Ultrasound backscattered power from *Cochlodinium polykrikoides*, the main red tide species in the Southern Sea of Korea

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Received February 26, 2009; accepted in principle December 29, 2009; accepted for publication January 3, 2010

Corresponding editor: William K.W. Li

The acoustic integrated backscattered power (IBP) of the phytoplankton *Cochlodinium polykrikoides*, which causes red tides in Korean waters, was measured in the laboratory and in the sea in situ to investigate the feasibility of observing red tides using high frequency ultrasound at 5 and 10 MHz. The IBP was measured with cultured *C. polykrikoides* at abundance levels of 90, 110, 200, 260, 300, 340, 360, 600, 700 and 850 cells/mL in the laboratory. Using the same high frequency acoustic transducers that were attached to the side of a research vessel, the IBP was measured in situ over a 9 km ship track near the Gumo Islands in Yeosu in the Southern Sea of Korea during the red tide season. The IBP was also measured simultaneously with positional information obtained from global positioning system data and by sampling the seawater in which *C. polykrikoides* was counted to survey the *C. polykrikoides* distribution in the study area. The IBP in situ was in agreement with that in the laboratory depending on the *C. polykrikoides* abundance. Consequently, we suggest that it is feasible to use underwater ultrasonic methodology for the observation of red tides in real time in situ.

KEYWORDS: red tide; *Cochlodinium polykrikoides*; integrated backscattered power; high-frequency ultrasound

INTRODUCTION

The term red tide derives from the discoloration of the seawater due to blooms of a specific species of phytoplankton. Red tides can adversely impact the environment in two ways: (i) the decomposition of the phytoplankton consumes dissolved oxygen, resulting in suffocation of fish species and (ii) virulent species of phytoplankton can kill fish and thereby disrupt the food chain. Recently, new species of red tides have appeared. They are not virulent themselves, but they enter the bodies of marine fish and collect in the gills, thereby causing suffocation. *Cochlodinium polykrikoides*, shown in Fig. 1, is one such species. From the late 1990s, the dominant species of phytoplankton responsible for red tides in Korean coastal water has been *C. polykrikoides* (Lee, 1999). The damaging effects of red tides are increasing every year in Korean waters.
To decrease red tide damage, it is important to observe red tides as early as possible. Therefore, techniques for red tide observation and monitoring are being actively explored. Counting the number of planktonic cells with a microscope is the most widely used method. However, this methodology has shortcomings as it is time consuming, expensive and laborious. To overcome these limitations, other techniques have been considered. One of these is the use of the advanced very high resolution radiometer (AVHRR) sensor on National Oceanic and Atmospheric Administration (NOAA) satellites (Suh et al., 2000; Ahn et al., 2005). However, early observation is difficult because AVHRR can only observe the physical and chemical changes in near-surface seawater after a bloom, and is also limited by weather conditions. Spectrophotometer monitoring could be another technique; however, it does not work in real time because it requires chemical pre-processing of the sampled seawater.

The aforementioned methods are not adequate for real-time in situ observation of early stage red tides. Hence, we propose a method to measure acoustic signals backscattered from the blooms using a high-frequency sonar for real-time in situ observation of red tides. Acoustical backscattering provides an indirect measurement of phytoplankton concentration, but can also be used to survey larger areas in less time. The acoustic volume scattering in the sea at the frequencies of 25 kHz–2.5 MHz and 2.5–25 MHz can be explained by the distribution of zooplankton and phytoplankton, respectively (Clay and Medwin, 1977). The minimum effective frequency in this paper was calculated by using an equivalent circumference of a single plankton with a radius equal to the wavelength. For example, the equivalent radii of most of zooplankton such as a euphausiid, an amphipod and a copepod were distributed between 0.1 and 10 mm, and those of most of phytoplankton such as a dinoflagellate and a diatom were between 10 and 100 μm. Considerable analysis of the morphology and physical properties of sound scattering organisms has been undertaken to obtain a better understanding of the scattering process. The technique is robust and can be used to estimate abundance as well as the size distribution in some cases (Holliday and Peper, 1980; Greenlaw and Johnson, 1982; Kristensen and Dalen, 1986; Stanton et al., 1996). However, the use of acoustical techniques for estimating abundances of C. polykrikoides is a challenge because the small size of organism requires very high frequencies. The work is further complicated by the small contrast in sound speed and density of the organisms relative to water. Accordingly, acoustical systems that can detect very low backscattered pressure levels must be used because of the expected weak backscattering (Johnson, 1977).

