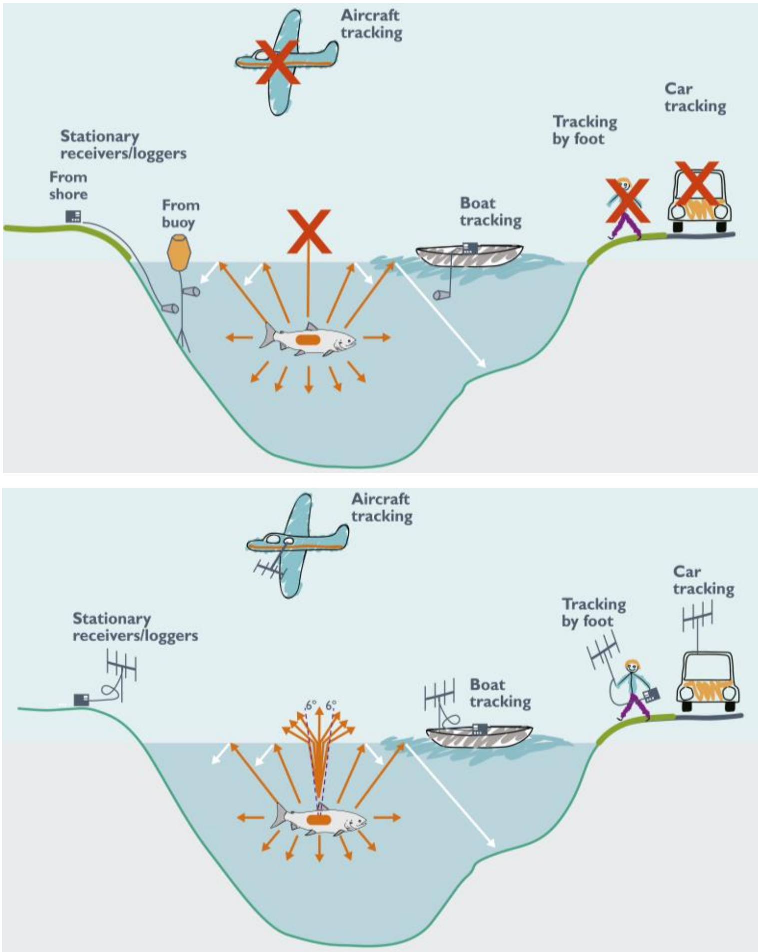

Figure 2. Illustration of the use of acoustic (upper figure) and radio (lower figure) telemetry methods. Fish tagged with radio transmitters can be recorded by using aerial antennas, and can therefore be tracked manually by foot, car, aircraft and boat, or by stationary loggers on the shore. Acoustic transmitters can only be recorded by hydrophones held in water, and tracking by car and aircraft are not feasible.

antenna (Thorstad *et al.*, 2003).

Individual fish can be recognised by using transmitters with a unique combination of radio frequency and pulse rate, or with coded signals (Cooke and Thorstad, 2012; Kuechle and Kuechle, 2012). A digitally coded signal consists of a unique sequence of pulses in time, which cannot be distinguished by the ear, but is recognised by the receiver. Tracking a large number of tagged fish can be more effective by using coded transmitters than transmitters of different frequencies, because many coded transmitters can be tracked on the same frequency (Cooke and Thorstad, 2012). When tracking a large number of fish with transmitters on different frequencies, it takes time to search through all the frequencies.

Attenuation of radio signals due to dissolved salts reduces the signal range to practically zero in brackish and sea water, so the method is only feasible in pure freshwater (Kuechle and Kuechle, 2012). The method is mainly used in rivers, streams and shallow lakes, for fish residing near the surface (Lucas and Baras, 2000).

Radio telemetry is a particularly useful method when studying fish behaviour and migrations in river systems, because tagged fish distributed over a large study area can be tracked for instance by driving a car or boat along the river, or flying over the river by an aircraft, with a portable receiver and aerial antenna. Tagged fish can also be recorded by stationary receivers/loggers. The method is widely used in studies to increase the general knowledge of river migrations of freshwater and diadromous fishes (e.g. Almeida *et al.*, 2002; Hodder *et al.*, 2007; Koehn *et al.*, 2009). It is also widely used to identify migration barriers and evaluate mitigation measures in rivers regulated for hydropower purposes, or impacted by other anthropogenic installations or regulations (e.g. Thorstad *et al.*, 2003; Calles *et al.*, 2010). Catch-and-release angling is increasingly practised by anglers, which involves releasing the live fish back to the waters where they were captured, presumably to survive unharmed. Radio tagging and other telemetry methods have been used in a number of studies to assess mortality rates, behavioural impairments, or to evaluate the effects of displacement on fish after catch-and-release (reviewed by Donaldson *et al.*, 2008).

Acoustic Transmitters

Acoustic transmitters are similarly to radio transmitters attached to the fish and transmit signals to a receiver at a distance of tens of metres to a few kilometres away (Pincock and Johnston, 2012) (Figure 2). The acoustic signals are pressure waves that propagate omni-directionally through water and not air, and the receiver antenna (termed hydrophone) must therefore be submerged in water to record the signals and determine the fish position. Individual fish can be recognised by using transmitters with a unique combination of frequency and pulse rate, or by using coded signals, as described for radio transmitters above. The method can be used both at sea, in estuaries, lakes and rivers, including both manual and automatic tracking. Manual tracking for acoustic transmitters is usually less effective than for radio transmitters since the hydrophone must be submerged in water. In freshwater, when searching for fish over a large study area, the use of radio transmitters may therefore be more feasible, at least for fish that do not reside too deep for radio signals. However, automatic receivers that are robust and relatively easy to deploy have been available on the market for some time, and studies based on recording tagged fish by a large number of automatic receivers are often based on acoustic telemetry, both in fresh water and at sea.

