Chapter 18
Biotelemetry and Biologging

Steven J. Cooke, Scott G. Hinch, Martyn C. Lucas, and Molly Lutcavage

18.1 INTRODUCTION

Our knowledge of fish behavior, ecology, and ecophysiology relies, in part, on the study of individual free-swimming fish in their natural environment. Biotelemetry and biologging allow us to acquire this knowledge (Lucas et al. 1993; Cooke et al. 2004a; Naito 2004; Block 2005). Both techniques involve remotely monitoring behavioral, physiological, or environmental information, but in biotelemetry a signal from a transmitter carried by the fish sends the information to a receiver whereas in biologging the information is recorded and stored in an animal-borne device and the information is downloaded after the logger is recovered.

Relative to other fisheries techniques, biotelemetry and biologging are recent innovations (Trefethen 1956), but both are now common tools in fisheries science (Lucas and Baras 2000; Cooke et al. 2004a; Block 2005; Nielsen et al. 2009). However, many researchers are unfamiliar with all of the diverse technological options that biotelemetry and biologging offer. This chapter provides an overview of these techniques for studying the behavior (Box 18.1) and physiology (Box 18.2) of free-swimming fish, emphasizing their application, methodology, potential, and limitations.

18.1.1 Advantages of Biologging and Biotelemetry

Advantages of biotelemetry and biologging include the ability to assess differences among individuals (Cooke et al. 2006; Young et al. 2006), to couple behavior and physiology, and to work across different spatial and temporal scales (Akesson 2002). Because telemetry is typically conducted in field settings, it provides realism that is not possible in the laboratory (but telemetry also has laboratory applications; section 18.4.4). These methods enable collection of behavioral and physiological data in remote or harsh environments such as deep oceans where conventional sampling or direct observation is difficult or inadequate (e.g., Priede and Smith 1986; Sims et al. 2003). Biotelemetry data can be collected in real time, providing the opportunity to modify experimental protocols and management strategies (e.g., Cooke and Schreer 2003; English et al. 2005). Moreover, data can be collected continuously under varying environmental conditions. These techniques are also effective for the study of endangered fishes because they are relatively noninvasive, are data rich for small sample sizes, and do not require the permanent removal of fish from their natural environment (e.g., Simpson and Mapleston 2002; Pearson and Healey 2003; Sims et al. 2003; Cooke et al. 2008).

18.1.2 Limitations of Biologging and Biotelemetry

Biotelemetry and biologging may not be the best or most cost-effective method for answering some questions. Obtaining an adequate sample size of independent data for strong statistical

Box 18.1 Behavior, Movement, and Spatial Ecology

Biotelemetry and biologging are especially useful for studying fish behavior, movement, and spatial ecology (Lucas and Baras 2001) in many habitats including the open ocean (Dagorn et al. 2000; Josse et al. 2000; Leroy et al. 2009). Researchers are able to assess fish spatial ecology and behavior at scales ranging from instantaneous fine-scale three-dimensional positioning to extended transoceanic migration. Telemetry studies have been instrumental in delineating the boundaries of protected areas and in assessing the effectiveness of those that already exist (Zeller and Russ 1998; O'Dor et al. 2001; Lindholm and Auster 2003; Afonso et al. 2009). Telemetry and logging studies have revealed that some marine fishes migrate long distances across management jurisdictions and have altered existing beliefs about stock structures (Block et al. 2001; Galuardi et al. 2010). Biotelemetry has provided insights into deep-sea behavior and spatial ecology of scavengers (Priede and Smith 1986; Collins et al. 1998). It has provided detailed information on the efficiency of riverine fish passage devices (Bunt et al. 2000), migration speeds (Keefer et al. 2004a; English et al. 2005), and areas of migratory difficulty (Hinch and Rand 1998; Boggs et al. 2004). It has also been used to compare dispersal of stocked and wild fish (Bolland et al. 2009; Fairchild et al. 2009) and to assess the effectiveness of fish barriers (Baxter et al. 2003). Telemetry is especially useful for identifying fish habitat use, preferences, and tolerances and critical habitats (e.g., Raibley et al. 1997; Cote et al. 1998; Berland et al. 2004; Rogers and White 2007).

Box 18.2 Energetics, Stress, and Disturbance

Energy is the currency of life. Bioenergetics models are therefore important tools in fisheries management and aquaculture (Hansen et al. 1993; Chapter 16). Biotelemetry has yielded insights into the bioenergetic costs of different behaviors of many fish species (Lucas et al. 1993). For example, telemetry has been used to quantify the energetic costs of spawning (Altimiras et al. 1996; Healey et al. 2003), parental care (Cooke et al. 2002a), migration, and fishway use (e.g., Hinch et al. 1996; Hinch and Bratty 2000; Standen et al. 2002). Positional telemetry has been used to determine fish activity and energetics (e.g., Diana 1980; Demers et al. 1996; Cooke et al. 2001). In marine systems, this technology has enhanced understanding of the thermal ecology of pelagic species such as bluefin tuna (Block et al. 2001) and salmons (Walker et al. 2000). Advances in tag miniaturization will make it possible to derive lifetime energetic budgets (Lucas et al. 1993; Ney 1993).

Telemetry has been used to assess in situ behavioral responses to angling (e.g., Thorstad et al. 2004), blasting (Shin et al. 2003), water quality (Scott et al. 2005), pollutants (Brodeur et al. 2001; Cooke and Schreer 2003), and herbicide treatment (Sammons and Maceina 2005). Heart-rate sensors (Anderson et al. 1998; Cooke et al. 2004b) and electromyogram telemetry (Cooke et al. 2000) were used to assess the physiological and energetic consequences of different catch-and-release angling strategies.

power (Chapter 2) and to make population level inferences can be difficult on a limited budget. On the other hand, large volumes of (possibly dependent) data can be produced that are difficult and time-consuming to interpret. Sensor calibration can be costly. Specialized skills (e.g., electronics and surgery) may be necessary. Approval to conduct biotelemetry or biologging by an institutional animal care and use committee (IACUC) may be required. Bioenergetic estimates derived using some technologies can be inaccurate (Thorarensen et al. 1996; Cooke et al. 2004c). If tagging causes changes in fish behavior or health (Mulcahy 2003), data will not be representative of the broader population; the assumption that tagged individuals are representative of their population is a central tenet of biotelemetry studies. Such considerations especially limit uses of telemetry on small fishes.

The appropriate technology to answer a particular question depends on cost, tracking method, fish size, environmental characteristics, range, resolution, sample sizes, tag longevity, and data requirements (Box 18.3). Practitioners are advised to consult equipment manuals or manufacturer Web sites to compare equipment specifications, capabilities, and performance because features vary widely. Involving a telemetry engineer in the early planning of a project can eliminate frustration associated with poor equipment choices.

18.2 BIOLOGGING SYSTEMS

18.2.1 Archival Tags

Archival data biologging tags such as data storage tags, time-depth recorders, and archival geolocation tags do not transmit data remotely; they require tag recovery to download data from onboard memory. Although tag recovery is usually fishery dependent, the location and behavior data recorded by the tag are not. These tags provide information on habitat use, movements, and oceanographic associations. Recorded data can provide estimates of locations from daylight records and independent information on depth and temperature associations (Welch and Eveson 1999; Arnold and Dewar 2001). Because of their small size, these tags can be externally attached to small fishes and have a high probability of being seen and recovered upon recapture.

Archival tag recovery requires planning. Each tag is expensive and can contain a large amount of data, but only a few are typically returned each season. Tag labels must be highly visible and clearly provide reward and telephone and e-mail contact information. Taggers need to identify the geographic areas and fisheries in which tags are likely to be recovered and mount a publicity campaign to provide explicit directions on fish and tag recovery, recapture data requirements, and reward processing. Direct contact with fishers who are most likely to recover tags and monetary rewards (Chapter 11) increases tag return rates.

Archival tags that record only temperature and depth are small (e.g., 9 mm in diameter and 20 mm long) and have finite storage capability and battery life. Archival tags can also include pitch, tilt, and compass recorders and other custom sensors (section 18.4). Specific features and capabilities such as potting material, shape, sampling interval, and storage capacity vary among manufacturers. Treatment of stored data after capacity has been reached is an important consideration; data collection can end or existing data can be overwritten. Also, consider how long data will be secure. If a battery fails, how long will data be preserved? Storage media and their limitations should be discussed with the manufacturer.

Larger, fully programmable, implanted archival tags can have pressure, internal and external temperature, and external light sensors and record information as frequently as once per minute

Box 18.3 Determination of Which Technology to Use

After your study question has been defined, the next step is to determine the biotelemetry or biologging device that best addresses it. Consider the following characteristics of common devices to make this decision.

Table Characteristics of common biotelemetry or biologging devices (PIT is the passive integrated transponder).

Characteristic	PIT	Acoustic	Radio	Archival	Satellite
Typical environments	Shallow streams and rivers, estuaries, confined spaces (e.g., fishways)	Quiet, slow-moving large rivers, lakes and oceans; all depths	Shallow (<5 m) streams, rivers, and lakes; low conductivities (<500 μS/cm)	All	Oceans; all depths, but data are transmitted only at the surface
Fish size	>6 cm	>12 cm	>8 cm	>20 cm	>80 cm
Common tagging methods	Intramuscular or intracoelomic	External, gastric, or intracoelomic	External, gastric, or intracoelomic	External or intracoelomic	External only
Transmission mode	Passive	Active	Active	Passive	Active
Detection range	0.1 to 1 m	10 to 2,000 m	5 to 1,000 m	None	Unlimited
Optimum spatial position resolution	0.05 m	0.5 m	0.5 m	>100 m	>100 m
Typical data	Simple time-stamped data at a specific antenna and logger	Periodic tracking records or time-stamped data from loggers	Periodic tracking records or time-stamped data from loggers	Time-stamped records of light levels used to estimate positions	Time-stamped records of light levels used to estimate positions; position of tag at time of jettison
Longevity	>3,000 d	5 to 1,000 d	5 to 1,000 d	10 to 600 d	10 to 600 d
Real-time tracking	Yes	Yes	Yes	No	No
Typical numbers deployed (sample sizes)[a]	100 to >100,000	10 to >100	10 to >1,000	10 to >1,000	10 to >100

Box 18.3 Continued

Table Continued.

Characteristic	PIT	Acoustic	Radio	Archival	Satellite
Common sensors	Temperature	Pressure and temperature	Pressure and temperature	Light, pressure, and temperature	Light, pressure, and temperature
Failure and malfunction rate	Low	Low	Low	Low	Moderate
Cost per tag (US$)	$2 to $5	$200 to $500	$100 to $400	$12 to $600	>$1,000
Data acquisition methods and equipment costs	Recaptured individuals; fixed and mobile antennas, readers, and loggers $2,000 to 10,000	Mobile tracking receiver and hydrophone ($2,000), with logger ($3,000); three-dimensional hydrophone arrays (>$30,000)	Mobile tracking receiver and antenna ($500); automatic logging arrays (>$6,000)	Recaptured individuals; data recovered with downloading interfaces ($100)	Transmitted to satellites; upload fees can be $1,000 per device

[a] Large sample sizes of acoustic and radio tags require coded transmissions.

for 2 to over 7 years depending on memory. If returned intact, such tags can provide information on long-term behavior and movements and, in some cases, information on potential spawning areas. With sufficient tag recoveries, geospatial data can be used for population modeling and simulation (Sibert and Fournier 2001). Internal temperatures can be used to estimate time and frequency of feeding in some tunas and sharks (Gunn et al. 2001; Bestley et al. 2008).

Archival tags use clocks and light sensors to estimate geolocation; light data are used to measure day length and determine time of local noon relative to Greenwich time (Wilson et al. 1992). Essentially, geolocation devices infer surface irradiance from measurement at depth (Teo et al. 2002). The time of local noon is used to estimate longitude; day length at the estimated longitude is used to estimate latitude. Peak solar (zenith) angle, time of year, and global position can all affect latitude estimation. Because day length at the equinoxes is similar across the globe, small errors in estimation of zenith angle or day length produce large errors in latitude (Welch and Eveson 1999; Sibert et al. 2003, 2009). Pressure is measured because attenuation of light by depth also affects geolocation estimates, and light measurements must be adjusted accordingly. However, pressure and thermal sensors require compensations for temperature and nonlinear responses of the sensors and electronics. Changes in light levels produced by clouds, storm systems, and turbidity also bias geolocation estimates. Light-based geolocation may not work well with species such as swordfish and bigeye tuna that undergo deep descents because of low ambient light levels (Neilson et al. 2009). Light sensor detection depths measured at sea with calibrated depth probes ranged from 380 to 440 m (Schaefer and Fuller 2005). Depth sensors are functional to 2,000 m, and tag housings are rated to over 2,500 m.

18.2.2 Pop-up Satellite Archival Tags

Satellite platform transmitter terminals, which identify tag location by real-time uplinks to orbiting Argos satellites, have limited utility in marine environments because their transmissions cannot pass through salt water; use has been restricted to a few studies on large, surface-swimming fishes (e.g., Priede 1984). Pop-up satellite archival tags (PSATs; Figure 18.1) offer a useful alternative. These external tags record time, light intensity, hydrostatic pressure, and temperature. On a preset date, they detach from the fish, rise to the sea surface, and transmit stored data to a satellite.

Pop-up satellite archival tags are similar to implanted archival tags but have reduced data storage capacity, are attached externally, and record data less frequently. They have been deployed on pelagic, demersal, estuarine, and anadromous species (Nielsen et al. 2009) to determine migrations, vertical movements, temperature associations, mortality and survival rates (Box 18.4), home ranges, habitat preferences, and essential habitats (Graves et al. 2002; Hobday et al. 2009). Tag miniaturization has enabled deployment on small species such as eels (Aarestrup et al. 2009). These tags are not suitable for freshwater species because the jettison mechanism depends on a link that corrodes in seawater. When choosing PSATs, ensure that frequencies used are compatible with receiving satellites and will be supported for the duration of the study. Antenna configuration and size can be customized to achieve project objectives best.

18.3 BIOTELEMETRY SYSTEMS

Biotelemetry tags transmit information to one or more receivers. The two types of signal propagation are electromagnetic radiation (radio) and acoustic (sound), the properties of which influence their use in telemetry. Normal VHF (very high frequency) radiotelemetry is not used in marine systems because these wavelengths are rapidly attenuated in seawater. However, low

Figure 18.1 **(A)** Pop-up satellite archival tag (PSAT) attached to dart and mounted on a tagging pole; **(B)** dart being plunged into the dorsal musculature of an Atlantic bluefin tuna alongside tagging vessel (photo [A] by A. Speers, Dalhousie University, with permission; photo [B] by M. Stokesbury, Acadia University, with permission).

frequency (LF) electromagnetic telemetry using battery-powered, actively transponding tags (Breukelaar et al. 1998; Smith et al. 1998b) or passively transponding PIT (passive integrated transponder) tags (Lucas and Baras 2000; McCormick and Smith 2004) can be used in marine and brackish systems, albeit over ranges of only a few meters for PIT tags and a few tens of meters for battery-powered LF tags. Sound is the only practical way to transmit a telemetry signal through seawater for more than a few tens of meters; it is therefore used in marine, brackish, and calm freshwater habitats (Stasko and Pincock 1977; Baras 1991; Priede 1992).

Biotelemetry systems are usually characterized as passive or active. Whereas active biotelemetry systems rely on the presence of an internal power source (battery) within an animal-borne tag to power transmission of information to a remote detector, passive systems do not employ an integral power source. Passive systems include PIT tags (radio), whereas active telemetry includes both acoustic and radio techniques.

Box 18.4 Mortality and Survival

Biotelemetry is used extensively to quantify natural and fishing mortality rates (Hightower et al. 2001; Domeier et al. 2003; Pine et al. 2003; Cooke and Philipp 2004; Young and Isely 2004; Waters et al. 2005; Donaldson et al. 2008). This approach is most common for assessing mortality rates of outmigrating anadromous salmonid smolts (Scruton et al. 2005) and upriver migrating adults (Keefer et al. 2004a; English et al. 2005). Expansive acoustic telemetry arrays in the marine environment assess coastal mortality (Welch et al. 2003). Telemetrically determined mortality rates are often similar to those determined with standard techniques (English et al. 2005), but telemetry studies also yield information on individual behavior and physiology (Cooke et al. 2006). Note that transmitter loss and failure can make it difficult to differentiate among mortality, harvest, and shed transmitters and can bias mortality estimates (Pahlke and Bernard 1996).

