CHAPTER

10

A Review of Length Validation Methods and Protocols to Measure Large White Sharks

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Introduction

The total length (TL) and mass of large (TL >6 m) white sharks *Carcharodon carcharias* are often difficult to measure, leading to much speculation (Randall, 1973, 1987; Cappo, 1988; Ellis and McCosker, 1991). Reported TLs are often rough estimates or speculations. For many large white sharks, only the jaw and teeth have been preserved, providing the only specimens for length validation. Less frequently, fins are preserved. Their dimensions might be suitable for length validation if measured when fresh or if a conversion for shrinkage were possible.

A white shark with an estimated TL of >7 m was captured in a gill net near Kangaroo Island, South Australia, on April 1, 1987 (Jury, 1987; Cappo, 1988). A photograph of the head and the pectoral fin (as well as the caudal fin in the background) of this white shark (designated KANGA) was included in the book by Ellis and McCosker (1991, p. 55). Following the method of Randall (1973), TL was estimated by Cappo (1988, personal communication) to be 6.4 and 5.8 m from the dried upper jaw perimeter (DUJP) and the enameloid height of the first upper tooth, respectively. This was about 1 m less than the estimated TL by fisherman Peter Riseley.

Sixteen days later, another large white shark of disputed 7 m TL was caught on an 8-mm steel line baited for tuna and swordfish 1.8 km southeast of Fifla Farallon, Malta, by Alfred Cutajar (Abela, 1989; Fergusson, Chapter 30). Photographs of this white shark (MALTA) were shown by Ellis and McCosker (1991, p. 56) and Fergusson (Chapter 30). From upper jaw perimeter and tooth enameloid height (UA1E2), following the technique of Randall (1973), TL was estimated to be 5.7 and 5.3 m, respectively. This was 1.5 m less than Abela's (1989) measurement. The relatively small dorsal and pectoral fins indicated that the shark was much shorter than 7 m, again contradicting the TL measurement. These low TL estimates also were in conflict with photographs that indicated a TL of at least 6–6.5 m (I. K. Fergusson, personal communication).

In the past, extrapolations from upper jaw perime-

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ters and UA1E2's, mass, vertebrae dimensions, and number of vertebral bands of smaller sharks (TL <5 m) were used to evaluate TL estimates >6 m (Randall, 1973, 1987). Mass was expected to be too variable for length validation (see Chapter 9, by Mollet and Cailliet). Jaw and teeth morphometrics of more recently captured white sharks, 5–7 m TL, indicated large variations for sharks of similar length (G. Hubbell and M. Cappo, personal communication; L. J. V. Compagno, unpublished data). This suggested to us that TL estimates from jaw and teeth data might not be suitable. At least, TL estimates had to be based on the regression 95% confidence band for a new observation rather than the regression line.

The preliminary analysis of our white shark morphometric data and the summary of proportional dimensions by Bass *et al.* (1975) indicated that the size of fins might yield more accurate TL estimates than would size of the jaw perimeter, UA1E2, or mass. The purpose of this chapter is to validate indirect TL estimates and evaluate extrapolated TL estimates for the Kangaroo Island and Malta white sharks.

Materials and Methods

Morphometrics for Existing Data

Measurements have been taken from more than 70 white shark specimens (Appendices 1 and 2), but many were not measured by us. Most of the TL measurements were probably taken with the caudal fin in the natural position. TL of four sharks was certainly measured with the caudal fin in a depressed (i.e., extended) position (Appendix 3) (Compagno, 1984a). We assumed that the jaws of each shark were prepared in an identical manner. We further assumed that the upper jaw perimeter and the UA1E2 of the first upper functional tooth (UA1) were measured according to the following definitions, both being modifications of the method of Randall (1973) (see illustrations in Appendix 3, but note that the tooth sketched and measured carried labels of the second upper tooth, UA2). (1) DUJP is measured, with a string, from one extreme corner of the mouth (i.e., the medial area of the widest part where the upper and lower jaws join), along the curvature of the upper jaw just above the base of the teeth, all the way around, to the other extreme corner. (2) UA1E2 is the vertical measurement on the labial surface of the first upper functional tooth, along the medial axis of the tooth from the apex of the tooth cusp to a line between the mesial and distal proximal edges of the enameloid.

