Available online at www.sciencedirect.com

SCIENCE DIRECT®

Fisheries Research 63 (2003) 393–403

FISHERIES RESEARCH

www.elsevier.com/locate/fishres

Detection and characterization of yellowfin and bluefin tuna using passive-acoustical techniques

Scott Allen[a,*], David A. Demer[b]

[a] Scripps Institution of Oceanography, Mail Stop 0214, Isaacs Hall, 9500 Gilman Drive, La Jolla, CA 92037, USA
[b] Southwest Fisheries Science Center, 8604 La Jolla Shores Drive, La Jolla, CA 92037, USA

Received 18 January 2002; received in revised form 4 February 2003; accepted 27 February 2003

Abstract

Underwater sounds generated by *Thunnus albacares* and *Thunnus thynnus* were recorded and studied to explore the possibility of passive-acoustical detection. Possible tuna sounds were recorded at the Monterey Bay Aquarium, Monterey, California, and Maricultura del Norte in Ensenada, Baja California, Mexico. At both locations, the most prevalent sounds seemingly associated with tuna were low-frequency pulses varying from 20 to 130 Hz, lasting about 0.1 s, and usually single and apparently unanswered. A behavior similar to coughing was coincident with these sounds: the animal's mouth opened wide with its jaw bones extended and its abdomen expanded, then contracted abruptly. On one occasion in Mexico, this behavior and associated signal were simultaneously recorded. Because these measurements were made in noisy environments, this study should be repeated under more controlled conditions before tuna vocalizations can be claimed with certainty. Nevertheless, the center frequencies of these sounds appear to vary with respect to the resonant frequencies of the tuna's swim bladder, suggesting a passive-acoustical proxy for measuring the size of tuna. Matched filter and phase-difference techniques were explored as means for automating the detection and bearing-estimation processes.

Keywords: Passive-acoustical detection; Vocalizations; *Thunnus thynnus*; *Thunnus albacares*

1. Introduction

Several species of fish internally generate sounds for the purposes of attracting a mate, communication, and navigation (Myrberg, 1981). Additionally, sounds from some communicative fish are not internally generated. For example, Myrberg and Gordon, 1976 noted that predatory fish are attracted to the swimming sounds of struggling fish and schools of feeding fish. He also proposed that vibrations play a role in schooling behavior. Underwater sounds generated by struggling and feeding fish are typically at frequencies between 20 and 40 Hz, while vocalizations are likely to be higher, in the range of 100–500 Hz with source levels (SLs) between 10 and 20 dB above ambient (Myrberg and Gordon (1976)). Sounds generated by fish differ from the sounds of other animals in that they rarely incorporate any frequency modulation, their sounds are limited to pulsed tones, and stridulatory sounds, with few exceptions (Zelick et al., 1999). There are, to our knowledge no published data regarding the capability of sound generation in *Thunnus* nor the mechanics of such signal generation.

* Corresponding author.
E-mail addresses: allen@sdsioa.ucsd.edu (S. Allen), david.demer@noaa.gov (D.A. Demer).

0165-7836/03/$ – see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0165-7836(03)00096-1

Most bony fishes (teleosts) have a gas-filled compressible cavity or swim bladder used to maintain neutral buoyancy. In some fish, the swim bladder may also be used for sound reception and generation (Sand, 1981; Chapman, 1976). Musculature surrounding the swim bladder may be used to cause rapid and repeated compressions of the bladder volume, resulting in a low-frequency pulse of sound. Stridulatory sounds may be generated by drumming or raking actions with bones near or touching the swim bladder (Fay and Popper, 1999). Additionally, in the species *Bathygobuis soporator*, low amplitude sounds are made by forced ejection of water through the gill rakers (Marshall, 1977).

To explore the feasibility of passive-acoustical detection and characterization of bluefin (*Thunnus thynnus*) and yellowfin tuna (*Thunnus albacares*) in the ocean, underwater sounds associated with encaged tuna were studied. It was hoped that contemporary hydrophones, low-noise amplification and filtering, high dynamic-range analog-to-digital converting and digital signal processing would yield some advantage over technologies previously used to study sounds from these animals.

2. Methods

Data were collected at the outer bay exhibit of the Monterey Bay Aquarium (MBA) on 26 and 27 August, 2000, and at offshore aquaculture farm, Maricultura del Norte in Ensenada, Baja California, Mexico (MNE), on 18–19 November and on 10 and 17 December 2000. The apparatus used for data acquisition and processing differed slightly for the two experiments (Figs. 1 and 2). The digital time-series from both sites were analyzed using matched-filtering, phase detection, intensity and Fourier analyses techniques.

2.1. Monterey Bay Aquarium

The Outer Bay exhibit of the MBA is oval shaped and approximately 11 m deep, 30 m long and 13 m wide. Tuna in the exhibit included bluefin (13) and yellowfin (48) as well as a skipjack (1) (Table 1). Almost all of the tuna present were adult, fork lengths ranging from 50 to 100 cm.