18.3.1 Passive Biotelemetry

A PIT tag uses the energy radiated by the tuned antenna of a reader (transceiver) to transmit a reply signal, which is decoded by the reader. This technology allows individual identification upon recapture (Chapter 11) or at large over short ranges. A PIT tag consists of an integrated circuit chip and coil antenna that transmits a unique identity code when energized by a low frequency radio signal (generally 125–400 kHz). Absence of an internal power supply allows tagging of smaller fish than do active telemetry systems, tagging of more fish because of reduced unit cost, and long-term identification of individual fish because tag life is not limited by an internal power supply (Lucas and Baras 2000) but only by component failure. Consequently, PIT tags are popular for studying behavior and survival of a variety of life stages (Prentice et al. 1990a, 1990b, 1990c; Skalski et al. 1998; Lucas et al. 1999; Zydlewski et al. 2005; Meynecke et al. 2008). Although PIT telemetry has been used mostly in lotic systems, it is also used in estuarine and marine environments (McCormick and Smith 2004; Jørgensen et al. 2005; Meynecke et al. 2008). The main limitation of PIT telemetry is the low range of detection (<2 m from the antenna).

Coded signals of read-only PIT tags are unique sets of either 12 digits or 10 hexadecimal characters defined by the manufacturer. Read–write tags can be given unique identity codes by the user. Tag temperature can also be transmitted (Roark and Dorcas 2000). The PIT components are usually factory sealed in a cylindrical tube of biocompatible glass with hemispherical ends. The tag is implanted with an injector or by surgery into the musculature or body cavity of the fish (section 18.5.4). Commercially produced PIT tags are as small as 11 mm in length by 2 mm in diameter and 70 mg in mass (Figure 18.2). Larger PIT tags have greater detection distances than small PIT tags, but detection ranges of all are short, varying from centimeters for small tags up to 1.5 m for large (e.g., 32 mm) tags. Detection distance is not important when PIT tags are used for the identification of recaptured fish but is significant for remote detection of fish in natural systems. Existing systems use a variety of frequencies and coding systems, but the International Organization for Standards specifies a standard frequency of 134.2 kHz and standard coding. Detectors and tags must share the same coding system.

Reading distance is a function of coil antenna size, power applied, and the relative orientations of the detecting antenna and tag coil. Even when large PIT tags and half-duplex (HDX)

Figure 18.2 Passive integrated transponder (PIT) tags. The three larger tags on the left are half-duplex (HDX) tags, and the two smaller tags are full duplex (FDX) (photo by S. Cooke).

interrogation systems are used (section 18.6.2), the detection range usually does not exceed 1 m. However, natural channels and large fishways (Figure 18.3) can be monitored using single or several juxtaposed antenna loops (Zydlewski et al. 2001, 2006; section 18.7.1). Effective loops approaching 30 m in width have been constructed using a figure-eight format (F. Berubé, University of Quebec, unpublished data). Maximum range from the antenna's transverse axis is obtained when the tag's long axis crosses the plane of the detecting loop antenna perpendicularly. The expected trajectories of tagged fish and the orientations of tags inside the fish should be considered when installing detecting antennas. Detection range can be increased by applying more power, especially where mains electrical (AC power) or generator power is available. However, care must be taken to avoid or filter electrical noise. In most field situations, rechargeable deep-cycle batteries (Zydlewski et al. 2001) or batteries recharged by solar panels are used, and power is limited.

18.3.2 Active Biotelemetry

Active biotelemetry systems rely on the presence of an internal power source (battery) within an animal-borne tag to power transmission of information to a remote detector. The two primary modes of transmission in active biotelemetry are radio and acoustic (also called sonic).

18.3.2.1 Transmitter Packages and Batteries

Transmitters should be selected in concert with manufacturers. A competent telemetry manufacturer will ask for details about the study objectives, species, your proposed method of attachment, and the technology that you expect to use. Details on fish size, morphology, and study duration are important (Jepsen et al. 2002). The manufacturer can provide you with information on available tags, their dimensions and shapes, possible programming options and sensors (section 18.4), transmitter output strength, and transmitter pulse intervals. All of these factors will affect the longevity of the device (Voegeli and McKinnon 1996). Pressures at depths occupied by some fishes can damage some devices. Similarly, some devices do not perform well in cold or hot

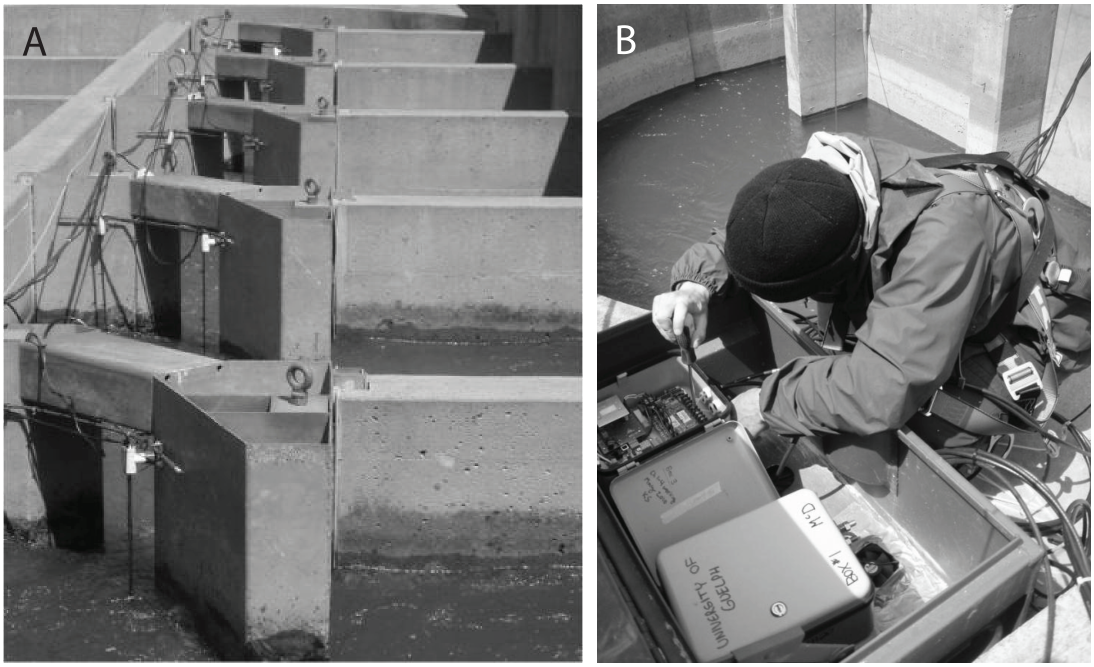

Figure 18.3 **(A)** Passive integrated transponder (PIT) tag array installed in a vertical slot fishway. The antenna wires encircle each of the vertical slots and connect to **(B)** an antenna multiplexer, logger, and power supply in a secure and weatherproof box (photo [A] by J. Thiem, Carleton University, with permission; photo [B] by S. Cooke).

conditions. Consult the manufacturer about the depth and temperature ratings for a given device. Ask about the history of a specific product and if other customers have experienced any notable problems. Also ask about price (including quantity discounts) and delivery schedule; prolonged storage is usually inadvisable for battery-powered devices, but delivery delays can cause major problems if tagging windows are narrow. Inquire about warranty details and get them in writing. What if transmitters fail prematurely or lack ordered features? Information discussed orally should be developed into a detailed quote that should be scrutinized by the study team to ensure that the proposed order matches study needs.

Battery power is a crucial consideration. Typically, a battery represents more than 50% of the volume and up to 80% of the mass of the transmitter. Battery choice is primarily determined by energy density (energy per unit mass or volume), cost, shelf life, initial voltage per cell, voltage drop during discharge, performance under given environmental conditions, and available sizes and shapes (Nelson 1978; Besenhard 1999). The important trade-offs are among transmitter life, pulse interval, tag size, and signal power output (range). Larger batteries have greater energy capacity and enable longer life or more frequent pulses, but they increase transmitter size. All batteries, but particularly silver oxide cells, lose a portion of their energy from self discharge during storage; use a refrigerator for extended storage. Lithium and silver oxide batteries are commonly used in transmitters. Lithium cells produce the highest voltage per unit mass and have excellent low and high temperature performance and tolerance, long shelf lives (up to 5 years), and good efficiency over a range of voltages. Lithium batteries are large (suitable for 3 g and larger transmitters) and tend to be cylindrical in shape. Silver oxide cells are disk or button shaped and smaller; however, voltages greater than or equal to 1.5 V can only be achieved by connecting cells in series. Silver oxide batteries perform more poorly at low temperatures and have shorter shelf lives (1–3 months) than lithium cells. Most manufacturers provide a guaranteed minimum life expectancy that is typically 25–30% less than the estimated tag life, but this can vary—ask the manufacturer. Many transmitters can be programmed with delayed activation or to transmit at only specified times to extend battery life. For example, if manual tracking is planned during only daylight hours, transmitters can be programmed to turn on and off daily at specific times. Devices can also be programmed to transmit only on specific days or during specific seasons. Such tactics can allow tracking of small fishes over long periods.

The general rule of thumb has been that tags which weigh less than 2% (in air) of the body mass of a fish can be safely implanted in or attached to fish (Winter 1983, 1996). The underlying premise is that many bony fishes have a swim bladder and can compensate for added weight in water. However, many fishes lack swim bladders, and predators often consume large meals greater than 2% of their body mass. Few experiments have explicitly examined the validity of the 2% rule, but researchers suggest that transmitters less than 2–3% of body mass are preferable (e.g., Lefrançois et al. 2001; Jadot et al. 2005; Zale et al. 2005). In some cases, heavier transmitters (up to 4% of body mass) may yield slight decreases in growth or swimming performance (Zale et al. 2005). Transmitters that weigh as much as 12% of body mass have been used in short-term assessments (Brown et al. 1999). Transmitters that weighed 8.5% of fish body mass had a slight but temporary negative effect on swimming performance (Lacroix et al. 2004). Jepsen et al. (2005a) concluded that no generally applicable rule exists and that tag selection should be driven by study objectives, the tagging method, species, and life stage. Exceeding 2% may be acceptable in certain situations, but the smallest and lightest transmitter should be used whenever possible. A target of 1% may be better for some fishes, such as laterally compressed species (Paukert et al. 2001) and juvenile lake sturgeon (Sutton and Benson 2003).

Tag volume and shape should also be considered relative to the study species (Brown et al. 1999; Paukert et al. 2001). Externally attached tags should be streamlined, especially for pelagic species. Lacroix et al. (2004) documented increased loss of larger implanted transmitters (but not mortality) and recommended that devices be less than 16% of body length of small salmonids. Many manufacturers provide dummy tags of similar dimensions and density as real devices for use in pilot studies to optimize attachment technique and assess negative effects on fish. They can usually modify the shapes of transmitters to meet specific needs (e.g., torpedo shape for oviduct insertion; section 18.5.2) by assembling electronic components in different ways. Holes can be added to enable external mounting, and devices can be labeled with information such as name, reward details, and contact information; such details should be specified when ordering.

Radio and acoustic transmitters require waterproofing and, particularly for internal tags, coverage with an inert, biocompatible material (Helm and Tyus 1992) such as epoxy, wax, resin, silicone, urethane, or plastic. Species known to expel transmitters (section 18.5.3.4) may require customized encapsulation. Tags can be encapsulated within a mold (potting), by dipping into potting material, or by spraying with the encapsulant. Some devices require soldering of wires for activation prior to waterproofing; others are activated by removal of a magnet or via infrared activation after waterproofing. Transmitters should be kept in their original shipping containers during storage and can be refrigerated to prolong battery life. All devices should be tested upon receipt to test equipment compatibility, to verify specifications, and to ensure that they are stored in the "off" position. Because transmitter frequencies can drift from factory settings, test signals of apparently nonfunctional devices on neighboring frequencies.

Sample size (i.e., number of transmitters) is dictated by the study question, statistical requirements, and cost. Tagging of only one or a few individuals may be appropriate for large and rare species (e.g., Boustany et al. 2002; Skomal et al. 2004). Minimum sample sizes for most species tend to be 10–20 fish. Studies have used more than 12,000 fish (e.g., Keefer et al. 2004a) and employed hundreds of fixed receiving stations (e.g., Moser et al. 2002). Power analyses (Chapter 2) and an assessment of the potential sources of fish loss and mortality should be conducted prior to initiating a study; considerations include the stock of fish, tag loss, fishing and predator mortality, and senescence. Contrasts of different sexes, behaviors, or fates require increased sample sizes to provide sufficient power for hypothesis testing. Most IACUCs require power analyses prior to approving projects. In some cases, researchers intentionally choose small sample sizes to collect detailed information on few individuals, particularly in physiological telemetry studies (Brown et al. 2001).

18.3.2.2 Signal Transmission

Transmitter pulse lengths, rates, and frequencies affect performance. Conventional (noncoded) transmitters emit signals of standard lengths at regular intervals at set frequencies. Typical pulse lengths are 10–20 ms; shorter lengths are difficult to detect. The time between pulses presents a trade-off between battery life and the ease of manual tracking. Longer periods between pulses increase battery life but make it more challenging to obtain position fixes. Typically, pulse intervals of 1–3 s are used for manual tracking; 1 s is favored for microhabitat or activity studies (Winter 1996). For applications such as gross movement studies, intervals from 3 s to several minutes may be appropriate, depending on the probability of missing a signal as a fish moves into and out of range. Pulse intervals are relevant for calculating frequency scan durations at fixed radiotelemetry arrays (section 18.7.2.2). Most manufacturers allow users to specify intervals in 0.1-s increments. Total transmission time (the duty cycle) is about 0.5–2%. Many radio frequencies are available such that individual frequencies can be assigned to individual transmitters to allow differentiation. Because fewer frequencies exist for acoustic transmitters, the pulse interval is varied (usually by at least 200 ms; e.g., 1,000 ms and 1,200 ms) to distinguish individuals on the same frequency. Select frequencies that are free of excessive background noise (and legal for telemetry in your area), and consult manufacturer databases, agencies, and other researchers (including wildlife biologists) in your area to avoid overlapping frequencies and coding that could result in confusion among studies. On the other hand, careful coordination of multiple studies to share receivers (especially permanent fixed stations) can be mutually beneficial.

Advanced telemetry systems use coding schemes to differentiate individual fish on the same frequency. For example, codes can be defined by interval lengths between successive pulses in a train of pulses, with longer resting intervals between the pulse trains. Unless the resting intervals are long, such tags usually have higher duty cycles than simple transmitters. Pulse interval strongly affects battery life. Although most frequently used for automated telemetry applications, coded systems also enhance manual tracking by precluding the need to switch among multiple frequencies, which can result in missed tags. Ask manufacturers about the maximum number of possible codes per frequency and options to minimize or resolve code collisions. Code division multiple access (CDMA) signaling can discriminate among thousands of acoustic codes per frequency. This approach improves signal to noise ratios and enhances resolution in acoustically noisy or shallow environments and at extreme hydrophone ranges (Niezgoda et al. 2002). It can be used to determine three-dimensional positions of fish in whole-lake telemetry arrays (Cooke et al. 2005; Hanson et al. 2007) and in aquaculture facilities (Box 18.5; Cubitt et al. 2005).

Radio tags use coiled or trailing antennas to transmit signals. Power transfer to the water, and therefore also the range, of trailing antennas is greater than that of coils. However, trailing antennas can become entangled with debris (Adams et al. 1998a, 1998b), elicit aggressive attacks from other individuals (Connors et al. 2002), and become fouled. Inflammation and infection at antenna exit sites of internal tags are common (Cooke and Bunt 2001; Collins et al. 2002; Isely et al. 2002). Although trimming the antenna can reduce drag, minimize swimming performance impairment, and reduce the chance of entanglement, signal transmission is reduced. Internally coiled antennas preclude such issues but require more space in the body cavity, limiting the ability to tag small fishes (Cooke and Bunt 2001). These trade-offs must be considered when deciding on antenna configuration (Isely et al. 2002). Short antennas and associated reductions in transmission strength may be acceptable in small streams. Antenna material, gauge, and color can be specified.

18.3.2.3 Signal Reception

A receiver collects (receives) radio or acoustic wave information emitted from a transmitter. The receiver filters input signals, amplifies them, and converts them to a form that is audible or can be stored. The transmitted signal must be detected by the receiver at a distance through water (acoustic and radio) or air (radio) or both (radio). Thus, system performance and transmitter detection depend on transmitter power, losses associated with transmission through the medium, noise level, signal to noise ratio, and the sensitivity of the receiver. The most important factors are the transmitted signal level and the noise level, or collectively, the signal to noise ratio.

