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Use of an implanted sound recording device (Bioacoustic Probe) to document the acoustic environment of a blacktip reef shark (*Carcharhinus melanopterus*)

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Abstract – Gaps in our knowledge of basic fish ecology have provided impetus for development of novel "ecology tags" to detect and quantify hard to observe behaviors such as spawning, schooling and feeding. The acoustic environment is one source of potentially useful information about these behaviors. We implanted an acoustic recording tag (Bioacoustic Probe) into the gut cavity of a blacktip reef shark to determine whether an implanted tag could successfully record external and internal sounds. The tag successfully recorded reef fish vocalizations, boat engine noise, the sound of the shark feeding and unidentified rhythmic sounds that may derive from shark tail beats. Technical challenges remain, but sound recording tags have the potential to provide novel insights into shark and fish ecology.

Key words: Bioacoustic probe / Hydrophone tags / Ecology tags / Internal tags / Implanted tags / Acoustic monitoring / Shark ecology

Résumé – Utilisation d'une sonde bioacoustique interne pour étudier l'environnement sonore d'un requin à pointes noires (*Carcharhinus melanopterus*). Des lacunes dans la connaissance de base de l'écologie des poissons ont provoqué un élan pour le développement de nouvelles marques écologiques afin de détecter et quantifier des comportements difficiles à observer tels que la reproduction, le comportement en banc et l'alimentation. L'environnement acoustique est une des sources d'information potentiellement utile en ce qui concerne ces comportements. Nous avons implanté une marque acoustique (sonde bioacoustique) dans la cavité viscérale d'un requin à pointes noires afin de déterminer si une marque interne pourrait enregistrer de façon satisfaisante les bruits externes et internes. La marque a enregistré avec succès les vocalises des poissons récifaux, les bruits de moteur de bateau, le bruit du requin lorsqu'il mange et des sons rythmés indéterminés qui pourraient provenir du bruit des battements de sa nageoire caudale. Des défis techniques demeurent mais ces marques ont le potentiel de fournir de nouvelles perspectives dans l'écologie des requins et des poissons.

1 Introduction

For decades, biologists have been using telemetry transmitters to study the movement patterns and physiology of free-ranging fishes (e.g., Yuen 1970; Carey and Lawson 1973; Carey and Robison 1981; Holland et al. 1992, 1996; Meyer et al. 2000; Meyer and Holland 2005). In addition to basic acoustic and radio "pingers", acoustic and "pop-up" transmitters are now available that store data before transmitting the archived record via underwater acoustic modem or to satellites (e.g., Voegeli et al. 2001; Bruce et al. 2006). More recently, non-transmitting data archiving tags have become available that have added greatly to our understanding of the horizontal and vertical behaviors of wide ranging species (Schaefer and Fuller 2002; Dagorn et al. 2006). In the latter case, the animal carrying the tag has to be recaptured so that the archived data can be retrieved. Despite these technological advances, major gaps remain in our understanding of basic fish ecology, especially for very active or wide-ranging species. For example, although we have successfully quantified the movement patterns of a wide variety of sharks and fishes, in most cases we can only speculate about when, where and how frequently these animals feed during their travels. Such gaps exist because we currently lack devices that can detect and quantify behaviors such as feeding, schooling and spawning. Gaps in

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Fig. 1. Resuscitation of 1.6 m (total length) blacktip reef shark (*Carcharhinus melanopterus*) after surgical implantation of the Bioacoustic Probe.

our understanding of fish ecology have provided impetus for development of new "ecology" tags intended to provide novel insights into the behavior and physiology of marine animals.