Recording equipment included a preamplified low-noise hydrophone (Wilcoxon H505L), powered 24 VDC by a regulated supply (HP 3631A), a

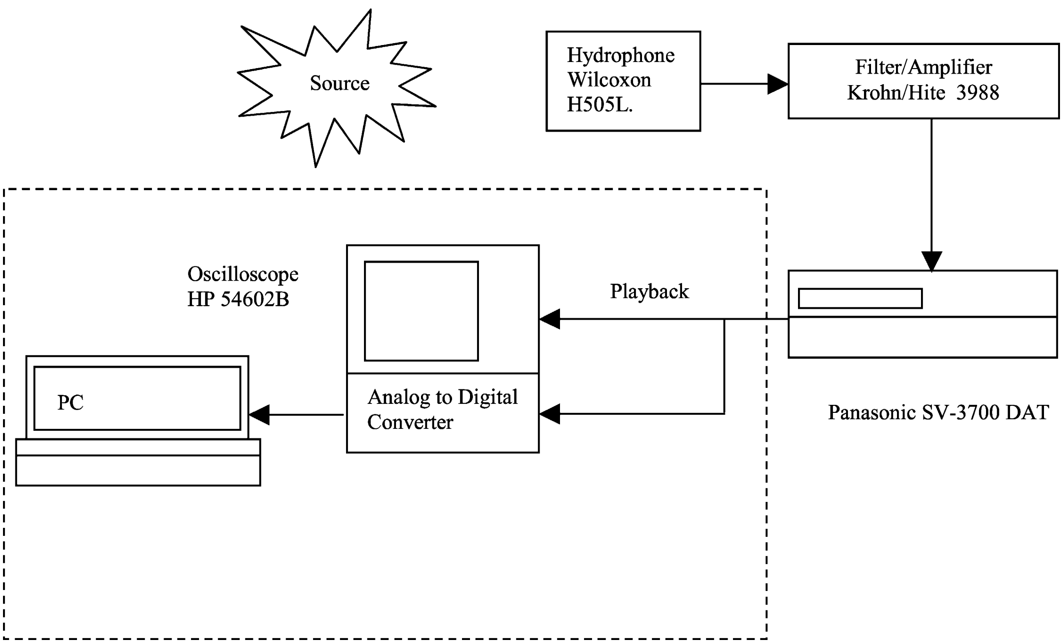

Fig. 1. Apparatus for recording tuna in the Outer Bay exhibit of the Monterey Bay Aquarium.

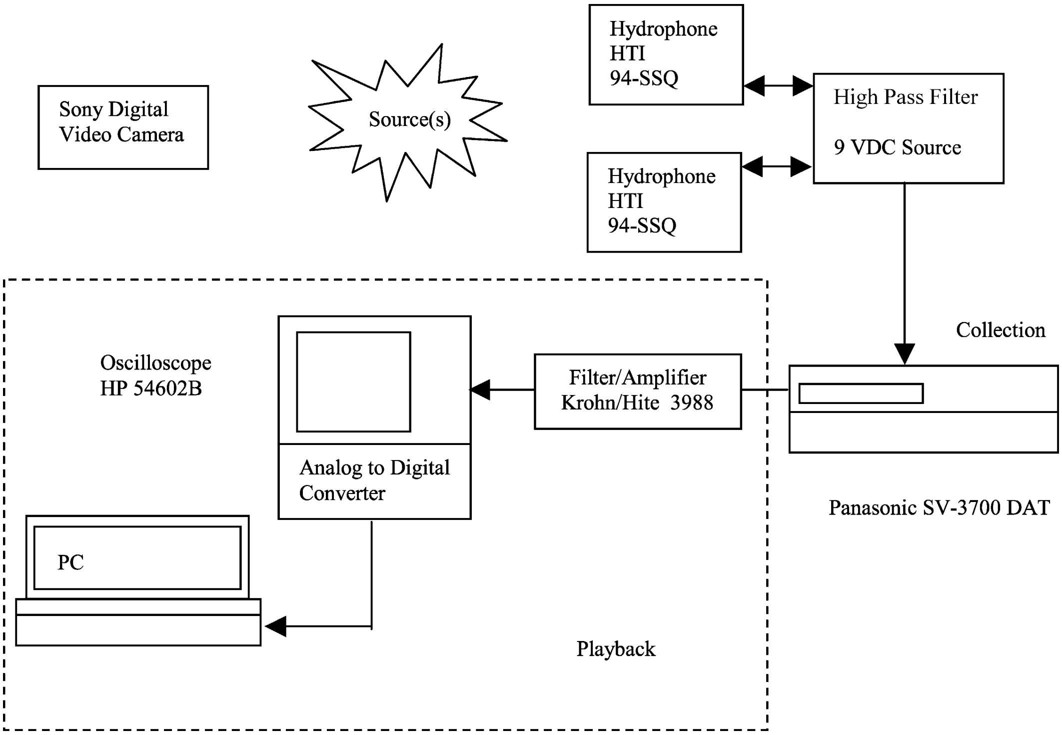

Fig. 2. Apparatus for audio and visual recordings of bluefin tuna at the Maricultura del Norte, Baja California.

low-noise amplifier–filter (Krohn/Hite 3988 Filter; K–H), and a digital audio tape (DAT) recorder (Panasonic SV-3700). The hydrophone was suspended from a catwalk near the center of the tank and at a depth of 7 m. Underwater acoustical signals were thus sensed, low-pass filtered ($f_c = 22$ kHz), and sampled at 44 kHz. Hardware to directly acquire the DAT signals on a computer was unavailable. Therefore, the DAT records were amplified 30 dB and low-pass filtered via the K–H ($f_c = 600$ Hz), monitored with headphones, and digitized (5 kHz) with a digital storage oscilloscope (Hewlett Packard 54602B; DSO).