A receiver should have noise rejection and filtering capabilities and should be able to switch among frequencies when tracking. The frequency selector should be accurate; modern receivers typically use digital key pads to specify desired frequencies. Advanced receivers automatically scan specified frequencies and skip them after a specific transmitter has been located during a tracking episode. Most receivers are small and include integrated batteries, but size can nevertheless be a factor when manually tracking in remote locations. Permanent systems designed for long-term,

18.5 Aquaculture

Biotelemetry techniques can be used to assess responses to different culture conditions and to assess fish fitness in aquaculture settings (Holand 1987; Baras and Lagardère 1995). For example, electromyogram telemetry techniques have been used to assess different stocking densities (Cooke et al. 2001), transport techniques (Chandroo et al. 2005), and feeding regimes (McFarlane et al. 2004). Passive integrated transponder tags have been used to assess use of demand feeders (e.g., Alanärä and Brännäs 1997). Telemetry has been used to assess crowding densities and feeding behavior (Bégout Anras and Lagardère 2004) as well as movements and habitat use of released cultured fish (Bridger et al. 2001a; Fairchild et al. 2009). Consequences of culture-induced cardiac abnormalities on fish performance were assessed using heart-rate telemetry (Mercier et al. 2000).

static deployments may require external power sources and data loggers. Receivers should be made from corrosion-resistant components. Exposure to excessive heat or cold can be problematic. If working in extreme conditions, consult the manufacturer regarding equipment suitability. Do not assume that all equipment from a manufacturer will be compatible. Manufacturers have a tendency to modify features such as coding schemes over time, which can create incompatibilities among receivers.

Most receivers are intended for outdoor use but are rarely waterproof. They must be kept dry to function appropriately. Do not assume that standard-issue cases are waterproof; invest in waterproof containers even if the cost is high. Equipment should be dried after use in moist conditions. If electronic equipment becomes wet, do not turn it on until it has dried completely. Equipment should be returned to the manufacturer at regular intervals for cleaning, battery replacement, and software updates. Antennas and hydrophones are reasonably robust and tend not to fail. However, cabling can become damaged, particularly near connections, and should be tested for short circuits by means of a multimeter and replaced regularly.

Redundancy is important because many studies take place in remote locations and rely on specialized equipment. A backup receiver, hydrophone or antenna, and data storage device (as well as extra tags) are advisable. It is almost certain that at least one or more crucial components of the system will fail during a study. A researcher should have the appropriate tools, parts, and diagnostic equipment needed to make repairs; these include a soldering iron, wire cutters, epoxies, fuses, crimpers, wire strippers, small screwdrivers, and a multimeter. Practitioners unfamiliar with electronics should consider taking a basic electronics course to understand their equipment better.

18.3.2.4 Radiotelemetry

Radiotelemetry is the preferred method in shallow (usually <5 m), low-conductivity (usually <500 μS/cm) freshwater systems. Radio transmitters (Figure 18.4) emit electromagnetic energy in the radio frequency range, usually in the VHF band between 30 and 300 MHz, and are believed to be undetectable by fish. Frequencies of conventional (noncoded) transmitters should be spaced by at least 10 kHz because limited frequency drift can occur. Radio signals propagate omnidirectionally in water, but only those perpendicular (<6° from vertical) to the air–water interface emerge into the air and can be detected by an aerial antenna. Water depth and conductivity attenuate radio signals (Velle et al. 1979), especially at high frequencies. Low frequencies (30–50 MHz) are therefore preferred in deep or high-conductivity environments (Table 18.1) but require larger, more cumbersome antennas, which may be impractical in some situations. Other factors affecting radio transmissions include attenuation by vegetation and reflection or diffraction from rock faces.

Receiving antennas used in radiotelemetry include Yagi, loop, H, and omnidirectional antennas (Kenward 2001). Yagi antennas are widely used because of their directional properties, sensitivity, and range. They can be carried by hand or mounted on towers, trees, or vehicles (Figure 18.5; Winter et al. 1978; Kenward 2001). These antennas are strongly unidirectional, with the strongest signal received when the end of the antenna with the smallest element is pointed at the transmitter. Loop antennas are bidirectional, meaning that the strongest signal is received when either edge of the antenna is pointed at the transmitter. Yagi antennas have twice the detection distance of loop antennas (Shroyer and Logsdon 2009). H-shaped antennas are widely used because of their ease of operation and small size. One element may be shorter than the other, result-

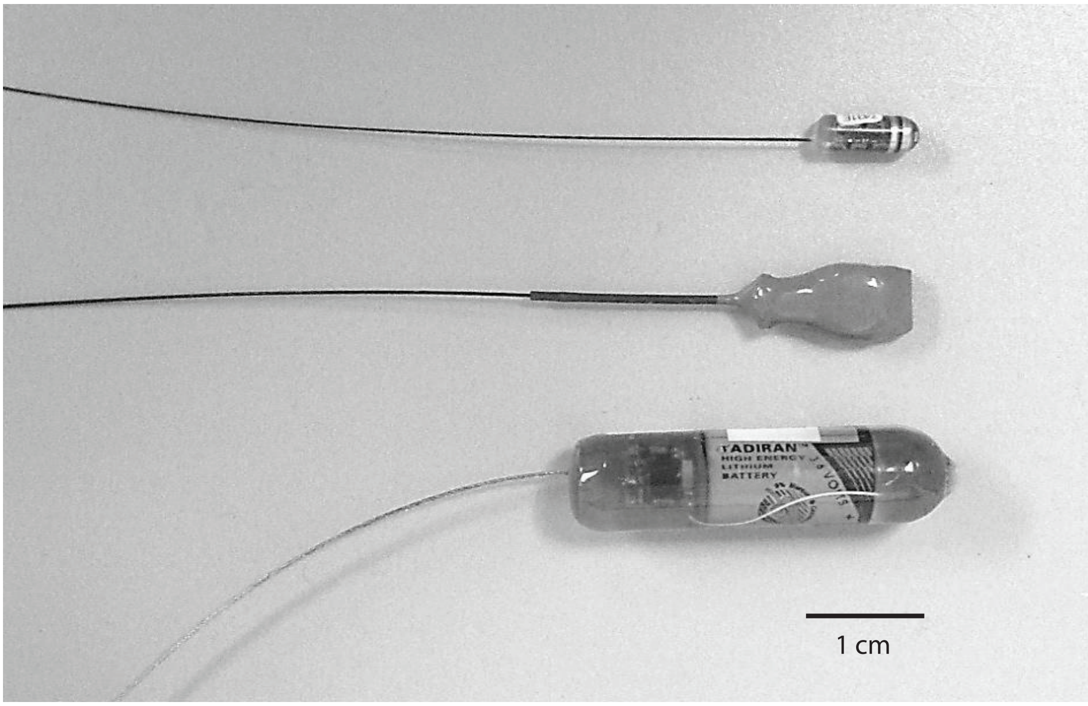

Figure 18.4 Radio transmitters (photo by S. Cooke).

ing in limited directionality. Omnidirectional antennas are usually a monopole (whip) design. Small, flexible whip antennas (<30 cm in length) are common. The most versatile antenna is a small H because it is affordable, easily transportable, and somewhat directional.

Underwater radio antennas are effective for locating fish in small streams, assessing subterranean habitat use, locating expelled transmitters or dead fish (Niemela et al. 1993; Martinelli and Shively 1997), and evaluating fishways (Bunt et al. 1999a, 2000) and entrainment at hydropower facilities (Cooke et al. 2000; Skalski et al. 2001). In its simplest form, an underwater antenna is a length of coaxial cable with one end attached to a radio receiver and the casing and shielding of the other end stripped to expose a length of the conducting coaxial core; the exposed length is dependent on the radio frequency used (Beeman et al. 2004). Specific situations may require more complicated designs (Adams et al. 1999; Beeman et al. 2004).

18.3.2.5 Acoustic Telemetry

Acoustic transmitters (Figure 18.6) use a transducer to convert electrical energy to acoustic energy. Transducers are made of lead zirconate titanate compounds in various shapes but typically are cylindrical to yield a near omnidirectional radiation pattern. Small transducers produce high frequencies and require more power to produce a given signal range than do large transducers, which produce low frequencies (Stasko and Pincock 1977). A compromise must therefore be made between transmitter size and transmitting efficiency to accommodate the largest diameter transducer possible. The typical range of frequencies used in fish telemetry studies is from 24 to 200 kHz. No evidence exists, as yet, that acoustic transmitters alter fish

Table 18.1 Effects of conductivity and radio transmission frequency on radio signal propagation loss (decibel/m) in water; based on Velle et al. (1979).

Conductivity (μS/cm)	Frequency (MHz) 30	50	100	150	200
10	0.42	0.51	0.53	0.93	1.14
20	0.57	0.67	0.70	1.12	1.35
50	1.02	1.13	1.22	1.69	1.97
100	1.76	1.91	2.08	2.64	3.01
200	3.25	3.46	3.81	4.54	5.08
400	6.22	6.57	7.26	8.33	9.22
600	9.19	9.68	10.71	12.13	13.36
800	12.16	12.79	14.17	15.93	17.50
1,000	15.14	15.90	17.62	19.72	21.64
1,500	22.57	23.68	26.25	29.21	31.99
2,000	30.00	31.45	34.88	38.70	42.34

behavior or increase predation risk (Anglea et al. 2004), although alosine shads are known to show aversion to high-intensity ultrasound in the range of 110–140 kHz (Lucas and Baras 2001).

A propagated sound signal is received by an acoustic telemetry system consisting of a submerged hydrophone connected to a receiver (Figure 18.7). When an acoustic signal is received by a hydrophone, another transducer converts the sound energy into electrical energy and generates an audible tone or records a unique signal. Omnidirectional hydrophones are used in fixed arrays and for recording sensor information. Directional transducers used either singly or in linear arrays provide accurate locations of transmitters. The most common and least expensive type of directional hydrophone is conical with a single transducer. Linear arrays are popular for ship-based tracking in open systems (Gardella and Stasko 1974).

Systems that use time-of-arrival differences among arrayed hydrophones for locating transmitters require at least three hydrophones for two-dimensional positioning and four for three dimensions (e.g., Urquhart and Smith 1992; Parkinson et al. 1996). Quality of data collected by an automated positioning system depends on the transmitter-encoding scheme, precision of the time measurement by receivers, geometry of the hydrophones, uncertainty in hydrophone locations, sound speed variability, and the specific positioning algorithm (Niezgoda et al. 2002).

Fixed acoustic-receiving systems are often moored (Figure 18.8). A disadvantage of moored hydrophones is that data can usually be downloaded only when the receivers are retrieved. Systems wired to shore-based receivers (e.g., Voegeli 1988) are used when large volumes of data are received at frequent intervals and real-time information is required (Niezgoda et al. 2002). Acoustic underwater modems can be used to download data remotely from moored loggers; they can also be used to assess memory and battery life and reprogram devices in the field. Wireless systems send information collected by hydrophones on buoys (Solomon and Potter 1988) by radio to nearby receivers and data loggers (McKibben and Nelson 1981; Bjordal et al. 1993; O'Dor et al. 1998; Lembo et al. 2002) and can provide fish location information in near-real time.

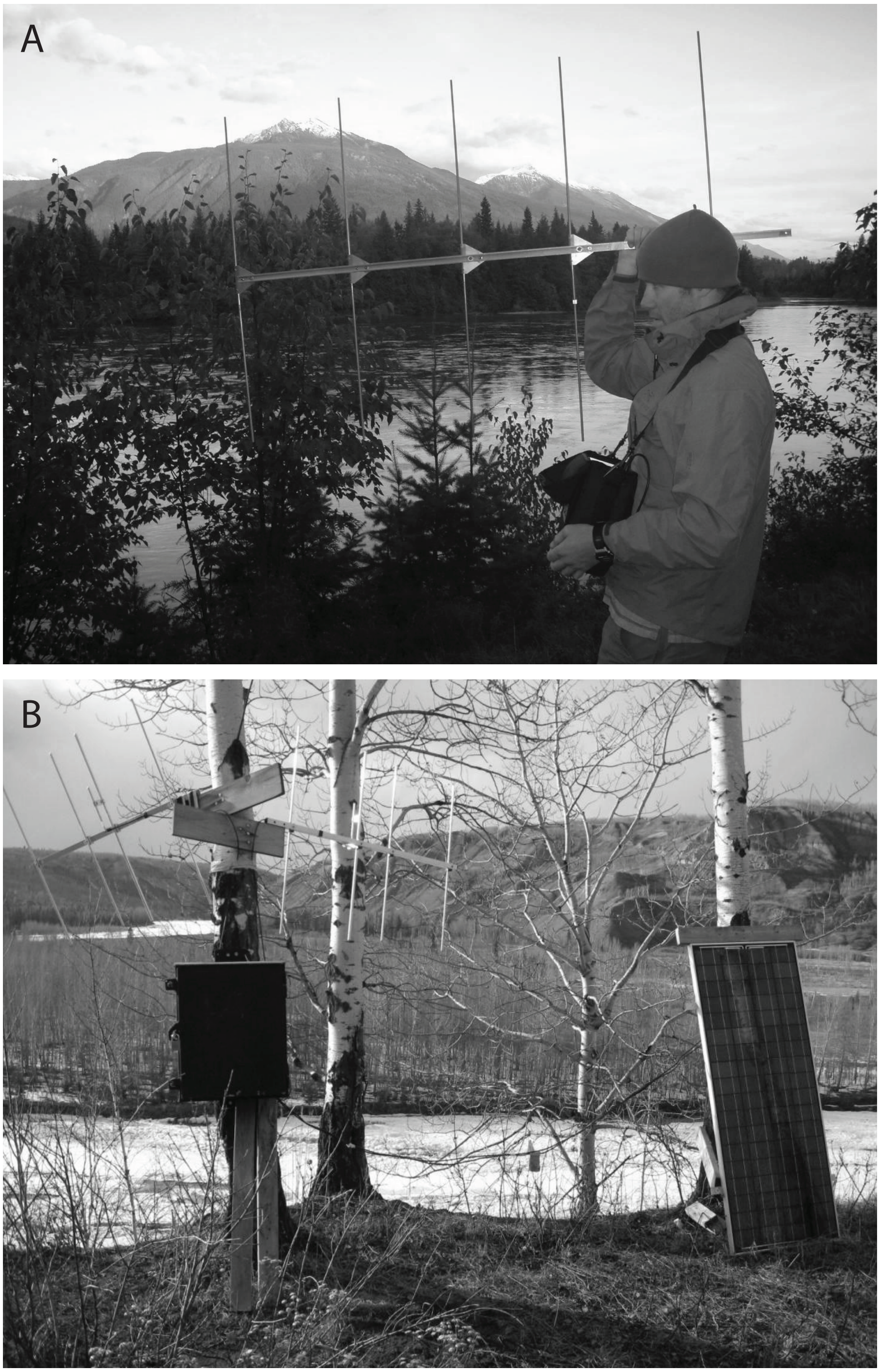

Figure 18.5 **(A)** Manual radio -tracking along a large river by means of a five-element Yagi antenna. **(B)** Fixed radiotelemetry station with two yagi antennas, solar panel, and a secure weatherproof box that contains a battery, antenna switcher, and receiver (photo [A] by S. Cooke; photo [B] by S. Tyerman, LGL Limited, Sidney, British Columbia, with permission).

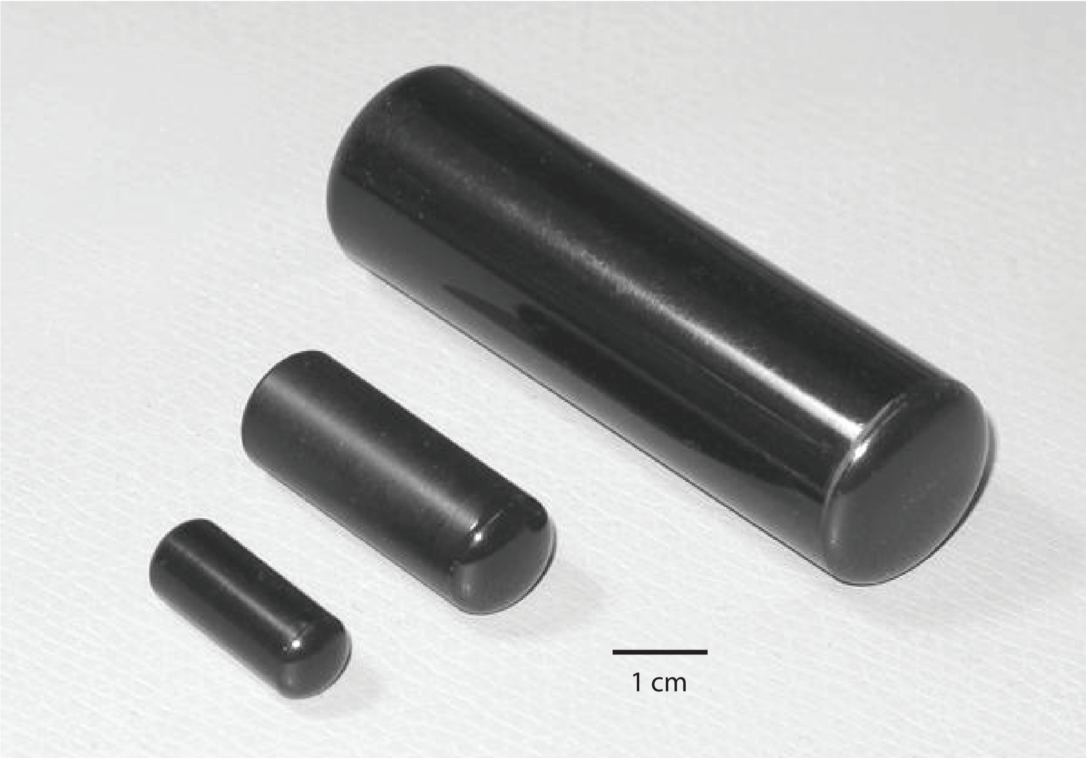

Figure 18.6 Acoustic transmitters (photo by N. Edwards, Vemco-Amarix Ltd., with permission).