The dried jaw and tooth data reported by Randall (1973) were reconstructed from 8-in. × 10-in. prints made from the negatives of the original figures (Appendix 2). Some reported jaw or tooth measurements required conversion. Data for fresh upper jaw perimeters were converted to DUJP, assuming a shrinkage of 4%, on the basis of mean shrinkage from three upper jaws (G. Hubbell and M. Cappo, personal communication). UA1E2 was calculated from the medial enameloid height (UA1E1), enameloid mesial (or distal) edge length (UA1EM or UA1ED), or tooth total height (UA1H), using the mean ratios of all the Hubbell data (Appendix 2): UA1E2/UA1E1 = 1.154 ± 0.018, N = 9; UA1E2/UA1EM = 0.908 ± 0.026, N = 9; and UA1E2/UA1H = 0.804 ± 0.010, N = 9. Here and throughout this chapter, means are reported ±1 standard error.

Morphometrics for KANGA and MALTA

The morphometrics on KANGA, reported initially by Jury (1987) and Cappo (1988, personal communication), are summarized in Table I. The fisherman who had collected KANGA, Peter Riseley, estimated a TL >7 m, by comparing the shark to the distance between fore and aft portions of his boat (Cappo, 1988). KANGA was too large to be brought aboard; mass was not estimated. Only the pectoral fin height, head size, and girth at the first gill slit were estimated.

More morphometric data and a mass estimate are available for MALTA (Abela, 1989, personal communication) (Table I). Additional pectoral fin, jaw, and tooth measurements were taken by one of us (A.D.T.) in Malta in March 1990. Abela distributed a table that contained tooth edge–length measurements, which are larger than the vertical measurements used by Randall (1973) and by us. The TL of MALTA (Abela, 1989, personal communication) was treated as an estimate after we thoroughly investigated all available correspondence (approximately 40 documents; see Acknowledgments). We concluded that there were too many inconsistencies and treated the reported MALTA TLs of 7 m (straight line) to 8.85 m (over the curve) as estimates. In fact, Ian Fergusson (personal communication) interviewed John Abela and Alfred Cutajar in autumn 1994 and concluded, without reservation, that Abela had measured the fish lying flat on the floor. His 7.14 m TL and 7.77 m over-the-curve TL should, accordingly, be considered credible. The 8.85 m over-the-curve TL quoted in *AQUA* (Abela, 1989) was a misprint or error; the 7.77 over-the-curve TL is consistent with a white shark measuring 7.14 m TL (H. F. Mollet, unpublished data).

Only a rough estimate of the pectoral fin height

TABLE I Kangaroo Island (KANGA) and Malta (MALTA) White Shark Morphometric Measurements for Length Validation

Measurement	FAO abbreviation	Other sharks, CV (N) (%)[a]	KANGA		MALTA	
			m	%TL	m	%TL
Total length	TL		<7.0	100	7.0	100
Prebranchial length	PG1	6.0 (37)	1.346*	19.2*		
Head height	HDH	20.0 (13)	1.219*	17.4*		
Head width	HDW	3.1 (10)	1.219*	17.4*		
Trunk height	TRH	21.0 (17)			1.0–1.2*	14–17
Girth at first gill slit	GIR(GS1)		3.830*	54.6*		
Girth at first dorsal fin (gutted)	GIR(D1)	14.0 (21)			3.2–3.5*	45–50
Pectoral fin anterior margin[b]	P1A	5.0 (49)	1.128*,**	16.1*,**	0.938**	13.4
Pectoral fin base	P1B	10.0 (33)			0.392**	5.6
Pectoral fin inner margin	P1I	15.0 (29)			0.228**	3.2
Pectoral fin posterior margin	P1P	8.4 (23)			0.742**	10.6
Pectoral fin height	P1H	9.1 (10)	1.0*	14.3*	0.833**	11.9
Pectoral fin length	P1L	5.6 (5)			0.536**	8.5
Caudal fin, tip to tip (span)	CFTT	8.3 (8)			1.372	19.6
Caudal fin dorsal margin	CDM	5.9 (42)			1.021**	14.6*
Caudal fin preventral margin	CPV	8.3 (42)			0.893**	12.7*
First dorsal fin height[c]	D1H	10.7 (34)			0.502	7.16
First dorsal fin height (dried)[d]	D1H(D)				0.457	6.62
Dried upper jaw perimeter	DUJP	9.2 (30)	1.250	17.8	1.120	16.0
Fresh upper jaw perimeter	FUJP		1.297	18.5	1.220	17.4
Dried lower jaw perimeter	DLJP				0.965	13.8
Fresh lower jaw perimeter	FUJP				1.000	14.3
Dried jaw, corner to corner	ca. MOW	13.0 (36)	0.829	11.8	0.615	8.77
Dried jaw, symphysis to symphysis	ca. 2×MOL	14.0 (28)	0.706	9.93	0.590	8.42
First upper tooth enameloid height (larger)	UA1E1	8.2 (48)	0.0516	0.736	0.0469[e]	0.66
First upper tooth enameloid height (smaller)	UA1E1		0.0501	0.715	0.0445[e]	0.79
First upper tooth total height (larger)	UA1H	13.0 (28)			0.0555[e]	0.79
Mass (kg)[f]	M				2400–3600	
Condition factor (kgm^{-3})	W/TL^3	23.0 (327)			7.0–10.5	

