PAPER

New Stereo Acoustic Data Logger for Free-ranging Dolphins and Porpoises

AUTHORS

Tomonari Akamatsu
Akihiko Matsuda
Shiro Suzuki
National Research Institute of Fisheries Engineering, Fisheries Research Agency, Japan

Ding Wang
Kexiong Wang
Institute of Hydrobiology, The Chinese Academy of Sciences

Michihiko Suzuki
Little Leonardo Inc.

Hiroyuki Muramoto
Marine Micro Technology Inc.

Naoki Sugiyama
Suruga Denshi Co. Ltd.

Katsunori Oota
Intertec Co. Ltd.

ABSTRACT

To observe the bio-sonar behavior of dolphins and porpoises, a miniature stereo acoustic data logger was developed to record the echolocation clicks of small cetaceans. The 'A-tag' device is small enough to be attached to a dolphin or porpoise. A-tag can record the sonar pulse intensity, precise inter-click-intervals, and time difference between sounds arriving at two different hydrophones. The A-tag works for up to 60 hours continuously and allows observation of the sonar target range of free-ranging odontocetes. The time of arrival at the two hydrophones on the tag allows vocalizations from nearby individuals to be identified. A less invasive tagging technique using a suction cup was also developed. A mean attachment time of 15 hours was obtained on free-ranging finless porpoises in a freshwater system in China. The A-tag proved to be a useful tool for investigating the underwater echolocation behavior of odontocetes.

INTRODUCTION

In the last two decades, the bio-sonar system of dolphins and porpoises (Au, 1993) has gained attention as a model for future underwater echo sounders. Fisheries, ocean engineering, and underwater construction and exploitation all require a reliable sensing technique to examine underwater objects.

A wide-band signal is useful for assessing target characteristics, depending on the specific frequency response of each target. However, most manmade echo sounders use narrow band signals (Furusawa, 1999) that only sense the echo level of a monochromatic frequency component. Although several echo sounders use multiple frequencies to examine target characteristics, a wide-band echo sounder, similar to the bio-sonar of dolphins and porpoises, has not yet been developed. Manmade underwater echo sounders are not "colorized". Therefore, we have lost frequency-dependent information about the target characteristics in underwater acoustical surveys.

Compared with manmade sonar, dolphins and porpoises use wide-band sonar for prey capture and environmental recognition. High-performance dolphin-like sonar has long been anticipated. An understanding of how dolphins and porpoises use their bio-sonar abilities would be beneficial in the design of future wide-band electronic sonar.

Although the acoustic characteristics and performance of the sonar of dolphins and porpoises have been extensively studied (Au, 1993; Richardson et al., 1995), the behavioral control and use of their bio-sonar systems are not fully understood. Especially puzzling is the ability of dolphins and porpoises to avoid jamming during group swimming and the mechanism they use to improve the signal-to-noise ratio in noisy circumstances. Hence, a study on how odontocetes use their wide-band sonar is needed. However, three major difficulties have slowed the progress of such research.

First, a particular vocalizing animal is difficult to identify, even in captivity. In cetaceans, sound production does not associate with typical behavior, such as mouth opening. However, this can be studied using a hydrophone array system, which is a powerful tool for determining the sound source direction (Au and Benoit-Bird, 2003). With the very short pulse duration of cetacean sonar signals, it is relatively easy to measure the difference in sound arrival times between several hydrophones forming a short base-line system. Still, it can be very difficult to distinguish the phonating individual within a tight group.

Second, ultrasonic sounds are difficult to record. The dominant frequency of sonar signals in dolphins and porpoises is in the range of several to 150 kHz (Richardson et al., 1995). Full bandwidth digital recording of such sonar signals requires a very high sampling frequency. With continuous recording, it is important to avoid missing any signals. This requires very large memory capacity. However, the waveforms of ultrasonic sonar signals in dolphins and porpoises are stereotyped (Amundin, 1991), so recording the transmission waveform is not essential for sonar behavioral studies. Conversely, the sound pressure levels, inter-pulse intervals, and number of sounds produced per unit time provide crucial behavioral information, such as the estimated target range and search effort. Therefore, a pulse event recorder with a low frequency sampling rate to record the sound intensity of sonar signals is needed for the long-term observation of the sonar behavior of dolphins and porpoises.

