Effects of Energy Intake and Water Temperature on the Body Shape of Whale Sharks at the Okinawa Churaumi Aquarium

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ABSTRACT: The Okinawa Churaumi Aquarium exhibit includes a male (total length (TL), 8.7 m) and a female (TL, 8.0 m) whale shark, in addition to several other marine attractions. The male has been successfully maintained for over 23 years, which is a world record. The tank housing the whale sharks is 35 m × 27 m × 10 m in dimension and has an open-water system (7500 m^3) without water temperature control. The water temperature in the tank ranges from 21 to 30°C, similar to that of the sea water near the aquarium. Typically, the whale sharks were fed *Euphausia superba*, *E. pacifica*, *Engraulis japonicas* larvae, *Sergia lucens*, *Scomber japonicas*, and *Marsupenaeus japonicas*. Average energy intake, water temperature, TL, and girth (G) were monitored monthly, between March 2017 and March 2018 for the male, and between December 2015 and March 2018 for the female. Their body shapes were expressed as ratios of G to TL (G/TL). The mean (± standard deviation) energy intake per day of the male and female was observed to be 11,483 ± 6,644 kcal and 12,638 ± 5,798 kcal, respectively. Interestingly, G/TL in the male decreased (-0.007) during periods of high temperature, in August 2017 (29.2 °C), even though its energy intake remained high (18,800 kcal). However, G/TL in the male remained unchanged in February 2018 (21.3 °C), despite lower energy intake (13,400 kcal). Similarly, G/TL in the female decreased (-0.004) in August 2017 (29.2 °C), even though it consumed over 16,600 kcal. Contrastingly, this value increased slightly in February 2018 (21.3 °C), despite lower energy intake (8,500 kcal). This suggests that the changes in body shape were caused by varying metabolic rates of the ectothermic whale sharks, which were in turn determined by the relationship between water temperature and food consumption.

INTRODUCTION

The whale shark, *Rhincodon typus*, is the world's largest fish. Being migratory in nature, it has a circumglobal distribution, ranging from the tropical to temperate regions, excluding the Mediterranean Sea (Compagno et al. 2005). This species has been afforded significant management and conservation attention. It is listed as Endangered in the IUCN's (International Union for Conservation of Nature) Red List of Threatened Species, and is also included in Appendix II of CITES (Convention on International Trade in Endangered Species of Wild Flora and Fauna). However, there is sparse information on its life history traits, viz. food consumption, habitat requirements, growth patterns, sexual maturation, and reproduction, largely because of the challenges of long-term observation of individuals, either in the field or in captivity.

Whale sharks are a planktivorous, migratory species; the filtering apparatus on their pharyngeal arches enable them to ingest small organisms (Motta et al. 2010). They aggregate seasonally to feed on abundant food resources such as fish spawn, zooplankton, small fishes, and crab eggs. These aggregations occur around the world, including in the Ningaloo Reef (Taylor 1996) and Christmas Island (Meekan et al. 2009) in Australia, Belize (Heyman et al. 2001), the Atlantic (de la Parra-Venegas et al. 2011), the Pacific coast of Mexico (Eckert and Stewart 2001), Qatar (Robinson et al. 2013), Seychelles (Rowat and Gore 2007), Madagascar (Jonahson and Harding 2007), the Maldives (Anderson and Ahmed 1993), Djibouti (Rowat et al. 2007), and Mozambique (Speed et al. 2008). However, information on whale shark food consumption patterns and energy requirement is lacking.

The Okinawa Churaumi Aquarium has accomplished the long-term husbandry of whale sharks since 1980. Two individuals of this species—a male and a female—form part of the main exhibit, and are maintained in a 7,500 m3 tank. The male has been maintained for over 23 years and measured 871 cm in total length (TL) in December 2017. The female has been maintained for 10 years, and measured 804 cm in TL in December 2017. Their food consumption, changes in body shape, growth rates, and other physical attributes are monitored, and depend on their health conditions.

