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Applications of radio frequency identification (RFID) in ornithological research: a review

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ABSTRACT. Radio frequency identification (RFID) technology allows the unique identification of individuals and automated recording of the presence of tagged birds at fixed locations. Investigators have used RFID technology to examine questions related to pair formation, feeding rates, incubation behavior, prospecting behavior by nonbreeding birds, temporal changes in body condition, postfledging movements, dispersal, homing behavior, and other areas of ornithological interest. This technology can enable researchers to explore novel areas of inquiry and gather previously unobtainable quantities of information, allowing birds to record their own behavior without repeated capture and handling. In addition, RFID technology can be linked with other instruments, such as automated weighing devices, video cameras, infrared beams to detect the direction of movement, and temperature loggers, to collect additional data. New, inexpensive RFID technology has removed cost as a major constraint to the wider implementation of RFID in ornithological research. Because the technology requires that focal individuals come near (<10 cm) a reading antenna, RFID is not appropriate for all study systems and research questions. However, integrating RFID technology with additional instrumentation platforms and external data sets will continue to revolutionize studies of avian biology and behavior.

RESUMEN. **Aplicación de la identificación de radio frecuencia (RFID) en investigaciones ornitológicas: una revisión**

La tecnología de identificación de radio frecuencia (RFID) permite la identificación particular de individuos y la grabación automática de la presencia de aves "marcadas" en localidades fijas. Los investigadores han utilizado la tecnología RFDI para obtener respuestas relacionadas con información pareada, tasas de alimentación, conducta de incubación, conducta prospectiva de aves no-reproductivas, cambios temporales en la condición corporal, movimiento de volantones, dispersión, conducta hogareña y otras áreas de interés en la ornitología. Esta tecnología le permite a los investigadores explorar áreas noveles de estudio y obtener buena información cuantitativa que antes no estaba disponible, inclusive permitiéndole a las aves grabar su propia conducta sin que sea necesario la recaptura y la manipulación de estas. Además, la tecnología RFID puede ser utilizada en conjunto con otros instrumentos, como balanzas automáticas de peso, cámaras de video, infrarrojo para detectar la dirección de movimientos y recopiladores (loggers) de temperatura, para coleccionar datos adicionales. El bajo costo de la nueva tecnología RFID, ha removido el alto costo como obstáculo para implementar el uso de esta en la investigación ornitológica. Debido a que la tecnología requiere el investigador tenga que acercarse (<10 cm) a una antena de lectura, el RFDI no es apropiado para todos los sistemas de estudio y preguntas de investigación. Sin embargo, la integración de la tecnología RFID a nuevos instrumentos, aparatos y bases externas de datos continuará revolucionando los estudios sobre la biología y conducta de las aves.

Key words: bird feeder, monitoring technology, passive integrated transponder, PIT tag, tag-reading device

Radio frequency identification (RFID) technology has been widely used in industry, commerce, animal and veterinary science, and fisheries research since the early 1990s (Schooley et al. 1993, Gibbons and Andrews 2004, Rehmeier et al. 2006). Although used in many ornithological studies (reviewed here), widespread application of this technology has been limited by financial barriers and, possibly, a lack of technological understanding. Historically, the expense of RFID readers has been a limiting factor for many researchers. Costs of commercial readers range from $800 to $10,000, and these high costs have been variously reported as "a limitation," "prohibitive," and "a main drawback" of the technology (Elbin and Burger 1994, Becker and Wendeln 1997, Boarman et al. 1998, Jamison et al. 2000, Gibbons and Andrews 2004, Nicolaus et al. 2008, Zangmeister et al. 2009). The recent development of inexpensive readers (~$40; Bridge and Bonter 2011) now makes the technology more accessible, and the technology is now poised to see broader

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application in ornithological research. Here, we briefly describe the technology, review past and ongoing ornithological research using RFID, examine the benefits and limitations of current RFID technology, and identify areas of future research.

