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How large is the world's largest fish? Measuring whale sharks *Rhincodon typus* with laser photogrammetry

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Laser photogrammetry was found to be a promising new cost-effective technique for measuring free-swimming whale sharks *Rhincodon typus*. Photogrammetric measurements were more precise than visual size estimates by experienced researchers, with results from the two methods differing by 9·8 ± 1·1% (mean ± s.e.). A new metric of total length and the length between the fifth gill and first dorsal fin ($r^2 = 0{\cdot}93$) is proposed to facilitate easy, accurate length measurements of whale sharks in the field.

Key words: demography; growth; size; visual estimate.

Length is a fundamental metric in the study of wildlife. Size-dependent population segregation and mortality rates are well documented (Cubbage & Calambokidis, 1987; Heupel *et al.*, 2007; Ramirez-Macias *et al.*, 2007; Rowat *et al.*, 2007; Bradshaw *et al.*, 2008; Holmberg *et al.*, 2009), and accurate measurements of length are necessary for assessing maturity status (Norman & Stevens, 2007), growth (Graham & Roberts, 2007) and estimating a suite of allometric rate relationships (Peters, 1983). Long-term changes in size distribution can also provide a signal of overexploitation (Stevens *et al.*, 2000). Although length measurements are easy to obtain for many species, obtaining an accurate length for large animals can prove challenging. Whale sharks *Rhincodon typus* Smith, for example, are the largest fish in the world, attaining a maximum length of 20 m (Chen *et al.*, 1997). The large size of these sharks makes them difficult and potentially dangerous to restrain, forcing most authors to report visual size estimates based on a known reference such as a snorkeller (Graham & Roberts, 2007) or boat (Hobbs *et al.*, 2009). This technique makes it difficult to achieve precise and repeatable measurements, with estimated mean error of *c*. 50 cm for experienced researchers (Graham & Roberts, 2007; Norman & Stevens, 2007).

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This large error has the potential to confound deduced demographic variables such as growth rate and size at maturity. Holmberg *et al.* (2009) suggested that present size estimates are not accurate enough to obtain growth rate, which is important for demographic models of the species to assess its vulnerability to decline (Dulvy *et al.*, 2004; Bradshaw *et al.*, 2007).

Photogrammetry, where measurements are taken indirectly from a photograph, offers a non-intrusive and more accurate alternative. Several different approaches to photogrammetry have been used. Measurements can be calculated from a photograph when two factors, the ratio of the focal length of the lens and the distance between the camera and the object, are known. This method has been applied to study gorillas *Gorilla gorilla* (Breuer *et al.*, 2007) and surfacing sperm whales *Physeter macrocephalus* (Jaquet, 2006) using a range finder to determine the distance between camera and object. Another approach is to use stereophotographs, where images are taken from a pair of aligned cameras and length measurements calculated from the overlap between the two images, which has been used with scalloped hammerhead sharks *Sphyrna lewini* (Griffith & Smith) (Klimley & Brown, 1983). More recently, the use of a parallel-laser system providing a scale bar of known length projected onto the animal eliminates the need for a range finder or complex analyses. This method has been applied to study morphological traits in Alpine ibex *Capra ibex* (Bergeron, 2007) and red colobus monkeys *Procolobus rufomitratus* (Rothman *et al.*, 2008), surfacing cetaceans (Durban & Parsons, 2006; Rowe & Dawson, 2008; Webster *et al.*, 2010), African elephants *Loxodonta africana* (Shrader *et al.*, 2006), bathydemersal fishes (Rochet *et al.*, 2006) and manta rays *Manta alfredi* (Krefft) (Deakos, 2010).

Here, the improved precision attained through the use of parallel-laser photogrammetry (photogrammetry) in the measurement of free-swimming *R. typus* is demonstrated. It is shown that visual size estimates differed substantially from photogrammetric measurements. A new length metric is established based on a small, stable body area that is already extensively used in photographic identification of the species. Photogrammetry combined with the regressions presented here will allow more accurate assessment of length, growth and size at maturity in *R. typus*.