Table 1
Species and quantities of animals present in the Outer Bay Tank at Monterey Bay Aquarium on August 26 and 27, 2000

Species	Quantity
Yellowfin tuna (*Thunnus albacares*)	48
Bluefin tuna (*Thunnus thynnus*)	13
Bonito (*Sarda sarda*)	38
Barracuda (*Sphyraenidae*)	36
Skipjack tuna (*Katsuwonus pelamis*)	1
Soupfin shark (*Galeorhinus galeus*)	4
Pilot fish (*Naucrates ductor*)	16
Sea turtles (*Dermochelydae*)	2
Bat rays (*Myliobatis californicus*)	2

2.2. Maricultura del Norte in Ensenada

The MNE is in open water, on the south side of Punta Banda (a narrow, 8 mile long peninsula forming the southern boundary of Bahia Todos Santos). Acoustical recordings were made on three occasions inside one of the farm's 12 floating cages (Northern Plastics) containing bluefin tuna of fork lengths approximately 80 cm. To locate the sound generating animal, directional information was garnered using two hydrophones (HTI-94-SSQ) and phase-difference techniques. The hydrophones were powered by a 9 V battery, deployed at 8 m depth with 3.35 m horizontal separation, and signals were high-pass filtered ($f_c = 10$ Hz). The data were recorded on DAT (Panasonic

SV-3700) that was powered by an inverter (Portawatts 600) and a 12 V gel-cell battery (Fig. 2). Additionally, a digital video recorder (Sony DCR-TRV900 encased in an underwater housing, Light and Motion Industries Stingray) was deployed at 2 m depth and roughly centered between the two hydrophones. During evaluation, the DAT tapes were played back through the K–H (LP $f_c = 300$ Hz), monitored with headphones, and digitized at 1 kHz with a data acquisition card (IOTech DAQ/216B).

2.3. Matched-filter detection

The matched-filter, described by Medwin and Clay (1998), performs a cross-correlation in the time-domain of a reference signal and a signal embedded in noise. The matched-filter will produce a high cross-correlation coefficient at time (t) when

$$h_M(t) = Ax(-t) \qquad (1)$$

where $x(-t)$ is the time-reverse recorded time-series $x(t)$, $h_M(t)$ the reference signal (in this case, a selected tuna sound), and A is a constant of proportionality. A matched filter was thus applied to detect tuna sounds in each 1 s segment of the records. Correlation coefficients (≥0.65) indicated a likely tuna sound to be investigated further.

2.4. Bearing estimation

The azimuth angle of a sound source with respect to the perpendicular bisector of two hydrophones (θ) was determined from the phase difference (ϕ_e) of the signals received by the two hydrophones (Fig. 3). After low-pass filtering the signals ($f_c = 100$ Hz), the time delay (Δt_z) between corresponding zero-crossings of the two tuna sound-waveforms was used to estimate ϕ_e at the dominant frequency (f):

$$\phi_e = 2\pi f \Delta t_z \qquad (2)$$

For each suspected tuna sound, the azimuth angles were estimated following Demer et al. (1999):

$$\theta = a\sin\left(\frac{\phi_e c}{2\pi f d}\right) \qquad (3)$$

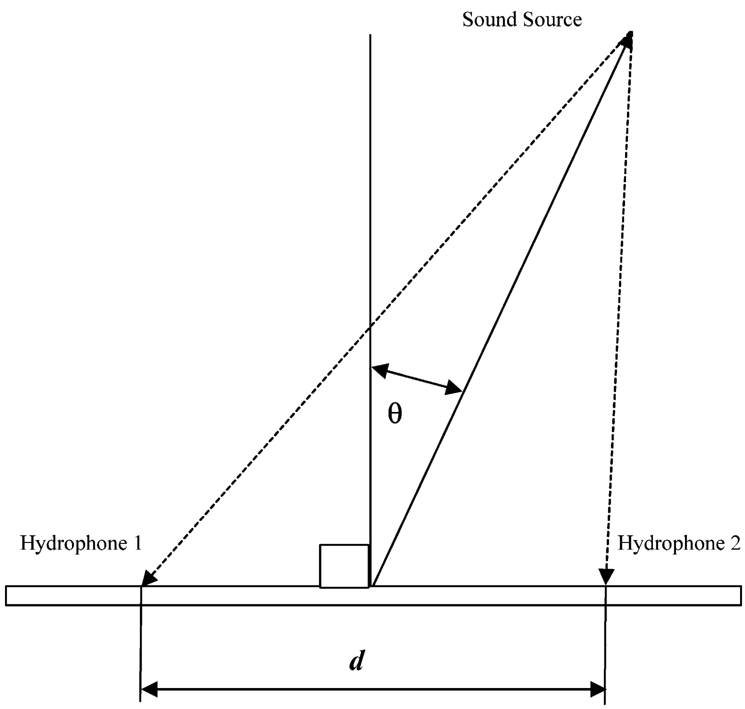

Fig. 3. Derivation of azimuth from phase difference. Azimuth is the angle of the source with respect to a normal bisector of two hydrophones and is described by Eqs. (2) and (3).

using estimates of sound speed ($c = 1512.3$ m/s) (Mackenzie, 1981) and the distance between hydrophones ($d = 3.35$ m).