FAO, Food and Agriculture Organization; CV, coefficient of variation.
*, estimated value; **, calculated value.
[a]CV (%) = 100 (SEE)/mean y of the sample, where SEE is the standard error of estimate of the regression.
[b]Pectoral fin measurements for MALTA were calculated assuming 10% shrinkage.
[c]A linear ratio-on-size regression is not suitable for first dorsal fin height (see text).
[d]The first dorsal fin height decreased by 8.9% in 3 months due to shrinkage (J. Abela, personal communication).
[e]Calculated from measurements made by A. D. Testi with calipers.
[f]Mass allows for removal of 1600–2400 kg of muscle; 300–600 kg of liver; 200 kg of stomach contents (1.8 m blue shark, 2.4 m dolphin, and 0.6 m turtle); a 180–250 kg head; 70 kg of pectoral, dorsal, and caudal fins; and 50 kg of body fluids.

was available for KANGA, and the anterior margin was calculated from the height estimate, using the mean margin/height ratio of 0.878 ± 0.014 (N = 11). The pectoral fin of MALTA became extremely desiccated from display in the Maltese bar where it was measured, and we considered shrinkages between 10% and 15%. Only the nonconventional caudal fin span of MALTA was available. The caudal dorsal margin was calculated from the margin/span ratio of 0.744, determined from a photograph of a 5.2-m female (Postel, 1958).

Regression Analysis and 95% Confidence Band for a New Observation

The linear ratio-on-size regression [y/TL × 100 = y (%TL) = a + b TL] was selected as the most suitable equation for our purpose (Parr, 1956; Bass, 1973; Compagno, 1984a; Mollet and Cailliet, Chapter 9). For all body morphometrics available for the sharks in Appendix 1, and the jaw and tooth data in Appendix 2, we regressed the morphometric data (expressed as %TL) on TL. Outliers with large studentized residuals and/or additional evidence of data error were deleted. KANGA and MALTA data were excluded in the calculation of regression lines and their confidence band. Female and male morphometrics were combined in all regressions after appropriate statistical tests (Neter *et al.*, 1983). In the jaw perimeter and tooth enameloid plots, we used different symbols for our data and those reconstructed from Randall (1973). However, the regression lines pertain to the combined data. We used the condition factor (MTL^{-3}) as the dependent variable for the analysis of the mass–TL relationship. We relied on the mass data (N = 327) of Mollet and Cailliet (Chapter 9, with the confidence band for the line) and calculated the 95% confidence band for a new observation. We checked that the calculated TL ranges were similar to the ones based on a geometrical mean (GM) power (log W versus log TL) regression. We combined the mass data of the white sharks <5.5 m TL of known sex used by Mollet and Cailliet (Chapter 9), Cliff *et al.* (Chapter 32), and Uchida *et al.* (Chapter 14) to determine the lack of a significant difference between the condition factor versus TL regressions for males (N = 218) and females (N = 281).

A regression coefficient of variation (CV, expressed as a percentage) was calculated for the relationship of all morphometrics with TL. It is given by CV (%) = 100 (SEE)/mean y of the sample (Bass, 1973), where SEE is the standard "error" of estimate (a standard deviation). The regression CV provided an indication of the suitability of a morphometric size for TL estimation. A regression with a CV of >10%, or a regression with CV <10% but based on a small sample (say, N < 20), is of questionable usefulness to reasonably estimate TL. To conserve space, the CVs are reported only for the morphometrics measured or estimated for KANGA or MALTA and were added to Table III.