Acoustic telemetry has been used to assess a wide range of research questions, such as movements of hatchery-reared fish after release (Mitamura *et al.*, 2008), schooling behaviour around fish aggregating devices (FADs) (Mitsanuga *et al.*, 2013), homing ability after displacements (Mitamura *et al.*, 2012), evaluation efficiency of marine protected areas (Knip *et al.*, 2012), harvest selection of behavioural traits (Olsen *et al.*, 2012), effects of water pollution (Thorstad *et al.*, 2013b) and movements of escapees from aquaculture fish farms (Chittenden *et al*., 2010; Solem *et al*., 2013). The method has also been used in a range of basic descriptive studies of fish behaviour in sea, estuaries and fresh water (Bendall *et al.,* 2005; Næsje *et al.,* 2007; Wang *et al.,* 2012).

How to Record Fish Tagged with Radio and Acoustic Transmitters

A tagged fish in the study area with a radio or acoustic transmitter can be located either by manual or automatic tracking (Figure 2). For manual, mobile tracking, a portable receiver and antenna are used. Manual tracking of fish with radio transmitters can be performed by different means of transport such as by boat, foot, car, aircraft and horseback (Östergren and Rivinoja, 2008; Koehn *et al.*, 2009; Gilroy *et al.*, 2010). Manual tracking of fish with acoustic transmitters is best performed by boat since the hydrophone needs to be submerged in water. Data can be collected through a standardised tracking programme, with tracking surveys performed at regular time intervals during which all fish in the study area, or part of the study area, are located.

Another manual tracking design is to follow continuously the detailed movement pattern of one individual fish at the time with a tag that transmits a continuous signal and by use of a sound directional hydrophone (Økland *et al.*, 2006). This is a labour-intensive tracking method, mainly suitable for short-term monitoring, as each fish can only be followed as long as people in the tracking team can sustain continuous tracking.

By use of receivers with manual regulation of gain (*i.e.*, sensitivity of the receiver), tagged fish can be located with high accuracy by reducing the sensitivity until signals are recorded only from a small area. With underwater antennas, range of both radio and acoustic receivers can be adjusted until it is less than 1 m. Hence, by reducing the receiver sensitivity, it is possible to locate a tagged fish with an accuracy of less than 1 m. Similarly, by reducing the gain, a radio tagged fish in shallow water, but not in deeper water, can be located with an accuracy of less than 1 m by using an aerial antenna. Locating fish with a high precision is time consuming, and may be impossible if the fish is moving during tracking (for instance if disturbed by the boat or wading of the tracker). Often, an accuracy of tens or hundreds of metres is sufficient for the acquired positions.

Fish with radio or acoustic transmitters can also be monitored by using stationary automatic receivers, also termed data loggers or automatic listening stations (ALS). Stationary loggers store time and ID for fish within the receiver range, and sensor data when using sensor tags (see below). Hence, fish outside the receiver detection range will not be recorded. For radio telemetry systems, automatic listening stations can be placed along the shores with one aerial antenna per station, or with several antennas covering separate ranges for more detailed positioning (Thorstad *et al.*, 2003). Listening stations can for instance be installed in lower parts of rivers to record when diadromous fish are entering and leaving the river, or at migration barriers to record duration of the delay - and when and during which conditions - fish are passing (Thorstad *et al.*, 2003). For acoustic telemetry systems, receivers can be anchored to the bottom, attached to a rope between an anchor on the bottom and buoy at the surface, or attached to other structures. Receivers can for instance be placed at strategic sites, in a grid format, or can be placed in transects so fish passing from one area to another will be recorded (Heupel *et al.*, 2006). In a large Canadian research program, acoustic receiver curtains are deployed in ocean ecosystems in combination with use of oceanographic technologies, aiming to better understand changing ocean dynamics and their impact on animal movements (Cooke *et al.*, 2011b). Within this program, specific projects occur in the Atlantic, Arctic and Pacific, and fishes of different species and other aquatic animals are tracked at each of the study sites (Cooke *et al.*, 2011b).

Data stored by stationary receivers can be downloaded to a computer by cable or bluetooth transfer, or via public telephone systems. Acoustic receivers are also available from manufacturers of telemetry equipment where data can be transferred from a floating surface buoy to shore-based modem (computer or telephone system) as radio signals, or to ARGOS satellites (Dagorn *et al.*, 2007).

Manual tracking and most stationary receiver systems provide data on the horizontal position and movements of fish. However, there are also stationary receiver systems that include recordings of vertical position and hence, the fish position can be determined in three dimensions (3D systems, Baktoft *et al.*, 2012). These systems are suitable for monitoring fish behaviour in small lakes or for instance areas above power station dams, but cannot cover large geographic areas. The data analysis is more resource demanding than from systems recording movements in only two dimensions. Fish position in three dimensions can be estimated based on the arrival times from the transmitter to different receiver locations (real 3D systems), or by combining horisontal location in two dimensions with depth recording by a depth sensor (see below) in the tag. The accuracy of 3D systems will vary with number of hydrophones, location of hydrophones and will also vary within the sampling area. Under ideal conditions, sub-metre accuracy can be obtained.