Finally, the recording of sonar signals from wild odontocetes for a prolonged period of time is extremely difficult. Dolphins and porpoises move quickly and do not stay in a fixed position. Moreover, it has been next to impossible to record individual behavior as well as the phonation simultaneously for a long period of time in the water. Bio-logging techniques (Naito, 2004) using data loggers have recently been used to reveal underwater animal behavior (Hanson and Baird, 1998; Burgess et al., 1998; Madsen et al., 2002; Akamatsu et al., 2002; Tyack et al., 2004; Nowacek et al., 2004). Data loggers are very small computers with sensors encapsulated in a pressure-resistant case. A data logger can be attached to an animal to record behavioral and physiological parameters, such as depth, swimming speed, body accelerations, the electromyogram, and stomach temperature, and to obtain underwater digital images (Naito, 2004). However, a limited number of studies have focused on the sonar behavior of odontocetes (Tyack and Recchia, 1991; Madsen et al., 2002, 2005; Blomqvist and Amundin, 2004; Akamatsu et al., 2000, 2005; Johnson et al., 2004; Zimmer et al., 2005).

In summary, an ideal device for observing the underwater sensory behavior of dolphins and porpoises should (a) have multichannel hydrophones to identify the sound source direction, (b) be an ultrasonic pulse event recorder suitable for long-term recording, and (c) be small enough to be attached on dolphins and porpoises without disturbing their normal behavior. In the remainder of this paper, we discuss the development of a miniature stereo acoustic data logger named '*A-tag*' that meets these specifications.

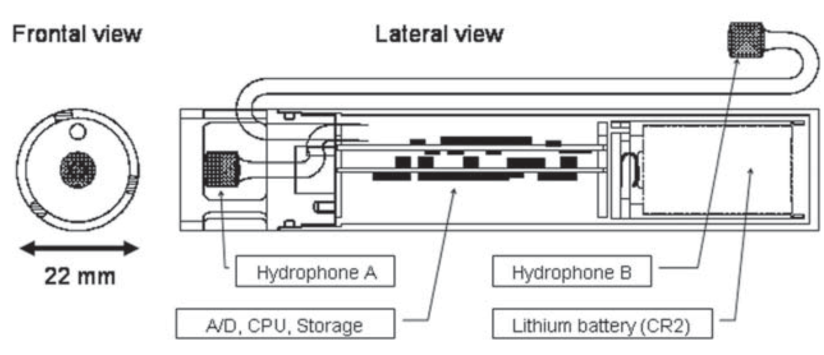
System Specifications

Hardware

The '*A-tag*' (W20-AS, Little Leonardo, Tokyo, Japan) contains a miniature stereo pulse event recorder and a CR123 lithium battery cell, encased in a waterproof tube, measuring 22 mm in diameter, 122 mm in length, and weighing 77 g (Figure 1). *A-tag* has two miniature ultrasonic hydrophones (System Giken, -210 dB/V sensitivity), one at each end of the logger. A band pass filter (70 to 300 kHz) is included to eliminate noise outside the frequency bands of porpoise sonar signals. The CPU is a PIC18F6620 (Microchip, USA) and is used for system control and signal processing. As a storage device, 256 MB flash memory is used. *A-tag* consumes approximately 10 mA electric current on average. The total recording time is approximately 60 hours, depending on the number of pulses that a dolphin or porpoise produces. The internal clock of *A-tag* drifts less than 1 second per day.

FIGURE 1

The frontal and lateral views of the *A-tag* (W20-AS). Hydrophone A is located at the front of the data logger and Hydrophone B with an extension cable is located at the rear of the tag to measure the sound time-of-arrival difference between the two hydrophones, revealing the rough direction to the sound source.