The three morphometrics available for both MALTA and KANGA, and three additional ones available for MALTA only, were examined in more detail to evaluate their usefulness for validating TL (Table II). In these cases, the analytical regression equation with the standard error of the parameters and the standard deviation of estimate of the regression were calculated using the MGLH module of SYSTAT (Wilkinson, 1988a). For the dorsal fin height, we also considered a three-parameter fitting equation following the method of Bass (1973), and used the NONLIN module of SYSTAT (Wilkinson, 1988a) to calculate the fitting parameters and their asymptotic standard errors. In this case, we also calculated the constant (intercept) of the one-parameter fitting equation for comparison with the results of Bass *et al.* (1975). One of these morphometrics was mass, and we used the results of Mollet and Cailliet (Chapter 9).

The procedure used to determine the possible TL range for a large shark of unknown TL from a measured morphometric size is best understood with reference to, for example, Fig. 1B. We used the 95% confidence band for a new observation, also known as the prediction confidence band (Sokal and Rohlf, 1981), to determine the possible TL range from a morphometric measurement of a shark with disputed TL. For example (see Fig. 1B), an observed morphometric datum [i.e., caudal fin dorsal margin (CDM) = 1.021 m] of a shark with unknown TL produces a hyperbola ($y = 102.1/x$) in a ratio-on-size plot, rather than the horizontal line that would occur in a size-on-size plot. Therefore, the possible TL range is determined by the intersection of this hyperbola with the confidence limits defining the 95% confidence band for a new observation. In this example, the TL of MALTA is between 4.6 and 7.0 m, predicted from the CDM of 1.021 m. Assuming that MALTA was, indeed, 7 m TL produces a data point (M) for the CDM (=14.6%) that falls on the lower limit of the 95% confidence band.

The graphical program used by us (SYGRAPH) (Wilkinson, 1988b) provided the 95% confidence band for the regression line of existing observations based on W (i.e., "Working and Hotelling") statistics (Neter *et al.*, 1983; Mollet and Cailliet, Chapter 9). Therefore, we had to calculate the required constants to produce the confidence band of a new observation based on t

TABLE II **Ratio-on-Size Regression Parameters for Morphometric Measurements of White Sharks**

Measurement	FAO abbreviation	N	Estimated TL Range (m)	Regression parameters[a] *a* (SE)	*b* (SE)	*c* (SE)	SEE	Reference
Pectoral fin anterior margin	P1A (%TL)	49	1.29–6.0	23.1 (0.3)	−0.902 (0.100)		1.03	This study
		34	1.70–3.91	25.0	−0.950		0.9	Bass *et al.* (1975)[b]
		90	1.3–6.0	23.1	−0.69			L. J. V. Compagno, unpublished data
Caudal fin dorsal margin	CDM (%TL)	42	1.26–6.00	23.9 (0.4)	−0.943 (0.134)		1.24	This study
		34	1.70–3.91	24.8	−0.769		0.55	Bass *et al.* (1975)[b]
First dorsal fin height	D1H (%TL)	34	1.31–6.0	14.8 (2.0)	−0.73 (0.32)	−7.2 (2.5)	0.92	This study
		34	1.31–6.0	9.2 (0.4)	0.15 (0.13)*		1.02	This study
		34	1.31–6.0	9.7 (0.2)			1.03	This study
		33	1.70–3.91	9.8			1.6	Bass *et al.* (1975)[b]
Dried upper jaw perimeter	DUJP (%TL)	31	1.98–6.1	19.7 (1.1)	0.21 (0.25)*		1.89	This study
		16	1.98–5.4	20.7 (0.5)	−0.17 (0.14)*		0.64	Randall (1973)[c]
Tooth enameloid height	UA1E2 (%TL)	49	1.96–6.4	0.97 (0.03)	−0.026 (0.007)		0.071	This study
		17	1.98–5.4	0.93 (0.04)	−0.009 (0.011)*		0.052	Randall (1973)[c]
Condition factor	M/TL^3 (kgm^{-3})	327	1.22–5.55	8.39 (0.33)	0.193 (0.093)		2.06	Mollet and Cailliet (Chapter 9)

FAO, Food and Agriculture Organization; SE, standard error; SEE, standard error of estimate.
*Not significant
[a]y(%TL) = a + b TL (+ c/TL for D1H); y (%TL) = a also included (see text).
[b]Parameters calculated with TL = 1.70 and 3.91 m.
[c]Parameters calculated from original figures.
*Not significant.

statistics. Details on this procedure, based on the method of Sokal and Rohlf (1981) or Neter *et al.* (1983) are available from H. F. Mollet upon request.

