

Evaluation of wave drag on bottlenose dolphin *Tursiops truncatus* from swimming effort

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Abstract—When animals move across the water surface, they push out surrounding water, creating waves. This work of wave formation is considered the largest drag component at the water surface and is known as wave drag. In order to avoid wave drag, most marine mammals travel submerged over longer distances and minimize the time spent swimming at the surface. We attached an accelerometer to a trained bottlenose dolphin and evaluated the effect of wave drag from the dolphin's swimming speed and stroking efforts such as stroke frequency and body amplitude. We found that the body amplitude was significantly larger at the surface than at a depth of 3 m within a given speed range; however, the difference was not clear enough to quantitatively evaluate the effect of wave drag. The reasons might be due to the limited size of the pool used in this study. Thus a more controlled experiment with longer swimming distance, a deeper pool, and better control of the dolphin's swimming speed is required to further our understanding of the effect of wave drag on dolphins.

Key words: accelerometer, stroking effort

Introduction

Aquatic animals live in a medium 820 times denser and 55 times more viscous than air. These two properties of water greatly increase body drag (Davis 2014), thus costing the animal large amounts of energy during under-water locomotive activities such as swimming and diving (Barta 2006). Needless to say, most animals rely on locomotion while foraging for food. A considerable amount of energy is utilized during travel to foraging sites and in the effort to capture prey. Cetaceans therefore, show several morphological and behavioral adaptations to benefit the life in aquatic environment (Barta 2006, Davis 2014). The most obvious morphological adaptation is the streamlined body shape, reduced limbs, modified flippers, and flukes. This streamlined body structure can reduce drag and minimize energy consumption, while flukes improve thrust generation and propulsive efficiency. Both of these factors enabled high maneuverability and stability (Davis 2014).

Along with morphological adaptation, various other behavioral strategies and modes of locomotion are known to further minimize the energy consumed. For example, porpoising, a behavior wherein the animal leaps above the water-air interface nose-first, is suggested to be an energetically cheaper way for animals to breath during continuous rapid swimming (Barta 2006, Fish and Hui 1991). Additionally,

wave-riding or bow wave riding by dolphins, wherein they ride waves in a similar manner as human surfers, is considered as an economical form of high-speed travel (Fish and Hui 1991, Williams 1993). Moreover, most marine mammals travel submerged and reduce their time swimming at surface (Davis 2014).

Specifically, four types of hydrodynamic drag are known to be acting on marine mammals swimming at a constant speed: 1) friction drag, due to animal's wetted surface area and viscosity producing shear stresses in the boundary layer, 2) pressure drag resulting from displacement of water due to animal's body structure causing distortion of flow outside the boundary layer creating pressure gradients, 3) induced drag components, produced from pressure difference created by hydrofoils (fins, flippers or flukes) mammals use to generate thrust 4) and lastly, wave drag (Barta 2006, Fish 1993). When an animal or an object travels along the water surface, due to increased area of water-air interface, the surrounding water is pushed out generating waves behind it. Thus, at the water surface, the work needed for wave generation, known as wave drag must also be considered in addition to frictional and pressure drag (Vennell et al. 2005, Vogel 1994). The dominant components of drag when submerged are frictional and pressure-related. Near the surface, wave drag is recognized to be the largest (Fish 1993, Vennell et al. 2005) and is estimated to be 5 times greater than the

drag felt at a depth 3 times the body diameter (height), which reduces with depth and further becomes negligible (Fish 1993, Hertel 1966, Hindle 2010).

Cetaceans that need to return to the surface to breathe cannot avoid the effect of wave drag. Vennell (2006) used mannequins to study the effect of wave drag on human swimmers. Williams (1985) also estimated surface and submerged drag by towing a harbor seal in the gliding position using load cell. However no direct study has been reported on wave drag with the animal swimming by its own effort. Therefore, by attaching animal-borne recorders to a dolphin trained to swim horizontally at the water surface and at pre-defined depths, we tried to estimate the effect of wave drag from the dolphin's stroking effort and the swim speed achieved by the animal while swimming by its own effort. If wave drag exerts a significant impact on swimming dolphins, stroke effort of dolphin swimming at the same speed is expected to be larger at the surface than below.