18.3.2.6 Other Active Biotelemetry Techniques

Low-frequency electromagnetic telemetry. Low-frequency (LF) radio systems employing the electromagnetic induction principle can be more effective than VHF radio or acoustic telemetry in brackish or marine environments with high noise levels and reflection. Passive integrated transponder systems use this principle, but powered LF tags are also used and give greater detection range (e.g., Ramm 1980; Smith et al. 1998a). Migratory fish were tracked in the lower Rhine and Meuse system using LF (33.25 kHz) radiotelemetry (Breukelaar et al. 1998). The system is brackish, deep, and used for shipping (i.e., noisy). Each detection site consisted of three cables, 10 m apart, stretched across the channel (up to 550 m) at a depth of up to 15 m. Interrogation signals were passed every 4 s. Tags within a range of about 20 m responded by transmitting unique signals that were detected by the cable antennas. Tags passing at several meters per second could be detected efficiently.

Combined acoustic radiotelemetry. Transmitters that combine different telemetry technologies are desirable in some cases. For example, diadromous fishes occupy both coastal marine environments where acoustic technology is required and shallow freshwater rivers where VHF radio technology is preferable. Separate radio and acoustic transmitters are an option, but redundancy in battery components would add bulk. Combined acoustic radio tag (CART) technology performs in any environment (Solomon and Potter 1988). The simplest version is an integrated tag in which both output modules transmit simultaneously; the dynamic CART senses the conduc-

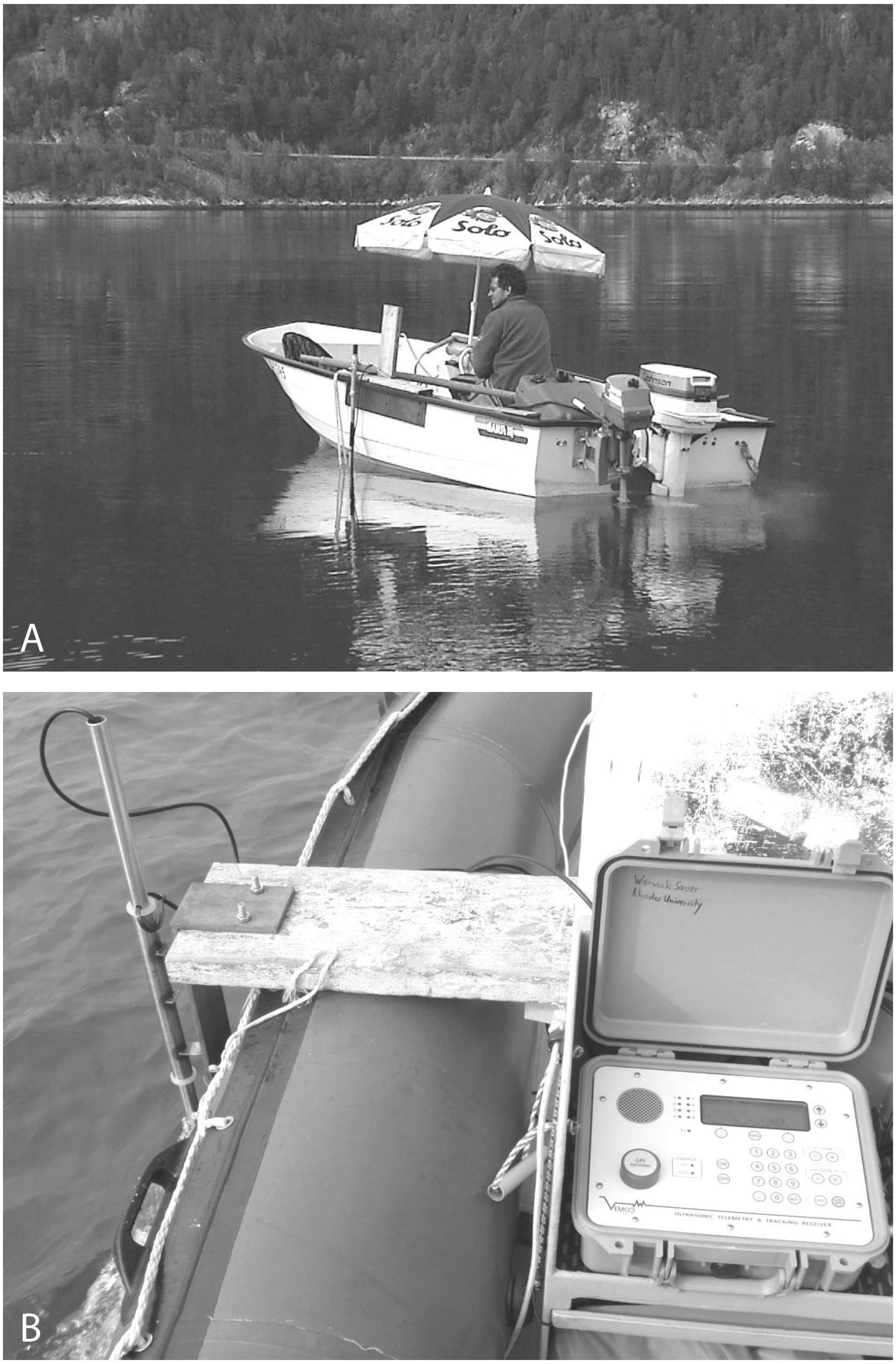

Figure 18.7 **(A)** Manual acoustic tracking; **(B)** swivel-mounted hydrophone (photos by E. Thorstad, Norwegian Institute for Nature Research, with permission).

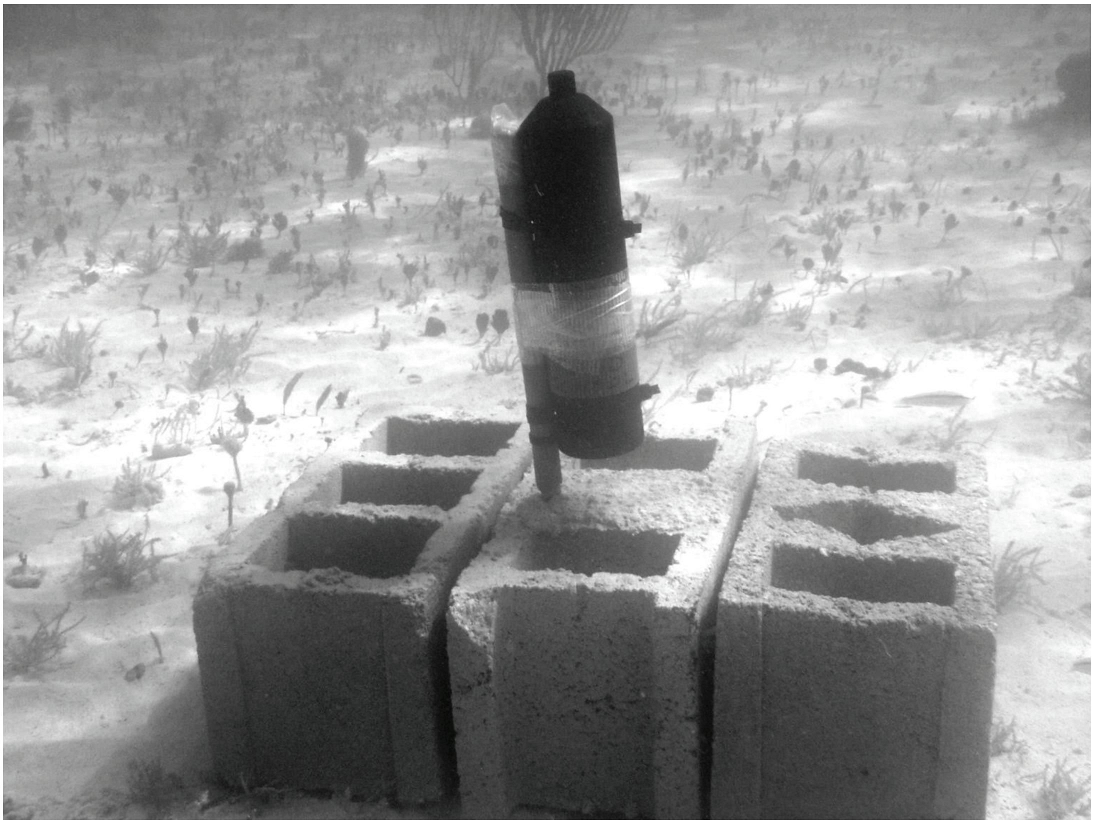

Figure 18.8 Fixed-station acoustic telemetry receiver with integrated hydrophone attached to cinder-block anchors (photo by A. Danylchuk, University of Massachusetts–Amherst, with permission).

tivity of the water with an external sensor and chooses the appropriate signal mode (Deary et al. 1998; Niezgoda et al. 1998). Such transmitters have been used to assess fish behavior in estuarine environments (Deary et al. 1998; Bridger et al. 2001a, 2001b). Combined acoustic and radio-telemetry is also employed in the RAFIX system (radio acoustic fixing; Armstrong et al. 1988), which uses the difference between arrival times of radio and acoustic signals to estimate distance to a transmitter; bearing is obtained with a directional hydrophone.

Acoustic archival modem telemetry. Communicating histogram acoustic transponders (CHAT) tags are hybrid loggers and transmitters, first logging data to memory and later transmitting the data when interrogated by a receiver. They are useful for wide-ranging fishes that have low recapture probabilities but that return to download sites (Klimley et al. 1998). The data are processed onboard to reduce transmission size. The tags include sensors (e.g., light sensors to provide geolocation information; Qayum et al. 2007), a micro-controller, memory, and a bidirectional acoustic communication system that enables the downloading of data, assessment of data quantity, and remote reprogramming to change the data sampling interval or averaging interval. Multiple CHAT tags in an area can be downloaded in sequence. The system can shift among tags to ensure that some data are downloaded from all tags, and receivers can be programmed to download only data not previously acquired.

Mobile receiver systems onboard survey vessels can interrogate CHAT tags encountered along predetermined routes. Moreover, the technology can be incorporated into animal-borne devices ("business card tags"; Holland et al. 2009) such that tagged individuals can download and store information about each other (inter-animal telemetry) in locations lacking receivers for later transmission to receivers (Rutz and Hays 2009).

Transponding acoustic tags. Acoustic transponders applied to fish can be used to obtain accurate estimates of depth and position of individual fish in the open ocean (Arnold and Greer Walker 1992; McCleave and Arnold 1999; Arnold and Dewar 2001). The transponders emit a pulse when ensonified by a high-resolution sector-scanning sonar (Greer Walker et al. 1971) or other acoustic transceiver (e.g., Collins et al. 1998).

18.4 SENSORS

Some devices can be fitted with sensors to provide information about the environment or physiological state of a fish. Ask manufacturers about sensors that are available for given devices and how they affect size, cost, coding, battery life, and other factors. Often sensor range must be selected. Determine the accuracy and precision of the sensors and the calibration needed. Some sensors require purchase of additional equipment (e.g., electrodes).

18.4.1 Temperature, Conductivity, and Dissolved Oxygen Concentration

Characterizing the external environments experienced by fish is a common use of biologgers and transmitters. Temperature is easily measured with thermal loggers and transmitters (Nelson 1978; Gupta et al. 1996) implanted internally, attached externally, or both simultaneously. External sensors respond quickly to varying environmental conditions, but body temperature of most fishes equilibrates to external conditions in a matter of minutes. Thermal telemetry tags were used to determine that tunas and sharks retain and shunt heat to specific body parts as they hunt in cool water (Carey and Lawson 1973; Marcinek et al. 2001). Simultaneous internal and external sensors can provide information on digestive processes by measuring the heat increment resulting from specific dynamic action in fishes in which visceral heat is retained (Gunn and Block 2001; Bestley et al. 2008). Sensor placement is critical, as is selection of sensors with adequate resolution and accuracy; 0.1°C resolution and 0.1°C accuracy are standard, with accuracy dictated largely by drift from initial calibration over time. Biologgers with higher resolution and accuracy are available at higher cost.

Direct biotelemetry measures of salinity experienced in estuaries are limited (e.g., Priede 1982), but conductivity is a good surrogate. Conductivity cells can be used to assess fish distributions relative to environmental contaminants. Research on hypoxia uses transmitters fitted with dissolved oxygen concentration sensors (Priede et al. 1988a, 1988b; Svendsen et al. 2006).

18.4.2 Pressure

Pressure sensors are commonly incorporated into biotelemetry and biologging devices to assess depths occupied (Luke et al. 1973; Aitken et al. 2000) but can also provide information on opercular rate (Dalla Valle et al. 2003), frequency and amplitude of tail beats (Webber et al. 2001), pericardial pressure (D. Webber, Vemco Inc., personal communication), and jet pressure of cephalopods (Aitken et al. 2000; O'Dor 2002). Depth-sensing transmitters are used to document diel vertical migrations and feeding behavior (e.g., Gowans et al. 1999; Marcinek et al. 2001) and can also indicate mortality. The resolution of pressure transducers is related to the pressure (depth) range over which they are sensitive; the greatest resolution is obtained for tags calibrated to shallow depths. Depth resolution of commercially available depth tags is about 0.1 m (±5% accuracy). Devices used for measuring opercular rate or tail beats as indicators of metabolic rate require additional calibration using respirometry (Lucas et al. 1993).

18.4.3 Light

Sensors capable of measuring light to document depth distribution and activity were incorporated into early fish-telemetry applications (Poddubny et al. 1971) but are now commonly used for geolocation of archival loggers (section 18.2.1). They are mounted externally or use a light stalk that protrudes from the fish's body. Light sensors work better in pelagic habitats of oceans or large lakes than in rivers where turbidity changes, vegetation, and physical structures can influence ambient light intensity. Light stalk shape, flexibility, and configuration can influence sensor performance and effects on fish. Modern tags have reinforced stalks with stress relief properties (Arnold and Dewar 2001). A stalk should protrude at an acute angle and minimize pressure on the exit site. Stalk length should allow light collection without producing unnecessary drag or encumbrance. However, a short light stalk may be reabsorbed into the body cavity if the tag migrates, making geolocation impossible. Biofouling or damage to the light sensor will reduce the quality of geolocation estimates.

18.4.4 Bioelectric Potential

Bioelectric potentials are measured remotely to examine electromyogram (EMG, muscle), electrocardiogram (ECG, heart), and electroencephalogram (EEG, brain) activity. Electromyogram telemetry studies monitor locomotory activity and energetics (Cooke et al. 2004c) by means of electrodes implanted in axial musculature (usually red muscle) to assess bioelectric potentials associated with muscular contraction (Weatherley et al. 1982; Dewar et al. 1999) or in opercular muscles to assess ventilation rate and energetics (Rogers and Weatherley 1983). Swimming speed, tail- beat activity, and metabolic rate can be inferred from calibrated EMG transmitter signals (e.g., Hinch et al. 1996; Briggs and Post 1997). Transmitters are implanted into the coelom (section 18.5.3), and the electrode wires are positioned using specialized plungers (e.g., Bunt 1999). Signals are coded and express activity as an integrated average relative number (Cooke et al. 2004c). Although the averaging period can be varied between 2 and 5 s, the shortest period is always preferable as natural variations in activity, especially intense activity, tend to occur at a fine time scale (Rand and Hinch 1998).