The calculation of hyperbolic confidence limits for a new observation (Sokal and Rohlf, 1981; Neter *et al.*, 1983) is tedious and not covered by the computer programs available to us. Therefore, we calculated confidence bands using Bass' (1973) simplified linear method, which defined the 95% confidence limits as $\pm d$ (± 2 standard deviations about the regression line). Bass' (1973) confidence band requires only the calculation of the standard deviation of the regression, which is standard output of a regression calculation in SYSTAT and most other statistical programs, and is called SEE (Wilkinson, 1988a). A comparison of the two confidence bands indicated that the differences were acceptably small for all linear relations (a factor of 1.15 maximum at TL = 7 m, if N > 20). In the future, we are planning to use Bass' (1973) method to calculate the 95% confidence band for a new observation. This method also justified the use of Bass' (1973) confidence band for a three-parameter (nonlinear) fitting curve, which provided a better fit for the existing first dorsal fin height (D1H) data for the white shark (Fig. 1C). The calculation of more accurate confidence limits for a three-parameter fit were beyond our statistical capabilities.

Results

Morphometrics for Existing Data

Our morphometric data, excluding those from KANGA and MALTA, were composed of measurements from more than 70 white sharks worldwide, spanning 100 years and 1.261–6.408 m TL (Appendices 1 and 2). In our database, all white sharks >4.75 m TL were females. The database included two embryos that were larger than five free-swimming pups.

The analysis of existing morphometric data indicated that variability, measured as CV, was high (Table I), thus decreasing the likelihood of validating a TL measurement using other variables. To predict TL within 10% of 7 m, a CV of <2–3% would be required (see Simpson *et al.*, 1960). Few variables [e.g., fork length, precaudal length (PRC), and presecond dorsal fin length) produced CV values this low. However, these morphometrics were not available for MALTA or KANGA, and therefore are not