In this paper, we suggest an acoustic method for the observation of red tides using correlation of data from laboratory experiments and field experiments. The acoustic integrated backscattered power (IBP) was measured at different numbers of C. polykrikoides cultured in filtered sea water. The IBP was then compared with the IBP measured in the Southern Sea of Korea in situ during a red tide season. The theoretical background, experimental methods and results both in the laboratory and in the Southern Sea of Korea in situ are described and discussed and a conclusion provided in the following sections.

**METHOD**

**Acoustic theory: integrated backscattered power (IBP)**

Acoustic wavelengths of <10 MHz are much larger than a typical linear dimension of a C. polykrikoides cell. Thus, scattering is in the Rayleigh regime. Using the notation of Clay and Medwin, the scattering function from a non-resonant sphere whose radius is much smaller than a wavelength is given by Clay and Medwin (Clay and Medwin, 1977) as

$$\zeta = \frac{1}{\pi} \left[ \frac{g}{3g} \right]^2 - \frac{g - 1}{2g + 1} \cos \theta \right]$$

(1)
where \( k \) is the acoustic wave number, \( a \) the radius of the sphere having the same volume as a cell, \( g \) the density ratio between the sphere and the medium, \( h \) the sound speed ratio between the sphere and the medium and \( \theta \) the angle between the incident and scattered direction. Equation (1) was derived for a sphere, but it has been shown that non-spherical effects can usually be ignored when scattering is in the Rayleigh region (Palmer, 1996). In any case, \( C. \) polykrikoides cells are close to a sphere. The length and the width of a cell are 20–35 \( \mu \)m and 15–20 \( \mu \)m, respectively (Fig. 1). The backscattering function, \( f_{bs} \), is obtained by setting \( \theta = 180^\circ \).

The total backscattering cross section, \( \sigma_{bs} \), was determined by integrating over the range of possible orientations, and is described by

\[
\sigma_{bs} = \left( \frac{ka}{\pi} \right)^4 \left[ \frac{gh^2 - 1}{3gh^2} + \frac{g - 1}{2g + 1} \right]^2 \pi a^2 \tag{2}
\]

The backscattering strength, \( S_b \), is the logarithm of equation (2) which is expressed as

\[
S_b = 10 \log_{10} \sigma_{bs} \tag{3}
\]

and the volume backscattering strength, \( S_v \), is given by

\[
S_v = 10 \log_{10}(\sigma_{bs}N) \tag{4}
\]

where \( N \) is the numerical abundance of scatterers. We assumed that multiple scattering can be ignored. \( C. \) polykrikoides exists as an individual cell in situ, where the backscattering cross section can be multiplied by the numerical abundance to obtain the volume scattering strength. However, it usually forms a chain of less than 8 cells, and rarely of more than 30 cells, during red tides. It is not simple to accurately compute the backscattering from those chains. A chain with less than six cells is smaller than a wavelength for 10 MHz, so each chain scatterer with less than six cells is assumed to be a Rayleigh scatterer of a compressible sphere with equivalent volume. For volume scattering, the backscattering cross section of a Rayleigh scatterer with equivalent volume is multiplied by the number of the chains.