Materials and methods

Experimental procedure

A male bottlenose dolphin *Tursiops truncatus* from Minamichita Beachland Aquarium in Aichi prefecture, Japan, was used for this study. The dolphin with a body length of 2.99 m, height of approximately 0.7 m, and mass of 289 kg, was trained for 3 months and selected based on its characteristics of being less sensitive, which allowed us to attach the instruments to its body (Fig. 1).

The study was conducted in a pool at the Minamichita Beachland Aquarium with dimensions of approximately 30 m width, 15 m length, and 3.5 m depth at the deepest point. The experiment was conducted for a total of 9 days between February and May 2013, with 2 to 3 sessions a day during the morning feeding time, between aquarium shows at daytime and the last feeding time in the afternoon. The number of trails per session depended on the animal's concentration and amount of fish left to feed for the day.

The dolphin was trained to swim horizontally at the surface and at depths of 3 m, which is approximately 4 times the body height. For surface trail, the dolphin was trained to fol-

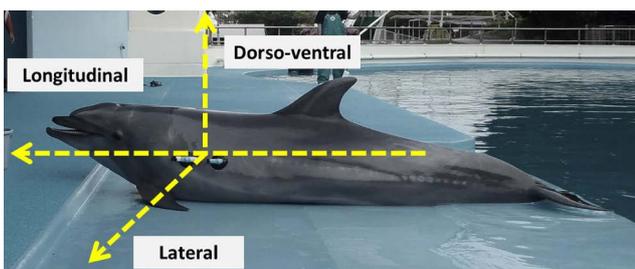


Fig. 1. Direction of 3-axis acceleration measured by an accelerometer.

low the trainer running along the edge of the pool. Its dorsal fin was always out of the water during surface trails. For 3-m trails, two sets of poles with a target attached at the end were used and were fixed at the depth of 3 m. The dolphin dove down and touched the first target with its rostrum and swam between the poles keeping a constant depth, then touched the other target and came up to the surface. To kill the momentum when diving, the dolphin was trained to stop at the first target for few seconds. Due to the limited area of the pool, the distance for surface trail and 3-m trail was approximately 20 m and 13 m, respectively.

Instruments

In this study, 2 types of animal-borne recorders (hereafter, accelerometer) W190L-PD3GT (22 mm in diameter, 114 mm in length, 60 g in air, Little Leonardo Corp., Tokyo, Japan) and W1000-3MPD3GT (26 mm in diameter, 175 mm in length, 140 g in air, Little Leonardo Corp., Tokyo, Japan) were used to quantify the animal's speed, stroking effort, and depth. W190L-PD3GT was programmed to record 3-axis acceleration at 32 Hz, speed at 8 Hz, depth and temperature at 1-Hz intervals. W1000-3MPD3GT was programmed to record 3-axis acceleration at 32 Hz and 3-axis magnetism, speed, depth, and temperature at 1 Hz, although temperature and 3-axis magnetism measurements were not analyzed for this study. Each accelerometer was mounted directly on a black rubber suction cup (85 mm in diameter, Canadian Tire Corporation., Canada) used to attach the accelerometer to the dolphins' body by landing the dolphin on the pool side (Fig. 1).

The speed of an animal was recorded as the rotation counts of propeller mounted on the accelerometer. We first used W190L-PD3GT accelerometers, which is smaller and considered to have less drag and effect on the dolphin. However, high speed swimming of the dolphin was too fast for the sensor to detect rotation counts of the propeller. Therefore, 3 blades were cut off from the propeller customarily consisting 6 blades and the nut was tightened before every session in order to decrease the propeller's rotation. Thus, this accelerometer needed to be calibrated after every session using the dolphin. The dimensions of the pool were measured and we had the dolphin swim around the pool at high speed. This "high-speed swim" was video-recorded from above using GoPro HERO3+ (GoPro., USA) and the speed of dolphin was calculated from the GoPro video recording. Conversion equation was obtained using calculated speed and the rotation number of the propeller. Regression coefficients for this method were relatively high, at 0.998 (n=4). The adjustment of the propeller of W190L-PD3GT accelerometer was a challenge and we obtained only a couple of successful data. Therefore, we changed to the W1000-3MPD3GT accelerometer. No adjustment of the propeller was needed for W1000-3MPD3GT accelerometer, and

rotation counts were converted to speed with the equation obtained from the calibration experiment using an experimentally designed water flow tunnel. Accelerometers were set inside the tunnel and rotation counts were obtained from flow speed ranging from 0.1 to $1.1 \text{ m}\cdot\text{s}^{-1}$ to plot a regression line. Regression coefficient was 0.999 ($n=10$).