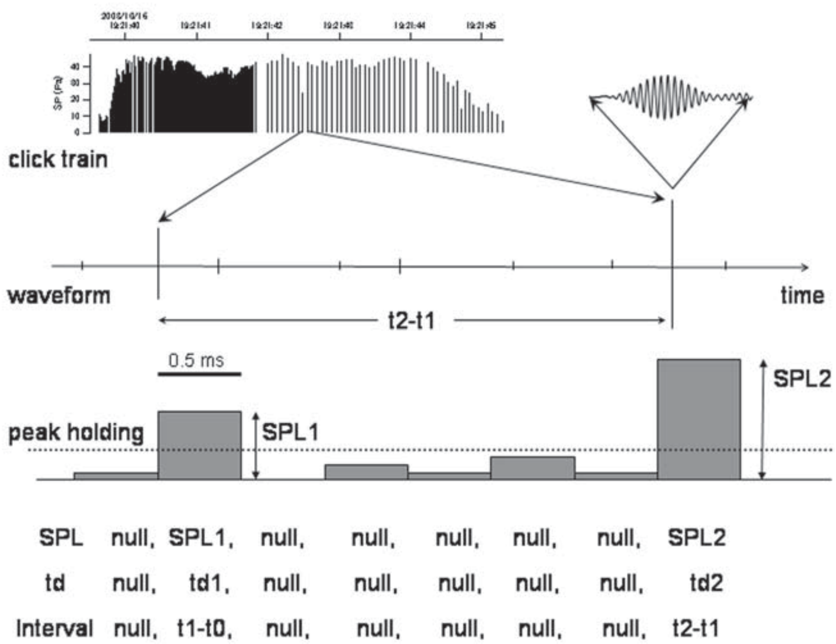
Signal Processing

The dynamic range of *A-tag* is between 129 dB peak to peak (reference pressure 1 μPa) to 157 dB. The signal output from hydrophone A is amplified with a gain of 60 dB. The noise floor at the output of the hydrophone is lower than 25 μV_{p-p} (depending on the sensitivity variation of each hydrophone), which corresponds to 118 dB_{p-p} re μPa. To avoid thermal or electronic noise contamination, a hardware detection threshold level corresponding to 129 dB re μPa is used. A variable resistor in *A-tag* sets the hardware detection threshold level. An analogue-to-digital converter with 10 bit resolution digitizes the peak intensity in every 0.5-ms time bin. If the peak intensity exceeds the hardware detection threshold level, the peak intensity is stored in the flash memory (Figure 2). If the peak intensity is below the hardware detection threshold level, the data is deemed null and is not saved in the memory. *A-tag* repeats this procedure every 0.5 ms (2 kHz sampling frequency).

The direction of the sound source is calculated from the sound time-of-arrival difference between hydrophones A and B. This feature is added to make it possible to exclude vocalizations coming from other individuals. The output of hydrophone B is fed into a second peak holder. If the peak levels of hydrophones A and B are both higher than the hardware detection threshold level, then the difference in the sound's arrival time is stored (Figure 2). The difference in the sound arrival time between hydrophones A and B should be within ±80 ìs, since the inter-hydrophone distance is 120 mm. *A-tag* is programmed to neglect time differences outside a ±139 μs time window to exclude any noise contamination. The time difference within this window is quantized in 10 bits, corresponding to a resolution of 271 ns. This gives a resolution of 0.4 mm in the travel distance difference between the hydrophones from a sound source in line with the unit. The absolute time of each pulse can be calculated by integrating the interval time, such as t2-t1 indicated in the lowest line of Figure 2. This calculation is automatically done by the software Logger Tools ver. 4.1 (Little Leonardo, Tokyo).

FIGURE 2

Signal processing in the *A-tag*. A typical sonar click train of a finless porpoise is shown in the upper trace in this figure. Two high-intensity sonar pulses and low-intensity pulse noise are shown in the middle trace waveform. The peak intensities of the signals in each 0.5 ms time bin are held electronically. Once the peak level exceeds the hardware detection threshold (lower trace: dotted line), the sound pressure level (SPL; SPL1 and SPL2) and time arrival difference of a sound between the two hydrophones (td; td1 and td2) and the time elapsed from the previous pulse (interval; t1-t0, t2-t1) are stored in the memory of the *A-tag*. The absolute time could be calculated by integrating the interval and adding the initial date and time.