2.5. SLs and power spectrum

SLs were also estimated for each sound thought to be associated with tuna. Following Kinsler et al. (2000), and using estimates of the root mean square voltages (V_{rms}) of the signals incident upon the hydrophones, the transducer sensitivities at MNE ($RS_1 = -170.0$ and $RS_2 = -169.9$ dB re 1 V/μPa), amplifier gain ($G = 40$ dB) and transmission loss ($TL = 20\log(r)$):

$$SL = 20\log(V_{rms}) - M_x - G + TL \quad (4)$$

where x corresponds to transducer 1 or 2, and $r = 5$ m is the estimated range between the tuna and the hydrophone. At MBA, the sensitivity of the Wilcoxon hydrophone was −178 dB re 1 V/μPa, the total amplifier gain was 70 dB (30 dB during recording and an additional 40 dB at playback), and the estimated distance to the sources was approximately 5 m. At this distance, the absorption losses are negligible.

Noise adjusted power spectral densities (PSDs) were also calculated for each sound thought to be associated with tuna. The PSDs were obtained using a 2048-point discrete Fourier transform (DFT), with Hanning-window and no overlap, to the region of interest in the filtered data set.

3. Results

3.1. Monterey Bay Aquarium

There were a variety of sounds present in the outer bay tank and associations with animal behaviors were therefore sought. Of the animals present in the tank, only rays (*myliobatis*) are known to generate sound (Myrberg, 1981). Coughing or yawning behaviors were visually observed in both yellowfin and bluefin tuna. Their mouths would open wide and the area about the operculum and abdomen would contract slightly and convulsively. Five such incidents were observed from the observation deck shortly after 0800 PST on 26 August. Apparently associated underwater sounds were short (∼0.1 s), low-frequency pulses (20–130 Hz; mean = 64.1 Hz; S.D. = 38.4 Hz). The estimated SLs were between 110.9 and 128.9 dB re 1 μPa at 1 m. Most sounds were single and unanswered (Fig. 4), but double pulses and a quadruple pulse train were also recorded. In addition to the low-frequency pulses, there were also a few high frequency (jaw snap sounds). The source of the jaw snap sounds is unknown at this time.

3.2. Maricultura del Norte in Ensenada

During three visits to the site, 47 sounds thought to be associated with tuna were recorded that were similar to those from MBA (Fig. 5). The mean center frequency was 62.4 Hz (S.D. = 6.2 Hz). The smaller standard deviation in center frequency was consistent with more uniform fish sizes in the aquaculture pen relative to the aquarium. The SLs were estimated to be between 103.4 and 126.9 dB re 1 μPa at 1 m.

Less than 1 h after a feeding, a bluefin tuna was simultaneously recorded on video and audio tape (Fig. 6). The cough-like behavior produced a low amplitude sound centered at 58.6 Hz with a phase difference indicating an angle of approximately 40° from a normal to the hydrophone pair. This azimuth is reasonable with respect to the visual image. The estimated SL was between 110.8 and 117 dB re 1 μPa at 1 m. In every instance where the sounds were observed, there was no obvious impetus for the sound and no discernable reaction to the sound from nearby animals. Due to the large variability in the intensities and spectra of the tuna sounds, the matched-filter did not provide binary indications of tuna sounds. That is, the maximum correlation coefficients only provided a relative indication of occurrence. However, from an arbitrary threshold (0.65) on the time-series of the maximum correlation coefficients (Fig. 7), the sounds thought to be from tuna were generally distributed randomly in time, suggesting that the tuna were not answering each other's sounds.

4. Discussion

These passive-acoustical observations of tuna suggest that a coughing or yawning behavior causes muscular contraction about the swim bladder and an associated short-duration sound pulse of