One potentially rich source of ecologically relevant information is the acoustic environment within and around marine animals (Rountree et al. 2006). For example, externally-mounted data logging hydrophone tags (e.g., the Bioacoustic Probe™; Greeneridge Sciences Inc.) have recently been used to quantify marine mammals' production of sound and their exposure and response to natural and anthropogenic sound (Burgess et al. 1998; Burgess 2000; Madsen et al. 2002; Johnson and Tyack 2003; Johnson et al. 2004; Madsen et al. 2006; Oleson et al. 2007). We hypothesized that measuring the acoustic environment of fishes and sharks could also provide valuable new insights into aspects of their basic ecology such as feeding, schooling, spawning and interactions with fishing vessels (Insley et al. 2004). As with marine mammals, useful information could potentially be obtained from both external and internal sources of noise. We assumed that long-term ecological studies would require implanted tags, because these can be retained for years and are less likely to impact the animals' natural behavior than externally-mounted tags. Here we describe a proof of concept study using an implanted Bioacoustic Probe to document the acoustic environment of a blacktip reef shark (*Carcharhinus melanopterus*). The specific goals of the study were to determine (1) whether a shark could be successfully implanted with a Bioacoustic Probe, and (2) whether the implanted tag could successfully record both internal and external environmental sounds.

2 Methods

2.1 Subject animal and study site

We selected a 1.6 m (total length) female blacktip reef shark (*Carcharhinus melanopterus*) for the Bioacoustic Probe implantation experiment (Fig. 1). The shark was maintained in captivity at the Hawaii Institute of Marine Biology in a 50×250 m fenced enclosure consisting of a shallow (<1 m) reef flat and a deeper (2 m) sand-bottomed channel bordered by live coral and mangrove. The enclosure contained a variety of naturally-occurring reef fishes and invertebrate species (some of which produce sound). The deepest end of the enclosure was joined to Kaneohe Bay via a channel through the reef, allowing sound from the bay to be recordable inside the enclosure.

2.2 Bioacoustic Probe characteristics and surgical procedures

The Bioacoustic Probe consisted of a hydrophone, pressure sensor, thermistor, 2D accelerometer, 16-bit digital recorder, 1-GB data storage and a field-replaceable battery in a single, self-contained instrument (Fig. 2, Table 1). Prior to implantation we set the Bioacoustic Probe duty cycle such that the instrument alternately recorded sound for one hour and then remained dormant for three hours, repeating this cycle for the duration of battery life or until the storage capacity was reached. We set the sampling rate to 2048 Hz, the built-in lower frequency cutoff was 8 Hz and the anti-aliasing upper frequency

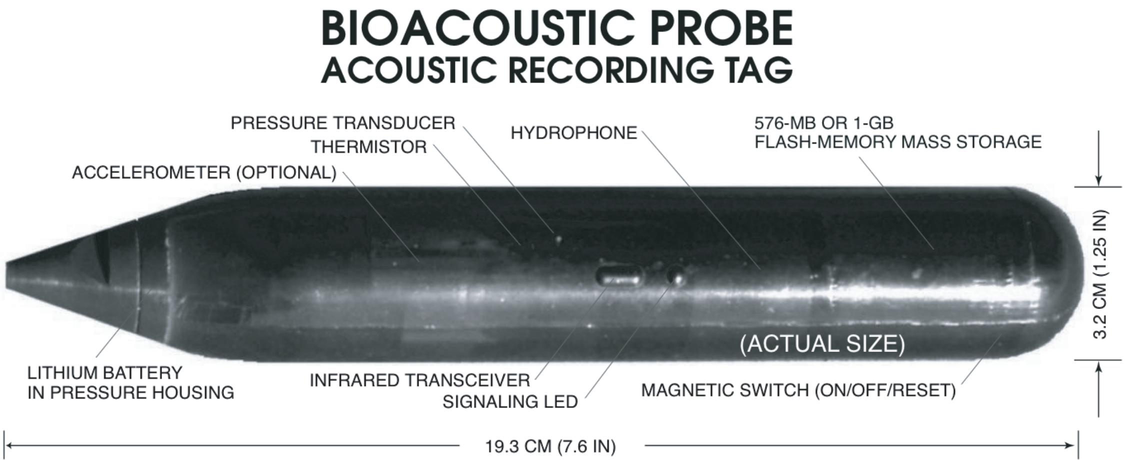

Fig. 2. The Bioacoustic Probe (acoustic recording tag) used in the implantation experiment.

cutoff for this experiment was 767 Hz. The gain was set to maximum (20 dB), resulting in an acoustic saturation limit of 170 dB re 1 μPa (0-pk) with broadband self noise of 97 dB re 1 μPa in the 8 Hz to 760 Hz frequency band. In addition to broadband self noise, tonal artifacts generated inside the Bioacoustic Probe between 370 Hz and 620 Hz were also present in the recorded data.