RFID TECHNOLOGY

RFID requires four main components: (1) a transponder attached to an animal, (2) a tag-reading device that generates a carrier wave and interprets data from the transponder, (3) an antenna for creating an electromagnetic field for reading the transponder, and (4) a power source. Transponders typically do not have an internal power source, and are often called passive integrated transponder (PIT) tags. PIT tags are energized when passed through an electromagnetic field created by a RFID reader. Most RFID communication occurs at one of three frequency ranges: low frequency (LF; 125–150 kHz), high frequency (HF; 13.56 MHz), and ultrahigh frequency (UHF; 868–928 MHz). LF transponders are commonly used in animal applications. LF signals penetrate wet tissue, making LF tags useful when implantation is necessary. However, LF tags also have the most limited read range (usually $<$0.3 m). HF tags may also be used for some animal applications because they perform reasonably well near wet tissue and have a typical read range up to 1 m. Because UHF tags require both special licensing and a line of sight to the reader antenna, they are rarely used in animal studies despite potential read ranges of several meters.

PIT tags consist of a microchip connected to an electric resonance circuit that acts as a receiving/transmitting antenna. Upon entering the electromagnetic field generated by the antenna on a RFID reader, PIT tags transmit a preprogrammed, unique identification number. The reader antenna that generates the electromagnetic field also receives the transmitted code (Jansen and Eradus 1999). Because they need no battery, PIT tags are small (a common size for ornithological applications is 2.12 mm $\times$ 12 mm, 0.095 g), and their lifespan is theoretically unlimited. In addition to the glass PIT tags familiar to many biologists, RFID transponders are available in a variety of tag shapes and sizes. There are also several standards for defining how communication between a tag and a reader occurs. A description of all of these standards is beyond the scope of this review; those considering the use of RFID technology in their research should ensure that their readers and tags are compatible.

METHODS

To review published ornithological studies that have involved the use of RFID technology, we conducted two separate searches in ISI Web of Science (Expanded) for "radio frequency identification" (N = 1298 hits) and "passive integrated transponder" (N = 293) on 30 March 2010. Papers with ecological, wildlife, veterinary, and animal science applications were then downloaded for review. Most ornithological applications of RFID were ultimately identified by examining the literature cited sections in papers selected for review. We found that RFID technology has been successfully implemented in basic and applied science investigations, and in both descriptive and experimental contexts. Although relatively few ornithological research projects have used RFID technology (Table 1), a broad range of research questions have been examined. Many of the studies described below could have been conducted using traditional marking techniques (i.e., color bands, field readable bands or tags, etc.), but the labor required to visually gather information on large numbers of birds over time is often prohibitive. RFID automates the observation process and may acquire heretofore unavailable information.

ORNITHOLOGICAL APPLICATIONS OF RFID TECHNOLOGY

Among the first and perhaps most productive uses of RFID technology for ornithological research is a project conceived by Peter Becker and his colleagues working with Common Terns (*Sterna hirundo*) near Wilhelmshaven, Germany. Since 1992, Becker and his colleagues have monitored as many as 530 pairs of Common Terns annually as the terns nest on man-made islands in two colonies 4 km apart in the North Sea. The colonies are equipped with perches fitted with RFID antennae, allowing researchers to record the presence of tagged individuals as they loaf on these favored, elevated perches (Becker and Wendeln 1992).

Table 1. Published studies where RFID technology has been used in ornithological research.