Here, we examined the relationships between body shape, including girth, and food consumption, including energy intake. The study will help to more accurately determine the daily feeding amounts of captive whale sharks. Furthermore, the results can provide valuable estimation of food consumption at the global aggregation sites.

MATERIALS AND METHODS

Rearing of the animals

The whale sharks examined in this study were both caught incidentally, by set-nets in Yomitan, Okinawa Prefecture. The male was caught on 11th March 1995, measuring 460 cm in TL at the time of capture. The female was caught on 2nd April 2008, and measured 500 cm in TL. The two individuals have been maintained for over 23 years and over 10 years, respectively, as of October 2018, in the Kuroshio tank (measuring 35 × 27 × 10 m in dimension, with a volume of 7,500 m^3). The Kuroshio tank contains seawater, supplied at a rate of 2,000 m^3/h, and has no water temperature control. The seawater is obtained from a location 300 m off the coast, from a depth of 20 m. It is filtered and circulated at a rate of 12 turnovers per day. Water temperature in the tank ranges from an average of 23.7 ± 1.2ºC in the winter (i.e. June to September) to 28.7 ± 1.2ºC in the summer (i.e. December to February).

Body shape measurements

The TL of each whale shark was calculated using the pre-first dorsal length (PD1), defined by Compagno (1984) as the length between the snout-tip and the origin of the first dorsal fin, based on the following equation (Matsumoto et al. 2017):

$$Log\ TL \text{ cm} = 0.964\ Log\ PD1 + 0.443$$

The PD1 was measured directly in water every month. Girth (G) measurements were also taken directly every month at the posterior margins of the pectoral fins of the free-swimming individuals. Body shape was expressed as the ratio of G to TL (G/TL).

Food consumption

Calorie consumption or energy intake of the whale sharks in captivity were calculated based on each food item consumed and expressed in kcal/100 g food ingested. The caloric values were determined from the total amounts of protein, lipid, and carbohydrate contained in each food, as per the Atwater system. The total amounts of protein, lipid, and carbohydrate in the food were analyzed using the macro-Kjeldahl method, acid digestion method, and direct ashing method , respectively (and were carried out by the Incorporated Foundation Okinawa Prefecture Environment Science Center). The two captive whale sharks were fed on *Euphausia superba* (660 kcal/kg), *E. pacifica* (620 kcal/kg), *Engraulis japonica* (690 kcal/kg), *Sergia lucens* (700 kcal/kg), *Scomber japonicus* (1270 kcal/kg), and *Marsupenaeus japonicus* (970 kcal/kg). The amount of food consumed was recorded daily.