The shark was captured, placed inverted on a stretcher and anesthetized by irrigating the gills with MS222 solution (0.15 g L^{-1}). The Bioacoustic Probe was coated with a triple antibiotic cream and was surgically implanted in the shark's gut cavity through a ventral incision (offset from the midline and 10 cm posterior of the pectoral fins). The incision was sutured closed, leaving a thin retrieval line trailing outside the body (the retrieval line was secured to one end of the Bioacoustic Probe). The shark was then resuscitated and released back into the shark pond (Fig. 1). One week later, the shark was recaptured, anesthetized and the Bioacoustic Probe was extracted by cutting the sutures and gently pulling it out using the retrieval line. The incision was then reclosed and the shark resuscitated and released, making a full recovery.

2.3 Data analyses

We used two strategies to analyze data recorded by the Bioacoustic Probe. First, we searched for relatively loud and distinctive sounds (e.g., reef fish vocalizations) by amplifying raw data, listening to playbacks and visually examining audio time series and spectrograms. Second, to quantify subtle modulations of background or flow noise and evaluate their potential association with the subject's motion, we used sequential Fast Fourier Transformations (FFTs) to extract the level (dB) of sound in the 200-Hz one-third octave band. We picked a center frequency of 200 Hz because visual inspection suggested that the modulation of noise was most significant in this band. Each FFT processing window covered 0.1 s of data and was shifted by 0.005 s from the previous window (20-times overlapping). This process produced a smoothed time series, effectively sampled at 200 Hz, of the fluctuating sound level within the 200-Hz one-third octave band. We then generated a spectrogram of this time series to identify any regular, periodic fluctuations in the band level and assess their time- and frequency-dependence. Spectrogram parameters were adjusted for visual clarity.

3 Results

The implanted shark resumed normal swimming immediately after resuscitation and resumed feeding six days after implant surgery. The shark also recovered quickly from the tag retrieval surgery and remains healthy to date (March 2007). While inside the shark, the Bioacoustic Probe recorded 0.6 gigabytes (42 hours) of acoustic data, including a variety of external sounds and possible internal noises. External sounds included reef fish vocalizations, boat engine noise, and splashing sounds associated with the subject's feeding. Fish vocalizations were identified as calls of male Hawaiian domino damselfish (*Dascyllus albisella*), an abundant occupant of the shark enclosure (Fig. 3). The boat engine noise recorded by the implanted Bioacoustic Probe was likely produced by the 40 HP outboard motor of a small shuttle boat that services the research facility. For example, changes in engine pitch associated with the shuttle slowing on approach to (or accelerating away from) the facility dock were clearly audible (Fig. 4). The acoustic record from the day that the experimental shark resumed feeding contained loud splashing sounds corresponding to the time when the shark was observed feeding in the shallow area of the enclosure.

In addition to a variety of distinctive and relatively loud, external sounds, the implanted Bioacoustic Probe also captured occasional modulated broadband noise likely associated with shark tail beats. We analyzed video footage of the shark swimming during the experiment and calculated an average tail beat period of 1.7 s. Fast Fourier Transformations of acoustic data from periods where the shark was swimming steadily around the enclosure produced a fundamental modulation period of 1.7 s (0.6 Hz) with a strong harmonic at 0.8 s (1.25 Hz) and weaker harmonics at 0.5 s (1.9 Hz) and 0.4 s (2.5 Hz) (Fig. 5). This harmonic structure is consistent with

Table 1. Bioacoustic Probe technical specifications.