Organism	Location	PIT attachment method	Reader placement	References
Domestic ducks	Captive experiment	Attached to wing	At feeders	Bley and Bessei 2008
Domestic chickens	Captive experiments	Subcutaneous injection in the neck or back	At feeders, hand-held, and at laying boxes	Jamison et al. 2000, Brännäs et al. 2001, Wall et al. 2004
Northern Bobwhite	Captive experiment	Subcutaneous injection at base of neck	Hand-held	Carver et al. 1999
Ring-necked Pheasant	Captive experiment	Subcutaneous injection in back	Hand-held	Applegate et al. 2000
Leach's Storm-petrel	Kent Island, New Brunswick	Attached to leg bands	At entrance to nest burrow	Zangmeister et al. 2009
Shorebird nests	Yukon Delta NWR, western Alaska	Tags placed in nest material	At nests	Booms and McCaffery 2007
Semipalmated Sandpiper	Barrow, Alaska	Glued to leg band, wrapped in colored tape	At nest cup	Cresswell et al. 2003
Common Tern	Wilhelmshaven, Germany	Implanted in the breast, glue	Readers at nests and loafing perches in colony	Becker and Wendeln 1997, Gonzalez-Solis et al. 1999, Dittmann and Becker 2003, Ludwigs 2004, Dittmann et al. 2005, Ludwig and Becker 2006, Limmer and Becker 2007, Becker et al. 2008a,b
King Penguin	Possession Island, Antarctica	Implantation in leg	Narrow path between breeding colonies and the sea	Gendner et al. 2005, Descamps et al. 2009
Adélie Penguin	Antarctica	Implantation subcutaneously at scruff of neck	Constricted path to/from breeding colonies, hand-held	Kerry et al. 1993, Ainley et al. 1998, 2004, Clarke and Kerry 1998, Ballard et al. 2001, Dugger et al. 2006
Magellanic Penguin	Punto Tombo, Argentina	Implanted in tarsometatarsus; site sealed with tissue adhesive	Narrow path between breeding colonies and the sea	Boersma and Rebstock 2009
White Stork	France & Belgium	Implanted	At feeders	Michard et al. 1994
Kakapo	New Zealand	Subcutaneous injection at base of neck	Hand-held	Low et al. 2005
Wryneck	Switzerland	Tags attached to leg bands	At nest boxes	Freitag et al. 2001
Black-capped Chickadee	Outdoor aviary	Epoxy to plastic leg bands	At feeders	Boisvert and Sherry 2000
Great Tit	Oxford, UK; Lauwersmeer, The Netherlands	Attached to colored leg band; injected in upper back	At nest boxes; hand-held and at feeders	Nicolaus et al. 2008, Wilkin et al. 2009
Dark-eyed Junco	Virginia, USA	Subcutaneous injection	At feeders	Keiser et al. 2005

One novel area of research made accessible by RFID technology on the tern islands is the study of "prospecting" behavior by nonbreeding juveniles. Using RFID technology at two potential breeding colonies allowed the researchers to quantify prospecting visits by the terns to natal and neighboring colonies. From 1992 to 2001, all fledglings ($N = 2081$) were marked with transponders, allowing monitoring and quantification of natal recruitment, including the timing of prospecting in prebreeding years and the age of recruitment into the breeding population. Most juveniles did not breed during the first year they returned to the nesting colonies (92.4% were just prospecting), and males tended to prospect longer than females (Dittmann and Becker 2003). A high proportion of tagged juveniles visited both nesting colonies during the prospecting stage, supporting the hypothesis that individuals compare potential breeding sites during their prebreeding period. Most birds favored their natal colony when prospecting, and prospectors were more likely to ultimately nest at the colony visited most often during the prospecting stage (Dittmann et al. 2005). RFID technology revealed that 66% of subadult prospectors were ultimately recruited to breed at the natal colony, and demonstrated that the timing of initial arrival at a colony during the first prospecting season was related to future reproductive success (Becker et al. 2008a). The sex ratio of young terns was female-biased at fledging, but a greater proportion of males recruited to the natal colonies than females (Becker et al. 2008b). Data for this kind of research would be nearly impossible to gather without an automated system operating continuously throughout the breeding season for multiple years.

Because RFID systems record the date and time of each visit to a loafing platform on the tern breeding islands, questions about the timing of pair formation and nesting can also be addressed. Divorce by these long-lived, socially monogamous birds was investigated, with support found for the asynchronous arrival hypothesis (Gonzalez-Solis et al. 1999). By integrating scales into the RFID recording systems, the relationship between body mass and breeding behavior was also examined. Researchers documented a negative relationship between the time of arrival at the nesting colonies and body mass (Dittmann and Becker 2003), and found that the body mass of first-time breeders was lower than that of experienced breeders (Limmer and Becker 2007).

In addition to integrating RFID readers into favored perching locations, the use of mobile readers at nests sites allowed researchers to identify the social pairings of all tagged breeders on the tern islands (Becker and Wendeln 1997). Unexpected events have also been recorded by the RFID system at the tern colonies, including documentation of the first case of cooperative polyandry wherein two males copulated with a single female and all three birds incubated the eggs, brooded young, and fed the chicks (Ludwigs 2004).