Size, Lifetime, Pulse Rates and Signal Reception Range of Radio and Acoustic Transmitters

Radio and acoustic transmitters are provided by commercial manufactures in a range of sizes. A major part of the transmitter consists of the battery. The signal strength and the lifetime of transmitters depend on the battery size, and hence the transmitter size. Increased lifetime, power output and pulse rate require increased battery capacity, and smaller transmitters therefore have limited capacity related to these factors compared to larger transmitters.

The commonly used transmitters for fish have battery lifetimes from a few weeks for the smaller transmitters and up to one to several years for the larger transmitters. Acoustic signals are more energy demanding to produce than radio signals. If comparing an acoustic and a radio transmitter with a similar function and battery lifetime, the acoustic transmitter will always be larger. For small fish in shallow fresh water, radio transmitters may therefore be more feasible than acoustic transmitters. With the smallest radio and acoustic transmitters on the market, fish down to 10 cm body length or less may be tagged, but this depends on fish species and body shape (especially whether there is space in the body cavity or not). The smallest transmitters have a short battery lifetime and a limited range.

The lifetime of transmitters can be extended by duty cycles and/or reducing interpulse interval. Duty cycles correspond to a programming mode that makes the transmitter silent (REST) for long periods of time, then it operates normally again, then REST, then ON, *et cetera*. The second way of optimising the energy of the battery is modifying the length of the interpulse interval. Typically, a tag transmits a pulsed signal, consisting in an alternation of beeps and silences. Most standard tags run between 30 and 90 bpm (beeps per minute), which is convenient for locating them with manual tracking, as the operator typically compares the strength of a beep to that of the previous one while searching for the line of the strongest signal with a directional antenna. The energy from the battery is drained mainly during the pulse. Henceforth, one way of making tag life longer is increasing the length of the interpulse interval.

A relatively high pulse rate (*i.e.,* short time between signal transmissions) may be recommended for manual tracking of fish, especially when accurate determination of position is required, or when the chance of detection is small when using stationary receivers (e.g. when the fish is expected to swim fast through the detection range). However, when using stationary receivers and coded signals, slower pulse rates can be used, because several transmitters can have signals on the same frequency and the receiver do not need to search through a large number of frequencies. When a large number of frequencies must be scanned through, the time listening on each frequency is reduced, and this in combination with a slow pulse rate increase the chance that a fish may pass without being recorded. Some producers use a random delay between codes to reduce the chance of code collision between signals.

Detection range of signals from radio and acoustic transmitters depends on a number of factors, in addition to power output. For radio transmitters, especially increased water depth gradually reduces range, and radio telemetry is mainly feasible to track fish swimming in the upper 5-10 metres of the water column (own experiences). Landforms between the transmitter and receiver will also reduce the range. For acoustic transmitters, especially gas bubbles in the water reduce the range, such as in turbid water in rivers and wind induced at sea (Thorstad *et al.*, 2000). Acoustic noise made by for instance wave action, flow, rain, snow, sonars, fish finders and boat motors, and even biological noise such as produced by snapping shrimp, can reduce the detection range of signals from acoustic transmitters (Pincock and Johnston, 2012). Acoustic transmitters have a shorter range in saltwater than in fresh water. Stratification of water with different salinity may reduce the range when the transmitter and receiver are within the different stratification layers. Range of acoustic transmitters is more complicated (How and Lestang 2012) than range of radio transmitters, and we recommend that the range should be tested specifically for the transmitters and study area in question.

Radio transmitters for aquatic animals have signals in the frequency range of 30 MHz to 225 MHz, with most usage in the 142 MHz to 172 MHz range (Kuechle and Kuechle, 2012, own experiences). Low frequency radio signals (30-50 MHz) have less attenuation with increasing depth and conductivity, and radio transmitters at these frequencies therefore have larger range in deep water or high conductivity environments (Lucas and Baras, 2000; Kuechle and Kuechle, 2012). However, these low radio frequencies require much larger antennas on both transmitters and receivers, which are impractical to use in the field. Tracking fish in deep water and high conductivity environments it therefore often better performed with acoustic transmitters. There is no practical difference in performance within the 142 MHz to 172 MHz range for radio transmitters, but the different countries may have different restrictions on the use of radio frequencies.

The main types of radio receiver antennas are loop, dipole and Yagi antennas. Yagi antennas are the most frequently used to track fish (Kuechle and Kuechle, 2012), also by the present authors. They are robust, have good gain and directivity, so the direction of the strongest signal can be used to determine the fish position. A four-element Yagi antenna is suited for handheld field use. Antennas with more elements have a greater reception range because they are longer, and they have a narrower main lobe of the beam, which increases direction finding accuracy (Kuechle and Kuechle, 2012). The present authors have used nine-element Yagi-antennas mounted on cars and boats for mobile tracking, or connected to stationary receivers, but they are too large to walk around with. An alternative to mounting a Yagi-antenna on the car is to use a magnetic dipole antenna that can easily be mounted on flat metal surfaces like the car roof. They have a shorter range than a nine-element Yagi-antenna and are omni-directional, which means the direction of the fish cannot be determined, only whether the fish is within the antenna range or not. However, they are practical to use during mobile car tracking when searching for tagged fish over large areas.