Parameter	Specification
Maximum depth (design)	Typically limited by choice of pressure sensor; max 2000 m
Maximum depth (tested)	Two units tested to 2000 m (March 2003)
Maximum continuous acoustic sampling rate	20 kHz (at room temperature; 10 kHz typical maximum)
Saturation at 0-dB gain, re 1 μPa zero-peak	172 dB (190-dB option available)
Acoustic gains, user selectable	0/10/20 dB
Acoustic sampling resolution	16 bits
Auxiliary sampling rate	1 Hz
Auxiliary sampling resolution	16 bits
Auxiliary sampling channels	Pressure Tag temperature 2-D acceleration/tilt, in g's (option)
Storage capacity	576 MB (1-GB option available)
Life at 2 kHz acoustic sampling rate	41 h (for 576-MB storage unit)
Maximum measured data download rate	5.3 kbytes s^{-1}, via infrared

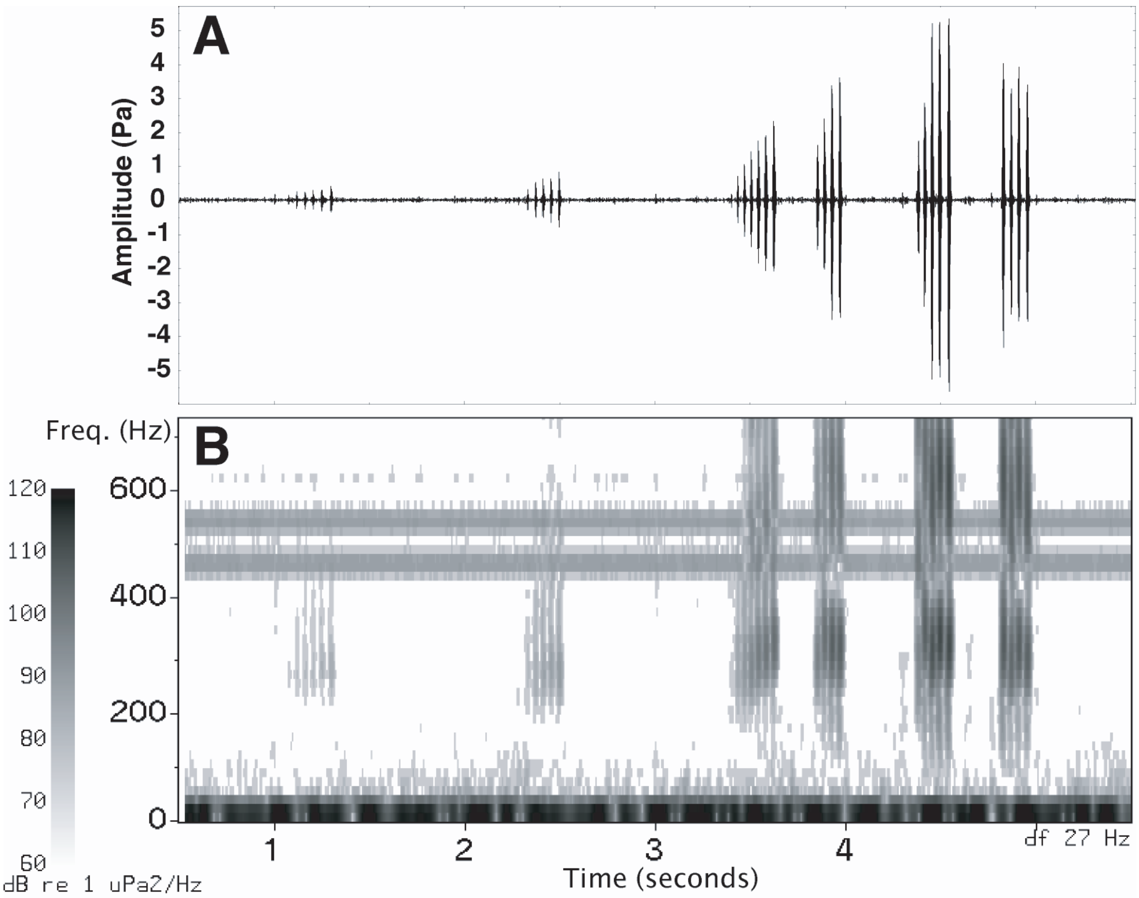

Fig. 3. Oscillogram (A) and spectrogram (B) of Hawaiian Domino Damselfish (*Dascyllus albisella*) calls recorded by the Bioacoustic Probe while implanted in the gut cavity of a blacktip reef shark. Horizontal lines in the spectrogram reflect instrumental noise generated inside the Bioacoustic Probe.