Rhincodon typus were studied at a coastal aggregation site off Praia do Tofo (23° 51′ S; 35° 32′ E), in southern Mozambique (Cliff *et al.*, 2007). Photographs were taken while snorkelling alongside *R. typus* using a compact digital camera in an underwater housing. Visual estimates of 23 individuals were recorded concurrently with photogrammetry by observers with 1 year and 5 years of experience with *R. typus*. A marine aluminium mount was custom-built to position two underwater green laser pointers (Sea Turtle Scuba Inc.; http://www.seaturtlescuba.us/) on individual arms 50 cm apart from one another on either side of the camera housing, which was screwed to the centre of the mount (Fig. 1). This set-up is cheap, lightweight and easy to use while snorkelling, allowing data to be collected by researchers or trained volunteers. Laser pointers are classified IIIA with a power output of <5 mW, meaning short, accidental exposure does not damage the eye. For extra precaution, lasers were not used with other observers nearby and were not pointed at the eyes of *R. typus*. Because of variable underwater visibility and the large size of *R. typus*, overlapping photographs were taken of the head, body and tail from a distance of *c.* 5 m.

There are three primary concerns to be managed when taking photogrammetric measurements. First, the animal has to be completely extended at the time the photograph is taken. For *R. typus*, which swim using sinuous propulsive strokes (Martin,

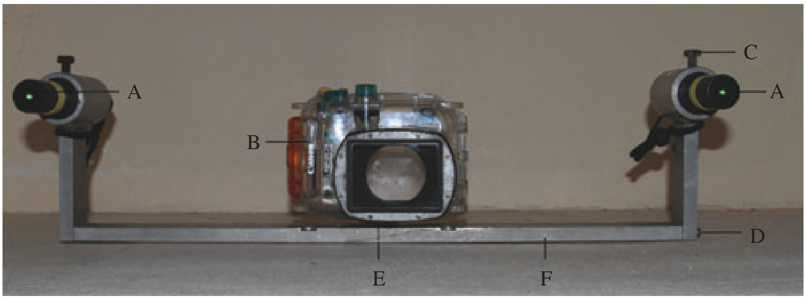

FIG. 1. Laser photogrammetry set-up used: A, green laser pointers; B, underwater camera housing; C, upper screw and D, lower screw (allowing calibration adjustments); E, screw attaching housing to the frame and F, aluminium frame.

2007), this occurs briefly between caudal fin strokes or when it is 'gliding'. In addition to whole-body side-to-side propulsion movements, the flexing of the caudal fin can significantly alter total length (L_T) measurements. To account for this body flexing, pre-caudal length (L_{PC}) was taken in preference to L_T (Fig. 2). Second, horizontal axis error or parallax error can occur if the photographer is not perpendicular to the animal and on the same plane. To counter this, any photographs that were not taken from a 90° angle to the *R. typus* on a vertical plane were not used in analysis. Last, an incorrect scaling factor can be applied if the lasers are not aligned perfectly parallel to one another. Hence, laser positions were calibrated using screw mounts and tested on land before and after each deployment.

Following image acquisition, the number of pixels between the two projected laser points was counted. A scaling factor was then applied based on the known distance between these points, allowing extrapolation of L_{PC} of each shark. Total length, measured as natural L_T (Francis, 2006), was projected from L_{PC} using a coefficient derived from directly measured body proportions of 41 *R. typus* (Uchida, 1983; Beckley *et al*., 1997; Wintner, 2000; Capapé *et al*., 2001; S. P. Wintner & G. Cliff, pers. comm.; this study). There was a highly significant relationship between L_{PC}

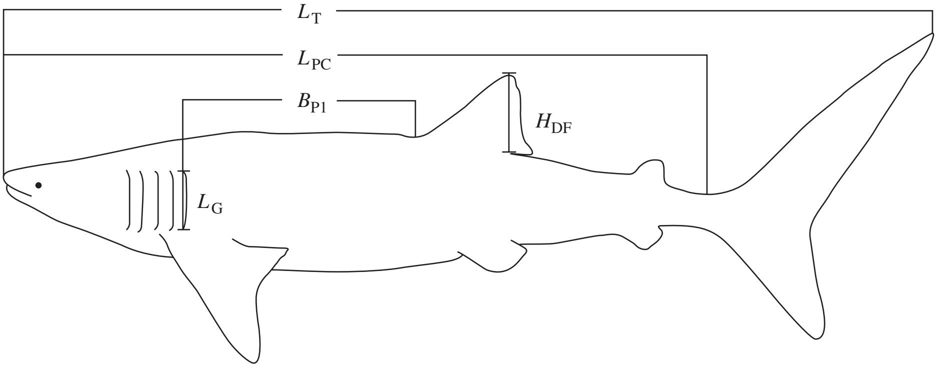

FIG. 2. Measurements taken for each *Rhincodon typus*: L_T, natural total length; L_{PC}, pre-caudal length; B_{P1}, fifth gill to start of first dorsal; L_G, fifth gill length and H_{DF}, first dorsal fin height.