Heart rate can be a good indicator of metabolic rate and stress (Priede 1983; Lucas et al. 1992; Lucas 1994; Cooke et al. 2004b) and feeding activity (Armstrong 1986; Lucas and Armstrong 1991) and provides insight into environmental relations (Claireaux et al. 1995; Lefrançois et al. 1998). Measuring heart rate as an indicator of cardiac output, and hence metabolic demand, can be problematic in some fish that modulate cardiac output through changes in stroke volume rather than heart rate (Thorarensen et al. 1996). Continuous wave-form telemetry (i.e., frequency modulation) is necessary to obtain a complete ECG but is associated with short range and tag life. Heart rate is therefore usually telemetered by setting a voltage threshold in the transmitter to a specific part of the heartbeat, which triggers a pulse to be sent from the transmitter (Cooke et al. 2002b). A proper threshold is essential to ensure that valid signals are received. A reference electrode measures background voltage. Surgeries are intricate because electrodes are placed near the heart. Tags can be mounted externally (Cooke et al. 2002b) or internally (Campbell et al. 2005). The surface of the transmitter can act as an electrode in a gastric version (Lucas et al.

1992). Archival heart-rate loggers generally allow longer monitoring than do transmitters (Arai et al. 2000; Campbell et al. 2005).

Electroencephalography enables researchers to evaluate the neural basis of behaviors (Mensinger and Deffenbaugh 2002; Palmer et al. 2003; Palmer et al. 2005) and has been incorporated into telemetry devices only in controlled settings such as experimental ponds or laboratory tanks because range is short (e.g., 5 m; Kudo et al. 1997) and data are collected at a high rate, thereby resulting in short tag life. The poor range and short tag life characteristics of continuous-wave frequency-modulated tags make them ineffective for field applications.

18.4.5 Flow

Sensors integrated into telemetry or logging devices can measure the flow of fluids inside or outside fish. Doppler sensors can monitor cardiac output (Webber et al. 1998) and magnetically or optically sensed rotors can be used to quantify fish swimming speed. Acoustic telemetry versions of these devices have been used in marine environments, typically on large fishes (Voegeli and Pincock 1981). They work well on continuously swimming, marine pelagic fishes, such as obligate ram ventilators. The rotors tend not to function effectively at low swimming speeds.

18.4.6 Appendage or Body Orientation

Appendages such as wings and fins can be outfitted with sensors to quantify beat rates (Wilson and Liebsch 2003), but most fishes are too small for such devices. Lowe et al. (1998) built a tag that measured caudal fin beats by means of a magnetic sensor and used it to monitor shark energetics (Lowe 2002). Transmitters that vary pulse rates with changes in body position can be used to quantify activity (Baras et al. 1998), mortality, feeding behavior (Perrow et al. 1996), and swimming direction and orientation. Loggers measuring and recording the earth's magnetic field in relation to fish orientation and movement are now increasingly being employed, for example, in oceanic homing studies of Atlantic salmon (J. Sturlaugsson, Salmon and Trout Research, Iceland, unpublished data).

18.4.7 Acceleration and Activity

Acceleration and activity sensors provide detailed information on animal activity or mortality by measuring movements. Mercury-tip switches are commonly used as mortality sensors in biotelemetry tags. The signal emitted by a transmitter changes if it is stationary for a predetermined period (Bettoli et al. 2000). Mortality and tag expulsion cannot be differentiated, and a fish that is preyed upon may not be immediately recognized as dead. Mercury switches can also be used to assess general activity but only in a binary active versus inactive sense (Eiler 1990). Accelerometers in loggers (Kawabe et al. 2003) and transmitters (Murchie et al. 2011) can be used to assess swimming dynamics and energetics. "Daily diary" tags are used to document movements and orientations of large pelagic fishes (Houghton et al. 2009). For long-term energetics studies, acceleration and activity devices may be preferable to those measuring bioelectric potentials because they do not require implantation of electrodes.

18.4.8 Imagery

Miniaturized cameras and video recorders can be attached to marine mammals (Marshall 1998) and large fishes to determine habitat use and study foraging behaviors (Heithaus et al. 2001, 2002). Acoustic transmitters are usually incorporated into the devices to track individuals; radio transmitters facilitate floating-camera recovery after release (Heithaus et al. 2001). Live transmission of videographic data from common carp by means of a VHF carrier in the television band (90–108 MHz) and an underwater antenna was limited to shallow waters, large fish, and a confined area where the antenna could be focused (Kudo and Takeuchi 2000). Improvements in deployment duration, signal transmission, battery longevity, data storage, and equipment size will increase fisheries applications of image sensing (Cooke et al. 2004a).

18.5 TAG ATTACHMENT PROCEDURES

Established techniques for attaching biotelemetry and biologging devices to fish include surgical placement in the body cavity (internal), insertion into the stomach (gastric), and attachment to the external surface of the fish (Table 18.2). Handling, attachment procedures, and physical presence of the device should not affect fish behavior or physiology (Bridger and Booth 2003), and fish welfare must be considered (Mulcahy 2003; Wilson and McMahon 2006). Anesthesia (Summerfelt and Smith 1990; Iwama and Ackerman 1994; Ross and Ross 1999) may be required depending on species, objectives, attachment method, and ethical and legal requirements. Attachment must be done with care and only after consultation with a veterinarian and someone experienced in the technique and approval by an IACUC (Mulcahy 2003; Cooke and Wagner 2004). Moreover, substantial interspecific variation in anatomy, morphology, and response to surgery dictates that even experienced personnel practice procedures on new taxa or with new devices in the laboratory prior to field applications if at all possible.

A disinfectable surgical suite with controllable light levels and environmental conditions is ideal for device attachment in laboratory studies (Figure 18.9) but is rarely available except in clinical veterinary situations (e.g., Stoskopf 1993; Lewbart and Harms 1999). Moreover, temporary laboratory occupancy is stressful to many wild fishes, and local regulations may prohibit release of fish back into natural systems after temporary removal.

Restraining and supporting fish during attachment is necessary. Minimally invasive tagging techniques such as external tagging, gastric implantation, and needle injection of PIT tags may not require full general anesthesia and can be done by placing a fish in a cooler, sling, or trough. However, in some countries such as the UK and Germany, light general anesthesia is required for such procedures as well. Anesthesia is generally recommended for all tagging to reduce stress. Restraint and anesthesia also promote human safety, as a tag injector needle could cause injury if a fish moves unexpectedly. Fish should never be held out of water because air exposure is stressful and can have negative physiological consequences (Ferguson and Tufts 1992). Ideally, water should be flowing and continuously aerated, but static water may be adequate in some situations. A soft padded trough (Cooke et al. 2005) with water inflow at one end, an integrated measuring tape, and containers for holding tools is ideal for restraining fish for external or gastric procedures. Large marine fish brought aboard boats are held on plastic sheets on the deck and provided with flowing water by means of a funnel-shaped mask (Block et al. 2001).

Laparotomies (abdominal surgeries) require restraint and general anesthesia (Mulcahy 2003). Exceptions exist (e.g., Humston et al. 2005) but are limited to specific situations (e.g., tonic immobility, in which restraint of a shark in an inverted position leads to the cessation of movement, and surgery is typically conducted in the water; Holland et al. 2001; Figure 18.10). Water flow into the mouth and over the gills is necessary (except for lampreys, which ventilate tidally through their gill slits). Water depth should be sufficient to submerge the gills fully. Because most laparotomies occur through the ventral surface, fish should be positioned supine (Figure 18.10). The head is usually positioned below the body so that water will submerge the gills but not enter

Table 18.2 Comparison of attachment procedures.

	Attachment procedure		
Factor	External	Gastric	Intracoelomic
Species limitations	Not suited for small fishes, migratory species, and fish in highly vegetated or high-velocity habitats	Limited to fish that are not actively feeding for forced insertion; voluntary ingestion in bait by scavengers	Expulsion possible in some taxa
Attachment in the field	Easy	Easy	Requires specialized equipment
Speed of procedure	Seconds to minutes	Seconds	3 to 10 minutes
Attachment complexity	Simple	Simple	Complicated
Anesthesia	Preferable	Preferable	Essential
Asepsis	Device cleanliness is irrelevant, but attachment harness or anchors should be clean and ideally sterile	Devices should be clean but need not be sterile	Devices must be sterilized
Infection potential	Possible at site of attachment	Unlikely unless esophagus or stomach is punctured	Possible after surgery and at transcutaneous antenna or sensor exit sites
Signal attenuation	None	Limited	Limited
Tag retention	Short to medium term; weeks to months	Short term; hours to weeks; can be regurgitated	Long term; months to lifetime; expulsion possible in some taxa
Drag and fouling	Significant	None	Trailing radio antennas can cause drag and become fouled
Behavior alteration potential	Drag may affect swimming; fish may attempt to rub off device; may attract predators	Minimal in fasting fish	Minimal after healing if device is not too big (mass or volume or length of antenna)

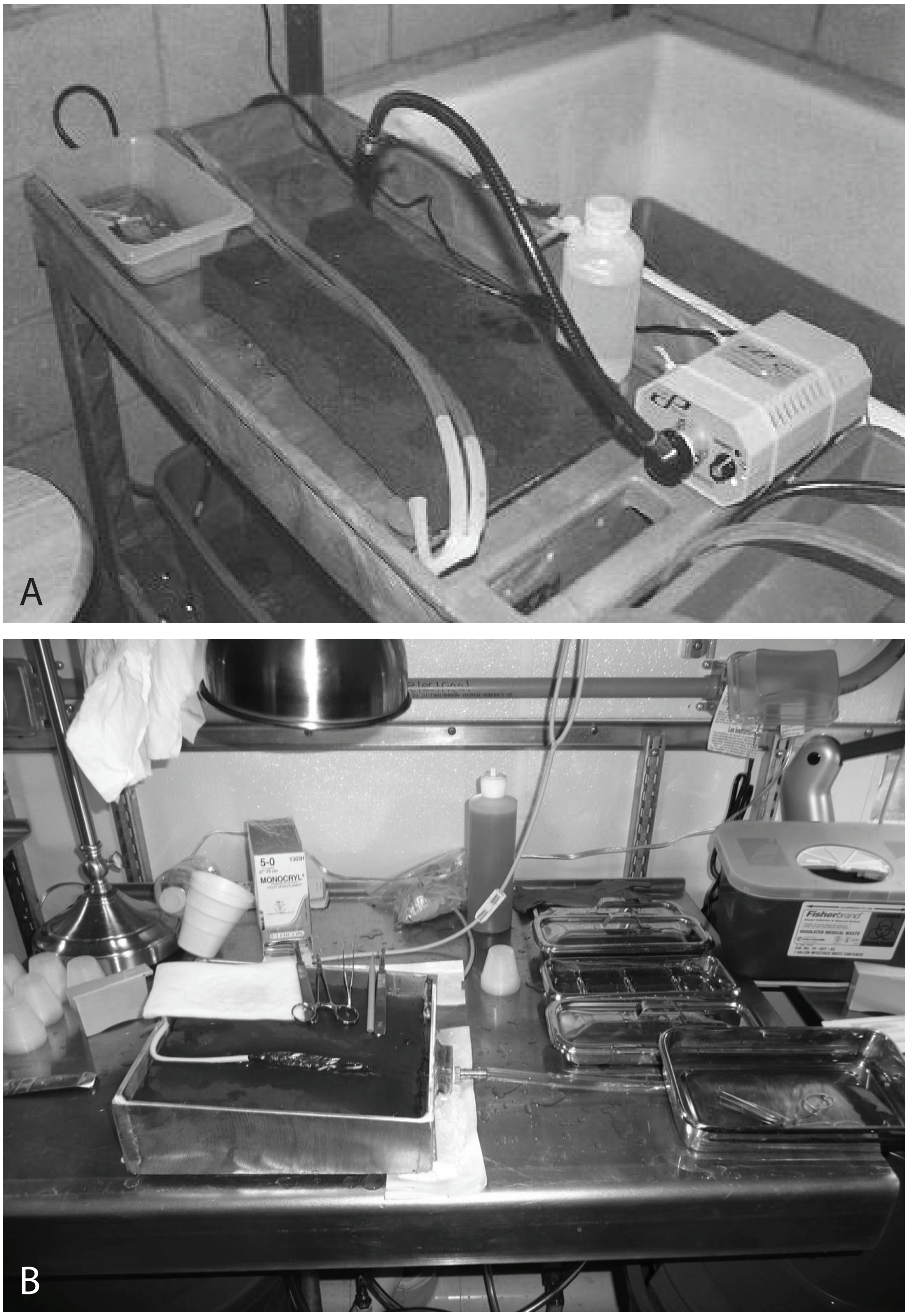

Figure 18.9 **(A)** A simple surgical tagging setup that can be used in most laboratory and field settings; **(B)** inside a tagging trailer built for annual implantation of thousands of Pacific salmon smolts. Visible in the photos are anesthesia baths, cleaning solutions, and supplies needed to conduct surgery (photo [A] by S. Cooke; photo [B] by R. Brown, Pacific Northwest National Lab, with permission).

Figure 18.10 **(A)** Intracoelomic implantation of a transmitter in an adult Pacific salmon. Note that the gills are constantly irrigated with aerated water. **(B)** Intracoelomic implantation of an acoustic tag in a juvenile lemon shark by means of tonic immobility. In this case, the fish is held in the water rather than placed on a surgery table, which is rather unique to sharks (photo [A] by S. Cooke; photo [B] by Edd Brooks, Cape Eleuthera Institute, with permission).

the incision. Foam rubber can be used to support fish evenly but should be covered with a clean plastic sheet and disinfected between surgeries.

18.5.1 External Attachment

External attachment of telemetry tags and loggers is effective for short studies (days to weeks; Ross and McCormick 1981; Mellas and Haynes 1985; Okland et al. 2003) and is often the only way to tag large, pelagic marine fishes effectively and safely. External tagging can be done quickly and without anesthesia if necessary and permitted. It may be less harmful than more invasive techniques for some species and situations (e.g., high temperatures) but should generally be avoided because of the potential for transmitter or sensor damage or loss and fish health considerations.

Large pelagic species can be tagged in the water alongside a boat (Holland et al. 2001) or using commercial fishing techniques (Lutcavage et al. 1999; Neilson et al. 2009; Figure 18.1). Spotters in light aircraft direct tagging boats to targets (Lutcavage et al. 2000; Eckert and Stewart 2001; Skomal et al. 2004). Transmitters are attached to medical-grade nylon tag heads by means of monofilament line and anchored in the dorsal musculature of free-swimming fish by free-throw harpooning (Chaprales et al. 1998). Coelacanths were externally tagged using pneumatic guns mounted on a manned submersible (Schauer et al. 1997). Dart or T-bar anchor tags (Chapter 11) attached to transmitters or loggers by cables can be applied externally by divers or from boats with tagging poles (Priede 1984) or spearguns (Sims et al. 2003).

Devices can be attached to dart tags that are inserted into fish tissue (e.g., Collins et al. 2002) or attached with single-strand surgical stainless steel wires (Figure 18.11), sutures, or nylon cable ties (Skomal and Benz 2004). Comparative performance of different attachment materials is unknown, but large-diameter absorbable sutures were retained longer than small-diameter sutures (Sutton et al. 2004). Nonabsorbable sutures are recommended for large marine species (Holland and Braun 2003). The wires or suture materials are passed through the fish by threading them through hypodermic needles; after removing the needles, the tag is pulled snugly against the fish. A backing plate is often used to secure the tag when wires are twisted. Sutures are tied in place or a crimp is used to secure them. Transmitters can be attached to the fin base (J. Pitlo, Iowa Department of Natural Resources, unpublished data) or spines (Campbell et al. 2005) of fish with spiny or robust dorsal fins.

Abrasion can occur at or near the attachment site, leading to dermal disturbance, fungal infection, and tag loss (Bégout Anras et al. 2003; Jadot 2003) even when soft harnesses made of neoprene or other cushioning materials are used (Beaumont et al. 1996; Herke and Moring 1999). Soft flexible materials such as rubber are preferable to neoprene (Herke and Moring 1999; Sutton et al. 2004). A ballast pannier that positions the battery on one side and other device components on the other (e.g., Lewis and Muntz 1984; Cooke et al. 2002b) helps fish compensate for off-center positioned transmitters.

External transmitters produce drag and can become entangled, thereby affecting behavior or tag retention or both. They can also become fouled with debris or living organisms (e.g., algae, mussels, and barnacles; Thorstad et al. 2001). Wounds in the dorsal musculature can result. External tags can also alter swimming performance (Lewis and Muntz 1984; Mellas and Haynes 1985) and cause substrate-scraping behavior (Collins et al. 2002). Transmitter shape can affect retention, with cylindrical shapes preferable to compressed designs for some fishes (Sutton and Benson 2003). In some cases, it may be possible to recapture fish and remove the devices (e.g., Connolly et al. 2002; Benson et al. 2005).