If \( g, h, a \) and \( N \) are given, then the theoretical value of \( S_v \) can be easily estimated using equation (4). However, it is difficult to obtain the values of \( g \) and \( h \) of a plankton cell, and thus it is not easy to compute the theoretical \( S_v \). It is much easier to compute the IBP instead of estimating the quantitative value of \( S_v \). The IBP is proportional to \( S_v \) if the same transducer is used in the same electronic system. The acoustic IBP is defined by

\[
\text{IBP} = 20 \log_{10}\left( \frac{V_{rms,bs}}{V_{rms,ref}} \right) \tag{5}
\]

where \( V_{rms,bs} \) and \( V_{rms,ref} \) are the root mean square (RMS) voltages of the backscattered signal from a scatterer and a reference, respectively. The IBP was computed for analysis of the acoustical data obtained from red tides, since the goal of this feasibility study is to estimate numerical abundance by the acoustic signals from \( C. \) polykrikoides and to compare the experimental results in the laboratory with those in the sea in situ. The beam pattern signal was used as the reference data in equation (5) at each frequency.

**Culture of Cochlodinium polykrikoides**

In culturing \( C. \) polykrikoides in the laboratory, we followed the methods of Guillard and Ryther (Guillard and Ryther, 1962) and Guillard (Guillard, 1975) as shown in Table I. Seawater from the Southern Sea of Korea (salinity of approximately 33 psu) was filtered with 0.45 \( \mu \)m glass filter paper, placed in a 10 L bottle (Nalgene, Rochester, NY, USA) and autoclaved. The chemical compounds were added, and the media was autoclaved again and kept at room temperature for 24 h. For these processes, f/2 media was prepared with autoclaved enriched seawater (Guillard and Ryther, 1962). An inoculum of \( C. \) polykrikoides was added to a 600 mL cell culture flask (Corning Inc., Corning, NY, USA) for an initial culture of 100 cells/mL. The inoculum (\( C. \) polykrikoides strain BWE0109) was obtained from the Biocenter at the Polar Applied Science Division of the Korea Polar Research Institute (KOPRI). The culture was maintained in an incubator at 23–24\(^\circ\)C under roughly 2500 lx fluorescent illumination for a light-to-dark cycle of 14–10 h (Lee et al., 2001).

The number of cells was counted frequently using a microscope (DW-THN, Dongwon Systems Corporation, Seoul, Korea). After pipetting samples of 100 \( \mu \)L of the culture medium into a counting plate (96 Well Cell Culture Cluster, Corning Inc., Corning, NY, USA), the samples were fixed in a Lugol’s iodine solution. The number of cells was counted with a magnification factor of \( \times 150 \). Counts were done in triplicate and cell numbers were averaged.

Figure 2 indicates the growth rate of \( C. \) polykrikoides in the culture media. The number of cells decreased after 1 month from the time the initial culture was started. Therefore, it was decided that cells cultured for 2 weeks would be used for the laboratory experiments.
Measurements of integrated backscattered power (IBP) of *Cochlodinium polykrikoides*

Two types of acoustic measurements were conducted: (i) laboratory measurements of the IBP for cultures of *C. polykrikoides* whose numbers of cells were also optically counted, and (ii) *in-situ* measurements of the same acoustic parameter during red tide blooms in the Southern Sea of Korea.
Beam pattern of transducers