Data analysis

The effect of wave drag was assessed from the swimming effort of the dolphin, such as stroke frequency and body amplitude. Time-series data obtained from the accelerometers were analyzed using *IGOR Pro* (WaveMetrics, Inc., Lake Oswego, OR, USA). Among the 3 axes of acceleration, dorso-ventral axis (Fig. 1) was used for calculating the stroke frequency. The acceleration sensor of the data logger measures both, gravity-based acceleration and specific acceleration related to propulsive activity (Tanaka et al. 2001, Sato et al. 2003); the latter was used for stroke analysis. The dominant stroke frequency of every independent session was determined by calculating the power spectral density (PSD) of the dorso-ventral axis (Fig. 2). PSD results showed an obvious peak around 2 Hz which is believed to be the dominant stroke cycle frequency (Sato et al. 2007) and 2 troughs around 1 and 3 Hz (Fig. 2). The smallest value of trough from all sessions was 0.7 Hz and the highest value was 3.4 Hz . Thus, in order to separate the stroking events from other movements, frequencies lower than 0.7 Hz and higher than 3.4 Hz were filtered (IFDL Version 3.1, WaveMetrics, Inc., USA). From the data, peaks with absolute amplitude greater than values ranging from 0.39 to $0.69 \text{ m}\cdot\text{s}^{-2}$ were extracted as strokes and a set of up-and-down durations was considered as a single flipper stroke. The number of strokes of each trail was then divided by the duration of the trail to obtain stroke frequency (Hz).

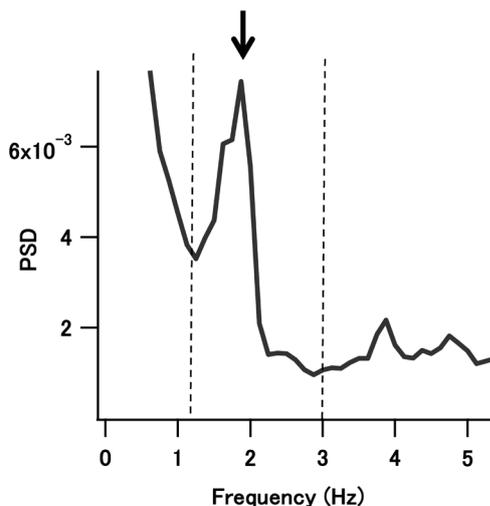


Fig. 2. PSD result of dorso-ventral axis with arrow showing the peak around 2 Hz which is the dominant stroke frequency and the range within the lines are filtered to separate the stroking events from other movements.

Dolphins generate thrust by oscillating their fluke and are known to oscillate their entire body while swimming (Fish and Hui 1991, Williams 1999). Because the amplitude of the fluke oscillation could not be measured, dorso-ventral amplitude of the body oscillation “ A ” was used in the analysis. The measured dorso-ventral acceleration ($\text{m}\cdot\text{s}^{-2}$) was integrated twice to obtain the position of the body (m). The position of the body oscillated and the mean amplitude of the body oscillation (A) in meters for each trail was used for analysis.

When animals are swimming horizontally in a uniform linear motion, thrust and drag is balanced. In order to determine whether dolphins swam in a uniform linear motion, speed was differentiated and the trails of value with high absolute acceleration were not used for analysis.

Statistical analysis

Single-factor ANOVA was used in order to compare swimming effort between the surface and at 3 m as previously described by Zar (1999). Values for significance were set at $P < 0.05$.