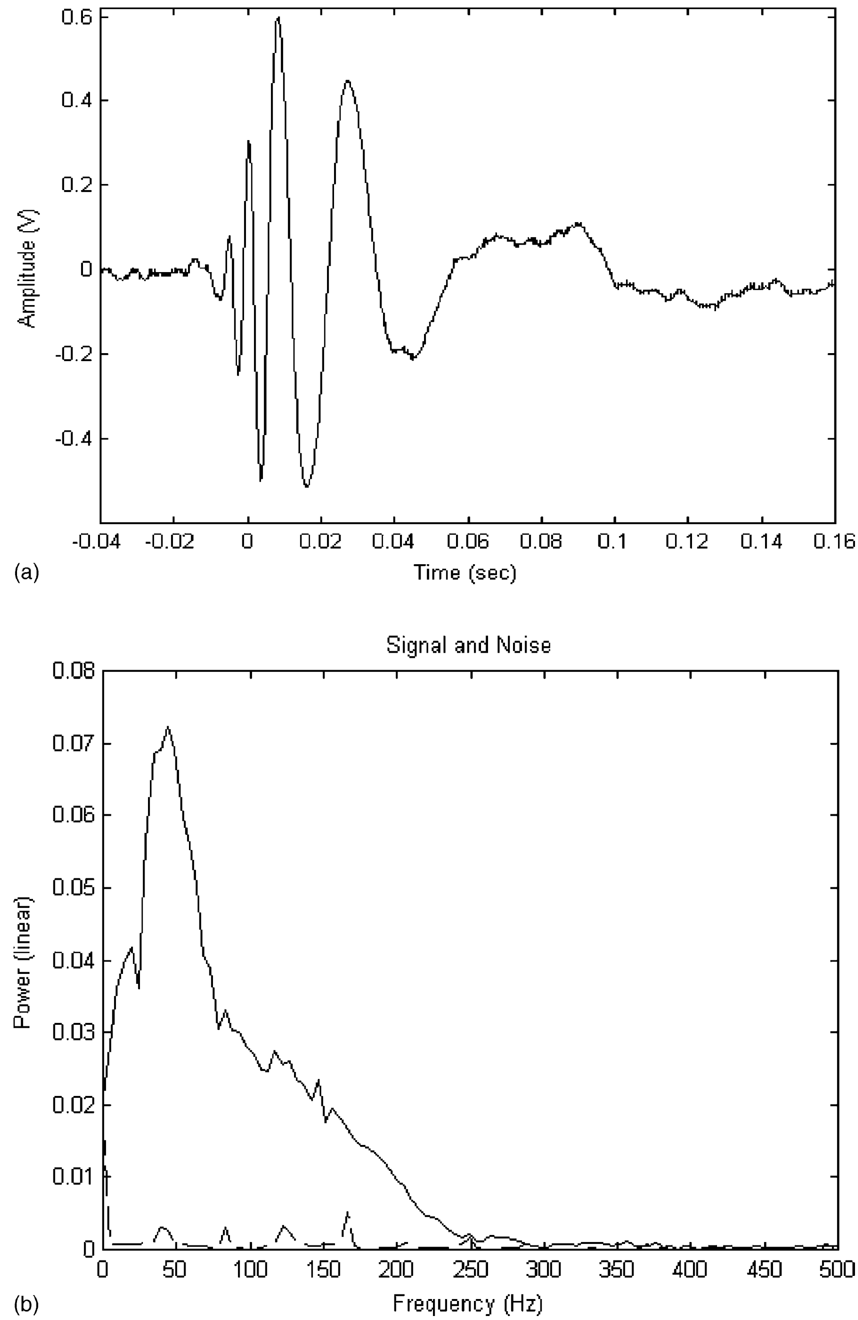

Fig. 4. Acoustical signal thought to originate from yellowfin tuna in the Monterey Bay Aquarium on 27 August 2000 (a), and its PSD (solid line) compared to that of the background noise (broken line) (b). In this example, the central frequency was 44 Hz, with an estimated SL of 114.5 dB re 1 μPa at 1 m.