Acoustic transmitters for aquatic animals usually have signals in the frequency range of 30 kHz to 400 kHz. The size of the tag is a function of the frequency, because lower frequencies require larger diameter resonant elements and higher frequencies require smaller resonant elements (Pincock and Johnston, 2012). The higher frequencies have a shorter maximum range. Therefore, small transmitters suitable for small fish have a shorter maximum range than larger transmitters (Pincock and Johnston, 2012).

Radio and Acoustic Transmitters with Sensors

Sensors recording environmental and physiological parameters can be used with radio and acoustic transmitters. There are transmitters available on the market with sensors recording pressure (provides information on water depth), temperature, salinity, dissolved oxygen, fish activity level, detailed activity and behaviour by use of accelerometers, inactivity (provides information on mortality or tag loss), body position, electromyogram (EMG, *i.e.*, muscle activity), heartbeat rate and differential pressure (used to record coughing, breathing and feeding activity) (e.g. Uglem *et al.*, 2010; Føre *et al.*, 2011; Murchie *et al.*, 2011; Hasler *et al.*, 2012). Most sensor transmitters are equipped with only one type of sensor each, or in some cases two different sensors. Information on the sensor recorded data are transmitted as radio or acoustic signals to the receiver as altered pulse rates, as coded signals, or as frequency modulated signals (transfer of complete signal curves). Signals with sensor recorded data can be transmitted to stationary automatic receivers when the fish is within receiver range, or to portable receivers during manual tracking.

When a tagged fish is eaten by a fish predator, the transmitter can remain in the stomach of the predator for several weeks (Thorstad *et al.*, 2012). This may result in erroneous conclusions on fish behaviour, if it is not detected that it is another fish than the one originally tagged that is recorded. In a study of Atlantis salmon post-smolt (*Salmo salar*), depth recordings were used to reveal if the tagged post-smolt had been eaten by marine fish predators, because the much deeper depths frequently used by the predators could be distinguished from the near-surface migration of the post-smolt (Thorstad *et al.*, 2012).

Transmitters with EMG sensors or accelerometers can be used to study swim speed, metabolic rate and energy expenditure of free-swimming fish in nature (Cooke *et al.*, 2004; Payne *et al.*, 2011). This can be done by first calibrating EMG or accelerometer recordings of sensor transmitters to swim speed and oxygen consumption rate of the tagged fish during forced swim trials in a swim speed tunnel with adjustable water velocity in the laboratory. Oxygen consumption at different activity levels can be calculated from the decline in oxygen level in the water of the sealed swim speed tunnel. EMG or accelerometer data collected from free-swimming fish equipped with a similar transmitter and released in nature can subsequently be used to estimate swim speed and oxygen consumption based on the calibration.

Data Storage Tags (DST)

Data storage tags (DST, also termed archival tags), are tags with sensors that store the recorded information in the tag. Hence, there is usually no transmission of signals in the field (which distinguishes DSTs from the sensor transmitters described above), and the fish needs to be recaptured to retrieve stored data from the tag. Alternatively, DSTs with floats have been developed. When the fish dies, the tag will rise to the surface as a result of the tag floats, and it may drift to shore and be found and returned to the labeled address (Thorstad *et al.*, 2013a). Data can be stored by DSTs as often as every 1-15 minutes. DSTs are available on the market with sensors recording different parameters, including pressure (provides information on water depth), temperature, light, salinity, earth's magnetic field, compass heading, tilt angle and detailed activity and behaviour by use of accelerometers (e.g. Rikardsen *et al.*, 2007; Reddin *et al.*, 2011). Most DSTs available on the market are equipped with between one and three different sensors.

It is possible to retrieve stored data from some types of DSTs by two-way communication with receivers without recapturing the fish (so-called CHAT-tags, Hight and Lowe, 2007). Stored data are downloaded from the tag to the receiver when the fish is swimming within range of the receiver (receiver range of 500 m in the study of Hight and Lowe, 2007). The tags used by Hight and Lowe (2007) are at present not provided by the manufacturer. At the moment there seem to be only a few tag models that are provided by manufacturers of telemetry equipment using a technology where sensor data (depth and temperature, or accelerometer data Almeida *et al*., accepted) are stored and processed in the tag and can be downloaded when the fish passes a receiver.

Pop-up Satellite Archival Tags (PSAT)

Pop-up satellite archival tags (PSAT) enable large scale ocean migration studies of large fishes (Figure 3). The PSAT collects information on the environment of the fish such as light, pressure (depth) and water temperature. After a pre-programmed period the slightly positive buoyant tag detaches from the fish and floats to the surface. Alternatively, if the tag measures constant depth for a pre-defined period (*i.e.*, indicating mortality or tag shedding) it will also release, surface and start transmitting a subset of the archived data to polar-orbiting ARGOS satellites until its battery runs out. The satellites then transfer the data to base stations on earth. Hence, this technology provides information on the fish position at pop-up time, and stored light, temperature and depth data can be used to calculate fish movements between tagging and the pop-up location (see below). PSATs are relatively large and have to be attached externally, which limits size and species of fish that can be tagged, although some PSATs are now small enough to be used on European silver eel (*Anguilla anguilla*) (Aarestrup *et al.*, 2009) and adult Atlantic salmon (Chittenden *et al.*, 2013b). The advantage with these tags is that they do not need to be recovered to retrieve data, data is also retrieved from fish that dies (which is often as important as getting data from only those surviving), and an accurate pop-up location is achieved. However, as the transmission success is dependent on several factors, including weather, area, remaining battery life and surrounding topography, usually not all collected data is successfully transferred to ARGOS satellites, often leaving several holes in the dataset (personal observation). Also, as most of these tags have an eroding release mechanism that depends on salt water, they do no release if a fish enters fresh water. Data return from PSATs has been poor in the Mediterranean region (De Metrio *et al*.

