Burst-Pulse Sounds Recorded from White-Beaked Dolphins (*Lagenorhynchus albirostris*)

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Abstract

Dolphin sounds are generally categorized as tonal whistles or pulsed clicks. Pulsed signals in dolphins are usually associated with echolocation; however, an increasing number of species have been found to produce burst-pulse signals, which may be used for communication. Groups of white-beaked dolphins (*Lagenorhynchus albirostris*) were recorded near Halifax, Nova Scotia, Canada, with a hydrophone towed 25 m behind the boat at a depth of approximately 5 m and an M-Audio 24/96 digital recorder (16 bit, 96 kHz). During one 50-min encounter, 10 burst-pulse segments were recorded. Mean burst-pulse duration was 0.33 s (SD 0.17 s, range 0 3 to 0.60 s). Peaks from burst-pulses were accurately identified with a *MATLAB* software-based signal detection and analysis program in nine segments of the recordings, totaling 521 individual peaks. Mean pulse rate was 719 Hz (SD 207 Hz, range 423 to 1,103 Hz), while the mean pulse period was 1.39 ms (SD 0.41 ms, range 0.91 to 2.36 ms). Mean peak frequency was 35.3 kHz (SD 11 kHz, range 1.5 to 46.5 kHz), and mean 3-dB bandwidth was 5.1 kHz (SD 1.4 kHz, range 3 to 10.5 kHz). Maximum received level was 159 dB re 1 μPa. The observed pulse rates were likely too rapid to be of use for echolocation. These sounds were made immediately before the group began actively swimming away from the boat at high speed, suggesting that they were used for communication as has been proposed for other species of dolphins. This is the first time burst-pulses have been quantitatively analyzed for this genus of dolphin.

Key Words: acoustic communication, burst-pulse, cetacean, echolocation, white-beaked dolphin, *Lagenorhynchus albirostris*

Introduction

Acoustic signals are a highly efficient method of communicating and gaining information about the underwater environment (Au, 1993). It is therefore not surprising that dolphins have evolved highly sophisticated acoustic production (Cranford, 1990; Au, 1993) and receiving mechanisms (Ketten, 1990) as well as sophisticated uses of sound (Au, 1993; Dudzinski, 1996; Herzing, 1996; Cook et al*.,* 2004). Whistles are produced by most delphinids; these are frequency-modulated tonal signals with fundamental frequencies typically below 20 kHz (Caldwell & Caldwell, 1965, 1971). A substantial body of research supports the role of whistles as social signals (e.g., Janik, 2000; Cook et al., 2004). In addition, all delphinids investigated to date produce pulsed, broadband clicks. These clicks have high peak frequencies (110 to 130 kHz in bottlenose dolphins [*Tursiops truncatus*]; Au, 1993; 106 to 115 kHz in white-beaked dolphins [*Lagenorhynchus albirostris*]; Rasmussen & Miller, 2002) and are usually produced at rapid rates (inter-pulse interval 25 to 175 ms in bottlenose dolphins; Au, 1993; 3 to 46 ms in white-beaked dolphins; Rasmussen & Miller, 2002). Studies on several captive species have determined that clicks are used for echolocation (Au, 1993), and this function has been confirmed in studies on free-ranging animals (e.g., Herzing, 1996).

Burst-pulse vocalizations have been recorded in an increasing number of dolphin species—for example, Pacific white-sided dolphins (*L. obliquidens*; Caldwell & Caldwell, 1967), bottlenose dolphins and Atlantic spotted dolphins (*Stenella frontalis*; Herzing, 1996), northern right-whale dolphins (*Lissodelphis borealis*; Rankin et al*.,* 2007), killer whales (*Orcinus orca*; Ford, 1991), and Hawaiian spinner dolphins (*S. longirostris*; Lammers et al*.,* 2003). Like echolocation trains these sounds are composed of pulsed signals; however, they are produced at very high rates (e.g., 940 Hz; Blomqvist & Amundin, 2004a). They have also been reported to have lower-frequency characteristics (Herzing, 1996), although such reports may have been in part due to narrow-band spectral analysis (Lammers et al., 2003), and

more recent broadband recordings indicate peak frequencies above 100 kHz for burst-pulses (e.g., Blomqvist & Amundin, 2004b).