Assembly

As shown in Figure 3, *A-tag* is assembled with a VHF transmitter (MM130, Advanced Telemetry Systems, USA), float (expanded polyvinyl chloride, Klegecell #55, pressure resistant to 80 N/cm^2, Kaneka, Japan) and suction cup (Product# 40-1525-0, 82 mm in diameter, Canadian Tire Corp., Canada). Suction cups are a less-invasive technique for attachment on animals and are commonly used to attach data logger systems to cetaceans (Hooker and Baird, 2001). Although the float consists of closed cells of polyvinyl chloride foam that do not allow the infiltration of water, the surface of the float is coated with urethane rubber to prevent mechanical damage and further minimize the amount of infiltration. The float is designed to have positive buoyancy for easier retrieval after the spontaneous release of the suction cup from the animal. The amount of buoyancy is critical for the long-term attachment and safe recovery of the system; greater buoyancy causes premature detachment because of the larger floatation force, while lower buoyancy increases the system's risk of sinking after detachment. The float lost a slight amount of its buoyancy in the validation experiment described below. A small amount of infiltration and shrinking due to the repeated change of water pressure during successive dives by the animals is thought to cause this buoyancy loss. A buoyancy margin of 15 to 20 g was found appropriate. In order to receive strong radio signals from the VHF transmitter after detachment, the transmitter antenna must be oriented vertically in the air. Therefore, the float is designed to have larger volume in the rear and a smaller volume in front of the system to make the antenna protrude from the water vertically.

To decrease the total weight of the data logger system, an acrylic supporting plate and acrylic screws were used instead of metal parts to secure the suction cup to the float. These were specially designed for this system (Suruga Denshi, Japan). The plate is fixed to the float with epoxy glue (Quick Set 30, Konishi, Japan). *A-tag* is fixed to the plate by a ribbon sealer (MH 908, Musahi Holt, Japan). The transmitter is situated just behind the *A-tag*. We confirmed that radio transmission did not affect data acquisition by the data logger. The total weight of the data logger system including the *A-tag*, battery cell, transmitter, float, and suction cup is approximately 203 g. When the animal is respiring, the data logger system is exposed to the air for short periods. In this condition, the data logger remains on the animal but records splash noises primarily.