Results

General swimming performance

During the 9 days of experiment, 23 sessions were conducted and 12 of them were used for analysis. The remaining 11 sessions could not be used as they lacked speed data due to problems with the propeller. The distribution of mean absolute acceleration of all trails within the 12 sessions was plotted (Fig. 3). Values of acceleration higher than $1.0 \text{ m}\cdot\text{s}^{-2}$ were not used for analysis because the dolphins were most likely not swimming at uniform linear motion during these sessions. Thus, data from 15 trails of 3 m and 16 trails of the surface were used for analysis. The mean values of speed,

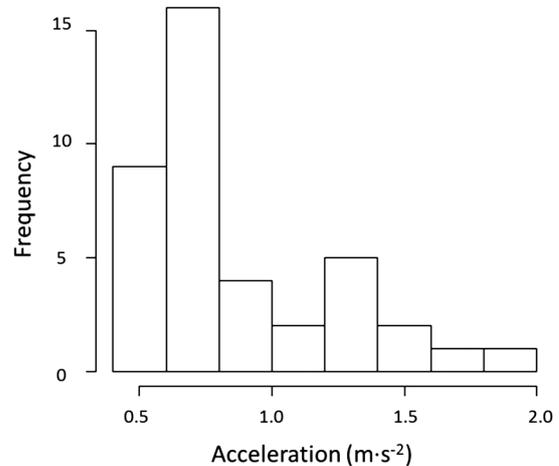
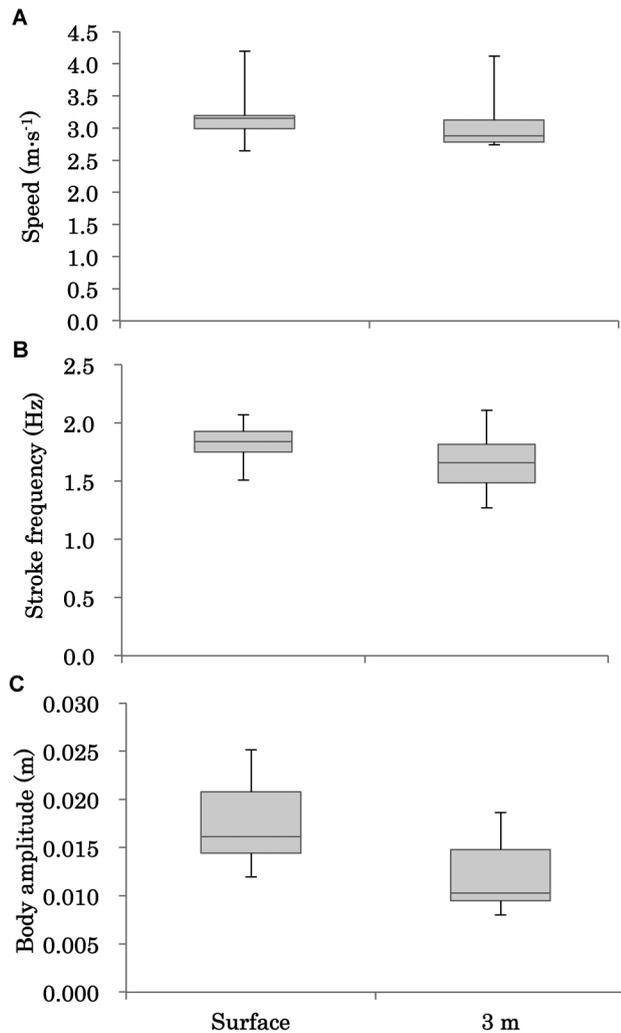


Fig. 3. Distribution of mean absolute acceleration in speed for all trails.

Table 1. Mean values of swim speed and swimming efforts obtained from experiment at the pool. Values are mean±SD.

Trails	Speed ($\text{m}\cdot\text{s}^{-1}$)	Stroke frequency (Hz)	Body amplitude ($10^{-2}\times\text{m}$)
3m (n=15)	2.8±0.3	1.7±0.3	1.4±0.4
Surface (n=16)	3.2±0.2	1.9±0.2	1.8±0.4

**Fig. 4.** Box plots of speed (A) stroke frequency (B) and body amplitude (C) of surface and 3m trail of the same speed range.

stroke frequency, and body amplitude for experiments are indicated in Table 1.