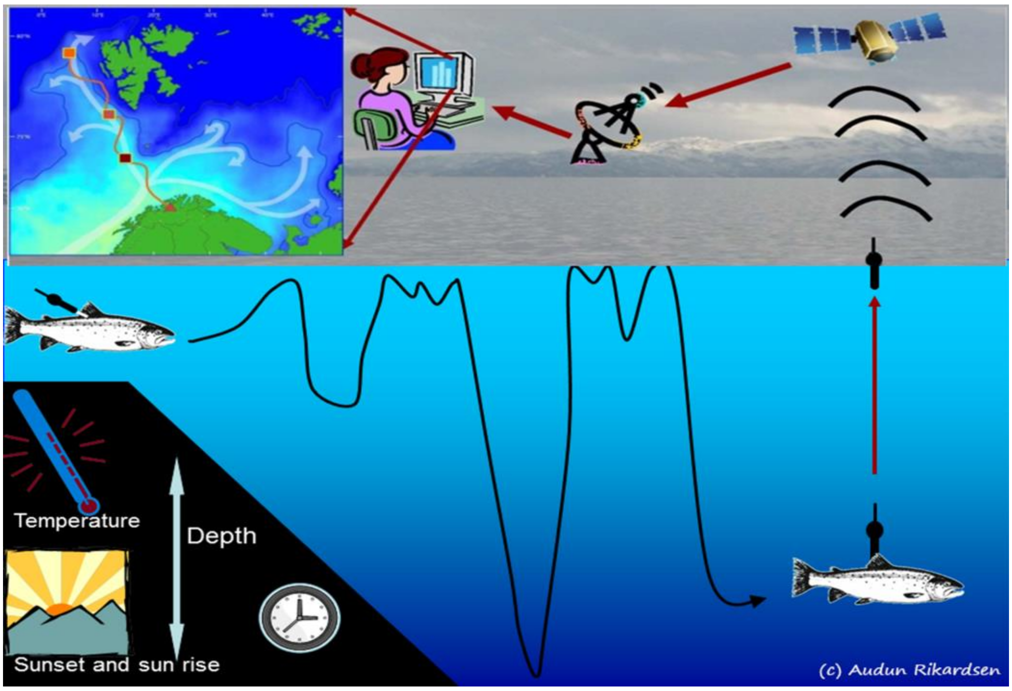

Figure 3. Illustration showing the principle by tracking fish with use of pop-up satellite archival tags (PSAT). The tag collects and stores data on depth, water temperature and light intensity as the fish migrates in the ocean. When the transmitter pops up to the surface, the position is recorded and stored data transferred to ARGOS satellites. Based on the stored data, migration routes of the fish can be calculated in retrospect.

2005; Musyl *et al*., 2011). There seems to be noise sources that interferes with the ARGOS frequencies at least in two areas of the world; the Mediterranean and near Taiwan (Musyl *et al*., 2011). For regions with known noise problems, it is advisable to discuss possible solutions with manufacturers of tags before designing the study. Despite these limitations, this is today the best method for large-scale tracking of completely submerged marine animals in the ocean.

Calculating Geographic Positions based on Archived Sensor Data from DSTs and PSATs

Geographic movements of the fish can to some extent be calculated in retrospect based on stored light data, because day length varies with latitude, and local time of noon or midnight vary with longitude. However, these geolocation methods have some limitations (Ekstrom, 2004; Teo *et al*., 2004; Chittenden *et al.*, 2013b). Longitude estimates are generally more accurate than latitude estimates (Seitz *et al.*, 2006). Further, quality of light level recordings, and hence accuracy of position estimates, may be reduced by fish diving behaviour, fouling of the light sensor, weather and water quality conditions and when the fish moves a large distance between sunrise and sunset. Estimates are difficult in days around the equinoxes when day length is nearly equal at all latitudes. Moreover, at polar latitudes, the long duration of twilight makes estimates of exact sunrise and sunset difficult during much of the year and the difference in irradiance between day and night is reduced, making light-based geolocation difficult (Chittenden *et al.*, 2013b).

Other sensor data than light can be used to estimate geographic movements of fishes in retrospect, either in combination with light data, or other sensor data alone or in combination with each other. Depth data combined with knowledge of bathymetry of lakes or sea basins can in some cases be used to analyse gross geographical positions, as well as water temperature data (Teo *et al*., 2004; Ådlandsvik *et al*., 2007; Chittenden *et al.*, 2013a,b). In a study of anadromous Arctic char (*Salvelinus alpinus*), Jensen and Rikardsen (2012) used relatively simple data storage tags that only recorded fish ambient temperature, and determined habitat use by the tagged individuals based on environmental temperature differences between the sea, estuary and river environments. Movement paths for demersal fishes can be simulated through geographic locations that match the recorded temperature and depth data (Righton and Mills, 2008).