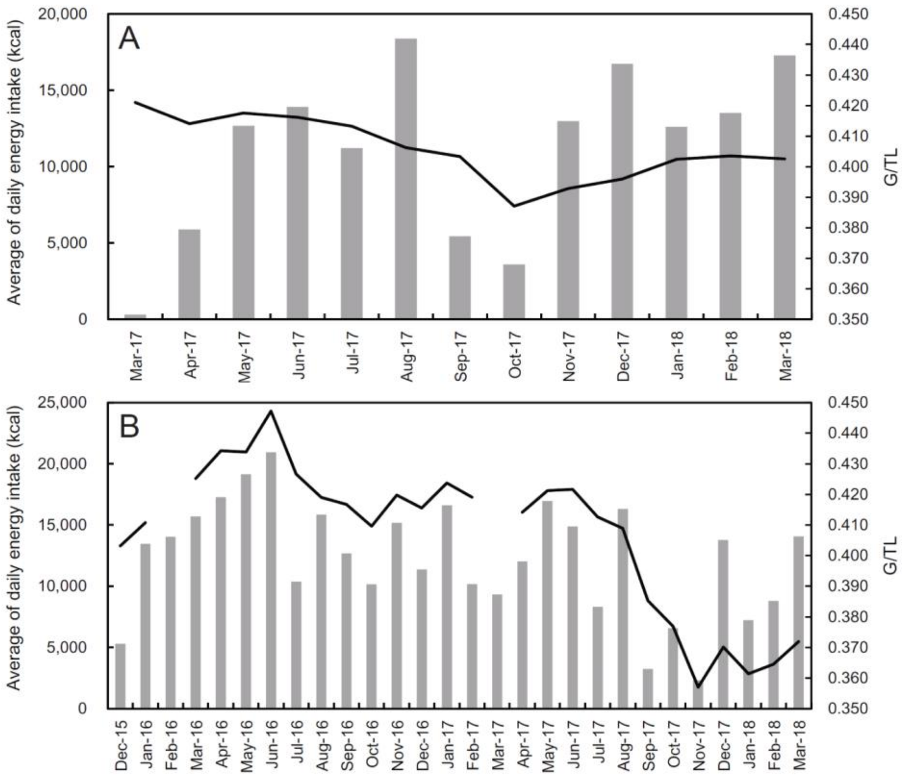

Fig. 1. Change in average daily energy intake and body shape (G/TL) of the male (A) and female (B) whale sharks. Bars and lines indicate the values of energy intake and G/TL, respectively.

RESULTS

The body shapes (G/TL) of the male (mean ± SD: 0.41 ± 0.01) and the female (0.41 ± 0.02) were similar throughout the monitoring periods (Fig. 1). During this time, the daily energy intake of the male and female were observed to be 11,483 ± 6,644 kcal and 12,638 ± 5,798 kcal, respectively. There were periods when the sharks did not feed at all (or consumed too little), such as in March, September, and October 2017, for the male shark (energy intake: 307 kcal, 5,443 kcal, and 3,607 kcal, respectively); and in December 2015, between September and November 2017, and in January 2018, for the female shark (5,320 kcal, 5,443 kcal, and 3,607 kcal, respectively) (Fig. 2). The female's girth was not measured between February 2016 and March 2017 because she intensely disliked being touched by the divers.

G/TL in the male gradually decreased, from 0.418 to 0.387, with a concurrent decrease in energy intake in the period between June (13,912 kcal) and October (3,607 kcal) 2017. Subsequently, this value increased to 0.404 in February 2018 (13,517 kcal). In the female, G/TL also increased between December 2015 (0.403) and June 2016 (0.447), with an increase in energy intake, from 5,320 kcal to 20,948 kcal, during this time. Conversely, when energy intake of the female decreased between June (20,948 kcal) and October (10,165 kcal) 2016, and between May (16,956 kcal) and November 2017 (2,324 kcal), there was a corresponding reduction in G/TL, from 0.447 to 0.410, and from 0.421 to 0.357, respectively.

DISCUSSION

Monitoring of the relationship between body shape and caloric intake can only be carried out accurately in a captive environment. There are few reports on food consumption in relation to whale shark husbandry. Schreiber and Coco (2017) described long-term changes in energy intake and the amount of food consumed by this species in the Georgia Aquarium. Dietary rations were set weekly to be within 3% to 5% of the whale sharks' body mass (BM). The daily food amounts were changed from 7,000 kcal to 40,000 kcal over 10 years, between 2006 and 2016. Changes to body shape were not described in their study. Motta et al. (2010) estimated the daily energy intake of whale sharks in the field to be 3,566 kcal for a 443 cm TL whale shark, and 6,717 kcal for a 622 cm TL whale shark, according to their estimated filtering abilities.