Attachment

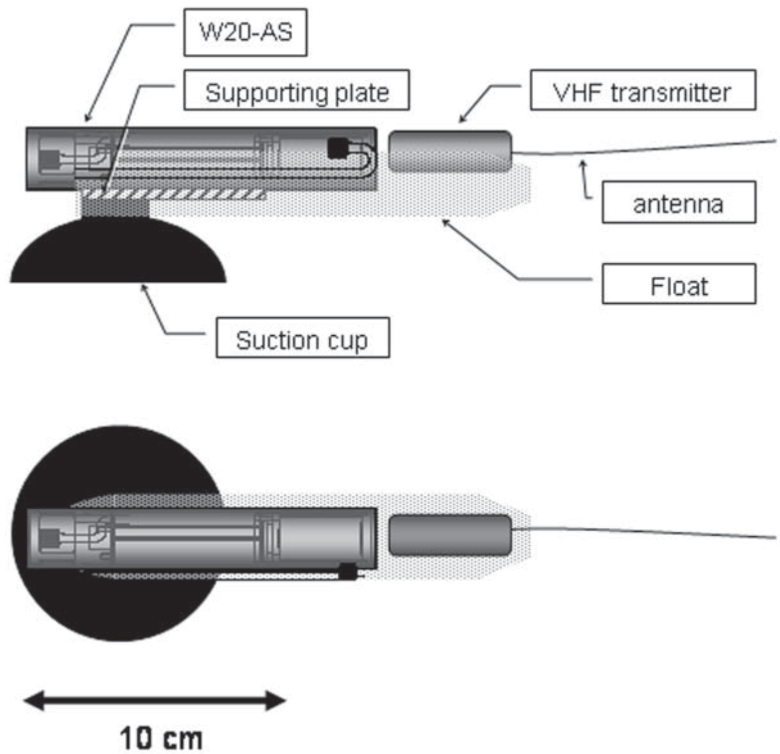
Basics of Suction Cup Attachment

A preliminary attachment test of the data logger system was carried out using two finless porpoises (*Neophocaena phocaenoides*) kept at the Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan, Hubei, China. We drained the water from a kidney shaped pool (20 × 7 m) and caught the animals one by one. The *A-tag* was fixed to the right side of the body behind the pectoral fin. This area was the least affected by body movements, which ensured a long attachment time. A behavior data logger (PD2GT, Little Leonardo, Japan) was attached in a similar position on the left side of the animal. The behavior data logger had four different instruments: a pressure sensor, propeller, two-axis accelerometer, and thermometer. It recorded the swimming depth, speed, heaving and surging body accelerations, and the temperature of the water where the animal was. The behavior data logger was 114 mm long, 21 mm in diameter, and weighed 59 g. Its size and weight were quite similar to those of the *A-tag* and a similar float and attachment system was used for both types of data logger.

In all, four data loggers were deployed on the two animals. We filled the pool with water just after attachment and observed the animals during the day. One data logger system detached after 4.0 hours on the animal. The other three data loggers were still attached after 26.2 hours, when the animals were re-captured the next day. This was done

FIGURE 3

Lateral and top views of the *A-tag*.



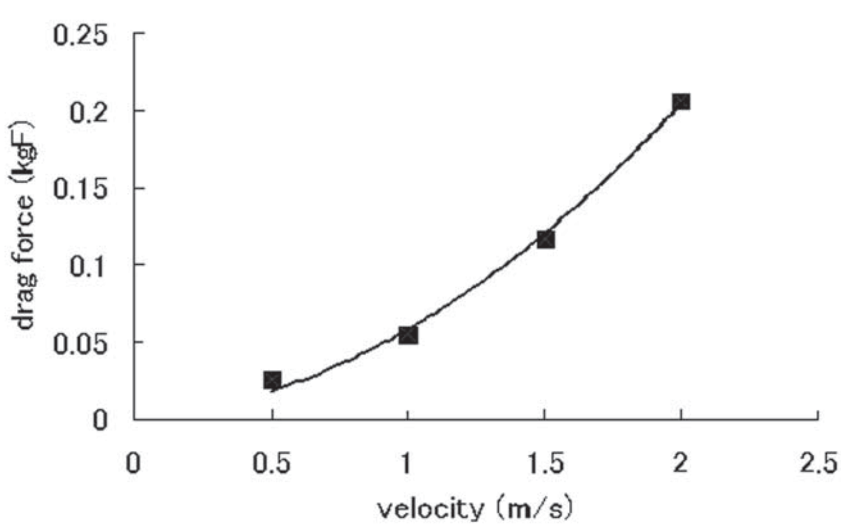
to avoid any damage to the skin of these captive animals from the suction cups. Having three of four devices remain attached to the animals after more than one day was considered acceptable given the use of this less-invasive attachment method. Previous suction cup attachments of data logger systems have been in the range of a few hours to two days (Hooker and Baird, 2001).

Drag Force

The drag force of the *A-tag* could potentially affect the behavior of the tagged animal. To evaluate this, the drag was measured in the Marine Dynamics Basin at the National Research Institute of Fisheries Engineering, Japan (Figure 4). This facility has a tank (60 × 25 × 3.2 m) with a control room above it. The control room can be moved horizontally in two directions. An aluminum plate (324 × 298 mm) was fixed with a load cell (FM-6H50S, Izumi Sokki, Tokyo, Japan) beneath the control room. Half of the aluminum plate was submerged in the water. After a calibration run to measure the drag force of the aluminum plate without the data logger system, the *A-tag* assembled with the float and radio transmitter was attached to the plate using a suction cup. The *A-tag* was pulled through the water at speeds ranging from 0.5 to 2.0 m/s in 0.5-m/s increments. The drag force increased with the square of the velocity, as predicted by fluid dynamics theory. At 1 m/s, which is similar to the normal cruising speed of finless porpoises (Akamatsu et al., 2002), the drag force of the data logger system was 56 gF.