Pop-up satellite archival tags attached to tunas and billfishes are usually anchored in the pterygiophore bones at the base of the second dorsal fin or in dorsal musculature by means of a biomedical nylon or metal dart attached to a monofilament tether (Figure 18.1). In whale sharks, the dart may be anchored near the first dorsal fin. Premature detachment and shedding is common in PSAT studies (Holland and Braun 2003; Sibert et al. 2006) and may result from

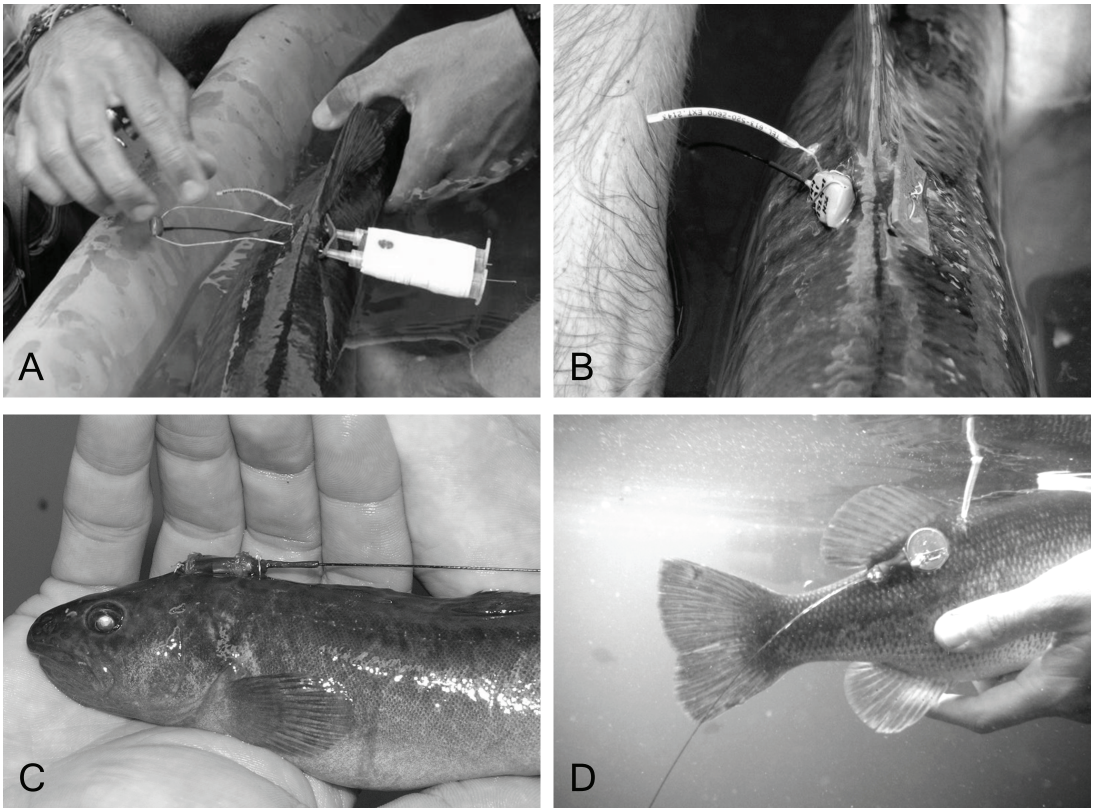

Figure 18.11 External radio tagging: **(A)** a pair of needles with a backing plate is pushed through the dorsal musculature of an adult muskellunge; **(B)** a stainless steel harness attached to a transmitter is passed through the lumens of the needles and secured to the backing plate. **(C, D)** Placement varies according to size and shape of the tag and the fish (photos [A] and [B] by S. Landsman, Carleton University, with permission; photo [C] by J. Thiem, Carleton University, with permission; photo [D] by S. Cooke).

inflammatory response and tissue rejection of the dart, inadequate anchoring in the body, predation by other fish, or physical tag failure. A tag's fail-safe release mechanism (invoked when a preassigned depth is exceeded) may be prematurely activated, or onboard software may fail. Although flat titanium darts have been used in shark and tuna PSAT tagging studies, biomedical nylon darts, such as the Billfish Foundation's large pelagics design, and umbrella anchors (Domeier et al. 2005) may be superior because their edges are not sharp and flat and are therefore less likely to migrate. Rotation and movement of PSAT tethers made from hard monofilament or fluorocarbon and braided stainless wire can excavate holes in skin and musculature and cause premature tag loss. This cutting action can be reduced by placing a silicone sleeve over the tether. Crimps or sleeves should be stainless steel to avoid galvanic interaction with the tag's corrodible link in the nose cone. Tether material or crimps can fail because of fatigue, improper application, or weathering. Tether length should allow the positively buoyant tag to trail behind the fish and not interfere with the dorsal fin.

18.5.2 Gastric and Urogenital Implantation

Devices can be passed through the esophagus (either forcibly or voluntarily) and into the stomach (Figure 18.12). Gastric insertion avoids invasive surgery, requires little handling, and allows for a short recovery time. It is good for short studies; long deployments often fail because

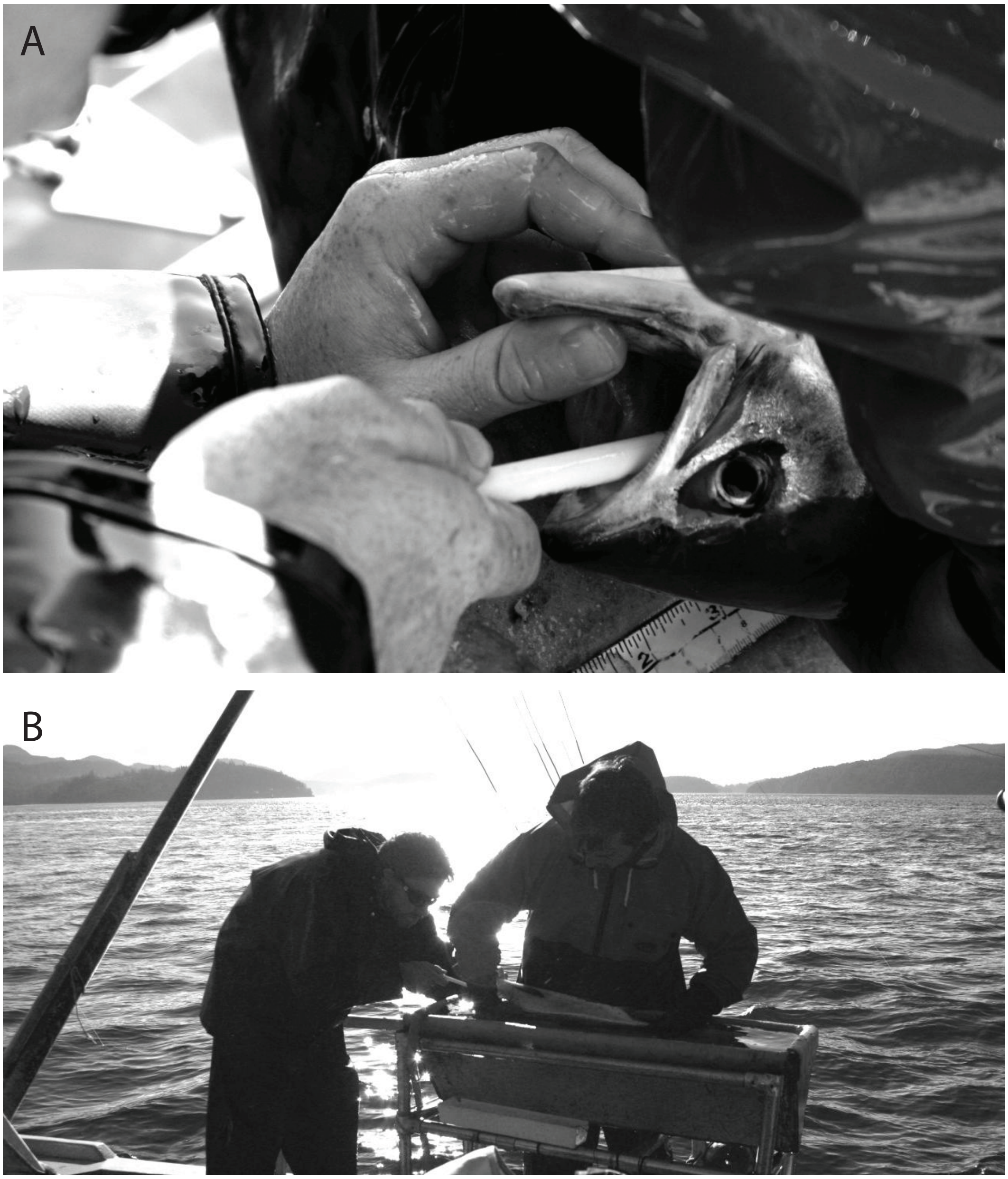

Figure 18.12 **(A)** Gastric radio tagging of an adult Pacific salmon using a smooth plunger. **(B)** The fish is held in a water-filled trough to minimize air exposure and to protect the fish from handling (photos by J. Burt, University of British Columbia, with permission).

of poor retention in actively feeding fish (Lucas and Johnstone 1990). Tagging-induced mortality is low, and fish can continue to feed with tags in their stomachs (Lucas and Johnstone 1990). Devices can be expelled by regurgitation or egestion. Voluntary ingestion of tags wrapped in bait may be the preferred or only viable method of tagging some fishes (e.g., Priede and Smith 1986). Gastric insertion has been widely used in long-term studies of migrating, nonfeeding adult salmonids (English et al. 2005; Cooke et al. 2006). Regurgitation rates were 15% in Atlantic salmon and can be higher for other species (Smith et al. 1998b). The rate of expulsion is influenced by fish species (Nielsen 1992; Ramstad and Woody 2003) and relative tag size. Large tags are more likely to be regurgitated whereas small tags are more prone to egestion (Nielsen 1992). Rubber bands or rings of surgical tubing around the transmitter increase roughness and may reduce regurgitation (Keefer et al. 2004b). Because retention rates vary, we recommend preliminary laboratory studies to assess retention rates before initiating large-scale field deployments. The method of capture can also influence retention rate (Marmulla and Ingendahl 1996).

Gastric insertion is the least invasive attachment method if done correctly. Care must be taken when inserting a transmitter to ensure that the esophagus and stomach are not ruptured (McCleave and Horrall 1970; Solomon and Storeton-West 1983). The method is most suitable for predators with well-defined muscular stomachs. Plungers used for insertion should be smooth; lubrication can aid insertion. Dentition or mouth morphology of some fishes necessitates use of a flexible plunger (Cooke and Philipp 2004). A transmitter with an antenna can be inserted by holding the antenna in place at the end of a smooth, rigid tube by its antenna, which has been threaded through the tube. Whip antennas can trail out of the mouth or exit through the opercular opening. Antennas can be sutured to the roof of the mouth or to the body wall of the fish to minimize abrasions and infections.

Transmitters can be inserted into the urogenital openings of females of some species such as salmonids prior to ovary development or after spawning (Peake et al. 1997). Expulsion of such tags was used to identify northern pike spawning sites (Pierce 2004).

18.5.3 Intracoelomic Implantation

Intracoelomic implantation of biotelemetry and biologging devices is the most frequently used technique of attachment (Lucas and Baras 2000) and is the best for monitoring long-term behavior of fishes (Cooke et al. 2011).

18.5.3.1 Aseptic Technique

Maintenance of sterile conditions during surgery is standard for mammals, birds, and even reptiles but is not feasible for fish because it is impossible to sterilize (remove all pathogenic organisms, for example, by autoclaving) or to disinfect (decrease pathogens) water during surgery (Wagner and Cooke 2005). However, sterilization of equipment is possible and beneficial and can be achieved in field settings by use of a hot-bead sterilizer or solutions such as Cidex followed by rinsing with sterile saline (Harms 2005). Inexpensive portable autoclaves can be taken into the field. Multiple sets of sterile surgical tools (one set per fish) can be prepared and packaged in the laboratory for use in the field. The long-term benefits outweigh the initial capital investment (Mulcahy 2003). Rinsing tools in water or cleaning with ethanol or povidone iodine solutions is insufficient for complete sterilization but does have some disinfection benefits (Harms 2005). Suturing material should be sterile. A new pair of surgical gloves should be used for every fish to protect the fish and the surgeon. Standard nonsterile surgical gloves are suitable provided that they do not touch the incision. Avoid touching the fish with gloves during surgery to maintain a clean field. Transmitters should be disinfected if sterilization would damage them. Tags can be soaked in antiseptic and thoroughly rinsed in sterile saline. A sterile plastic drape helps maintain a clean surgical area, keeps the fish moist, prevents fin and skin desiccation, and prevents water from entering the incision site (Harms 2005). Water should be kept out of the incision because it can promote bacterial growth in the peritoneal cavity and result in mortality (Nemetz and MacMillan 1988). The incision site should not be disinfected because topical antiseptics disrupt the protective cutaneous mucus layer of fish, allowing easier penetration by pathogens, and provide no benefit to wound healing (Hart and Summerfelt 1975; Wagner et al. 1999).

18.5.3.2 Incision and Device Placement

Incisions are typically made along the ventral midline or just lateral to it; pros and cons exist for both sites (Wagner et al. 2011). The incision site must not be impeded by bony structures such as the pelvic girdle or by associated paired-fin musculature. For strongly laterally compressed species with thick ventral body walls, incision on the lower part of the lateral surface may enhance access to the body cavity but will probably result in greater disruption of muscle and bleeding. Scale removal may facilitate surgery (e.g., Parsons et al. 2003).

Because the color of body wall musculature is often similar to that of the underlying viscera, the incision must be made in a careful and controlled manner (Harms 2005; Figure 18.10). Curved forceps with blunt tips can be used to lift the body wall upward from the viscera, and insertion of a scalpel shield can help avoid cutting the viscera. When possible, the incision should be made with a single cut to prevent maceration of the tissue. It should be of sufficient length that the transmitter can be inserted without touching the surrounding skin. Typically, bleeding during surgery is minor and can be controlled with sterile swabs or pads. Use sterile saline solution to clean a bleeding wound. Under the supervision of a veterinarian, advanced techniques such as bipolar electrocautery can control bleeding in specialized applications.

Electrodes, antennas, and external sensors should be inserted before the main device. Antennas or sensors should always exit the lateral body wall and not the primary incision site (Harms 2005). The antenna or sensor stalk should be threaded through a cannula passed through the body wall at an acute angle, maximizing the distance between the internal and external transcutaneous openings to reduce the potential for contamination of the coelom (Harms 2005). If going from the inside of the body outward, make sure that the entire cannula can be removed by pulling it through the cavity. It is also possible to enter from the outside and feed the antenna back through; a needle shield can be used to protect the viscera (Ross and Kleiner 1982). After the transmitter package has been placed in the coelom, it should be positioned away from the incision to minimize the likelihood of pressure necrosis in the vicinity of the wound and subsequent tag loss (Marty and Summerfelt 1986).

18.5.3.3 Closure Materials and Techniques

The majority of fish surgeons use monofilament suture material to close incisions; 47% use absorbable and 27% use nonabsorbable sutures (Wagner and Cooke 2005). Braided silk sutures are used by 13%. Monofilament sutures reduce tissue inflammation and promote long-term wound healing (Kaseloo et al. 1992; Thoreau and Baras 1997; Wagner et al. 2000; Wagner and Stevens 2000; Hurty et al. 2002; Cooke et al. 2003; Wagner et al. 2011). Braided silk (or other multifilament material) is easier to tie and cheaper than monofilament but is suitable for only short-term laboratory deployments or fish that will be euthanatized shortly after tagging (Harms 2005). In freshwater, absorbable materials can still be present after one year; however, in the more ion-rich marine environment, absorbable materials tend to dissolve more rapidly. Absorbable suture materials tend to break down more rapidly at high temperatures (Walsh et al. 2000). The most common suture sizes used for small to medium fishes are 2/0, 3/0, and 4/0; larger diameters are used on larger fish (e.g., sizes 0, 1, and 2). The effect of suture diameter on healing is not well understood but small diameter sutures (4/0) can cut tissue. Cutting-tip suture needles are preferable over round needles. Suture kits in which the strands are attached to the needles with swages are convenient.