The transducer is one of the most important components of the ultrasound measurement system. Therefore, the beam pattern of the transducer was measured. Our experimental equipment included an acoustic intensity measurement system (AIMS) (NTR Systems Inc., Sunnyvale, CA, USA). Water conditioner provides microprocessor-controlled heating, degassing, filtration and deionization. Transducers with a 19 mm diameter aperture at central frequencies of 5 and 10 MHz (A308S, A315S; Panametrics, Waltham, MA, USA) were fixed at a point in a tank filled with the fresh water, and a needle hydrophone (TNU001A, NTR Systems Inc., Sunnyvale, CA, USA) was moved at intervals of 1 mm along the scan axis by an electric motor drive system (EMDS) as shown in Fig. 3. Two types of scanning were conducted: a one-dimensional (1-D) scan (Fig. 3B) and a two-dimensional (2-D) scan (Fig. 3C). A pulse was generated with the Pulser/Receiver (5800PR, Panametrics, Waltham, MA, USA). The signal detected by the needle hydrophone was amplified with a preamplifier (30 dB Preamplifier, NTR Systems Inc., Sunnyvale, CA, USA). A digital oscilloscope (54615B, Agilent Technologies, Santa Clara, CA, USA) was used for analog-to-digital conversion and display of the received signals. The data were transferred to a PC for further processing. The characteristics of two transducers are shown in Table II, and the measured beam profiles of the transducers are shown in Fig. 4. The near field distance, $N_F$ in Table II is given by (Anonymous, 2006)

$$N_F = \frac{D^2}{4\lambda}$$

where $\lambda$ and $D$ are the wavelength and the diameter of the transducer, respectively. The near field distance of each transducer is 30 and 60 cm (Table II), respectively. We could not measure the beam profile in the range of longer than 45 cm due to the limited size of the water tank of the measurement system. The −3 dB distance-of-field was measured over 20–35 cm for 5 MHz and over 20–45 cm for 10 MHz as shown in Fig. 4.

Laboratory measurements

According to the red tide forecast system (Table III) developed by the National Fisheries Research and Development Institute (NFRDI) in Korea, the precautionary and the warning levels are above 300 and 1000 cells/mL, respectively (NFRDI, 2004). Because the final goal of this research is to measure the IBP of _C. polykrikoides_ before a red tide warning level is reached, the IBP was measured from cultured media with densities of 90, 110, 200, 260, 300, 340, 360, 600, 700 and 850 cells/mL.

Our experimental setup is schematically shown in Fig. 5 and the parameters were tabulated in Table IV. To achieve a uniform distribution of _C. polykrikoides_ in the culture media, a magnetic bar rotated by a magnetic stirrer was placed at the bottom of the water tank (with an inner radius of 5 cm and a height of 15 cm). A Pulser/Receiver (500PR; Panametrics, Waltham, MA, USA) generated the pulses, and received the backscattered signals from the culture media with _C. polykrikoides_. The parameters of the pulser/receiver were as follows: the damping was 5, the gain was 8 and the pulse repetition frequency was 500 Hz. The pulse lengths were 0.4 $\mu$s at 5 MHz and 0.8 $\mu$s at 10 MHz. A digital oscilloscope (LT322; LeCroy, Santa Clara, CA, USA) was used for data acquisition and display of the generated and backscattered signals, and these signals

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**Table II: Acoustic properties of two transducers; frequency $f$, wavelength $\lambda$, diameter of transducer $D$, beam angle $\alpha$ and near field distance $N_F$**

| Model number | $f$ (MHz) | $\lambda$ (mm) | $D$ (mm) | $\alpha$ (°) | $N_F$ (cm) |
|--------------|-----------|----------------|----------|---------------|------------|
| A308S        | 5         | 0.3            | 19       | 0.92          | 30         |
| A315S        | 10        | 0.15           | 46       | 0.46          | 60         |

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Fig. 3. Block diagram of the beam pattern measurement system (A) and the scan method; 1-D scan (B) and 2-D scan (C).
were transferred to a personal computer for further processing. The backscattered signals from *C. polykrikoides* media and the beam profile data were used as $V_{\text{rms,bs}}$ and $V_{\text{rms, ref}}$ respectively, in equation (5). The average and the standard deviations of the IBP were calculated from the signals of 20 pings for each medium.