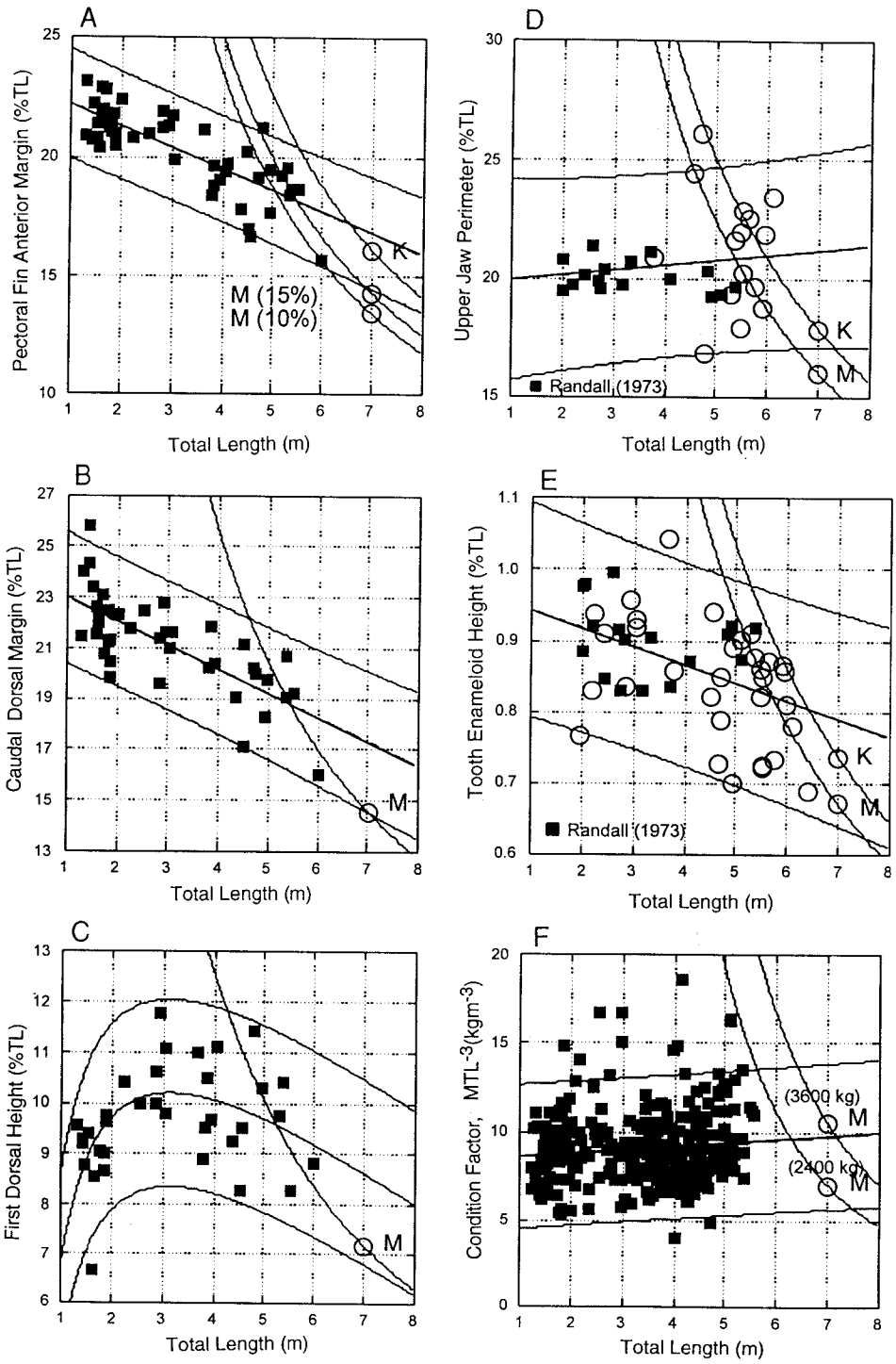

FIGURE 1 Ratio-on-size regression plots with a 95% confidence band for a new observation: (A) pectoral fin anterior margin (P1A), (B) caudal fin dorsal margin (CDM), (C) first dorsal fin height (D1H), (D) dried upper jaw perimeter (DUJP), (E) tooth enameloid height (UA1E2), and (F) condition factor (MTL^{-3}). The following apply: data points for KANGA and MALTA, assuming 7 m TL, are labeled K and M, respectively; 10% and 15% shrinkages are assumed for the pectoral fin anterior margin of MALTA (A); D and E identify the Randall (1973) data, but regressions are for all data; a mass range of 2400–3600 kg was used for MALTA (F); and intersections of the confidence band with the more vertical lines defines the TL ranges for KANGA and MALTA (see text).

listed in Table I. Only the pectoral anterior margin and the caudal dorsal margin had sufficiently low CV values and reasonable sample sizes to potentially predict TL. All other variables had CV values exceeding 6% or had small sample size. The regression from many morphometrics showed large variability, as indicated by a CV of over 10% (Table I).

Using various regression techniques, the relationships between the six morphometric variables available for KANGA or MALTA and TL ranged from negative and positive allometry to isometry (Table II). The pectoral fin anterior margin, CDM, and UA1E2 all showed significant negative allometry using a two-parameter fitting equation. D1H, however, was best described with a three-parameter fitting equation with the maximum of the curve at 3.1 m (Fig. 1C). This indicated positive allometry for small sharks and negative allometry for large sharks. In contrast, the standard two-parameter fit produced a nonsignificant slope (isometry) and was not useful. The two-parameter fit was no better than assuming that the first dorsal height was constant. The upper jaw perimeter regression also yielded a nonsignificant slope, indicating that isometry would be a good first approximation. The condition factor indicated barely significant positive allometry [$T = 0.193/0.093) = 2.08$ (see Chapter 9, by Mollet and Cailliet)].

Most of the data for upper jaw perimeter and tooth enameloid for the smaller white sharks came from Randall (1973) and were less variable (Fig. 1D and E and Table II). The upper jaw perimeter plot showed a pronounced increase in variability for sharks larger than 4 m TL, and this could be substantiated statistically. The variance F test [$F^* = 15.2 >> F(0.025,17,10) = 0.34$ to $F(0.975,17,10) = 2.94$] confirmed highly significant heteroscedasticity for the jaw regression of large sharks. UA1E2 data produced negative allometry, because the larger sharks had relatively smaller teeth, a result that differs from that of Randall (1973), who had data only from small sharks.

We found no difference between males and females for the six morphometrics of interest. This was confirmed by statistical tests. Thus, we combined all data regardless of sex.