As demonstrated by the Common Tern study, numerous aspects of reproductive biology can be studied with RFID. Incubation behavior, for instance, can be examined by placing an RFID antenna around a nest. For example, Cresswell et al. (2003) experimentally manipulated the costs of incubation by Semipalmated Sandpipers (*Calidris pusilla*) using insulated nest cups and were able to quantify the relationship between the energetic demands of incubation and incubation behavior (bout length). RFID technology allowed the continuous recording of incubation time and bout lengths by parents at nests. In another study of incubation behavior, Zangmeister et al. (2009) made use of RFID by tagging Leach's Storm-petrels (*Oceanodroma leucorhoa*) and placing RFID antennae at the entrance to nesting burrows. Storm-petrels that failed to successfully reproduce exhibited truncated incubation bouts (<12 h) prior to the ultimate failure of the nest. RFID technology also allowed researchers to document birds visiting burrows that were not their own—a behavior exhibited primarily by individuals from unsuccessful nests.

By attaching RFID readers to nest boxes, the provisioning behavior of male and female Wrynecks (*Jynx torquilla*) was quantified (Freitag et al. 2001). Similarly, Wilkin et al. (2009) studied the provisioning rates of Great Tits (*Parus major*) and showed that rates declined seasonally (negative relationship between hatch date and provisioning rates), but failed to detect any significant environmental predictors of provisioning rates. By integrating RFID technology with nest-box cameras, Wilkin et al. (2009) were also able to categorize the types of food provided to chicks and relate the condition at fledging to nestling provisioning rates and diet.

In Australia, a similar combination of RFID readers and video cameras deployed at nests of cooperatively breeding Chestnut-crowned Babblers (*Pomatostomus ruficeps*) has aided studies of group membership, nest attendance, and social networks (A. Russell, pers. comm.).

RFID has also been used to study the provisioning behavior of penguins. By integrating RFID technology with scales placed along narrow passages between the sea and an Adélie Penguin (*Pygoscelis adeliae*) nesting colony, Kerry et al. (1993) determined that males and females delivered similar amounts of food on each visit to the breeding colony. In addition, this RFID system automatically recorded the fledging weight of Adélie Penguin chicks as they left the breeding colony for the sea (Kerry et al. 1993). In another study, Descamps et al. (2009) used RFID technology to test the center-periphery model of colonial nesting that predicts greater nesting success for birds at the center of a colony. By implanting PIT tags in 150 King Penguins (*Aptenodytes patagonicus*) and examining patterns of colony visitation by nesting birds, the authors were able to quantify nesting success and determine that proximity to the center of the colony did not influence success.

Postfledging and other movements have been studied in systems where tagged individuals are likely to be attracted to a network of RFID reading stations. For instance, Nicolaus et al. (2008) used a network of RFID readers integrated with feeding stations to examine postfledging movements by Great Tits under various experimental conditions where sex ratios and fledgling densities were manipulated. Postfledging movements of White Storks (*Ciconia ciconia*) were also tracked using RFID and a network of feeding stations in Europe (Michard et al. 1994).

As in the dispersal studies, RFID is well suited for studies of feeding behavior because tagged individuals are highly motivated to visit (and hence be recorded at) centralized food resources. Feeding behavior has been examined in laboratory situations, where the food intake of domestic ducks (*Anas platyrhynchos domestica*; Bley and Bessei 2008), Ring-necked Pheasants (*Phasianus colchicus*; Applegate et al. 2000), Northern Bobwhites (*Colinus virginianus*; Carver et al. 1999), domestic chickens (*Gallus gallus domesticus*; Jamison et al. 2000, Brännäs et al. 2001), and Black-capped Chickadees (*Poecile atricapillus*; Boisvert and Sherry 2000) was recorded. The aviary experiment with chickadees revealed daily and seasonal variation in feeding rates, caching behavior, and body mass among individuals, with dominance status determining priority access to food (Boisvert and Sherry 2000). A recent field study of Florida Scrub-Jays (*Aphelocoma coerulescens*) has advanced supplemental feeding of wild birds to a new level by combining an RFID reader and a food-dispensing system. These "smart" birdfeeders can recognize individual birds via their RFID tags and dispense food to specific individuals. Currently, these feeders are being used to examine the effects of food supplementation on the provisioning behavior of different members of cooperative family groups (Schoech, Small, and Bridge, pers. comm.).