**Field measurements**

Red tides usually occur off the Korean coasts from July to September of almost every year. Based on the laboratory results, we undertook field experiments during the red tide season using a research vessel (Tamgu No. 7 of the NFRDI) near Gumo Islands in Yeosu in the Southern Sea of Korea in August 2005 as shown in Fig. 6. The operation of the acoustic equipment was identical to operation in the laboratory. The transducers (5 and 10 MHz) were connected to the end of a stainless steel pipe. The pipe was attached to the side of the vessel so that the transducers were immersed at a water depth of 2 m, because blooms of *C. polykrikoides* are usually found between the surface and 5 m of water depth (Park et al., 2001). The latitudes and longitudes corresponding to the acoustic data were acquired using the global positioning system (GPS) while the vessel was moving a speed of about 4 kn. The interval of acquisition time of the datum was 4 s, so the interval of acquisition distance was ~8 m. The vessel moved 9 km in total. The backscattering windows were 267–467 μs

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**Fig. 4.** Measured beam patterns of 5 and 10 MHz transducers. (A) and (B) 2-D scanned figures along the cross section of the beam propagation range, (C) 1-D scanned figure along the beam axis. The dotted box indicates the time window for the integrated backscattered power.
(20–35 cm) at 5 MHz and 400–600 μs (30–45 cm) at 10 MHz unlike laboratory experiments, because each range is as close as possible to the transition zone of the near- and far-field, and is within $\pm 3\ dB$ field in on-axis profile as shown in Fig. 4. This window may also minimize the effects of air bubbles, since the sample was taken far before the transducer disturbed the sea water to produce air bubbles.

To compare IBP in situ with that in the laboratory, the seawater was sampled at three stations (Table V) in the experimental area. The number of cells of C. polykrikoides in the sampled seawater was counted using the microscope. Acoustical attenuation should be compensated because the scattering window of the lab experiment was different from that of the field experiment in the time domain. The attenuation coefficients are 0.066 and 0.26 dB/cm ref. at 15°C seawater at 5 and 10 MHz, respectively (Clay and Medwin, 1977). To compare the IBP in the red tide area with the IBP in an area without red tide, another field experiment was conducted in Jinhae Bay in Korea in May 2005.

**RESULTS**

Backscattered signals were obtained for the 10 different values of numerical abundance $N$ (cells/mL) at two frequencies (5 and 10 MHz) in the laboratory. The presence of C. polykrikoides and the increase of the numerical abundance resulted in an increase in the amplitude of the backscattered signals. Figure 7 shows the IBP versus the number of C. polykrikoides at two frequencies. The squares and x-marks are the IBP values averaged over 20 pings, corresponding to the number of C. polykrikoides at 5 and 10 MHz, respectively, and the standard deviation limits are shown as error bars. The two solid lines are curve fits to the IBP. At 5 MHz in the laboratory experiment, the curve-fitted IBP values were about $-28$ and $-23\ dB\ ref.\ V_{rms}$ from fresh water at 5 MHz with the density of 300 and 850 cell/mL, respectively. At 10 MHz, IBPs were about $-40$ and $-36\ dB\ ref.\ V_{rms}$ from fresh water at 10 MHz with the density of 300 and 850 cell/mL, respectively.

At 5 MHz in the field experiments, the IBPs were distributed between $-35$ and $-12\ dB\ ref.\ V_{rms}$ from fresh water at 5 MHz as shown in the left side of Fig. 8. The IBPs were almost below $-30\ dB$ across the whole area. The IBP values higher than $-30\ dB$ were shown at three stations named St. 1, 2 and 3. At St. 1 and 3, IBPs are higher than $-30\ dB$ and the numbers of C. polykrikoides were counted as 680 and 180 cells/mL.
respectively. According to our laboratory results, −28 and −23 dB ref. $V_{\text{rms}}$ from fresh water at 5 MHz were the lower and upper boundaries of the red tide precaution (300–1000 cells/mL), respectively. As shown in Fig. 8, a value of 680 cells/mL at St. 1 is reasonable considering the cell number and the IBP; however, 180 cells/mL at St. 3 is not. This is thought to be due to a different method of seawater sampling. The seawater was sampled when the vessel was stopped at St. 1, and when moving at St. 3. The IBP at St. 2 was higher than −25 dB, and in some cases even higher than −15 dB. The number of *C. polykrikoides* was 1320 cells/mL. We note that St. 2 was the area in which the red tide was recognized even by the naked eye. However, IBP values in Jinhae Bay were mostly below −30 dB when there was no red tide, except at some sites which showed values between −30 and −25 dB.