Morphometrics for KANGA and MALTA

We confirmed that both KANGA and MALTA could be 7.0 m TL. The pectoral fin, jaw, and teeth indicated that KANGA was bigger than MALTA (Table III). The other morphometrics listed were, unfortunately, not available for both sharks. All three reported KANGA morphometrics, assuming the 7 m TL to be correct, fell within the 95% confidence band for a new observation (Fig. 1A, D, and E). However, the TL ranges determined from these morphometrics were broad, ranging from 2.2 to 3.6 m (Table III). Therefore, based on the mean TL range, KANGA

TABLE III **Summary of Estimated Total Length Ranges of Large White Sharks**

Measurement	FAO abbreviation	Observed		Estimated TL range		Comments
		KANGA (m)	MALTA (m)	KANGA (m)	MALTA (m)	
Jaw perimeter	DUJP	1.250	1.120	5.1–7.3 (2.2)*	4.5–6.5 (2.0)*	
Tooth enameloid height	UA1E2	0.0516	0.0469	5.3–8.9 (3.6)*	4.7–7.5 (2.8)*	
Pectoral fin anterior margin	P1A	1.128	0.938	5.5–8.3 (2.8)*	4.3–6.1 (1.7)	10% shrinkage for MALTA
Pectoral fin anterior margin	P1A		0.993		4.7–7.0 (2.3)*	15% shrinkage for MALTA
Pectoral fin base	P1B		0.392		4.5–7.3 (2.8)	10% shrinkage for MALTA
Pectoral fin inner margin	P1I		0.228		4.0–>10	10% shrinkage for MALTA
Pectoral fin posterior margin	P1P		0.742		3.9–6.5 (2.6)	10% shrinkage for MALTA
Pectoral fin height	P1H	1.0	0.833	5.0–>10	4.0–>10	10% shrinkage for MALTA
Caudal fin	CDM		1.021		4.6–7.0 (2.4)	
Dorsal fin	D1H		0.502		4.2–7.5 (3.3)	
Body mass (kg)	BM		2400 3600		5.6–7.3 (1.7) 6.3–8.3 (2.0)	
Mean total length[a]	TL			5.3–8.2	4.6–7.0	

FAO, Food and Agriculture Organization; TL, total length.
[a]The upper and lower limits of the ranges indicated by * were used to estimate a mean range.

could have been 5.3–8.2 m long, consistent with the >7 m TL estimate of Riseley.

The majority of the MALTA morphometrics, assuming the 7 m TL to be correct, also fell within the 95% confidence band for a new observation (Fig. 1). This is true for all but the upper jaw perimeter (Fig. 1D). Also, only the pectoral fin anterior margin, using a 15% shrinkage rate, fit near the confidence band (Fig. 1A). The TL estimates from these morphometrics were also broad (Table III). Based on the mean of the same three morphometrics used for KANGA,-MALTA could have been 4.6–7.0 m long, making the 7 m TL estimate by Abela possible. The TL estimates for MALTA, using the estimated mass range limits of 2400 and 3600 kg, were also broad and in the range of 5.6–7.3 and 6.3–8.3 m, respectively. This demonstrates that even the lower mass estimate was compatible with a 7 m TL shark (Fig. 1F).

None of the other pectoral fin morphometrics (Table III), nor any remaining morphometrics (Table I) for KANGA or MALTA, ruled out a length of 7 m for either shark. In fact, some even supported it. Again, a shrinkage between 10% and 15% for the MALTA pectoral fin was sufficient to produce a TL range that included 7 m. The pectoral fin inner margin and height produced TL ranges with indeterminate upper limits for both KANGA and MALTA, because insufficient existing data were available or the regression CV was >10%. The pectoral fin anterior margin is easiest to measure consistently, and the consideration of additional pectoral fin morphometrics probably amounts to duplication. Prebranchial length, head size, girth, and additional jaw morphometrics for KANGA, and trunk height, girth, and additional caudal fin and jaw morphometrics for MALTA (Table I), also supported a TL of 7 m for either. We did not expect these morphometrics to produce precise TL ranges, so no plots are shown, nor were TL ranges estimated.

Discussion

Morphometrics for Existing Data

Our white shark data, after adjusting for the lack of standards, proved to be remarkably useful and agreed in general with the results of Bass *et al.* (1975). The regressions for the pectoral fin anterior margin and CDM were in good agreement, although CDM variability in our data was twice as large. We suggest that approximately 0.5% of the difference for small white sharks was due to the incorrect assumption of a constant angle between the sagittal (median) plane and the caudal fin by Bass *et al.* (1975). They calculated TL as PRC + 0.8 CDM, with 0.8 equaling the cosine of 37° (an approximation of the heterocercal angle). Accordingly, our pectoral fin anterior margin results for small sharks were in better agreement with results from 90 white sharks of the eastern North Pacific, the North Atlantic, South Africa, and Australia (L. J. V. Compagno, unpublished data).