In a novel study of homing behavior, RFID-enabled feeding stations were used to test the ability of migratory and nonmigratory populations of Dark-eyed Juncos (*Junco hyemalis*) to return to their territories after being relocated. In this landscape-scale experiment, 400 juncos were relocated 1–40 km from their wintering areas. Birds were recorded by RFID readers upon return to their original capture location. Both migratory and nonmigratory birds demonstrated strong homing abilities, with no differences in homing speed or success between subspecies (Keiser et al. 2005).

RFID technology employed in fisheries research has even contributed information about food-web relationships that are relevant to ornithological research. More than 115,000 RFID tags initially injected into fish released in the Columbia River were recovered on a Caspian Tern (*Hydroprogne caspia*) and Double-crested Cormorant (*Phalacrocorax auritus*) rookery island near the mouth of the river, demonstrating a clear relationship between stocked fish and the diets of these birds (Collis et al. 2001, Ryan et al. 2001).

BENEFITS OF RFID TECHNOLOGY

As the above examples demonstrate, RFID technology can revolutionize data collection by automating the recording of animal behavior and movements (Table 2). Indeed, the volume of data collected can be staggering. Whereas many behavioral studies are limited by small sample sizes and field crew constraints, an indefatigable RFID system can record enviable data sets such

Table 2. Summary of the benefits and limitations of RFID applications in ornithological research.

Benefits:	
(1)	Automated recording of bird behavior and movements
(2)	Minimizes disturbance; can uniquely identify individuals without repeated capture and handling
(3)	Ability to record enormous amounts of data with minimal effort
(4)	Small, lightweight transmitter (2.12 mm × 12 mm, 0.095 g) allows use with smaller birds than radio and satellite transmitters
(5)	No need to attach battery to transmitter/study organism
(6)	Transmitters remain viable longer than the life span of most birds
(7)	Millions of unique alphanumeric codes available, allowing for individual identification of entire populations
(8)	Potential for integration with additional instrumentation such as scales and cameras
(9)	Relatively inexpensive with new, low-cost readers
Limitations:	
(1)	Discreet central location required where birds will reliably come near an RFID reader
(2)	Limited read range (<1 m at best)
(3)	Waterproof housing and maintenance of power supply for circuit board and antenna required
(4)	Potential effects of tag implantation or attachment on birds
(5)	Potential for tag loss
(6)	Basic training in use of technology is advised
(7)	Large volume of data requires proper data management system

as several hundred visits to a feeder by an individual bird per day (Boisvert and Sherry 2000), 80,000 colony-to-sea movements by penguins in three months (Kerry et al. 1993), or continuous, 24-h patterns of incubation behavior during an entire nesting attempt (Cresswell et al. 2003). In the study of Common Terns at nesting colonies in Germany, 4,737,352 individual PIT tag codes were recorded from 653 marked birds during the 2003 breeding season alone (Becker et al. 2008b). In theory, similar results could have been obtained from color-banded birds, but the labor required to record data over the long term makes such research unrealistic in most contexts and necessitates the use of an automated system.

The ability to remotely identify all individuals in a study population with limited disturbance is another advantage of RFID technology. PIT tags provide millions of unique alphanumeric codes that permit the individual identification of all tagged members of a population. The automated system allows birds to record their own behavior without repeated capture and handling, thus minimizing disturbance and potential changes to behavior caused by the presence of an observer. Minimizing disturbance can be particularly important when repeated captures may interfere with the behavior or physiology of birds, and reducing human disturbance near breeding colonies is often advisable (Gauthier-Clerc et al. 2004).

PIT tags are small and lightweight, permitting use with smaller organisms than radio and satellite transmitters. RFID technology is even being used in ant (Robinson et al. 2009), paper wasp (Sumner et al. 2007), and bumblebee research (Stelzer et al. 2010). The passive, battery-free tags have proven resistant to preservation in formalin and ethanol, and remain viable even after the complete decomposition of host animals (Freeland and Fry 1995).

Linking RFID technology with additional instrumentation is providing an ever-increasing array of new data streams. To date, RFID has been successfully integrated with automated weighing devices (Kerry et al. 1993, Becker and Wendeln 1997, Dittmann and Becker 2003), video cameras (Gendner et al. 2005, Descamps et al. 2009, Wilkin et al. 2009), infrared beams to detect the direction of movement (Kerry et al. 1993), temperature loggers (Cresswell et al. 2003, Zangmeister et al. 2009), and motors to control the supply of supplemental food (Schoech, Small and Bridge, pers. comm.).