**DISCUSSION**

The volume backscattering strength, $S_n$ has been measured in many cases of acoustical measurements in the sea, and can be obtained by theoretical and
The theoretical value of $S_v$ is calculated using properties such as density ratio $g$, sound speed ratio $h$, scatter size $a$ and numerical abundance $N$. The scatterer size and the numerical abundance are easily obtained using a microscope, but the density ratio and the sound speed ratio are not simple. The compressibility of a scatterer is not easy to be measured. In order to obtain the experimental $S_v$ on
the other hand, the transmitting voltage response (TVR) and receiving voltage sensitivity (RVS) should be known in addition to the transmission loss, attenuation, source power and scattering volume. TVR and RVS are the characteristics of correlation between the acoustic transducer and the transmitter/receiver systems; however, they are difficult to measure. Hence, in this study, the IBP (which is relatively easy to estimate) was experimentally measured to check the feasibility of a correlation between acoustic signals and C. polykrikoides, although IBP is a relative value depending on the reference data. A quantitative estimation of the theoretical and experimental determination of \( S_j \) remains for future research.

In our laboratory experiments, we confirmed that IBP at 5 MHz was distributed between −32 and −23 dB ref. \( V_{\text{rms from fresh water at 5 MHz}} \) in the fitting curve. At 10 MHz, the IBP was between −44 and −23 dB ref. \( V_{\text{rms from fresh water at 10 MHz}} \). According to equations (2) – (4), if the frequency doubles, the backscattering strength theoretically increases by 12 dB because the backscattering cross section is proportional to the fourth power of frequency in the Rayleigh regime. Frequency dependence could not be considered in this study because the reference data from the fresh water were different at each frequency. However, because the scatterer size is related to wavelength, the correlation between the IBP and frequency can be examined through quantified measurements of volume backscattering strength in future studies.

IBP values from the laboratory experiments can be compared with those from the in situ experiments. If the IBP is above −25 dB ref. \( V_{\text{rms from fresh water at 5 MHz}} \) in the field experiments, the numerical abundance of C. polykrikoides is thought to be more than 830 cells/mL, which is close to the red tide warning level (more than 1000 cells/mL in Table III) according to the forecasting system. This assumes that IBPs were obtained during a red tide season in the sea area where other environmental factors such as suspended particulate matter, phytoplankton, zooplankton, air bubbles etc. were minimally affected. Among these factors, the effects of other plankton could be minimal, since C. polykrikoides is known to be dominant in the seawater during red tides (Yoo et al., 2002). Air bubbles were minimized by the sample being taken far away from the transducer face, which can be inferred from the measured IBP of −30 to −25 dB for 680 cells/mL of C. polykrikoides at St. 1, and from the higher IBP values of −25 dB for 1320 cells/mL at St. 2. However, the field experiments may be limited to a calm day with light winds since stronger winds over about 8 kn would create bubbles. The limitation may be partially overcome by monitoring ambient conditions with bubbles and assessing the potential interference from the bubbles. Moreover, there is less chance for red tides to develop when the wind is strong since the surface water is mixed or circulated by strong winds.