Burst-pulses have typically been defined as pulses produced at rates exceeding human auditory thresholds for temporal discrimination (inter-pulse interval < 5 ms; Murray et al., 1998), which appear as harmonic bands on spectrograms (Watkins, 1967). The sounds perceived by human listeners have resulted in a variety of descriptions in the literature (e.g., "squawks" and "barks"; Caldwell & Caldwell, 1967; Herzing, 1996; Corkeron & Van Parijs, 2001). Most studies have attributed a communicative role to burst-pulse vocalizations in dolphins, based on the behavioral context in which they are used. For example, Blomqvist & Amundin (2004a) recorded burst-pulse vocalizations only during agonistic encounters in captive bottlenose dolphins, and Herzing (1996) found that burst-pulses were associated with behavior such as courtship and excited states in Atlantic spotted and bottlenose dolphins. In addition, the pulse rates of the signals may be too high to be useful for echolocation purposes (Au, 1993; Lammers et al., 2003).

White-beaked dolphins are found throughout the cold temperate regions of the North Atlantic (Lien et al., 2001), including the coastal waters near Halifax, Nova Scotia, Canada, from May to July (Simard et al., 2006). Like many dolphins, this species produces both whistles and clicks (Rasmussen & Miller, 2002). In this paper, the spectral and temporal characteristics and behavioral context of a single episode of white-beaked dolphin burst-pulse vocalizations recorded near Halifax are described.

Materials and Methods

Field work was conducted in the summer of 2007 near Halifax, Nova Scotia, Canada (Figure 1). Groups of white-beaked dolphins were visually located and followed in a 4.2-m rigid inflatable boat with a 25-hp, 4-stroke engine. During encounters, a single HTI-96-MIN hydrophone (sensitivity: -180 dBV/µPa, ±3 dB from 10 kHz to 50 kHz) was towed 25 m behind the boat at a depth of approximately 5 m. Acoustic recordings were made with an M-Audio 24/96 digital recorder (16-bit resolution, 96 kHz sample rate, gain of 3.9 dB between 20 Hz and 50 kHz, anti-aliasing filter with corner frequency of 47.8 kHz). While towing the hydrophone, vessel speed was restricted to 5 kts (9.25 km/h) or lower to reduce noise from water flow and to keep the hydrophone at depth. Continuous recording was attempted during all encounters. Recordings were not reviewed in real time on the vessel.
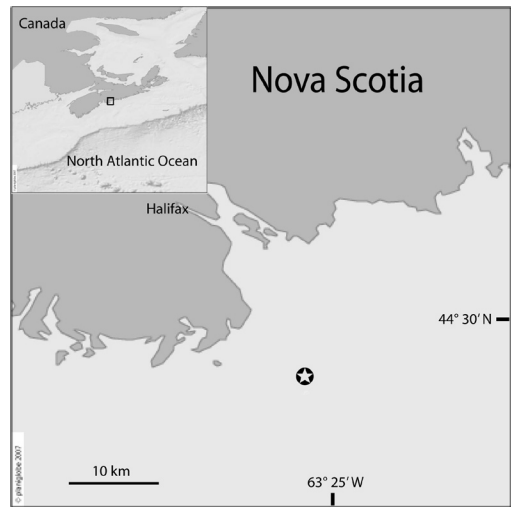

Figure 1. Map of the study area—Halifax, Nova Scotia, Canada; star indicates position of white-beaked dolphins during burst-pulse recordings.