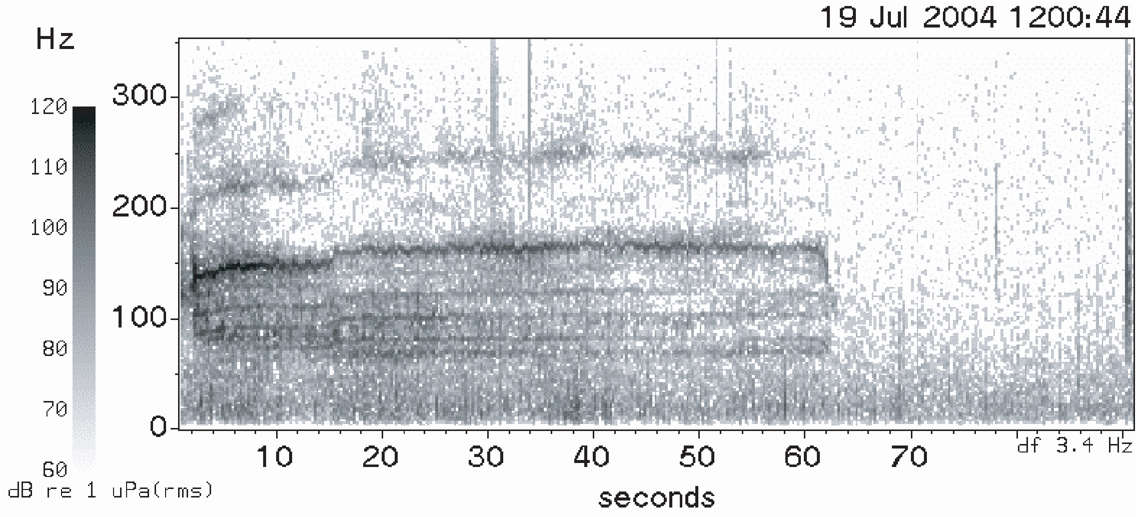

Fig. 4. Spectrogram of boat engine noise recorded by the Bioacoustic Probe.

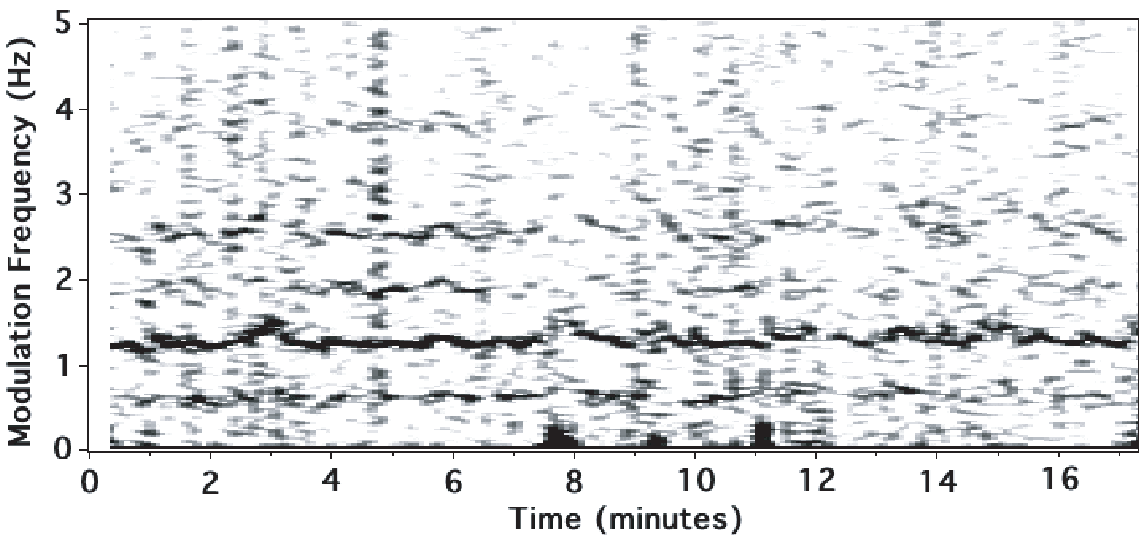

Fig. 5. Spectrogram of noise modulation rates within the 200-Hz 1/3- octave band from 17 min of sound recorded while the shark was swimming steadily around the enclosure. The harmonic structure is consistent with strongly periodic modulation of noise within the analysis band.