IBP values measured from field experiments at 5 MHz were distributed between −35 and −12 dB ref. \( V_{\text{rms from fresh water at 5 MHz}} \) as shown in Fig. 8. At three stations (St. 1, 2 and 3), the IBP was higher than −30 dB and at two stations (St. 1 and 2), numerical abundances of C. polykrikoides were more than 300 cells/mL. During the experiments, the red tide did not occur over the whole area of ~9 km because of the known patchy nature of the bloom. In order to compare IBP in the red tide sea area to IBP in the normal sea area, another acoustic measurement was conducted in Jinhae Bay. As shown on the right side of Fig. 8, the IBP was lower than −30 dB ref. \( V_{\text{rms from fresh water at 5 MHz}} \) except for a few data points. This is thought to be due to different local suspended particulate matter in Jinhae Bay. Moreover, the damping was set to zero in the pulser/receiver in the Jinhae Bay experiments, whereas it was set to 5 in the study area experiments. This means that the IBP values in Jinhae Bay (right panel of Fig. 8) could be decreased if the damping is compensated, which is not easy to do. Thus, we suggest measuring the background IBP as a baseline study in any interesting sea area under non-red tide conditions for a better estimation. Even though C. polykrikoides are weak scatterers, the acoustical techniques can be used to recognize the presence of C. polykrikoides and to estimate the numerical abundance during red tides. This approach provides the basis for acoustical observation of C. polykrikoides in the open ocean in situ.

If IBP is obtained with GPSs positional data and the data processing time is fast enough, then real-time mapping may be possible, as shown in Fig. 9. The position of each line was mapped using the GPS data to show where the acoustic data was acquired. The height of each line represents the IBP at that position. Real-time acoustic measurements can be conducted in the sea with certain assumptions of neglecting the effects of other scatterers such as suspended particulates, fish and other plankton. It was assumed that other factors that affect the acoustic signal, such as a school of fish, were not to be present.

Not much variation was measured at 10 MHz except near St. 3, where the IBP was higher than −35 dB ref. \( V_{\text{rms from fresh water at 10 MHz}} \). According to the laboratory experiments, an IBP value higher than −40 dB ref. \( V_{\text{rms from fresh water at 10 MHz}} \) can be considered to be numerical abundance over 300 cells/mL, but this was not verified because seawater was not sampled. As the
numerical abundance increases, the *C. polykrikoides* chain becomes long and the equivalent volume gets larger. In this case, 10 MHz is not appropriate for this study since it is over the Rayleigh regime.

Consequently, based on IBP values both from the laboratory and from the sea *in situ*, even though measurements were limited, this study suggests the feasibility of measuring acoustical signals from *C. polykrikoides*, the main species of red tide in the Southern Sea of Korea.

**CONCLUSION**

Acoustic IBP from the major phytoplankton (*C. polykrikoides*) that causes red tides in Korean coastal waters were acquired and analysed to investigate the feasibility of observing red tides in the sea *in situ*. IBP values from culture media with *C. polykrikoides* were calculated from acoustic backscattered signals, and the signals increased with the number of cells in the laboratory. Following the laboratory experiments, the backscattered signals were collected from red tides *in situ* near Gumo Islands in Yeosu in the Southern Sea of Korea. The seawater was sampled during backscattering measurements and the number of *C. polykrikoides* was counted using a microscope. The experiments confirmed the feasibility of measuring IBP from red tides using high frequency ultrasound. This research is not limited to red tides, and could be applied to the study of plankton distribution, pollution monitoring and suspended particulates in the sea. Further studies concerning the observation of red tides in terms of occurrences, locations and duration are recommended. This research is only the first step in acoustical measurements of the abundances of *C. polykrikoides* in red tides.

**SUPPLEMENTARY DATA**

Supplementary data can be found online at http://plankt.oxfordjournals.org.

**FUNDING**

This work was supported by the “Development of ubiquitous management technologies for marine useful/harmful organisms” grant (no. PE98474), promoted by the Korea Ocean Research and Development Institute.

**REFERENCES**

Ahn, Y.-H., Shanmugam, P., Chang, K.-I. *et al*. (2005) Spatial and temporal aspects of phytoplankton blooms in complex ecosystems off the Korean Coast from satellite ocean color observations. *Ocean Sci. J.*, 40, 67–78.