Acoustic files were manually inspected for burst-pulse segments using Adobe *Audition,* Version 2, software (Adobe Systems, Inc.). The onset and termination of burst-pulse vocalizations were defined by the onset and termination of multiple harmonic bands visible on the spectrogram, characteristic of pulses being produced at high rates (Watkins, 1967; Cranford, 1990). Burst-pulse segments were imported into *MATLAB*, Version 7.5, software (Mathworks, Inc.) for further analysis in a custom signal processing program (developed by P. Simard). In this program, the time domain signal is rectified and filtered to facilitate automatic identification and labeling of peaks. The ability of the program to accurately detect peaks could be verified visually by comparing labeled peaks to the original time domain waveform. Only segments of files in which all peaks were accurately identified were used in the analysis (although the lengths of burst-pulse vocalizations were determined from the original files). For files with accurately identified burst-pulse peaks, the spacing between individual peaks was used to determine the pulse rate (pulses per s) and pulse period (time between amplitude maxima).

In the literature, inter-pulse interval (IPI) is commonly reported, but it is often not adequately defined. IPIs that are determined by the onset and termination of pulses can be influenced by background noise levels. Alternately, IPIs that are defined as the time between amplitude maxima are a more robust measurement but are more correctly termed a *pulse period*. Due to the short durations of the pulses, the pulse period can be considered roughly equivalent to the IPI calculated from

pulse onset and termination. From the corresponding unfiltered time domain signal, the maximum amplitude was recorded, and 64-point fast Fourier transforms (FFTs) were performed. FFTs were centered on individual peaks, and the low FFT size was chosen to focus spectral analysis on the peak itself, omitting parts of the signal between peaks. The peak frequency and 3-dB bandwidth was calculated for each FFT. The average power spectrum for the burst-pulse clicks was determined by averaging the FFT results from individual clicks.

Results

Four groups of white-beaked dolphins were encountered in 2007. No other species of cetaceans were observed during any of the white-beaked dolphin encounters. During these encounters, 64 min 13 s of recordings were made. Electrical interference made 7 min 17 s unusable, resulting in 56 min 56 s of recordings available for analysis. Burst-pulse vocalizations were identified in recordings from a single 50-min encounter (20 June 2007, group size = 15, including one first-year calf and one older juvenile, as defined in Simard et al., 2006) at approximately 44° 25' N, 63° 30' W (Figure 1). The burst-pulse recordings took place immediately before a rapid change in the group's behavior from slow swimming with frequent direction changes to rapid and sustained straight-line swimming. Due to deteriorating weather and the behavioral changes noted, the dolphins were monitored at distances greater than 200 m for approximately 20 min, but the group was not closely followed, and no other acoustic recordings were obtained.

A plot of the waveform and corresponding spectrogram of a white-beaked dolphin burst-pulse is shown in Figure 2. Ten distinct burst-pulse

sequences defined by the presence of harmonic bands were found, totaling 3.30 s (Table 1). The *MATLAB* program was able to accurately identify peaks in nine file segments (as determined by manually comparing identified peaks to original waveform as described in "Materials and Methods"), totaling 0.73 s, and 521 pulses were analyzed. From these pulses, the maximum recorded amplitude was 159 dB re 1 μPa_{peak}. Mean pulse period was 1.39 ms, and mean pulse rate was 719 Hz (Table 1). A histogram illustrating the distribution of pulse period values is in Figure 3. FFTs were performed on 520 pulses (one pulse was very close to the end of the file and omitted from this analysis). The mean peak frequency was 35.3 kHz, and the mean 3-dB bandwidth was 5.1 kHz. The average energy spectrum of the 520 clicks used in spectral analysis is found in Figure 4.

Discussion

Although the length of burst-pulse recordings and the sample size of analyzed pulses are low, this is the first quantitative analysis of burst-pulses from the genus *Lagenorhynchus*. The sounds produced by white-beaked dolphins have been studied in detail in Faxaflói Bay, Iceland (Rasmussen & Miller, 2002; Rasmussen et al., 2002, 2004). Despite an extensive library of recordings analyzed, burst-pulses and IPIs of less than 5 ms were rare, with only one possible burst-pulse found (Rasmussen & Miller, 2002). Burst-pulse vocalizations were recorded in captive Pacific white-sided dolphins, another species of *Lagenorhynchus* (Caldwell & Caldwell, 1967); however, these vocalizations were described in a behavioral context only.