FIGURE 4

Drag force of the data logger system. The drag force was measured in fluid dynamic experiments (squares) and showed good agreement with a theoretical fitting by a quadratic function (solid line).



Validation

Field Test

The experimental site was an oxbow of the Yangtze River, which was cut off from the main stream of the river in 1972. Water still enters the oxbow from the main stream during the flood season (Wei et al., 2002). This oxbow lake, part of Tian-e-Zhou Baiji National Natural Reserve of the Yangtze River, Hubei, China (29°30'-29°37'N, 112°13'-112°48'E), is approximately 21 km long and 1 to 2 km wide. It was established by the Chinese government in 1992 as a reserve for baiji (*Lipotes vexillifer*) and finless porpoises. Since 1990, 49 finless porpoises have been introduced from the main population in the river. These finless porpoises in the lake survive without supplemental food and reproduce annually. The environment of the lake is considered similar to the natural habitat of this species (Zhang et al., 1995).

FIGURE 5

A finless porpoise with the *A-tag* and behavior data logger attached on either side. This individual was released immediately after attachment.

Finless porpoises in the reserve were captured for the test in October 2004. Eighteen fishing boats drove finless porpoises from the upper end of the oxbow to the lower end. A net approximately 1 km long was used to divide the oxbow transversely. A fine-mesh net was used to encircle the animals. In the final stage, fishermen wearing life jackets entered the water and captured the animals individually. In the meantime, 18 boats surrounded the seine net and more than 50 fishermen carefully watched each section of the net to prevent entanglement of the animals. The water was less than 1 m deep in the capture area, allowing the fishermen to handle the animals safely. All animals inside the net were captured and were then temporarily released into a net enclosure to calm them. In total, 6 animals were captured. The enclosure was established close to shore and measured approximately 30 × 60 m with a maximum depth of 3.5 m. After the calming period, the animals were fitted with the *A-tag* (Figure 5) and released back into the lake.

To ensure retrieval of the data loggers, the radio signals were monitored using two antennae (RX-155M7/W, Radix, Japan) from the top of a three-story field station building beside the oxbow. When a continuous radio signal was received, a data logger was considered to be floating. Retrieval operations were started six or more hours after release to avoid disturbing the animals. All of the data logger systems were safely retrieved and found to be working while they were attached. The average attachment duration of the *A-tag* on the animals was 18.1 hours (range: 2.9 to 29.7 hours), which compares favorably with previously reported suction cup attachment durations (Hooker and Baird, 2001).