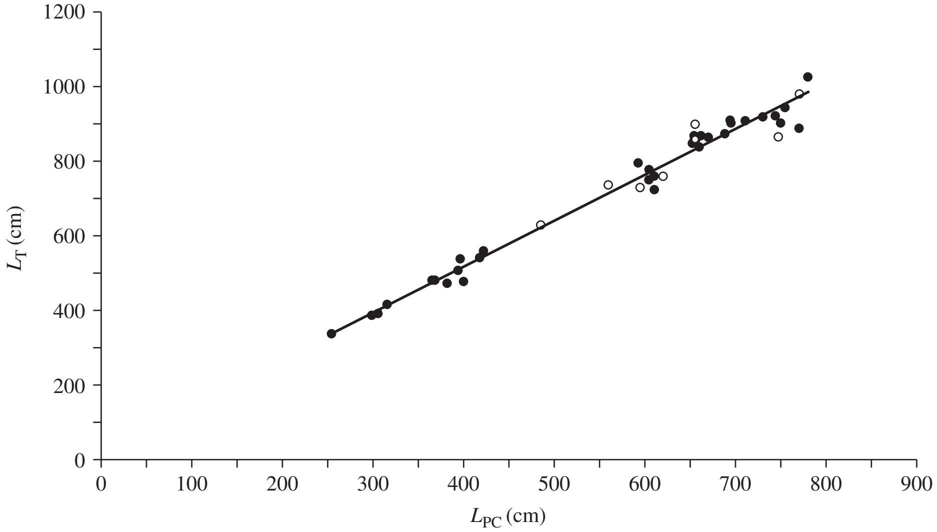

FIG. 3. Linear regression of pre-caudal (L_{PC}) and total lengths (L_T) ($y = 1{\cdot}2182x + 33{\cdot}036$; $r^2 = 0{\cdot}98$) from 41 *Rhincodon typus*. Published records (●) (Uchida, 1983; Beckley *et al.*, 1997; Wintner, 2000; Capapé *et al.*, 2001) and unpublished records (○) (S. P. Wintner & G. Cliff, pers. comm.; this study) are presented.

and L_T (Fig. 3; $r^2 = 0{\cdot}98$). This linear regression is an extension of the equation presented in Wintner (2000), increasing the number of direct measurements from 21 to 41. The use of L_{PC} thus eliminates the problem of caudal fin flexion (Francis, 2006) while still allowing confident projection of L_T for comparison with visual estimates.

As a key objective of the present study was to provide a useful body proportion to use as a proxy variable for L_T, several other morphometrics were also collected (Fig. 2). Three different morphometric measurements were evaluated for their usefulness in estimating L_T, using mainly photogrammetric measurements supplemented, where possible, with direct measurements (Uchida, 1983): (1) fifth gill to start of first dorsal fin, (2) length of fifth gill and (3) first dorsal fin height (Fig. 2). The length from the fifth gill to the start of the first dorsal fin was the most significant linear regression (Fig. 4; $r^2 = 0{\cdot}93$). Straight-line horizontal distance rather than a point-to-point measure was taken to minimize potential parallax error. The latter metric showed a tighter correlation than first dorsal fin height, which has previously been used to extrapolate L_T in *R. typus* (Meekan *et al.*, 2006), and avoids the problem of occasional partial or full amputation of the dorsal fin (Speed *et al.*, 2008). This proposed length metric also has the advantage that it is based on the body area used for standardized photographic identification of the species (Arzoumanian *et al.*, 2005) and is virtually unaffected by body flexion. Hence, a single photograph can be used to both identify the shark and estimate its L_T.