the visually-observed fundamental tail beat period of 1.7 s (for the tail to come full cycle), while the predominant noise modulation period is 0.8 s, consistent with the dominance of flow-noise modulation by each "half-cycle" lateral tail movement rather than by the "full-cycle" tail beat. The tempo of this rhythmic sound was apparently linked to shark activity. For example, the tempo was relatively constant throughout most of the acoustic record, including immediately before the shark fed on day six, but more than doubled during and immediately after feeding (Fig. 6), when the implanted shark became highly active and increased both tail beat rate and swimming speed. Note that although modulated broadband noise was clearly evident in the acoustic time series during highly-active periods (Fig. 6B), spectral analysis failed in this case to show harmonic structure such as that evident in Fig. 5. This may indicate that tail movements were not only more rapid but also more erratic when the shark was very active than during slower, steady swimming.

4 Discussion

This experiment marks the first time that a self-contained, low frequency acoustic recording device has been implanted inside an animal, and demonstrates that implanted hydrophone tags can record a variety of external (and possibly internal) sounds. For example, fish vocalizations, boat engine noise and sounds associated with feeding were all clearly discernable in the acoustic record recovered from the implanted Bioacoustic Probe. Although sharks detect the particle acceleration component of the sound field rather than the pressure component recorded by the Bioacoustic Probe, the dominant frequencies