LIMITATIONS OF RFID TECHNOLOGY

Despite the great potential for further use of RFID technology in ornithological research, a number of limitations and requirements need to be considered (Table 2). First and foremost, the system requires that tagged birds repeatedly visit a discreet central location where they will come near an RFID reader. Potentially productive locations include food or restricted-water sources, nest sites, leks, burrows, well-defined movement corridors, frequently visited perches, or a perch in a lab or aviary environment.

Read ranges are typically <5 cm for the LF PIT tags generally used in wildlife applications (Freeland and Fry 1995). Read distances of up to 1 m have been achieved in studies using larger PIT tags (32-mm long) in King Penguins (Gendner et al. 2005) and White Storks (Michard et al. 1994). The ability to record a PIT tag depends on antenna geometry and the orientation of the transmitter in relation to the antenna. Antenna configuration can be modified to record organisms either visiting a specific point or crossing a line in space. The antenna must yield a resonant frequency that matches the output frequency of the transmitter; construction of home-made antennae is possible, but requires knowledge of antennae design.

RFID systems require a waterproof casing around the circuit board whereas the antenna is often exposed to the elements. A power source is required to power the circuit board and antenna; many researchers have successfully integrated photovoltaics into an RFID reader system to maintain a constant source of power (Boarman et al. 1998, Boersma and Rebstock 2009) because battery failure leads to loss of data (Cresswell et al. 2003).

When attaching any tags, bands, or instruments to birds, investigators should always ensure that the birds are not being adversely affected. This is especially true when tags are implanted subcutaneously, as they often are in RFID studies. Many countries (and universities), in fact, require that researchers obtain special permits or licenses before attaching or implanting PIT tags in wild birds; researchers should investigate all laws and regulations before proceeding with RFID studies. Fortunately, PIT tags have been used in a wide variety of species in recent years and much has been learned about proper attachment and implantation techniques. In a study with PIT tags implanted in 444 Great Tits, Nicolaus et al. (2008) examined the effect of subcutaneous tag implantation on fledging success, winter condition, survival, and recruitment into the breeding population. No negative effects of PIT tags were detected for any of these measures for either juveniles or adults. Similarly, Keiser et al. (2005) detected no differences in the homing abilities of untagged Dark-eyed Juncos and those implanted with PIT tags. In addition, Gonzalez-Solis et al. (1999) reported no effect of PIT implantation on the number of chicks fledged by pairs of Common Terns. In the lab, Carver et al. (1999) found no evidence of changes in the behavior of Northern Bobwhites injected with PIT tags, and no differences in survival between PIT-tagged birds and birds marked with patagial wing bands. In domestic chickens, Jamison et al. (2000) found no difference in survival or rate of mass gain between untagged chicks and those implanted with tags. Finally, no complications, health effects, or changes in growth rates were detected in Kakapo (*Strigops habroptila*) following PIT tag implantation (Low et al. 2005).

Considerable attention has been paid to the effects of PIT tags and other marking methods in the penguin literature. Clarke and Kerry (1998) noted development of a biofilm that harbored potentially pathogenic organisms on some tags implanted in Adélie Penguins. Despite this, survival of PIT-tagged penguins was greater than that of birds marked with flipper bands. In addition, Ballard et al. (2001) found no significant effects of implanted PIT tags, radio transmitters, or time-depth recorders on foraging trip duration by Adélie Penguins. Using PIT tags may, in fact, be preferable to alternative marking methods. Dugger et al. (2006) studied foraging trip duration and survival of Adélie Penguins and found that foraging trip length for PIT-tagged birds was shorter than for birds marked with flipper bands, and apparent annual survival was 11–13% greater for birds implanted with RFID tags than those fitted with flipper bands. Similarly, Gauthier-Clerc et al. (2004) compared survival rates of King Penguins implanted with PIT tags and those with flipper bands, and found that survival rates of PIT-tagged chicks was approximately double that of chicks with flipper bands after 2 to 3 years. Combined, all of these studies provide compelling evidence that implantation of PIT tags is relatively safe for many species. Of course, PIT tags do not need to be implanted, and researchers have experimented with various methods of attaching tags to leg bands and feathers (Boisvert and Sherry 2000, Cresswell et al. 2003).