Choice of the appropriate knot for a given situation and proper execution of it are critical (Wagner et al. 2011). Satisfactory patterns are simple continuous, simple interrupted, horizontal mattress, and continuous Ford interlocking (Wagner et al. 2000; Harms 2005). The simple interrupted suture is the most common type in fish surgery and is also the easiest. If this suture method is used, the first suture should be placed in the midpoint of the wound, with successive sutures made distally in alternate directions at 2–4-mm intervals. Appropriate tension ensures that opposing tissues are evenly aligned upon closure, making the wound watertight and snug (Harms 2005) but not puckered from too much pressure. Some applications may require inner muscular suturing with absorbable sutures prior to an external closure to minimize knot surface area and reduce drag (Harms 2005).

Surgical staples have been used infrequently for fish surgery (Wagner and Cooke 2005) even though they can be used quickly and with minimal skill (Mulford 1984; Filipek 1989; Mortensen 1990). Healing of incisions is variable and can result in high rates of transmitter loss (Haeseker et al. 1996; Swanberg et al. 1999; Starr et al. 2000). Staple size must be matched to the organism to eliminate tissue tearing and minimize necrosis of the wound margins (Wagner and Cooke 2005).

Veterinary grade cyanoacrylate glue can be used to close wounds (Nemetz and MacMillan 1988; Petering and Johnson 1991), but the wounds may reopen and inflammation and tissue necrosis can occur (Petering and Johnson 1991). Glue is best employed for only small incisions and for locking sutures into place. In one study, European eels bit at their wounds and removed the glue; however, a biological bandage made from freshly cut eel fin suppressed this behavior and enhanced healing (Baras and Jeandrain 1998).

18.5.3.4 Tag Expulsion

Tag expulsion is common and occurs in several ways. A tag can be expelled through the incision soon after implantation if the incision does not heal correctly or if sutures fail. After healing, transmitters can be expelled through the site of the incision (Marty and Summerfelt 1986), another part of the body wall (Lucas 1989; Baras and Westerloppe 1999), the antenna exit site (Isely et al. 2002), or the intestine (Summerfelt and Mosier 1984). Factors that appear to affect expulsion include tag size and density, tag placement relative to the incision site (Baras and Westerloppe 1999), species, and transmitter coating (Sakaris et al. 2005). Tag expulsion is especially common in catfishes (Baras and Westerloppe 1999) but has also occurred in blue trevally (Meyer and Honebrink 2005), rainbow trout (Lucas 1989), striped bass (Walsh et al. 2000), and Atlantic salmon (Moore et al. 1990). It does not always lead to fish mortality (Marty and Summerfelt 1986; Lucas 1989; Baras and Westerloppe 1999). Suturing the implanted device to the pectoral girdle (cleithrum) with nylon suture material reduces the probability of expulsion and enables long-term monitoring (Siegwarth and Pitlo 1999). Prophylaxis and antibiotics may minimize or prevent expulsion of tags (Baras and Westerloppe 1999).

18.5.3.5 Postoperative Care

Surgery, anesthesia, and related handling are stressful, and fish require time for recovery (Lower et al. 2005). This is often a neglected aspect of transmitter attachment; fish are often released immediately after they have become alert and responsive. Fish must be monitored closely during recovery, and efforts should be made to assist with their revival. It may be necessary to hold surgically implanted fish temporarily to enable recovery and acclimation to the presence of devices if a high predator burden exists in the release area (Zeller 1999) or if water velocity or depth will create problems (Perry et al. 2001). Blue tilapias needed 3–4 d to compensate completely for the negative buoyancy resulting from anesthesia and tagging (Thoreau and Baras 1997). However, captivity can also generate additional stress, especially for wild fish (Jepsen et al. 2001). If fish are temporarily held in captivity, they must be provided with adequate water quality. Before release, observe their condition and behavior. Fish that are not in the best possible condition should not be released with a valuable electronic tag because they are a poor survival risk and unlikely to provide useful information. Fish that appear distressed should be euthanatized humanely.

18.5.4 Procedures for PIT Tags

Passive integrated transponder tags are implanted internally by insertion into the dorsal musculature or body cavity or subdermally (but can be attached externally for short-term experiments; e.g., Castro-Santos et al. 1996). Light anesthesia is recommended. Intramuscular insertion of 12-mm tags with 12-gauge needles in large fish minimizes risk of damaging vital organs (Bergersen et al. 1994); tags can be purchased in ready-to-use sterilized needles or single-shot injectors. Tags purchased loose or in blister packs are less expensive but must be sterilized if they are to be implanted. Plastic-coated (rather than glass) PIT tags are more acceptable for use in commercially harvested fishes. Muscular injections are made at a 20–30° angle to the sagittal axis of the fish. The tip of the needle is passed between scales and inserted about 20 mm into the muscle. The needle is gently removed as the plunger is pressed to deposit the tag in place. The tag becomes encapsulated by host connective tissue within a few days and is generally retained over the life of the animal if it has been inserted deeply enough. The wound heals within a few days or weeks and is rarely visible after one month.

The body cavity is the preferred PIT tag site for small fishes (<40 g) because their musculature is generally too thin for insertion of 12-mm tags; tag loss, mortality, or tissue damage can result. Prentice et al. (1990a) recommended insertion into the body cavity for all fish regardless of size because viscera are rarely consumed by humans. Larger PIT tags are usually inserted into the body cavity also. To minimize the risk of internal damage when inserting a PIT tag into the body cavity, the anesthetized fish is placed supine so that the viscera lie away from the abdominal body wall. The needle of the injector is held obliquely to pierce the body wall and then gently rotated 180° so that the cutting edge is farthest from the viscera. The needle is then pushed close to the body wall, the tag is injected, and the needle is removed. This protocol was used successfully in salmonids weighing less than 2 g (Prentice et al. 1990b).

Needle injectors are difficult to use on scaleless species as well as those with thick scales. For fish with thin body walls or when large PIT tags are used, the sterilized tag can be manually inserted or injected through a small incision made with a scalpel (e.g., Baras et al. 1999; Roussel et al. 2000; Skov et al. 2005). Such wounds heal rapidly and usually do not require suturing when small tags are used; however, sutures or tissue adhesive are beneficial when large tags are used or if healing is slow.

When assistants provide anesthetized fish ready to tag, PIT-tagging rates of 40 fish per hour can be achieved for surgical insertion with suturing, 100 fish per hour for surgical insertion without suturing, and 150 fish per hour for insertion with handheld injectors. Tagging rates of over

300 fish per hour are possible using semiautomatic injection systems equipped with clips containing over 100 tags (Prentice et al. 1990c; Achord et al. 1996). Tag retention is close to 100% when appropriate procedures are used.

18.6 MANUAL-TRACKING TECHNIQUES

18.6.1 Frequency of Tracking

The frequency of tracking depends on study objectives and logistic constraints. High-frequency positioning gives an accurate view of fish movements but may be impossible because of environmental constraints, costs, or transmitter life span (Baras 1998). However, low-frequency tracking can reduce estimate accuracy because less information is collected (Baras 1998). For example, tracking at 24-h intervals resulted in several hundredfold lower activity estimates than did tracking every 10 s using a fixed two-dimensional acoustic positioning system (Hanson et al. 2007). Activity estimated by physiological telemetry tends to be higher than that estimated from manual tracking or fixed telemetry (Lucas et al. 1993; Demers et al. 1996; Cooke et al. 2001). Sampling intervals longer than 1 d generate substantial bias, reducing accuracy of home range estimates by 0–82% and mobility estimates by 5–92% (Ovidio et al. 2000). Increasing the time interval between successive locations from 2 to 28 d caused high losses of accuracy for mobility and lower losses for home range (Baras 1998). Time of day must also be considered because repeatedly locating fish at the same time of day can bias activity estimates (Lucas and Baras 2000).

Fixes made at close intervals (e.g., <4–6 h; Winter 1996) are unlikely to be statistically independent, affecting the applicability of some statistical procedures (Swihart and Slade 1985; Cresswell and Smith 1992; Samuel and Fuller 1994; Chapter 2). Standard statistical tests such as repeated measures analysis of variance (Hinch et al. 1996) can account for this problem. The Animal Movement extension of ArcView (Hooge and Eichenlaub 2000; Hooge et al. 2001) incorporates Schoener's t^2/r^2 ratio for assessing autocorrelation (Schoener 1981). Most tools for dealing with autocorrelation produce a greater bias by excluding points than that caused by autocorrelation itself (e.g., Otis and White 1999).

18.6.2 Mobile PIT-Tag Detection

Mobile relocation of PIT-tagged fish and shellfish (or shed tags) is possible in small water bodies at shallow depths or through ice by use of a backpack-mounted reader, battery, and logger connected to a handheld loop antenna (Morhardt et al. 2000; Bubb et al. 2002; Roussel et al. 2004; Hill et al. 2006). The technique is ideal for detection of fishes with cryptic or burrowing habits but has limited value for fishes that flee on approach. Temporal patterns of habitat use can be inferred from repeated surveys. Tags shed by fish or egested by predators can also be located and identified. The maximum range achievable with full-duplex (FDX) backpack systems and 12-mm tags is about 40–50 cm (Cucherousset et al. 2005); ranges to 1 m (Roussel et al. 2000) are possible with half-duplex (HDX) systems and 23-mm tags.

18.6.3 Active Biotelemetry

Any telemetry study in which locations of tagged animals are determined should include an objective assessment of tag location accuracy; accuracy can be determined by estimating locations of independently hidden tags (White and Garrott 1990). Systematic sampling of all habitats equally and in areas that extend beyond the ostensible study site increase the probability of locating highly mobile individuals and not biasing findings (Gowan et al. 1994). Bias can be produced by focusing searches where fish were last detected. Varying start location and direction of tracking randomly helps to minimize bias.

18.6.3.1 Zero-Point Tracking and Triangulation

A simple method to locate a transmitter is to use a series of successive gain reductions, which is known as zero-point tracking (Nelson 1990). Most receivers have an audible speaker as well as a signal-strength indicator. Using either, the tracker moves closer to the signal at a specific gain until it is saturated. At that point, the gain is adjusted downward and the process is repeated until the tracker has localized the signal near a zero gain. The signal will be omnidirectional when very near the device (Zeller 1999). Elements of some radio antennas can be collapsed to reduce gain still further to assist localization. Location at the zero point is typically determined using a handheld global positioning system (GPS; Chapter 4) and entered into a geographic information system (GIS) or specific space-use analysis software for further analysis.

Location of transmitters by triangulation is common, particularly in radiotelemetry studies (Kenward 2001), and can be effective and accurate when coupled with GIS techniques (James et al. 2003). A GPS is used to determine location coordinates on the streambank and the compass bearing (to the nearest 0.5°) toward the strongest signal. The tracker then moves to a different location and repeats the process. The intersection of the compass bearings from the locations is the estimated location of the radio transmitter; GIS software can be used to make such estimates. Triangulation sites that result in bearings close to perpendicular minimize error around the point of intersection. Taking three readings rather than two does not increase accuracy (James et al. 2003). Triangulation can produce accuracies of about 6 m (which may be unacceptable for microhabitat studies); water depth, velocity, conductivity, habitat type, signal reflection, and distance between the transmitter and receiver can affect accuracy (White and Garrott 1990; Winter 1996; Simpkins and Hubert 1998; James et al. 2003). The magnitude of location error should be reported for all manual radiotelemetry studies (Simpkins and Hubert 1998).

Location of acoustic transmitters by means of triangulation is also best at perpendicular bearings; directional bias occurs at angles greater than 90° (Zeller 1999). The hydrophone and transmitter should normally be about 50–100 m apart. Use the zero-point approach when uncertainty exists about the location or direction of a signal.

18.6.3.2 Boat-Based Tracking

Small boats are effective for locating tagged fish in lakes, rivers, and nearshore marine environments because they are maneuverable and responsive (Holland et al. 1992; Figure 18.7). Kayaks can be outfitted with directional hydrophones for use in shallow habitats (Meyer and Holland 2001), and canoes are particularly useful for radio-tracking in rivers (Bunt et al. 2002). Commercial fishing vessels about 12 m long equipped with a tracking system (Holland et al. 1985) are used for offshore tracking.

Triangulation and zero-point tracking are used to locate fish from boats, but general locations must first be identified. Some motors interfere with radio-receiving equipment, requiring stop–start tracking. Acoustic tracking can be conducted while the vessel is moving slowly provided that the hydrophone is directional and suited to active tracking. A single-direction hydrophone can be swivel mounted to determine relative bearings of transmitters at distances of up to several kilometers (Figure 18.7). The hydrophone should be located as far forward of the propeller as possible to avoid interference by cavitation and noise.

Specialized automated acoustic manual-tracking receivers with quad hydrophone arrays (that provide 360° of coverage by means of four hydrophones positioned starboard, bow, port, and aft) determine transmitter bearings without rotating (Arnold and Dewar 2001). These systems use integrated software for determining positions and include automated noise filtration. They perform well in open-water environments, can save time in tracking, and are effective for following individual fish to quantify and describe individual behavior. When tracking fish continuously, the tracking boat should remain within signal range and be at close range every 10–20 min to secure a specific fix. Quad hydrophone arrays can be towed behind vessels at desired depths to determine general positions of fish distributed over large areas.

Zero-point tracking from a boat is accurate because the researcher can be positioned directly above the fish (Nelson 1990); habitat characteristics there can be determined. However, fish may alter their behavior to avoid survey boats in shallow habitats at distances less than 10 m (Draštík and Kubečka 2005). This may be acceptable if fish relocations are infrequent and large-scale movements are being examined.

18.6.3.3 Tracking on Ice

Tracking fish on ice is similar to tracking fish by boat (especially radio-tracking), but different safety issues apply, and holes must be made to submerge hydrophones. General radio locations can be found by walking, skiing, or snowshoeing (Margenau 1987; Brown and Mackay 1995; Brown et al. 2001); underwater antennas (section 18.3.2.4) can then be used to reveal exact positions. Ice does not appreciably reduce radio signal strength. Detailed telemetry using EMG (Brown et al. 2000; section 18.4.4) and two-dimensional under-ice positioning (Hanson et al. 2007) has revealed that many species are active during winter.

18.6.3.4 Aerial Tracking

Airplanes and helicopters enable tracking movements over long distances and in difficult-to-access areas (Modde and Irving 1998; Harvey and Nakamoto 1999). When budgets allow, aerial tracking is often used to supplement fixed-station and ground level manual tracking to determine locations of widely dispersed tagged fish and to ensure detection of movement (English et al. 2005). Tracking by airplane is more common, but helicopters can hover above locations (Bunt et al. 1999b).

Aircraft use is limited to radio-tracking. At a minimum, an antenna, radio receiver, and GPS system are required. An ideal configuration for fixed-wing aircraft is a bidirectional H antenna mounted on opposite wing struts and one forward-mounted Yagi antenna. The directional antennas are used in unison or separately to determine the direction of a transmitter (Roberts and Rahel 2005). Zero-point tracking by making circles of decreasing circumference is effective when using a single antenna (Mech 1983). Noise-reducing headphones reduce interference with signal detection.

The detection range of aerial tracking is greater than detection on the ground or in water because of the high vantage point. However, fish that are deep and barely detectable can be missed, as can be those sought while scanning multiple frequencies from a rapidly moving aircraft. The accuracy of aircraft-determined position estimates is poor relative to other tracking techniques, with errors as high as 400 m (Irving and Modde 2000). Sources of error include pilot judgment and experience (Hoskinson 1976), GPS accuracy, weather, and environmental conditions (White and Garrott 1990; Roberts and Rahel 2005). Aerial tracking is therefore not effective for examining fine-scale movements or habitat use; it is useful for assessment of gross movements and reach level habitat use.

18.7 AUTOMATIC DETECTION OF FISH

18.7.1 Passive Telemetry Systems

Automated PIT tag stations are used to detect and log passing tags in fishways, downstream bypasses, rivers, and tidal creeks (Prentice et al. 1990a; Castro-Santos et al. 1996; Lucas et al. 1999, 2000; Zydlewski et al. 2001; Riley et al. 2003; Scruton et al. 2003; Ibbotson et al. 2004; Zydlewski et al. 2006; Bolland et al. 2009) and to study competition in experimental enclosures and aquaculture systems (Alanärä and Brännäs 1993, 1996). Mobile deployment of automated systems has been used to scan piscivorous bird colonies for tags from predated fish (Ryan et al. 2003) and for trawling through estuaries and inshore waters (Jørgensen et al. 2005). Automatic PIT detection systems are expensive, but the benefits of remotely obtained, high-quality information on spatial behavior of tagged fish often outweigh the costs (Prentice et al. 1990a; Zydlewski et al. 2006).