Visual size estimates by experienced observers differed from photogrammetric estimates by a mean ± S.E. of $68{\cdot}77 \pm 8{\cdot}86$ cm or $9{\cdot}80 \pm 1{\cdot}10\%$ of L_T (Table I). They were slightly skewed towards underestimating *R. typus* L_T. Visual estimates from experienced researchers in the present study were less accurate than has previously

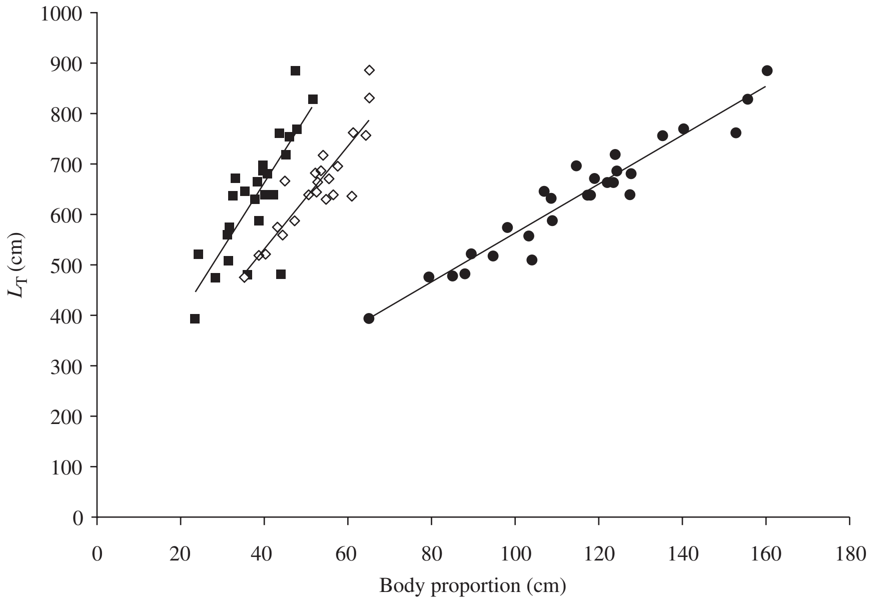

FIG. 4. Linear regression of total length (L_T) and the body proportions of *Rhincodon typus*: length between fifth gill and start of the first dorsal fin (●; $y = 4{\cdot}8373x + 80{\cdot}994$; $r^2 = 0{\cdot}93$), fifth gill length (■; $y = 12{\cdot}903x + 144{\cdot}55$; $r^2 = 0{\cdot}63$) and first dorsal fin height (◇; $y = 10{\cdot}288x + 118{\cdot}24$; $r^2 = 0{\cdot}80$), based on photogrammetric and direct measurements (Uchida, 1983).

been assumed (Graham & Roberts, 2007), but more accurate than estimates from untrained observers (Holmberg *et al.*, 2009). These results suggest that the estimation of size in *R. typus* can be significantly improved by the routine use of photogrammetry.

Photogrammetry does have some limitations. As light is rapidly attenuated in water, the laser's range is dramatically reduced compared to terrestrial applications and photogrammetry can only be used in close proximity to the fish in turbid water conditions. Visual estimates are, however, similarly affected by environmental factors. Generally, photogrammetry represents a simple measurement technique that can be easily combined with existing photographic identification methods to improve the accuracy of size estimates in *R. typus*. The new length metric presented here is based on a body area that is not subject to flexing due to movement and thus further facilitates easy and accurate size estimates. Given that coastal *R. typus* aggregations

TABLE I. Discrepancy of visual size estimates by experienced researchers compared with photogrammetric estimates of 23 *Rhincodon typus*

	L_T differences (cm) Mean ± S.E.	Percentage of L_T differences Mean ± S.E.	Number
Underestimate	78·64 ± 13·92	10·93 ± 1·67	13
Overestimate	55·94 ± 8·52	8·34 ± 1·24	10
Total	68·77 ± 8·86	9·80 ± 1·10	23

often appear to consist of a proportion of philopatric individuals (Holmberg *et al*., 2008; Rowat *et al*., 2009; Riley *et al*., 2010), there is potential for individual sharks to be repeatedly measured over time. A particular focus of such efforts should be to obtain an estimate of natural growth rates in *R. typus*, which could be used to refine demographic models for the species and enable accurate assessment of the species' vulnerability to decline (Dulvy *et al*., 2004; Bradshaw *et al*., 2007; Holmberg *et al*., 2009). Laser photogrammetry is a useful, simple and affordable tool to improve the precision of size estimates and, in doing so, improve understanding of the species.

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