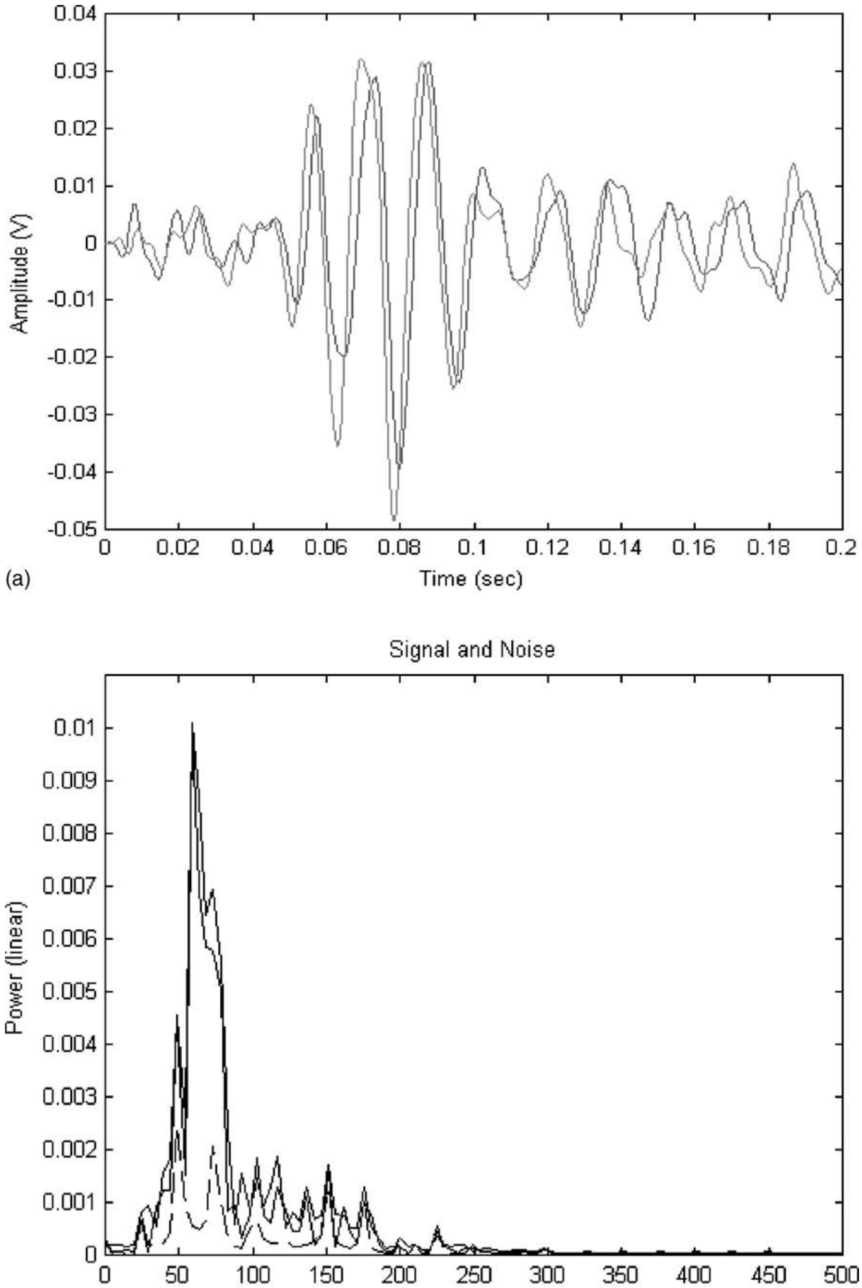

Fig. 5. Bluefin sounds recorded at Maricultura del Norte, 18 November 2000 using two hydrophones (a) and their PSD (solid line) compared to that of the background noise (broken line) (b). Signals were low-pass filtered (Butterworth, order 4, $f_c = 600$ Hz). The estimated SL is 110.8 dB re 1 μPa at 1 m.

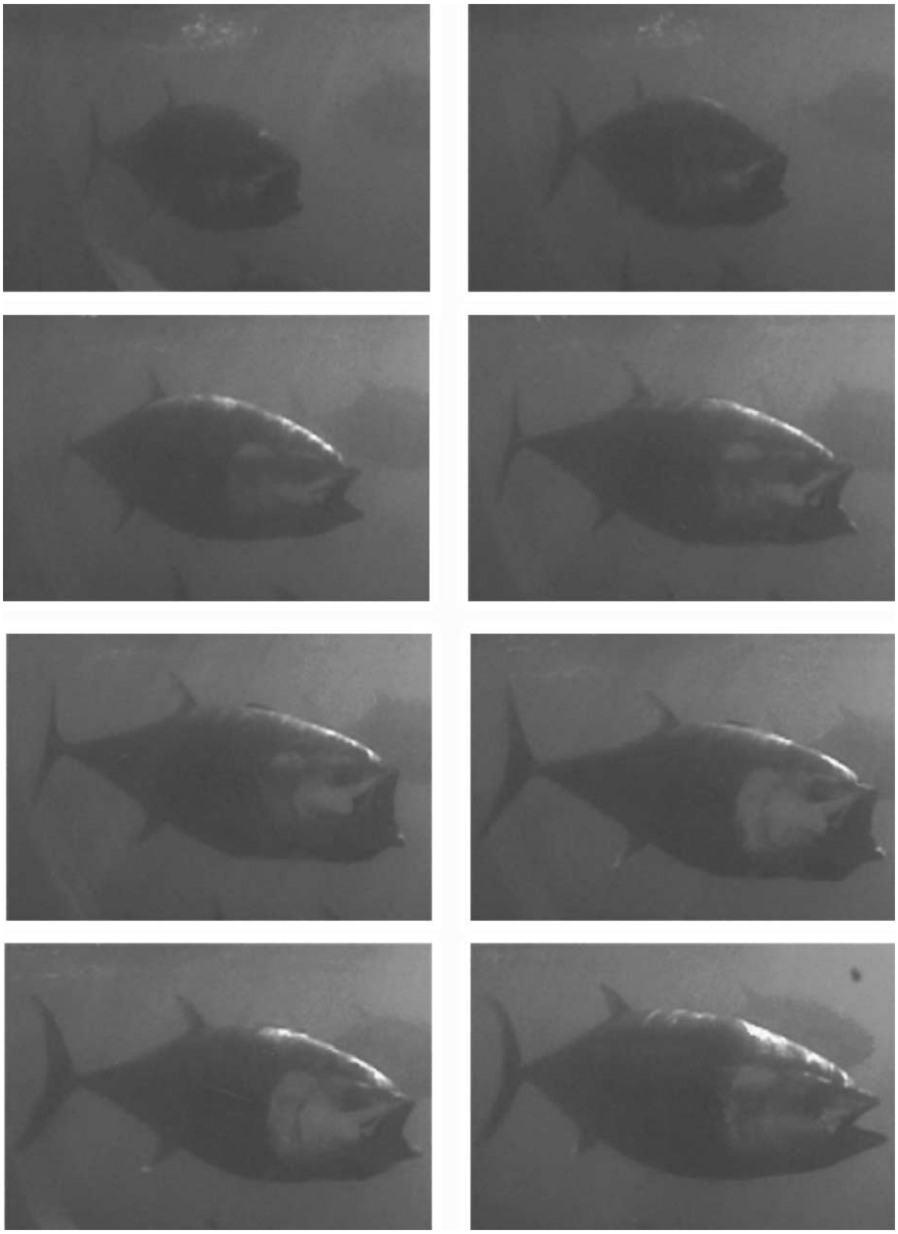

Fig. 6. A bluefin tuna at Maricultura del Norte Ensenada exhibiting the cough-like behavior thought to coincide with sound generation. The animal's mouth opened wide with its jaw bones extended and its abdomen expanded, then contracted abruptly.

narrow-bandwidth and low-frequency and intensity. It is unknown whether the tuna sounds are generated as a by-product of some biological function such as clearing of the gills, or an intentional form of communication. The sound and associated behavior recorded on audio and video tape at MNE occurred less than 1 h after feeding, but the observations at MBA occurred throughout the day with no detectable correlation with feeding. In general, the swim bladder in tuna species is reported to be underdeveloped