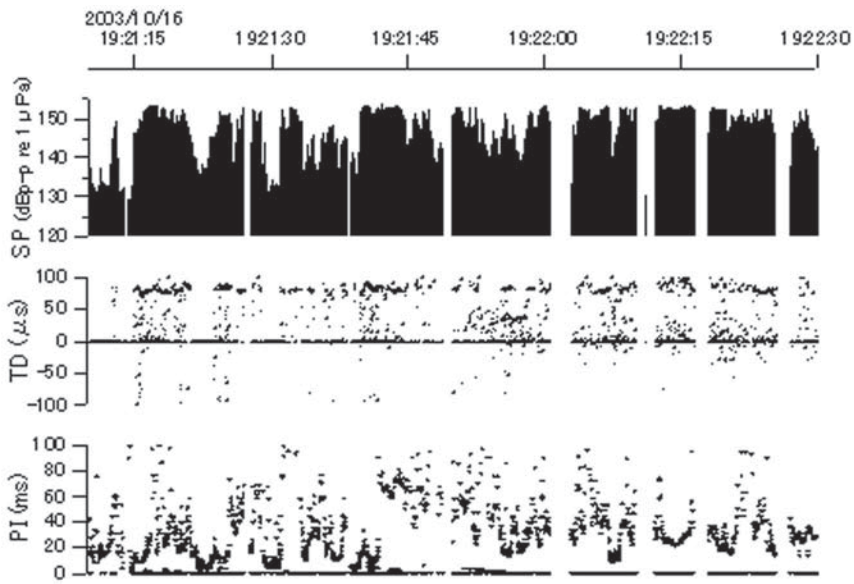
Data Processing

As shown in Figure 6, *A-tag* recorded the sound pressure (upper trace) and time difference between the two hydrophones (middle trace) of the individual sonar signals. In addition, the inter-pulse interval was calculated as indicated in the lower trace of Figure 6. Low-intensity signals below the software detection threshold level were excluded to eliminate noise contamination. Newly developed pre-processing software written on MATLAB (The MathWorks, MA, USA) was used for this purpose. The software detection threshold level can be selected arbitrarily, as appropriate for the purpose of the analysis. For this study, a software detection threshold level equivalent to 136 dB re μPa was selected for the individual sonar behavior analysis, and 129 dB was selected for the analysis of the water surface reflection of the sonar signals.

The porpoise changed the sound pressure (SP) as well as the inter-pulse interval (PI) frequently (Figure 6), which suggests that the sonar range of this individual varied from second to second (Akamatsu et al., 2005a). The time difference between hydrophones A and B (TD) was approximately +80 μs, which corresponds to the sound coming from the individual animal carrying the particular *A-tag*. Dolphins and porpoises produce sonar signals from their nasal duct located just below the blowhole (Cranford et al., 1996). The sonar signal reaches the front hydrophone first, travels along the long axis of the *A-tag*, and is then picked up by the rear end hydrophone. The frequent detection of a +80 μs time difference (middle trace of Figure 6) indicates that most of the received sounds came from the sound source of the host animal carrying the *A-tag*. Some of the signals had time differences significantly different from 80 μs and these were considered to come from other individuals. For the individual sonar behavior analysis, we excluded sounds with other time differences to avoid contamination of the signal by vocalizations of other animals. When there was insufficient intensity at the rear end hydrophone, null data was recorded as the time difference and that is shown as a zero value in the middle trace. Akamatsu et al. (2000) showed that measurable sound energy can be picked up at the position of the tag, although the main energy is focused in a narrow beam directed forward of the animal's melon (Au, 1993).

FIGURE 6

The sound pressure (SP) in dB re μPa (upper trace), time difference between the two hydrophones (TD) in ìs (middle trace), and calculated inter-pulse interval of sonar signals (PI) (lower trace) recorded by the *A-tag*.



Conclusion

An acoustic data logger (*A-tag*) designed for observing sonar behavior in small cetaceans was developed. The *A-tag* was successfully used to collect data on free-ranging finless porpoises in an open-water environment. A less invasive attachment technique was also developed. We applied *A-tag*s to free-ranging finless porpoises and confirmed that they were capable of collecting relevant sonar behavior data. The underwater sensing behavior of this species is being investigated using the data obtained by the *A-tag* (Akamatsu et al., 2005a, 2005b).

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References

Akamatsu, T., Wang, D., Wang, K. and Naito, Y. 2000. A method for individual identification of echolocation signals in free-ranging finless porpoises carrying data loggers. J Acoust Soc Am. 108:1353-1356.

Akamatsu, T., Wang, D., Wang, K., Wei, Z., Zhao, Q. and Naito, Y. 2002. Diving behavior of freshwater finless porpoises (*Neophocaena phocaenoides*) in an oxbow of the Yangtze River, China. ICES J Mar Sci. 59:438-443.

Akamatsu, T., Wang, D., Wang, K., and Naito, Y. 2005a. Biosonar behavior of free-ranging finless porpoises. Proc R Soc Lond. B, 272:797-801.

Akamatsu, T., Wang, D. and Wang, K. 2005b. Off-axis sonar beam pattern of free-ranging finless porpoises measured by a stereo pulse event data logger. J Acoust Soc Am., 117:3325-3330.

Amundin, M. 1991. Sound production in odontocetes, with emphasis on the harbour porpoise, *Phocoena phocoena*. Swede Publishing AB, Stockholm, pp.128.