Recording stations typically are made up of one or more remote antennas and one or more readers. Several antennas can be multiplexed to a single reader and interrogated sequentially. The distance between the antenna and reader must be short; otherwise, shielded connection cables are needed. Reading distance, detection rate, and decoding systems must be tuned to minimize the possibility that a tagged fish can cross an instrumented site unnoticed. If antenna-tuning boxes are used separately from readers, the tuning boxes must be close to the antenna coils. Data (e.g., date, time, antenna, and tag code) are recorded each time a PIT-tagged fish crosses the plane of the antenna and are stored on the reader's inboard memory, buffer memory for periodic downloading to a computer, or compact flash card for downloading in the laboratory. Internal clocks of separate readers should be set to the same time to avoid erroneous interpretation of records.

Remote antennas used in studies of fish movements, migration, and dispersal in streams and tidal creeks are generally of tubular or open-loop construction and orientated perpendicular to the expected movements of fish (Zydlewski et al. 2006; Figure 18.3). Antennas of HDX systems can be constructed to suit the shape of the channel at a particular site whereas FDX antennas require greater technical detail and cost and cannot be built as large (Zydlewski et al. 2006). However, the reading cycle of FDX systems is faster than that of HDX systems, which enhances detection efficiency of fast-swimming fish. Flatbed antennas are commonly plank-shaped plates that can be camouflaged within the substrate or suspended within the water column. They have been used to examine behavioral responses to low-flow conditions in streams and channels (Armstrong et al. 1998) and efficiency of bypass channels (Aarestrup et al. 2003) as well as in fish passage studies (Nunnallee et al. 1998; Lucas et al. 1999, 2000). Their main limitation is the height of the water column that can be surveyed, which is generally limited to 10–20 cm on both sides of the plate. Efficiencies vary with flow and must be calibrated accordingly. Multiple horizontal flatbed antennas can be arrayed at different depths (Lucas et al. 1999) or oriented vertically (Ibbotson et al. 2004).

Detection can be affected by the presence of ferrous metals and electrical noise from electrical wiring near the antenna. Ferrous metals can occur in structures such as fishways (e.g., rebar). Select antenna installation materials and sites accordingly. Full-duplex antennas systems are generally more susceptible to environmental effects than are HDX systems.

A tagged fish that remains within antenna range can repeatedly relay its code and fill available memory; logger software can be programmed to omit or infrequently log such "sitters." Such tags can also interfere with detection and logging of other tags entering the area. Solutions include limiting the detection range to minimize the occurrence of stationary fish, carefully siting antennas to avoid holding areas, and using multiple, adjacent antennas and fast scanning to detect multiple tagged fish in close proximity.

Detection can be impaired when the residence time within the detection field is less than the interrogation time of the system (Castro-Santos et al. 1996). Similarly, detection is compromised when the number of fish passing through the antenna simultaneously exceeds the detection rate of the system. This increases the actual interrogation time of the system and the probability of missing a fish when several tagged individuals cross the antenna plane at the same time or at high speed. Closely situated antennas that are interrogated nearly simultaneously, either by the same or different readers, can generate electromagnetic field interference that compromises detection and reading. However, such configurations are widely used because they enable assessment of direction of movement and detection efficiency. Successive scans of nearby antennae are therefore typically separated by short gaps during which no antenna is interrogated, but this results in increased interrogation times. Excessive interference can be avoided by using a separate reader for each antenna and phase locking their signals. The lower the radio frequency and the greater the number of antennas connected to a single reader, the longer the interrogation time and the lower the overall performance of the system.

18.7.2 Active Telemetry Arrays

Automated fixed telemetry stations are widely used to monitor locations of active acoustic and radio transmitters (Solomon and Potter 1988; Klimley et al. 1998; Bunt et al. 1999a; Hockersmith et al. 2003). Unlike manual tracking, automated systems can be deployed continuously over long periods. Many systems permit remote programming and retrieval of data by telephone, digital subscriber line cable, or satellite (e.g., Eiler 1995), thereby reducing expenses by minimizing visits to remote field sites and enabling in-season analyses. Fish behavior is often best monitored by integrating fixed-telemetry arrays with mobile manual tracking (Lembo et al. 2002).

18.7.2.1 Acoustic Telemetry Arrays

The first step in developing an acoustic array is to plot hydrophone locations prior to deployment. Common acoustic arrays use submerged receiver–loggers with omnidirectional hydrophones distributed in series of cells. Standard omnidirectional hydrophone detection ranges vary from less than 250 m to more than 500 m in radius (Voegeli et al. 2001); detection range is influenced by transmitter power output, water depth, and noise. Shallow water (Humston et al. 2005) and high noise levels decrease the range of detection. Noise can impair detection and logging of valid signals and can generate spurious coded values; CDMA technology is useful in such situations (section 18.3.2.2). Ideally, hydrophone reception cells overlap minimally to detect all fish while maximizing coverage. Weak transmitters with limited detection ranges can be used to increase spatial resolution. Calibrated arrays of overlapping independent omnidirectional acoustic receivers, together with recorded tag signal strength information, enable estimation of locations by processing the logged data mathematically. In situ range testing at all hydrophone sites under various sea states or water levels is necessary because site characteristic vary (Domeier 2005; Heupel et al. 2006). The radii of the reception cells can be plotted on maps to identify the number of receivers required, maximize coverage, and ensure that the array will provide data conducive to meeting project objectives.

The simplest acoustic arrays function as gates or checkpoints that monitor fish movements. Such arrays are most effective in linear systems but can also be used in lakes and coastal ocean environments. Hydrophones are placed at key points such as the inlets and outlets of lakes, confluences of rivers, and other constrictions where fish are forced through narrows. Receivers are spaced such that a fish cannot move past a gate without being detected (Heupel et al. 2006); a single hydrophone may suffice in a narrow constriction. Several nearby hydrophones can provide information on direction of movement and speed of travel (e.g., Thorstad et al. 2000). In coastal marine environments, a gate could consist of multiple receivers extending outward from shore to a depth or distance greater than that used by the species of interest. Gates can be deployed around the periphery of protected areas (Chapman and Park 2005) or along entire coasts (e.g., Welch et al. 2003). Grid systems are used less frequently than gates but provide detailed information on fish use of specific habitats (Fabrizio et al. 2005) and movements within instrumented areas.

Automatic positioning of fish requires a minimum of three hydrophones arranged in a triangular configuration; locations of transmitters can be determined within the triangulation zone (Espinoza et al. 2011). Some transmitter encoding systems such as CDMA (section 18.3.2.2) are resilient to other array geometries and can also estimate locations outside the footprint of the array. Array geometry can be determined a priori if bathymetry is known by means of commercially available analysis tools and is particularly important in shallow systems. Hydrophones must remain in fixed, known locations to determine fish positions accurately. An accurate GPS should be used to configure an array and to verify positions periodically during the study.

A variety of hydrophone deployment techniques exist (Domeier 2005; Heupel et al. 2006; Figure 18.8). A primary consideration is ensuring that hardware and data are secure, placed precisely, and can be retrieved (Domeier 2005). Global positioning systems combined with detailed field notes and use of landmarks can be used. Generally, it is best to moor hardware subsurface to minimize attention; a surface buoy can attract attention. Receivers can be attached to existing infrastructure by means of industrial cable ties and marine-grade rope (5–10 mm diameter), provided appropriate approvals are obtained. Docks, pilings, and underwater timber can be used if they are stable and not subject to removal. Placement of hydrophones depends on the type of deployment, depth, and biology of the fish. Transducers placed near the bottom should be oriented toward the surface; near-surface transducers in deep water should point down.

Equipment moored in shallow water can be deployed and retrieved by diving or snorkeling. The receiver should be securely fixed to a rope between an anchor on the bottom and a float that has adequate buoyancy to support the mass of the receiver. Hard-plastic floats should be used for deep deployments because foam and inflatable floats collapse under pressure. Choice of rope and mooring tackle is critical, particularly in lotic and corrosive marine environments.

Remote deployment is necessary in deep water. A shallow-water system can be deployed from a boat in an inland lake after modification with a sinking retrieval line that extends from the anchor to shore, where it is secured and hidden. An additional floating line placed along it at some distance from the receiver allows for grappling should the shore attachment be lost. A davit is used to haul in the line and anchor system. Acoustic-release devices are used in open water or where use of a retrieval line is impractical (Domeier 2005). These devices are placed on the line above the anchor and release the float, line, and receiver when triggered by a signal. Multiple release devices provide redundancy in case of device failure. Because the releases are battery powered, it is important to query the unit periodically to assess battery life. A string of acoustic receivers can be joined with a ground line. Acoustic-release devices on the units at the ends of the string allow the entire array to be retrieved by lifting one end. This approach can fail if the ground line becomes entangled. A safer strategy is to place an acoustic-release device with every receiver along the ground line.

18.7.2.2 Radiotelemetry Arrays

Radiotelemetry arrays are commonly deployed in river or stream systems, at tributary mouths, at inflows or outflows of lakes, and in and around utility infrastructure such as dams, fishways, and discharge canals (Solomon and Storeton-West 1983; Bunt et al. 1999a; Hockersmith et al. 2003; Cooke et al. 2004d). Underwater antennas (section 18.3.2.4) are used where noise interferes with aerial antennas (Cooke et al. 2004d). Antennas are most commonly arranged as a series of gates, often in triplicate from a single receiver, to determine direction of movement (English et al. 2005). Grid deployment is also used (Berland et al. 2004). On-site field trials must be conducted to establish reception ranges prior to setting up an array. Use of multiple antennas with a single receiver is common, but different cable lengths can lead to differences in reception strength; on-line amplifiers can be used to boost signals along long cables. Use of different antenna types on the same array can provide different types of coverage (Cooke et al. 2004d). Because radio-receiving stations are based on land, they must be concealed or deployed in secure areas (e.g., Keefer et al. 2004a). Receivers, antennas, and solar panels placed high in trees are secure and hidden. Receivers and batteries are often housed in water resistant, locked environmental chambers attached to permanent surfaces (Figure 18.5).

Fixed radiotelemetry arrays require programming to optimize performance. Gain of each antenna is adjusted, but automatic gain adjustment may be useful in noisy locations to preclude the logging of spurious signals. Dwell times among antennas and frequencies can be adjusted to prevent fish from passing a site undetected. For example, a dwell time of 3 s per frequency is used if transmitters emit a signal every 2 s. If tracking fish on five frequencies, then 3 s × five frequencies = 15 s per antenna before switching to the next antenna to repeat the scan. A given frequency and antenna combination would therefore be monitored about every 45 s, which may be inadequate for monitoring rapid events such as passage through a fishway. A possible solution is digital spectrum processing whereby the receiver monitors all antennas and frequencies simultaneously and prioritizes logging signals based on where they are being actively detected (Bunt et al. 1999a).

18.8 ANALYSIS

Analysis techniques for biotelemetry and biologging data have evolved to address the massive volume of data being generated and to move away from descriptive studies to mechanistic understanding, testing of hypotheses, and development of quantitative relationships. The analytical tools are often sufficiently complex that they require specific training (e.g., university or professional development courses in GIS, R, or other software). Increasingly, quantitative tools are also used a priori to help identify appropriate sample sizes (i.e., power analysis; Chapter 2) and to configure arrays and tag settings. Analytical problems encountered in telemetry studies include lack of independence among data points (i.e., data are autocorrelated) and pseudoreplication. Repeated-measures approaches (Hansen et al. 2007) are used to analyze such data.

18.8.1 Manual Tracking

Standard data analysis techniques for fish telemetry data collected using manual tracking are well-developed and covered extensively in Rogers and White (2007). These analyses include determination of spatial distribution, movement patterns and rates, diel activity patterns, behavioral interactions among individuals, animal orientation, home range, survival (section 11.5.1, this volume), and habitat use and selection (Winter 1996). Many of these techniques were developed for terrestrial studies of mammals (e.g., White and Garrott 1990) but are equally applicable to aquatic systems. However, terrestrial applications (Grünbaum 1999, 2000) may require modification for use in aquatic environments because habitats are constricted (e.g., Bolden 2001; Knight et al. 2009).

Simple mathematics can be used to determine the time required for a fish to move between two points to estimate swimming speed. However, null models (e.g., random walk and diffusion behavior; Okubo 1980; Morales et al. 2004) can be used to determine whether movements are directional or random (e.g., Wilde 2003). Movement models and designation of motion and search types, first passage time (Fauchald and Tveraa 2003), kinesis, and restricted search and displacement analyses (Humston et al. 2004; Newlands et al. 2004; Gutenkunst et al. 2007) can provide a robust understanding of movement and habitat use. Spatial mapping tools such as GIS and spatial statistics are used to analyze fish movement data comprehensively. For example, the Animal Movements module of ArcView (Hooge and Eichenlaub 2000; Hooge et al. 2001) defines home range kernels.

18.8.2 Fixed Telemetry Stations

Data collected using fixed-telemetry stations are often imported into GIS software, enabling determination of home ranges, habitat characteristics, and movement rates (e.g., Zamora and Moreno-Amich 2002). Presence and absence data among overlapping reception cells of omnidirectional receivers can be converted into a position estimate based on weighted means of the number of signal receptions at each receiver during a specified time period; the estimate is analogous to a short-term center of activity (Simpfendorfer et al. 2002). This approach assumes that a linear relationship exists between the number of detections and the distance from a receiver. Minimal positioning error exists where four or five reception cells overlap (Giacalone et al. 2005). Software incorporating this technique (Fish-finder Software for Automated Receivers; Giacalone et al. 2006) is used to manage large data sets and calculate activity centers of individual transmitters. The software collates data collected by each receiver in a unique Microsoft Access cross table and uses the Simpfendorfer et al. (2002) algorithm. Local polynomial regressions can also be used to interpolate the positions and speeds of tagged fish within an array (Hedger et al. 2008). Variation in signal strength received by a fixed receiver can be used to measure fish activity (David and Closs 2001). A robust understanding of the detection efficiency of an array is necessary when using it to estimate mortality (Heupel et al. 2006). Fish that swim past a receiver gate but that are not detected could be erroneously characterized as mortalities. Quantitative tools are available to incorporate different levels of receiver detection efficiency into estimates of mortality (Welch et al. 2011).

18.9 SUMMARY

Biotelemetry and biologging provide advanced capabilities for studying basic and applied fisheries questions. They provide enhanced understanding of spatial ecology and population dynamics (Lucas and Baras 2000; Nielsen et al. 2009) and responses to management efforts. These tools can be used to estimate the energetic costs of behaviors for incorporation into bioenergetic models (Lucas et al. 1993; Cooke et al. 2004a, 2004c) and evaluations of life history theory (Cooke et al. 2002a). Biotelemetry and biologging are effective tools for evaluating the effects of stressors on individuals and populations (Wikelski and Cooke 2006). These techniques are particularly useful in marine systems to obtain information on the ecology of large pelagic fishes (e.g., Block et al. 2002). Innovations such as business card tags enable inter-animal telemetry in inaccessible areas (Holland et al. 2009). As device size continues to decline, opportunities for research on smaller species and earlier life stages will be possible. Integration of these technologies with independent techniques and approaches such as stable isotope analysis, hydroacoustics, and physiological biopsies provides the capability to span the continuum from molecules to ecosystems (Box 18.6; Cooke et al. 2008).

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Box 18.6 The Coupling of Biologging and Biotelemetry with Other Techniques

Integrating biologging and biotelemetry with other techniques can provide valuable insights into basic and applied fish ecology (Cooke et al. 2008). For example, collection of blood and gill tissue of tagged fish (Martinelli-Liedtke et al. 1999; Cooke et al. 2005) enabled linking behavior with physiological and energetic status in migration (Aarestrup et al. 2000; Cooke et al. 2006) and angling studies (Skomal and Chase 2002). Combined laboratory and lake measurements of ionoregulatory competence and spatial behavior showed that fish tolerated poor water quality apparently to gain trophic benefits (Scott et al. 2005). Jepsen et al. (2005b) combined genetic analyses with radiotelemetry to link individual migratory behavior of Atlantic salmon to their genetic origin. Nonlethal stable isotope analysis was combined with PIT telemetry to study movement and feeding ecology (Cunjak et al. 2005). Coupled telemetric and hydroacoustic surveys allow extrapolating from the individual to the population (Robichaud and Rose 2002), for example, by simultaneously examining individual movement and activity and population density and distribution (Lyons and Lucas 2002). Integrating genetic, biochemical, and electronic tags and quantitative approaches provides a comprehensive understanding of population status, spatial structure, and vital rates of highly exploited marine fish populations (Fromentin et al. 2009). Integrated modeling of spatial ecology data from pop-up satellite archival tags and multi-species population dynamics allows investigation of the mechanisms that lead to observed population fluctuations through detailed spatiotemporal prediction (Lehodey et al. 2008).

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