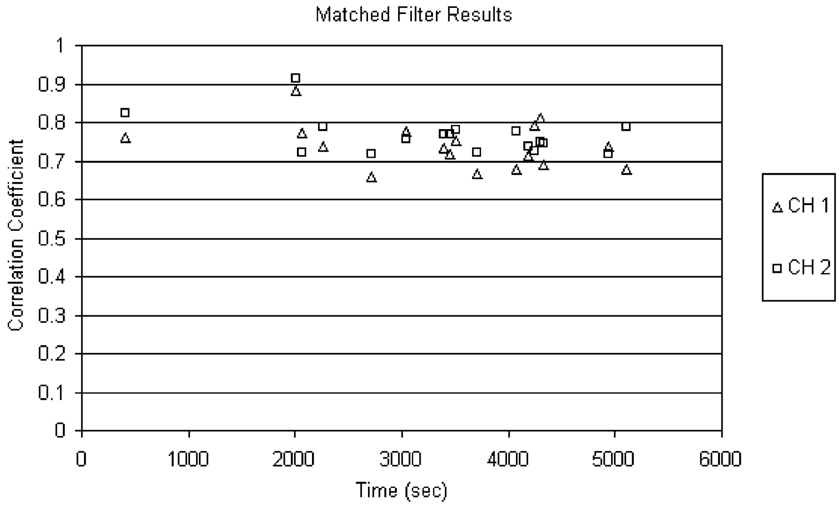

Fig. 7. Maximum cross-correlation coefficients for 1 s segments of a 90 min recording session of bluefin tuna at the Maricultura del Norte, Baja California. Time-series segments were cross-correlated to a reference record thought to be indicative of bluefin tuna sounds. Shown are maximum correlation coefficients where both channels had values above 0.65. The average rate of sounds with high correlation coefficients is $\sim 13\,\mathrm{h}^{-1}$.

in animals under 40 cm in fork length. The swim bladder grows slowly in animals over 40 cm then grows proportionally in those animals larger than 70 cm (Magnuson, 1973). If the recorded sounds are indeed generated by swim bladder resonance, then the size of the swim bladder determines the center frequency of the sound pulse. Extrapolating relationships from Magnuson (1973), the swim bladder radius (a, cm) is assumed to be related to the fork length (L, cm) by

$$a = 0.051\,L \tag{5}$$

Approximating the swim bladder by a gas-filled bubble having the same radius, the associated resonant frequency (f_r) can be estimated by

$$f_\mathrm{r} = \frac{1}{2\pi a}\sqrt{\frac{3\gamma P}{\rho_0}} \tag{6}$$

where γ is the ratio of heat capacity, P the hydrostatic pressure, and ρ_0 the density of seawater (Kinsler et al., 2000).

At MNE, the bluefin tuna were quite uniform in size with an average fork length estimated to be 80 cm. From Eq. (5), the corresponding average swim bladder radius is estimated to be 6.8 cm. Applying Eq. (6) for seawater ($\rho_0 = 1026\,\mathrm{kg/m^3}$) at a depth of 8 m ($P = 80.44$ kPa), and using the ratio of heat capacity for an ideal diatomic gas ($\gamma = 1.4$), $f_\mathrm{r} = 70.8$ Hz (Fig. 8). This is close to the observed center frequencies of the sounds thought to be from tuna. Also recall that the standard deviation of the center frequencies at MNE was quite low (S.D. = 6.14 Hz). In contrast, at MBA, the tuna lengths varied from 50 to 100 cm and correspondingly the standard deviation of the measured center frequencies was much higher (S.D. = 38 Hz).

Clay and Horne (1994) determined that the gas bubble model is not sufficient to model sound scattering from fish with a swim bladder. They proposed another model that idealizes a swim bladder as a gas bubble contained in thick rubber that has a strong dampening effect on the resonance. Consequently, sounds generated by a resonating swim bladder encased in large amount of flesh would have relatively small amplitudes. Judging from Magnuson (1973), the swim bladder constitutes only about 5% of an adult tuna's body volume. Correspondingly, the amplitudes of tuna sounds recorded in this study (SLs ∼117.5 dB re 1 μPa at 1 m) are low compared to smaller fish with demonstrated vocalization capabilities (Myrberg, 1981), and higher swim bladder to flesh volume ratios (e.g. toadfish, catfish, and Pacific yellowtail).