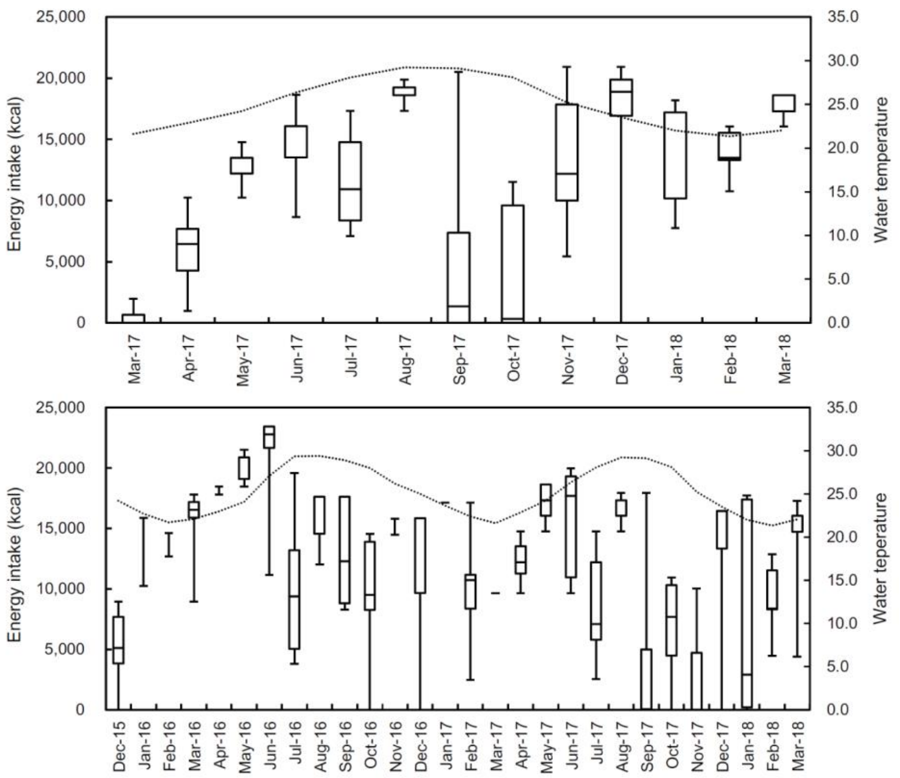

Fig. 2. Changes in daily energy intake and water temperature in the male (A) and female (B) whale sharks. The box indicates the 25th and 75th percentiles, the whiskers indicate the minimum and maximum values, and the line within the box indicates the median value of daily energy intake. Doted lines show water temperature.

However, they advised treating these caloric estimates with caution because of possible errors, including an underestimation of the number of feeding hours per day, and failure to account for sub-surface feeding, which could contribute to the feeding hours. The results of our study are more consistent with the results of whale shark energy consumption monitoring in the Georgia Aquarium than with those obtained from field observations. Therefore, we suggest that ex situ research be conducted to clarify the optimal energy intake of whale sharks.

We monitored changes in relationship between energy intake and G/TL, and water temperature. G/TL in the male decreased (-0.010) during periods of high temperature, between June (G/TL: 0.416; 26.4°C) and August 2017 (G/TL: 0.406; 29.2°C), even though its energy intake was 14,982 ± 3,968 kcal (mean ± SD). However, its G/TL increased slightly (+0.002) in the low temperature season, from January (G/TL: 0.402; 22.0 °C) to February 2018 (G/TL: 0.404; 21.3 °C), despite its lower energy intake (13,484 ± 2,889 kcal). Similarly, G/TL in the female decreased (-0.013) from June (G/TL: 0.422; 26.4°C) to August (G/TL: 0.409; 29.2°C), even though it consumed 13,583 ± 4,846 kcal. Contrastingly, this value increased slightly (+0.004) between January (G/TL: 0.361; 22.0°C) and February (G/TL: 0.365; 21.3°C), even after lower energy intake (8,252 ± 6,131 kcal). This suggests that changes in whale shark body shape (G/TL) were caused by changes in the metabolic rates of these ectothermic animals, which were in turn determined by the relationship between the water temperature and food consumption (i.e., energy intake). The present study has demonstrated that girth measurements provide an effective method of monitoring such relationships. Further studies are needed to calculate and estimate suitable food amounts for whale sharks, in captivity as well as in the field.

ACKNOWLEDGEMENT

The authors express their gratitude to the Yomitan Fisheries Cooperative for netting the whale sharks studied. The authors gratefully acknowledge Hirokazu Miyahara, Keiichi Sato, and Isao Kawazu for providing the opportunity to carry out this research. We thank Masakatsu Kino and Akane Murakami for assisting us with the whale shark body measurements. We are also thankful to Senzo Uchida, Minoru Toda, Makio Yanagisawa, Atsushi Yamashiro, and other colleagues for providing valuable information and advice.

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