Burst-pulse vocalizations in other species are generally found to be short in duration. For example, the burst-pulse vocalizations of northern

Table 1. Summary of data from burst-pulses recorded from white-beaked dolphins near Halifax, Nova Scotia, Canada; number of sounds recorded, total time recorded, and duration of sounds from initial analysis in Adobe *Audition*. Remaining data from analysis in *MATLAB*.

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Number of burst-pulses recorded	10
Total time of burst-pulses recorded (s)	3.3
Duration of sound (s)	$\bar{X} = 0.33$, SD = 0.17, range 0.03-0.60
Number of pulses analyzed for temporal analysis	521
Number of pulses analyzed for spectral analysis	520
Total time of burst-pulse vocalizations analyzed (s)	0.73
Maximum peak received level (dB re 1 μPa)	159
Pulse period (ms)	$\bar{X} = 1.39$, SD = 0.41, range 0.91-2.36
Pulses per s (Hz)	$\bar{X} = 719$, SD = 207, range 423-1,103
Peak frequency (kHz)[a]	$\bar{X} = 35.3$, SD = 11.0, range 1.5-46.5
3 dB bandwidth (kHz)[a]	$\bar{X} = 5.1$, SD = 1.4, range 3.0-10.5

[a]Nyquist frequency 48 kHz
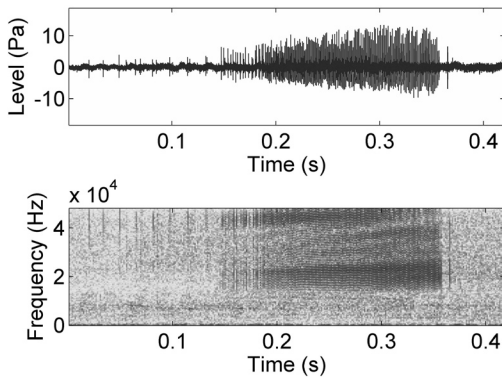
Figure 2. Amplitude plot (top) and spectrogram (bottom) showing white-beaked dolphin burst-pulses (approximately 0.15 to 0.35 s, identified by horizontal harmonic banding; see Watkins, 1967) with preceding echolocation clicks
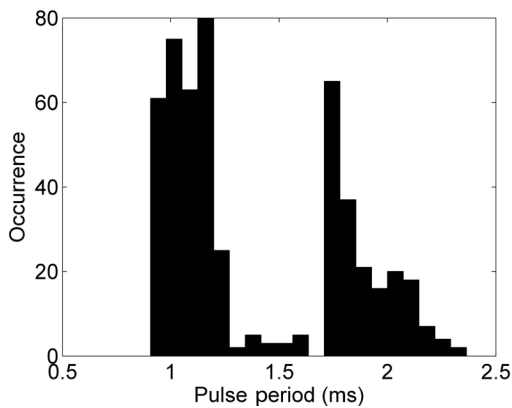

Figure 3. Histogram of pulse period of white-beaked dolphin values between 521 white-beaked dolphin pulses
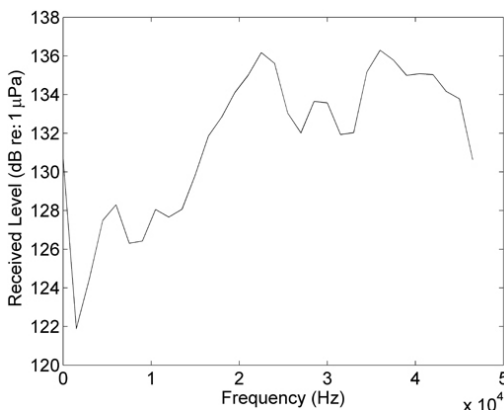

Figure 4. Average energy spectrum (64 point FFT, 1,500 Hz resolution) of 520 white-beaked dolphin pulses

right-whale dolphins had a mean length of 26.98 ms (Rankin et al., 2007), and Blomqvist & Amundin (2004a) found that 92.7% of burst-pulse vocalizations of captive bottlenose dolphins were less than 500 ms. Results in this study (mean duration 330 ms) are therefore not unusual for delphinid burst-pulses. The burst-pulses (termed *barks*) were reported to be as long as 12 s in Risso's dolphins (*Grampus griseus*; Corkeron & Van Parijs, 2001), indicating that at least some delphinids are capable of producing long bouts of rapid pulses.