Passive Integrated Transponder Tags (PIT-Tags)

Passive integrated transponder tags (PIT-tags) (Lucas and Baras, 2000) are the smallest electronic tags (9-22 mm long tags, the smallest weighing less than 0.1 gram, Figure 4). The tags are termed passive because they have no battery, whereas the other groups of tags described here can be termed active tags, because they have their own battery. The microchip of the PIT-tag remains inactive until read with a scanner. The scanner/reader powers the tag circuitry by radio frequency induction and then

Figure 4. Tagging with a passive integrated transponder tag (PIT-tag). This tag is commonly inserted in the body cavity by use of a syringe implanter, or by cutting a small hole in the body wall with a scalpel and inserting the tag like in the picture. Photo: Audun H. Rikardsen.

receives the unique code back from the tag. PIT-tags are usually encapsulated in glass. The estimated lifetime of tags is several decades. The advantages with these tags are their small size (fish down to about 5 cm in body length can be tagged), the large number of unique codes and the long lifetime of tags. The disadvantage is the short detection distance of the readers (<1 m). PIT-tags are frequently used in tagging and recapture studies (Hedger *et al.*, 2013), and the tag ID can be identified using a hand held reader (Burnett *et al.*, 2013). Automatic stations with tubular or square shaped antennas, or flat-bed antennas, can be installed at suitable sites in small rivers and in fish passes to detect PIT-tagged fish passing the station (Lucas *et al.*, 1999; Aarestrup *et al.*, 2003). Portable readers can also be used to search for tagged fish in shallow areas of ponds and small rivers, but the efficiency is restricted by the short range. Signals can be detected through water and air. Detection range is dependent on tag size, operation frequency, antenna power, tag orientation and interference from other devices (Lucas and Baras, 2000). Detection range is reduced in saline waters, but stationary PIT-tag systems have also been used in marine environments (Meynecke *et al*., 2008).

Tagging Methods – How Can Telemetry Tags be Attached to the Fish

There are three main methods for attaching electronic tags to fish, which are 1) surgical implantation in the body cavity, 2) external attachment, and 3) gastric insertion via the mouth (Figure 5, Figure 6 and Table 1) (Jepsen *et al.*, 2002; Bridger and Booth, 2003; Cooke *et al.*, 2011a). The choice of tagging method depends on the morphology, size and life stage of the fish, habitat, duration of study, tag type and research question.

Surgical implantation in the body cavity is the most commonly used tagging method for electronic tags in fish (Cooke *et al.*, 2011a). The tag is inserted via an incision made by a scalpel, and the incision is closed usually with 2-3 surgical sutures (Figure 5). The advantages with surgical implantation are that the tag does not interfere with the streamlined body shape of the fish, the tag is placed close to the centre of gravity, the tag does not attract predators, and it is ideal for long-term studies. One of the disadvantages with surgical implantation is that it requires more practice and skills than other tagging methods and should be adapted to the study species and body size and shape of the tagged fish. Furthermore, wounds may not heal easily for fish that are in periods of high activity, and sutures may open up when fish are jumping and swimming in waterfalls and strong currents (own experiences). Implantation is less suitable for flatfishes or other species with little space available in the body cavity. Monitoring of environmental variables with sensor tags requires sensors to be passed through the body wall if the tag is surgically implanted (Figure 5), with risk of negative impacts due to the additional wounds. Similarly, body implanted radio transmitters usually have trailing antennas that must exit the body cavity, which may increase tag loss because tags can be expelled through the antenna exit, and imply other negative tagging effects (Cooke *et al*., 2011). An internal coiled antenna within the radio transmitter can be less detrimental to the fish, but may reduce signal reception range (Lucas and Baras, 2000). Internal tags cannot easily be identified by fishers at recapture, so an additional external tag with information for fishers may be needed (*e.g.* with reward information and address for return of tags).

No suture material for closing incisions has been developed specifically for fish, and many different suture materials are available. The choice between absorbable and permanent sutures is a trade-off

Figure 5. Internal tagging where an archival tag is inserted into the body cavity, with an external light and temperature sensor trailing through the body wall. A similar tagging method may be used for implantation of radio tags with an external antenna trailing through the body wall. After insertion, the wound was closed with two suture stiches. Photo: Audun H. Rikardsen.

Figure 6. External attachment with a radio transmitter on one side and a data storage tag (DST) on the other side of the dorsal fin. Such double tagging is only suitable for large fish. Photo: Audun H. Rikardsen.

Table 1. Potential advantages and disadvantages for the three main tagging methods for electronic tags on fish (based on the authors' own experiences)

	External attachment	Surgical implantation in body cavity	Gastric insertion
Advantages	Easy attachment procedure Low immediate tag loss (6-12 months) Visible for fishers and no secondary tag needed for recognition Increased chance of recapture in gillnets Anesthetization not always necessary Well-suited for studies < 1 year Well-suited when using sensor tags recording environmental variables	The tag is placed close to the centre of gravity of the fish, and does therefore not impact the balance No interference with the streamlined body shape of the fish and less risk of reduced swimming performance than external tags No fouling or drag of tag Well-suited for long-term studies (but potential tag expulsion first months) Well-suited on long term even for fast growing or starving fish Invisible for predators	Works well on non-feeding fish Easy and fast tagging (can potentially be done without anesthetization) The tag is placed close to the centre of gravity of the fish, and does therefore not impact the balance No interference with the streamlined body shape of the fish and less risk of reduced swimming performance than external tags No fouling or drag of tag Invisible for predators
Disadvantages	Interferes with the streamlined body shape of fish and increases drag, which may reduce swimming performance Risk of fouling on tag (coastal areas), which may further reduce swimming performance The tag can be entangled in vegetation and structured environments Increased predation risk May provoke attacks from other fish Not well-suited for fast growing or fasting fish on long term (> 1 year) Attachment wires may on long term cause damage to muscle. Potential for large tag loss on long term (> 1 year, size/shape dependent)	Immediate tag expulsion may occur (first weeks/months) External mark needed for visual recognition of tagged fish Complicated implantation procedures, which require practice and skills Anaesthetisation always required Fish should not be too active after tagging (e.g. in waterfalls) to ensure wound healing. Not well-suited for fishes with limited space in the body cavity External radio antennas and sensors need to be exited through the body wall	Regurgitation rate may be high, especially in feeding fish May decrease feeding and growth in feeding fish Tag/fish-size must be adjusted (e.g. rubber ring) Danger of rupturing the stomach wall during tagging External mark needed for visual recognition of tagged fish Long-term effects?