Au, W. W. L. 1993. The sonar of dolphins. New York: Springer. 277pp.

Au, W. W. L. and Benoit-Bird, K. J. 2003. Automatic gain control in the echolocation system of dolphins. Nature 423:861-863.

Blomqvist, C. and Amundin, M. 2004. An acoustic tag for recording directional pulsed ultrasounds aimed at free-swimming bottlenose dolphins (*Tursiops truncatus*) by conspecifics. Aquat Mamm. 30:345-356.

Burgess, W. C., Tyack, P. L., Le Boeuf, B. J. and Costa, D. P. 1998. A programmable acoustic recording tag and first results from free-ranging northern elephant seals. Deep-Sea Res. II 45:1327-1351.

Cranford, T.W., Amundin, M. and Norris, K.S. 1996. Functional morphology and homology in the odontocete nasal complex: implications for sound generation. J Morphol. 228:223-285.

Furusawa, M. 1990. Study on echo sounding for estimating fisheries resources. Bulletin of National Research Institute of Fisheries Engineering, 11, 173-249 (in Japanese).

Hanson, M.B. and Baird, R.W. 1998. Dall's porpoise reactions to tagging attempts using a remotely-deployed suction-cup tag. Mar Technol Soc J. 32(2):18-23.

Hooker, S.K. and Baird, R.W. 2001. Diving and ranging behaviour of odontocetes: a methodological review and critique. Mamm Rev. 31:81-105.

Johnson, M., Madsen, P. T., Zimmer, W. M. X., Aguilar de Soto, N. and Tyack, P.L. 2004. Beaked whales echolocate on prey. Proc. R. Lond. B (Suppl.) 271, S383-S386.

Madsen, P. T., Johnson, M., Aguilar de Soto, N., Zimmer, W. M. X., and Tyack, P.L. 2005. Bisonar performance of foraging beaked whales (Mesoplodon densirostris). J Exp Biol. 208:181-194.

Madsen, P. T., Payne, R., Kristiansen, N. U., Wahlberg, M., Kerr, I. and Mohl, B. 2002. Sperm whale sound production studied with ultrasound time/depth-recording tags. J Exp Biol. 205:1899-1906.

Naito, Y. 2004. New steps in bio-logging science. Mem Natl Inst Polar Res Spec Issue. 58:50-57.

Nowacek, D. P., Johnson, M. P. and Tyack, P. L. 2004. North Atlantic right whales (*Eubalaena glacialis*) ignore ships but respond to alerting stimuli. Proc. R. Soc. Lond. B 271:227-231.

Richardson, W.J., Greene, Jr. C.R., Malme, C.I. and Thomson, D.H. 1995. Marine mammals and noise. San Diego, New York, Boston: Academic Press. pp.576.

Tyack, P. L., Johonson, M., Madsen, P. T. and Zimmer, W. M. 2004. Echolocation in wild toothed whales. J Acoust Soc Am. 115:2373

Tyack, P. and Recchia, C. A. 1991 A data logger to identify vocalizing dolphins. J Acoust Soc Am. 90:1668-1671.

Wei, Z., Wang, D., Kuang, X., Wang, K., Wang, X., Xiao, J., Zhao, Q. and Zhang, X. 2002. Observations on behavior and ecology of the Yangtze finless porpoise (*Neophocaena phocaenoides asiaeorientalis*) group at Tian-e-Zhou Oxbow of the Yangtze River. The Raffles Bulletin of Zoology, Supplement 10:97-103.

Zhang, X., Wei, Z., Wang, X., Yang, J. and Chen, P. 1995. Studies on the feasibility of establishment of a semi-natural reserve at Tian-e-zhou (swan) oxbow for baiji, *Lipotes vexillifer*. Acta Hydrobiologica Sinica 19:110-123.

Zimmer, W. M. X., Johnson, M. P., Madsen, P. T., and Tyack, P.L. 2005. Echolocation clicks of free-ranging Cuvier's beaked whales (Ziphius cavirostirs). J Accust Soc Am. 117(6):3919-3927.