Stroke frequency and body amplitude

The dolphin's swim speed could not be controlled and speed range differed between the values observed at the surface and at 3 m. Thus, in order to statistically compare the difference in swimming effort at these 2 depths, we only used speed data within the range of $2.65\text{ m}\cdot\text{s}^{-1}$ and $3.35\text{ m}\cdot\text{s}^{-1}$ (surface: n=13, 3 m: n=11) so there would be no significant

difference between speed at the surface and at 3 m (ANOVA, $F_{(1,1,23)}=2.005$, $P=0.171$; Fig. 4A). The swimming effort at the surface and at 3 m indicated no significant difference in stroke frequency (ANOVA, $F_{1,23}=3.02$, $P=0.096$; Fig. 4B) but significantly greater body amplitude at surface (ANOVA, $F_{1,23}=10.5$, $P<0.05$; Fig. 4C).

Discussion

Fish (1994) and Williams (1999) indicated changes in stroke frequency but none in fluke amplitude during uniform linear motion over various speed ranges. In our study, we found no significant difference between stroke frequency at the surface and at 3 m, however a difference was noted in body amplitude within the same speed range. This result indicates that dolphins can achieve the same speed with less effort at deeper depths, thus suggesting the effect of wave drag at surface.

Although we were able to detect the effect of wave drag, results from this study showed only a slight difference between values observed at the surface and at 3 m; the results were not clear enough for quantitative analysis. Morphological features of the dolphin are highly adapted to aquatic activity. Fineness ratio (FR), a measure of body streamlining for dolphins, approaches the optimum value of 4.5, which represents the lowest drag ratio of maximum body volume to minimum surface area (Fish and Hui 1991, Berta 2006). Thus, it is more likely that the effect of wave drag on dolphins will be less than the commonly stated estimate of 5 times the drag experienced below a depth of 3 times the body diameter, estimated by towing a dead pike with a soft and flexible body (Hertel 1966). In fact, a study of body drag using harbor seal having similar FR as dolphins indicated a 2.5-fold increase as compared to the submerged value at the surface, at a speed of $2.0\text{ m}\cdot\text{s}^{-1}$ (Williams and Kooyman 1985).

This study had a few limitations. One is the small experimental area. For this experiment, the dolphin was expected to swim horizontally at a constant depth and speed in order to achieve a steady state where drag is equivalent to thrust. However, due to limited experimental area we could not obtain enough swimming distance where the dolphin could continue to swim constantly at high speed. After the dolphin touched the first target and accelerated, it perhaps already detected the second target, therefore, slowed down. During the analysis we eliminated data with high values of acceleration, however, the remaining data were also not of complete uniform linear motion. If swimming distance was longer we may have been able to obtain a more meaningful constant time-series data at a constant speed. Depth might be another reason. The experiments were performed in shallow water, about 3.5 m at the deepest point. Theoretically 3 m is more

than 3 times the body diameter of the dolphin, therefore, the water level was deep enough to reduce the effect of wave drag by one-fifth based on previous knowledge. However, in this circumstance, during 3-m trails the dolphin was swimming very close to the bottom; this might have physically affected the dolphins' swimming characteristics, such as swimming postures and stroke amplitude. Furthermore, there could have been different aspects of drag acting on the swimming dolphin, for instance, waves reflecting back from the bottom of the pool.

Another weakness of this study was that the swim speed of the dolphin could not be controlled; therefore we could not test various speed ranges. Williams et al. (1993) indicated that heart rate, respiration rate, and post-exercise blood lactate concentration of the bottlenose dolphin swimming horizontally at constant speed below 1 m from the surface showed no significant difference until it approached a speed of $2.9\text{ m}\cdot\text{s}^{-1}$. The dolphins were to swim at their favorable speed at 3 m trail where the mean swim speed was $2.8\pm 0.3\text{ m}\cdot\text{s}^{-1}$. If speed was increased over $2.9\text{ m}\cdot\text{s}^{-1}$, we may have seen a clearer trend of change in swimming effort with speed and that between swimming at the surface and at 3 m as well. In either case, controlling speed is fundamental and a better-controlled experimental design is required to further our understanding of the effect of wave drag on the bottlenose dolphin.

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