between risks of expulsion through an unhealed incision as a result of premature loss of absorbable sutures, and the risk of infection due to the presence of permanent sutures (Thorstad *et al.*, 2013a). Permanent sutures will over time be shed from the fish (Figure 7), and inflammations may be seen around sutures during the shedding process. The advantage of absorbable sutures is that they may remain in the fish for a shorter time than permanent sutures, and the period with inflammations may be reduced. However, the present authors mainly use permanent sutures to reduce the risk of premature suture loss, and the healing is usually successful and inflammations disappear once the sutures are shed. The use of monofilament sutures instead of braided materials may reduce the inflammations, but this may be species specific (Thorstad *et al.*, 2013a).

External tags are often attached with steel wires or strings through the muscle at the dorsal fin (Figure 6). Advantages with external tagging is that the procedure requires less training than other tagging methods, it can be used in fishes not suitable for surgical implantation, external placement is an advantage if sensors are used to measure the external environment, and fishers can easily detect the tag at recapture. The disadvantages are that the tags interferes with the streamlined body shape of the fish and increases drag, it can be entangled in aquatic vegetation, and seaweed and sessile animals may grow on the tag and antenna (fouling) and increase the drag (Thorstad *et al.*, 2001). As the external tags also may be entangled in gillnets, externally tagged fish can be more easily recaptured (Rikardsen and Thorstad, 2006), which is sometimes a benefit if the tags needs to be recaptured (e.g. archival tags). Tags with a flat shape (Figure 6) are better suited for external attachment than cylindrical tags because they interfere less with the streamlined body shape, rest steadier to the fish and are therefore less likely to loosen and cause long-term negative impacts. However, due to the components of acoustic tags, they usually produced with a cylindrical shape, and are therefore less suitable for external tagging than radio transmitters and archival tags, which are available in both cylindrical and flat shapes. Cylindrical shapes are preferred for internal tagging, because this shape fits better into the body cavity and stomach.

Gastric insertion of tags is a quick tagging method, but is mainly suitable for fish at life stages when they have ceased feeding, such as for instance European eel during the silver eel stage when migrating to feeding grounds (Økland and Thorstad, 2013). Advantages and disadvantages with this tagging method are mainly similar to surgically implanted transmitters, but in addition there is a risk of tag loss by regurgitation, causing a premature end of the study. The tags size should be adjusted to the size of the stomach of the fish to reduce regurgitation rates. Some scientists have used a rubber ring of vulcanization tape around the tags to reduce regurgitation rates (Rivinoja *et al.*, 2006).

In addition to the three main tagging methods, there is a fourth method sometimes used, which is wrapping a transmitter in a bait and make the fish voluntarily ingest the transmitter when taking the bait (Winger *et al.*, 2002). This may especially be an appropriate method for deep-water fish that cannot be brought to the surface for tagging. The disadvantage is that it is difficult to control which fish is tagged as fish of several species, sizes and life stages may take the bait. Video can be used to attain information on the fish that is tagged. Further, it is difficult to know how long the fish will retain the tag.

Potential Tagging Effects

The tag should have minimal effects on the

Figure 7. Healing of surgical incision of a *Capoeta angoare* with an implanted radio transmitter with a trailing antenna. The fish was recaptured in Ceyhan River in Turkey 20 days after tagging. Two sutures had already been shed, whereas the last suture was during the shedding process, which caused the irritated area around the incision. Once all sutures are shed, the sign of irritation usually disappears, and after some time it can be difficult to see where such incisions have been made.
Photo: Ahmet Alp.

tagged animal. If not, an anomalous behaviour caused by the tagging may be recorded and not the natural fish behaviour, and the study is a failure from a scientific point of view. Furthermore, optimal anaesthetic and tagging methods are required to meet the ethical standards for use of experimental animals, and to ensure fish survival and welfare (Table 1).

There are numerous studies of tagging effects in different fishes (reviewed by Jepsen *et al.*, 2002; Bridger and Booth, 2003; Cooke *et al.*, 2011a). Negative effects by surgical implantation may be inflammations, infections, tag expulsion, altered behavior, decreased swimming performance, reduced feeding, reduced growth and increased mortality (Jepsen *et al.*, 2002; Bridger and Booth, 2003; Thorstad *et al*., 2009; Cooke *et al.*, 2011a). Expulsion of implanted tags may occur; through the incision, through an intact part of the body wall, or through the intestine (Jepsen *et al*., 2002, own observations). This usually happens within the first weeks or months after tagging, and the degree of shedding seems to be dependent on species, life stage and the shape, size and type of tag (own observation). Using small and cylindrical tags with rounded ends and no sharp edges may reduce the expulsion risk. External tags tend to have a lower immediate tag loss rate than sometimes experienced for internal implanted tags (own observations). However, after several months or years, the swimming muscles can be injured (dependent on tagging location), and the external tags may grow out of the fish. This is species, size and life-stage dependent. For example if a starving fish is tagged, the tag attachment may loosen over time when the fish loses body mass, and the chances of injuries and tag loss increase. Gastric insertion of tags may decrease feeding and growth in tagged fish because the tag may block feed intake, the stomach volume available for ingesting feed is reduced, and the fish may feel satiated due to the mass and volume of the tag in the stomach (Bridger and Booth, 2003).