Burst-pulses by their definition have more rapid pulse rates than seen in typical echolocation. For example, Hawaiian spinner dolphin burst-pulses were found to have a mean IPI of 3.85 ms, and were as low as 1.5 ms (Lammers et al., 2003, 2004), while the burst-pulses of northern right-whale dolphins had a mean IPI of 1.15 ms and were as low as 0.28 ms (Rankin et al., 2007). The pulse rates of captive bottlenose dolphin burst-pulses were reported to be 940 Hz in bottlenose dolphins (Blomqvist & Amundin, 2004a), while pulse rates in free-ranging melon-headed whales (*Peponocephala electra*) were as high as 1,200 Hz (Watkins et al., 1997) and up to 2,000 Hz in Atlantic spotted dolphins (Herzing, 1996). The burst-pulses observed in this study were also produced at high rates (mean pulse period 1.39 ms, mean pulse rate 719 Hz, minimum pulse period 0.91 ms, maximum pulse rate 1,103 Hz; Table 1).

Varied results can be found for the spectral qualities of burst-pulse (and other) high-frequency vocalizations due to variations in the sampling rate of the recordings and the bandwidth of the recording instruments. Several studies emphasize the importance of lower-frequency components in burst-pulses in comparison to echolocation clicks (e.g., Herzing, 1996). However, other studies do not support the conclusion that burst-pulses vary in spectral qualities from echolocation clicks (e.g., Lammers et al., 2003) and suggest that the lower sampling rates of earlier recordings lead to claims of lower frequencies in burst-pulses. The maximum Nyquist frequency in this study was 48 kHz, thus spectral analysis is restricted to this frequency and lower. Therefore, studies reporting values within this bandwidth are more relevant for comparisons to our results. Rankin et al. (2007) recorded burst-pulse vocalizations from northern right-whale dolphins at a Nyquist rate of 125 kHz, although the upper bandwidth of the hydrophone was only 40 kHz. The mean peak frequency for northern right-whale dolphins was 18.2 kHz (Rankin et al., 2007). Lammers et al. (2003) and Lammers et al. (2004) reported a mean peak frequency for Hawaiian spinner dolphin burst-pulses of 32.3 kHz and for Atlantic spotted dolphin burst-pulses of 40.3 kHz, despite

a Nyquist rate of 130 kHz. The peak frequency of white-beaked dolphins reported here (35.3 kHz) is similar to the results of these other studies.

Lammers et al. (2003) found no differences in the energy spectra from burst-pulse clicks and regular echolocation clicks in Hawaiian spinner dolphins, and, therefore, the spectral qualities of white-beaked dolphin echolocation clicks are likely a valid comparison to our results. Mean peak frequencies for white-beaked dolphin clicks were reported to range between 106 and 115 kHz (Rasmussen & Miller, 2002); therefore, it is very likely that the peak frequencies of white-beaked dolphin burst-pulses are much higher than we report here.

Most studies report broader 3-dB bandwidths for burst-pulse clicks than we report here (mean 5.1 kHz). For example, the 3-dB bandwidth of northern right-whale dolphins was found to be 10.3 kHz (Rankin et al., 2007). Rasmussen & Miller (2002) found a 3-dB bandwidth of 42 kHz to 70 kHz for white-beaked dolphin echolocation clicks; however, their sampling rate was far higher than in this study.