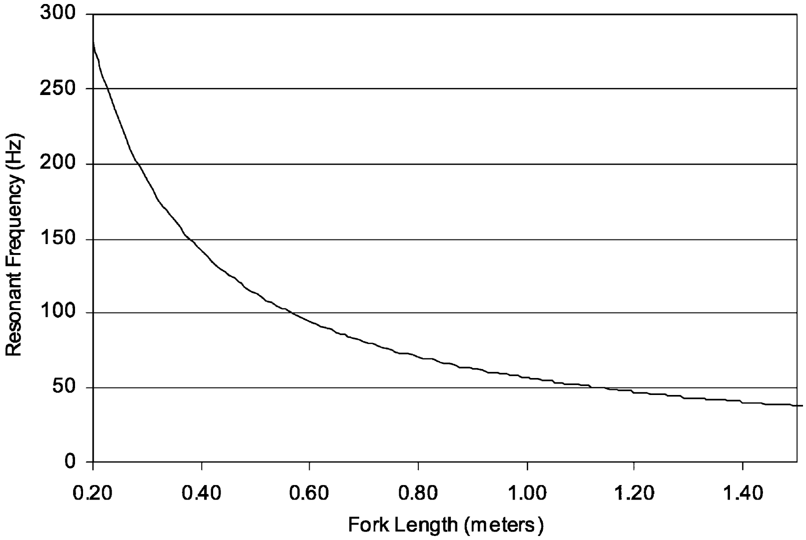

Fig. 8. Resonance frequencies for tuna having fork lengths ranging from 0.2 to 1.5 m. Magnuson (1973) derived a model for estimating spherical swim bladder radii from the fork lengths of yellowfin tuna (Eq. (5)). The resonance frequencies of gas bubbles of the same radii are described by Eq. (6) from Kinsler et al. (2000). If tuna sounds are the result of muscular action about the swim bladder, the resonant frequency of the swim bladder should determine the frequency of the sound pulses.

5. Conclusion

This study suggests that adult bluefin and yellowfin tuna are capable of generating sounds. The acoustical signals recorded in the presence of these tuna are short (~0.1 s), narrow-bandwidth pulses of low frequency (20–130 Hz) and amplitude (~117.5 dB re 1 μPa at 1 m), possibly caused by contraction of muscles about the swim bladder. Because these sounds were recorded in the presence of other species and in noisy tank and open ocean environments, the results of this study should be considered tentative rather than definitive. That is, this study should be repeated under more controlled and lower noise conditions before tuna vocalizations can be claimed with certainty.

Nevertheless, propagation and detection of these low intensity sounds will largely depend on spherical spreading losses and ambient noise levels. In some short-range ocean applications, it is thought that passive-acoustical detection and characterization may be achievable with a simple hydrophone, signal conditioner and correlation receiver. The maximum detection range (r) can be estimated by the passive sonar equation:

$$20\log(r)\,\mathrm{SL}-\mathrm{NL}-\mathrm{DT} \tag{7}$$

For a SL = 117.5 dB re 1 μPa at 1 m, a noise level (NL) of 35 dB (sea state 1; Kinsler et al., 2000), and detection threshold (DT) of 3 dB, $r = 9.4$ m.

Acknowledgements

We thank Dr. Rennie Holt, Director of the United States Antarctic Marine Living Resources Program and Dr. John Hunter, Head of the Fisheries Resources Division, SWFSC, for providing the laboratory and equipment resources necessary to complete this study. We also thank Dr. Kenneth Baldwin of the University of New Hampshire Center for Ocean Engineering for allowing S. Allen to conduct his Master's Thesis research at SWFSC. Thanks also to Mr. Ted Dunn, founder of Maricultura Del Norte of Ensenada, Mexico for graciously supporting this effort with access to his fish pens. Thanks finally to Dr. Charles Farwell, the manager of pelagic displays at the Monterey Bay Aquarium in Monterey, California.

References

Chapman, C.J., 1976. The hearing capacities of fish. Dev. Aqu. Fish. Sci. 5, 19–26.

Clay, C.S., Horne, J.K., 1994. Acoustic models of fish: the Atlantic cod (*Gadus morhua*). J. Acoust. Soc. Am. 96, 1661–1668.

Demer, D.A., Soule, M.A., Hewitt, R.P., 1999. A multiple-frequency method for potentially improving the accuracy and precision of in-situ target strength measurements. J. Acoust. Soc. Am. 105 (4), 2359–2376.

Fay, R.R., Popper, A.N., 1999. The auditory periphery in fishes. In: Comparative Hearing: Fish and Amphibians, Springer, New York, NY, 438 pp.

Kinsler, L.E., Frey, A.R., Coppens, A.B., Sanders, J.V., 2000. Fundamentals of Acoustics, 4th ed., Wiley, New York, NY, 533 pp.

Mackenzie, K.V., 1981. Nine-term equation for sound speed in the oceans. J. Acoust. Soc. Am. 70, 807–812.

Magnuson, J.J., 1973. Comparative study of adaptation for continuous swimming and hydrostatic equilibrium of scombroid and xiphoid fishes. US Fish. Bull. 71, 337–356.

Marshall, N.B., 1977. The biology of sound producing fishes. In: Sound Production in Fishes. Dowden, Hutchinson and Ross Inc., Stroudsburg, PA, pp. 202–217.

Medwin, H., Clay, C., 1998. Fundamentals of Acoustical Oceanography. Academic Press, San Diego, CA, 712 pp.

Myrberg, A., 1981. Sound communication and interception in fishes, hearing and sound communication in fishes. In: Proceedings of the Life Sciences, Springer, New York, NY, pp. 400–414.

Myrberg, A., Gordon, C., 1976. Attraction of free ranging sharks by low frequency sound with comments on its biological significance. Dev. Aqu. Fish. Sci. 5, 205–228.

Sand, O., 1981. The Lateral Line and Sound Reception, Hearing and Sound Communication in Fishes. Springer, New York, NY, 608 pp.

Zelick, R., Mann, D.A., Popper, A.N., 1999. Acoustic communication in fishes and frogs. In: Comparative Hearing: Fish and Amphibians, Springer, New York, NY, 438 pp.