There is no generally applicable rule for how large the tag can be related to fish body size without impacting the fish negatively (Jepsen *et al.*, 2005). Despite this, some researchers rely on a general rule of thumb, "the 2% rule", to argue that the tagging protocol did not affect the results of a study because the tag mass was less than 2% of the body mass of the fish. Tag effect studies indicate that this is not a valid argument; in some cases tag effects are demonstrated when using smaller tags, and in other cases larger tags can be used without any significant tagging effects (Jepsen *et al.*, 2005). The appropriate maximum relationship between tag size and fish body size is determined by the specific study objectives, the tagging method and the species/life stage involved. Information on this can be found in published studies on tagging effects from the same species and tagging methods, from related species, or it may be advisable to perform new investigations of tagging effects before the study is initiated. It is often advisable to design the study so as to use as small tags as possible.

While there has been large focus on tagging effects in published studies, there is less focus on methods and effects of catch and handling fish for tagging. It is equally important to make sure catch and handling is not impacting the fish or fish behaviour negatively as it is to evaluate effects of the tag. Adverse catch and handling methods may in worst case significantly impact fish survival and behavior.

The present authors often release wild fish back to their natural environment as soon as possible after tagging, without keeping them in any holding facilities. Hence, the fish is released immediately if not anaesthetised, or as soon as they have recovered from the anaesthetisation and can swim normally. Keeping wild fish in captivity may increase stress compared to being released back to the familiar environment. However, the release strategy must be evaluated carefully in each case. If there are potential predators present in the area, the tagged fish must be released in a time and place when the predation risk is as low as possible.

Conclusions

Since the first fish telemetry studies during the 1950s and 1960s, there has been a tremendous increase in the use of electronic tagging methods, especially during the last 10-20 years. This has resulted in a huge amount of new information on fish behaviour in freshwater, brackish and near coastal waters, and ocean environments - in many parts of the world. Most of the studies have been performed in North America, Western Europe, Japan and Australia/New Zealand, but to an increasing extent also in other parts of the world.

Electronic tagging can be used for a range of approaches in fish biology, from descriptive studies of fish behaviour in different environments to sophisticated hypothesis testing. The methods are relatively expensive, but in many cases the only possibility to provide some types of data. The perfect tag – the long lasting, very small tag with a number of sensors and a long range in all environments – does not exist. The different telemetry methods provide new opportunities, but are also confined by methodological and technical constraints. The different methods are characterised by different strengths and limitations (summarized in Table 2). In telemetry studies, it is therefore particularly important to ask clear research questions, identify and prioritise the most important research questions, and to carefully choose the method and study design that will ensure reliable answers to the prioritised research questions.

There has been and will be a continuous development in telemetry technology and methods used in fish research. Manufacturers of telemetry equipment will likely in the future provide more advanced sensor transmitters for measuring

Table 2. Comparisons of the five main types of electronic tags. Rating of different criteria is done from not suitable (-), suitable (+) to highly suitable (++). The main types of tags are radio and acoustic transmitters, data storage tags (DST, also termed archival tags), pop-up satellite archival tags (PSAT) and passive integrated transponder (PIT) tags

	Radio	Acoustic	DST/archival	PSAT	PIT
Freshwater use	++	++	++	-	+
Saltwater use	-	++	++	+	(+)
External tagging	++	+	++	++	(+)*
Internal tagging	+	++	+	-	++
Gastric insertion	+	+	-	-	-
Useable for small fish	+(+)	+(+)	+	-	++
Remote data logging in air	++	-	-	++	-
Remote data logging in water	+	++	-	-	(+)
Measures of several parameters	+	+	++	++	-
Deep water measurement	(+)	+(+)	++	++	-
Long identification range	+(+)	+	-	++	-
Manual tracking with receivers	++	+(+)	-	-	(+)
Automatic tracking with receivers	++	++	-	-	+
Long term study (> 1 year)	+	+	++	+	++
Possibility for 3D-tracking	+	++	-	(+)	-
Low cost studies	+	(+)	+	-	++
Continuous data sampling	(+)	(+)	++	+	-

PIT-tags are normally not suited for external tagging, but PIT-tags can be moulded into standard external fish tags such as T-bar tags and dart tags and thereby be suitable for external tagging.

environmental and physiological parameters, and improved technologies to transmit stored data from archival tags to remote receivers, enabling data to be retrieved without recapturing the tag. Satellite technologies will likely improve, as well as different other geolocation tags and methods. More powerful analytical methods for telemetry data are also likely to develop during the coming years.

Number of studies using multidisciplinary approaches to increase the explanation power, and where fish telemetry is only one of the methods used, seem to have increased over the years. Fish telemetry methods have for instance been coupled with physiology, genetics and experimental biology (Cooke *et al.*, 2008; Östergren *et al.*, 2012; Thorstad *et al.*, 2013b). Coupling with these and other tools and techniques such as diet analyses, isotope and fatty acid analyses and oceanography will likely to an increasing extent in the future be used to yield new insights into fish biology.

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