Burst-pulses (like echolocation clicks) are energetic signals with high sound pressure levels. For example, the peak-to-peak source level for Hawaiian spinner dolphins was estimated to be 205 dB re 1 µPa (Lammers et al., 2004). Echolocation clicks are highly directional (Au, 1993), and it is likely that burst-pulse clicks are highly directional as well (Lammers et al., 2003; Blomqvist & Amundin, 2004a). We have no way of knowing in this study if dolphins were on axis to the hydrophone when they were vocalizing or how far away from the hydrophone they were. Also, burst-pulses with an energy peak in lower frequencies (e.g., 20 kHz) may not be directly in the acoustic beam (Blomqvist & Amundin, 2004a). The average energy spectrum of our burst-pulse clicks suggests that this may be the case in this study. In addition, the peak frequencies for white-beaked dolphin echolocation clicks (106 to 115 kHz; Rasmussen & Miller, 2002) are far higher than we were able to record (Nyquist rate 48 kHz); hence, we were likely not recording the frequencies containing maximum energy levels. Therefore, it is likely that the received levels recorded in this study (159 dB re 1 µPa$_{peak}$) are lower than would be measured with broadband recording.

Dolphins may categorize their sounds in a variety of ways, and each category may or may not have exclusive functions (e.g., foraging or communication). Previous authors addressed this question and described burst-pulses as a range of sounds on a spectrum of possible sounds, ranging from discrete clicks to tonal whistles (e.g., Murray et al., 1998). In addition, cetacean behavior is notoriously difficult to observe and quantify, and behaviors themselves are not necessarily mutually exclusive. Therefore, it is difficult to unequivocally determine the function of burst-pulse vocalizations.

Despite this, quantitative analysis of the temporal and spectral features of burst-pulse clicks allowed comparison to more typical echolocation clicks. For example, Lammers et al. (2004) found that the IPIs of Hawaiian spinner dolphin clicks were strongly bimodal. Burst-pulse clicks were centered at 3.5 ms, while more typical echolocation clicks were centered at 80 ms. The low numbers of clicks produced between these modes suggests the existence of functional categories of clicks for echolocation and communication (Lammers et al., 2004).

Several behavioral studies support the hypothesis that burst-pulses serve a communication purpose. Captive bottlenose dolphins have been observed producing burst-pulses exclusively in intraspecific agonistic encounters, and they appear to use these vocalizations in a ritualized behavior sequence (Blomqvist & Amundin, 2004a). Free-ranging Atlantic spotted dolphins have been observed using burst-pulses in a variety of behavioral situations, including courtship, aggression, and play (Dudzinski, 1996; Herzing, 1996). Burst-pulses of Pacific white-sided dolphins were thought to be used in "emotional contexts" (p. 889) by Caldwell & Caldwell (1967), and communicative killer whale signature calls are composed of burst-pulse signals (Ford, 1989, 1991). However, there is little evidence supporting an echolocation function for burst-pulses, and burst-pulses have not been observed in controlled echolocation experiments (Lammers et al., 2003). For a pulse to be used effectively for echolocation, it is generally believed that the pulse must return to the animal for processing before a second pulse is produced (Au, 1993). The travel time of a pulse is dependent on the distance to the target, and the processing time has been determined to be between 19 and 45 ms for bottlenose dolphins (Au, 1993). Therefore, pulses in burst-pulses are likely produced at too rapid a rate to be useful for echolocation. However, knowledge of dolphin sonar may not be complete, and dolphins could possibly be selecting specific echoes or processing multiple clicks (Au, 1993; Lammers et al., 2003). Echolocation using clicks produced at faster rates than the two-way travel time has been observed in a non-delphinid odontocete (beluga whale [*Delphinapterus leucas*]; Turl & Penner, 1989).

The burst-pulses recorded in this study took place before a change in behavior in the group. The dolphins were swimming slowly with frequent changes in direction, producing echolocation

clicks and occasional whistles, and the research vessel was able to stay near the group. However, the burst-pulses marked a change in behavior to rapid, straight-line swimming sustained for at least 20 min. This observation suggests that the vocalizations may have been related to the change in behavioral state.

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