The potential for tag migration, the movement of a tag from the initial site of implantation, also deserves attention because migration may reduce the likelihood of successful detection of tags by an RFID reader. Tag migration of up to 5 cm was "common" in Adélie Penguins (Clarke and Kerry 1998). Tag migration can also lead to tag loss if the transmitter migrates out of the hole created by the injection process. The probability of tag loss should be considered and minimized because tag loss can significantly affect the results of a study. As with any new technology, experience has led to better implantation and attachment methods over time. In Common Terns, unacceptably high rates of tag loss (41%) dropped to 4% by changing the location of injection and gluing the incision shut (Becker and Wendeln 1997). Similarly, Clarke and Kerry (1998) reported tag losses of up to 30% in Adélie Penguins, with tags migrating out of injection holes within 3 weeks of implantation. Tag loss declined to 3–5% following a change in injection technique, and to 1% after tissue adhesive was used to seal implantation sites. A tag loss rate of 2.5% was reported for Magellanic Penguins (*Spheniscus magellanicus*) where tags were injected in the tarsometotarsus and the injection site was sealed with tissue adhesive (Boersma and Rebstock 2009). In smaller birds, no tag loss was reported for 78 Kakapos (Low et al. 2005), and tag loss was "negligible" in Great Tits when injection sites were sealed with a topical adhesive (Nicolaus et al. 2008).

Elbin and Burger (1994) recommended intramuscular implantation of PIT tags in birds to decrease the chances of tag loss. Comparison and experimentation with various implantation or attachment techniques is likely required in novel applications because previous researchers have noted a considerable learning curve before techniques were finalized (Clarke and Kerry 1998). Ultimately, the behavior of the species being studied will dictate the best implantation or attachment method.

FUTURE DIRECTIONS OF RFID IN ORNITHOLOGICAL RESEARCH

As RFID technology continues to develop and be applied in novel contexts, some questions about the technology remain. The lifespan of RFID tags in field situations has not been tested and needs quantification. Little research has focused on efforts to validate RFID reads, but Boersma and Rebstock (2009) found that foraging trip duration in penguins recorded by RFID was highly correlated with data recorded by satellite transmitters attached to the same individuals.

As noted above, RFID technology can allow researchers to record enormous amounts of data. But what does each event recorded by an RFID reader mean? Validation, through field observations, of the significance of RFID events is needed. For example, was food taken from a supplemental feeder? Were chicks at a nest being fed? Observations intended to identify the nature of RFID-recorded events, however, are rarely reported in the literature. One effort to categorize the data gathered by RFID systems involved examination of food delivery to nest boxes by Wrynecks (Freitag et al. 2001). Observations were conducted to record the behavior of the birds on a subset of visits, allowing quantification of the proportion of visits by adults that resulted in food delivery to the chicks. More observational work of this type is needed; the technology is well-suited for informing a researcher that a marked individual was present at a specific location at a defined point in time, but the behavior exhibited by birds may be ambiguous if only the RFID data are available.

Significant progress has been made in combining RFID data with other sources of information by integrating an array of devices with RFID readers. As mentioned above, scales, cameras, and other tools for collecting data have been combined with RFID to gather information in addition to the identification/time data recorded by RFID. Further integration of additional tools with RFID is possible and will continue to provide new research opportunities, as will further miniaturization of PIT tags as the technology develops.

Linking outside data sets with RFID data is also an area for future research. For instance, Cresswell et al. (2003) integrated weather data with RFID information to study the incubation behavior of Semipalmated Sandpipers and discovered an inverse relationship between incubation bout length and precipitation. Food provisioning rates of Wrynecks obtained using RFID were also related to weather data, revealing the influences of brood size, temperature, precipitation, and time of day on feeding rates (Freitag et al. 2001).

We do not propose that RFID technology could or should replace traditional methods of marking individual birds (i.e., banding). Rather, marking a bird with a numbered leg band in addition to a PIT tag will allow the continued generation of valuable recovery data. Using RFID in any new study system requires experimentation and learning through trial and error. In the appropriate context, however, RFID technology can enable investigators to explore novel areas of research and gather heretofore unobtainable quantities of information. New, inexpensive RFID readers are making this technology more accessible to the ornithological community, and application of RFID in additional appropriate study systems will allow researchers to improve our understanding of avian behavior and biology.

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