Anonymous. (2006) *Ultrasonic Transducer Technical Notes*, Olympus NDT, http://www.olympus-ims.com/data/File/panametrics/UT-technotes.en.pdf, last accessed on 21 December 2009.

Clay, C. S. and Medwin, H. (1977) *Acoustical Oceanography: Principles and Applications*. John Wiley and Sons, New York.

Greenlaw, C. E. and Johnson, R. K. (1982) Physical and acoustical properties of zooplankton. *J. Acoust. Soc. Am.*, 72, 1706–1710.
Guillard, R. R. L. (1975) Culture of phytoplankton for feeding marine invertebrates. In Smith, W. L. and Chanley, M. H. (eds), *Culture of Marine Invertebrate Animals*. Plenum Press, New York, pp. 26–60.

Guillard, R. R. L. and Ryther, J. H. (1962) Studies of marine planktonic diatoms. 1. *Cyclotella nana* Hustedt and *Detonula confervacea* (Cleve) Gran. *Can. J. Microbiol.*, 8, 229–239.

Holliday, D. V. and Pieper, R. E. (1980) Volume scattering strengths and zooplankton distributions at acoustic frequencies between 0.5 and 3 MHz. *J. Acoust. Soc. Am.*, 67, 135–146.

Johnson, R. K. (1977) Sound scattering from a fluid sphere revisited. *J. Acoust. Soc. Am.*, 61, 375–377.

Kristensen, A. and Dalen, J. (1986) Acoustic estimation of size distribution and abundance of zooplankton. *J. Acoust. Soc. Am.*, 80, 601–611.

Lee, J. H. (1999) A review on red-tides and phytoplankton toxins in the coastal waters of Korea. *Korean J. Environ. Biol.*, 17, 217–232 (in Korean).

Lee, C. K., Kim, H. C., Lee, S.-G. et al. (2001) Abundance of Harmful Algae, *Cochlodinium polykrikoides*, *Gymnodinium impudicum* and *Gymnodinium catenatum* in the Coastal Area of South Sea of Korea and Their Effects of Temperature, Salinity, Irradiance and Nutrient on the Growth in Culture. *J. Korean Fish. Soc.*, 34, 536–544 (in Korean).

NFRDI. (2004) National Fisheries Research and Development Institute, Standard of Harmful Algal Blooms Forecast in Korea., http://portal.nfrdi.re.kr/external/environment/redtide/webpage/operation/operation_04.jsp, last accessed on 21 December 2009 (in Korean).

Palmer, D. R. (1996) Rayleigh scattering from nonspherical particles. *J. Acoust. Soc. Am.*, 99, 1901–1912.

Park, J. G., Jeong, M. K., Lee, J. A. et al. (2001) Diurnal vertical migration of a harmful dinoflagellate, *Cochlodinium polykrikoides* (Dinophyceae), during a red tide in costal water of Nambae Island, Korea. *Physiologia*, 40, 292–297.

Stanton, T. K., Chu, D. and Wiebe, P. H. (1996) Acoustic scattering characteristics of several zooplankton groups. *ICES J. Mar. Sci.*, 53, 289–295.

Suh, Y.-S., Kim, J.-H. and Kim, G. (2000) Relationship between sea surface temperature derived from NOAA satellites and *Cochlodinium polykrikoides* red tide occurrence in Korean coastal waters. *J. Korean Environ. Sci. Soc.*, 9, 215–221 (in Korean).

Yoo, Y. D., Jeong, H. J., Shim, J. H. et al. (2002) Outbreak of red tides in the coastal waters off the Southern Saemankeum areas, Jeonbuk, Korea; 1. Temporal and spatial variations in the phytoplankton community in the summer-fall of 1999. *J. Korean Soc. Oceanogr. The Sea*, 7, 129–139 (in Korean).