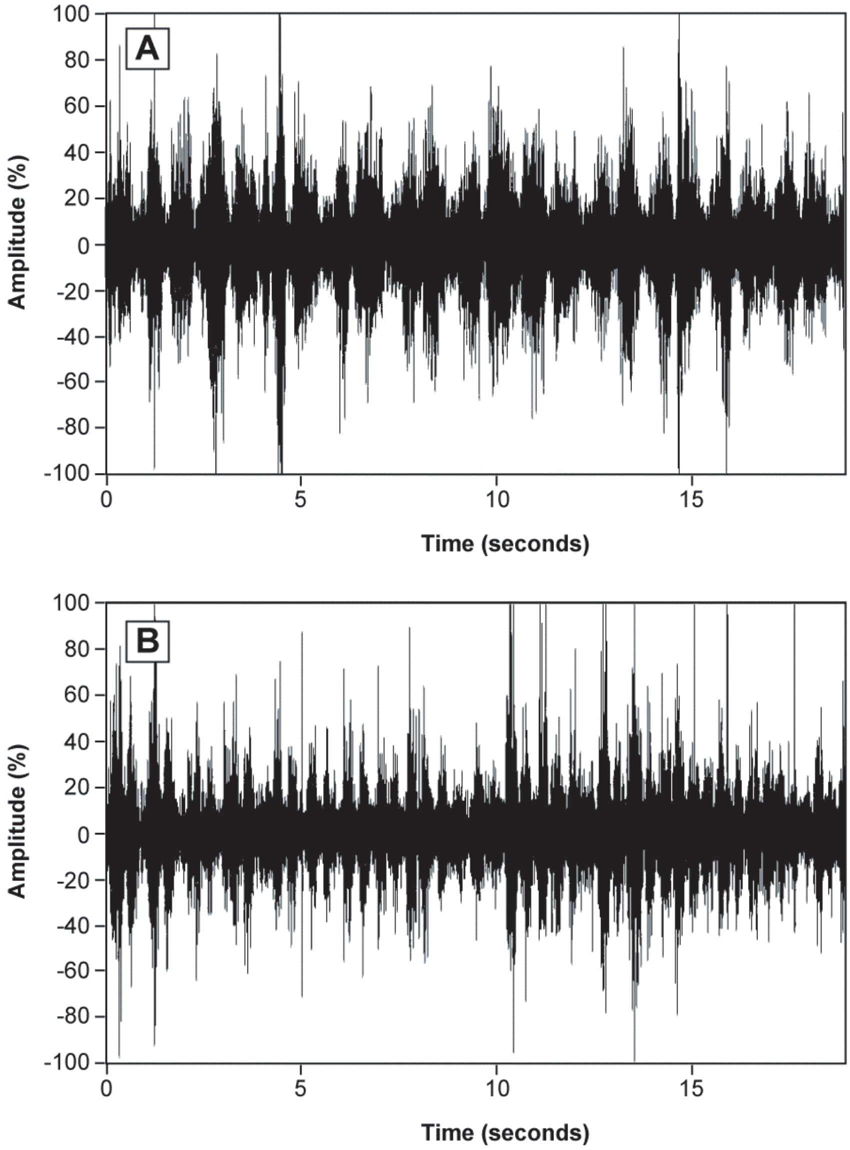

Fig. 6. Oscillograms of unidentified rhythmic sounds recorded by the Bioacoustic Probe, (A) immediately before feeding the implanted shark, and (B) immediately after feeding the shark.

of the recorded sounds were within the hearing range for sharks (40 Hz to approximately 800 Hz; Myrberg 2001), and several of these sounds are known to attract sharks in natural settings. For example, previous studies have shown that reef fish vocalizations and sounds associated with fish feeding activity attract sharks (Banner 1972; Nelson and Johnson 1976; Nelson et al. 1969).

Each of the sounds recorded by the Bioacoustic Probe could potentially provide useful information on fish ecology. Fish vocalizations are often associated with specific behaviors such as mating and spawning (e.g., Mann and Lobel 1998), and such sounds could reveal when fish implanted with hydrophone tags are associating with spawning events. Boat engine noise could tell us how frequently fish are in proximity of fishing vessels (Insley et al. 2004), or at locations where fishing boats congregate such as Fish Aggregating Devices or seamounts. Sounds associated with feeding could reveal fish foraging strategies. The rhythmic tail beat sounds that varied in tempo with shark swimming speed, suggest that hydrophone tags could also provide information on shark or fish physiology and activity rates, as has been the case with marine mammals (Burgess et al. 1998). For example, the ability acoustically to recognize full-cycle as well as half-cycle tail beats indicates that the character of the flow noise recorded as the subject swam was different between right-to-left and left-to-right tail movement. This may suggest that the subject swam asymmetrically, or may reflect asymmetric reception of noise by the Bioacoustic Probe.

Although there is clearly considerable potential for using acoustic recording tags to increase our understanding of fish ecology, there are also significant technical challenges associated with creating small, implantable acoustic recording devices suitable for long-term studies. For example, we were able to recognize sounds recorded by the Bioacoustic Probe by manually identifying them during playback but this required a large tag memory and was a labor intensive process. One solution would be to enable tags to automatically "recognize" sounds in real-time but record them only as simple "events" to minimize data storage requirements and simplify subsequent analyses. This would require on-board processing of acoustic data by the tag which could be simplified by focusing on sounds with distinctive "signatures". For example, most fish sounds are either simple pulsed broad-band sounds or tonal type sounds, where the pulse rates or dominant frequency are species-specific (e.g. Lobel and Mann 1995; Mann and Lobel 1998; Mann 2002). Fish sounds do not typically exhibit complex frequency modulations seen in many marine mammal vocalizations (Mann 2002). This makes it possible to describe most fish sounds with a few metrics, such as sound duration, peak frequency, and bandwidth (Mann 2002). Timing between pulses can be recorded by storing the time of onset of each pulse (Mann 2002). By recording these simple metrics, a system could be developed to automatically detect and process sounds of interest and greatly reduce the amount of data that would be acquired by simply recording continuously (Mann 2002).

The recovery of stored data from implanted acoustic recording tags presents another logistical challenge. Either the tags must be physically recovered as in this study, or data remotely recovered from free swimming animals via acoustic modem. Implanted data logging archival tags are already routinely recovered from commercially exploited fishes such as tunas (e.g., Schaefer and Fuller 2002; Dagorn et al. 2006), suggesting that this would be a feasible approach for heavily targeted species. However other species of interest, such as large sharks, are not commercially harvested and the probability of recovering implanted archival tags from these animals is far lower. In these situations remote data retrieval using acoustic modems will be required, and could be accomplished by deploying underwater receivers in areas utilized by species of interest (e.g., Voegeli et al. 2001). If these technical hurdles can be overcome then acoustic recording tags could provide valuable new insights into little-known aspects of fish ecology.

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