Our data for height of the first dorsal fin was fit by a three-parameter regression, with a maximum at 3.1 m (Table II and Fig. 1C). This was a refinement of the method of Bass *et al.* (1975) and explained the observed small dorsal fin height of MALTA. We suggest that such a maximum for fin height is expected for any shark and any fin that becomes more erect after birth. Following birth, the dorsal fin becomes more erect, producing *apparent* accelerated growth for D1H. Once the form of the fin becomes stable, we saw that growth decelerates. Bass *et al.* (1975) reported a constant dorsal fin height for the white shark (N = 33) but large positive allometry for the shortfin mako *Isurus oxyrinchus* (N = 18). Garrick (1967) demonstrated the importance of dorsal fin shape in the systematics of the shortfin mako, and this led to synonymy of the three shortfin mako species. Bass (1973: Fig. 4) observed a dorsal fin maximum for the blacktip shark *Carcharhinus limbatus* (N = 128) and, among carcharinid sharks in general, an initial accelerated growth rate (positive allometry) in the first dorsal fin followed by decelerated growth (negative allometry) as the fish grew.

We used TL as the reference length in the analysis because we were unable to convert our data to the less ambiguous PRC. In principle, if the PRC and CDM were measured, in addition to TL, one can determine how TL was measured and then use a consistent TL. Unfortunately, for almost 50% of the white sharks in our database, the PRC had not been measured. In addition, TL for several sharks was allegedly measured with the caudal fin in the natural position, but the sum of PRC and CDM was <100%, instead of the expected 102–106%. Francis (Chapter 15) reported PRC + CDM = 101.8% (heterocercal angle 23°) for a 1.521 m TL female pup. We estimated PRC + CDM = 105.9% (heterocercal angle 49°) for the Gans Bay female with 6.00 m TOT (total length with the caudal fin in the depressed position) to 5.67 m TL (caudal fin in the natural position).

Our morphometric regressions indicated a generally larger variation about the regression line compared to the findings of Bass *et al.* (1975) (Table I, CV column). Some morphometrics showed much larger

variation than was expected from natural variability (Simpson *et al.*, 1960), indicating that methodological uncertainties were apparent: (1) the use of ill-defined TL (with the caudal fin in the natural or depressed position), instead of PRC, as proposed by Parr (1956), Springer (1964), Van Dykhuizen and Mollet (1992), and Mollet and Cailliet (Chapter 9), and as used for lamnoids by Gruber and Compagno (1982), Gilmore (1983), and Cliff *et al.* (1989); (2) the guess about the exact location of the origin of the fins (M. P. Francis and R. H. Rosenblatt, personal communication); (3) the lack of standards before the work of Compagno (1984a) [e.g., the height of the first dorsal fin was used to designate the anterior margin (Tortonese, 1956)] and the confusion about fin origin and insertion (M. P. Francis, R. H. Rosenblatt, and J. Seigel, personal communication); (4) the distortions due to removing the shark from the water, gutting, freezing, or preservation (Olson, 1954; Springer, 1964; Bass, 1973); and (5) the absence of experienced scientists before the press had arrived and possible interference by onlookers.

Better definitions for certain morphometrics, along with a standard protocol for measuring white sharks, are presented in Appendix 3. Use of the protocol will ensure consistent measurements (see also Cappo, 1988). For example, in our database, we assumed that the jaws were always prepared in the same manner and shrank by the same amount during the drying process. However, the jaw of the Gans Bay shark had an upper perimeter of 1.375 m but appeared to be subjectively smaller than the KANGA jaw (1.250-m perimeter), suggesting different methodologies for preparation or measurement. We assumed that the first upper tooth was the largest, a point supported by the data we were able to check. However, the term *largest tooth* (Randall, 1973) is ambiguous. The first upper tooth (UA1) can be slightly larger, about equal, or slightly less than the second upper tooth (UA2) (L. J. V. Compagno, unpublished data on 80 white sharks). We assumed that reported UA1E2's were measured vertically and consistently, following the method of Randall (1973), and that the shape of the first upper tooth from different sharks was the same, thus allowing calculations from ratios if necessary. Often, the easier-to-measure tooth enameloid edge (UA1EM and UA1ED; see Appendix 3) is reported without stating what was measured. All these questionable assumptions may have contributed to the large variation of jaw and tooth data of larger sharks. However, most of the jaw and tooth data of large sharks used in this analysis were measured by Gordon Hubbell.

Morphometrics for KANGA and MALTA

The most valid TL estimates for KANGA and MALTA are still the original ones provided by Riseley and Abela, respectively. The TL of large white sharks has to be directly measured if a precision >10% (0.7 m range at 7 m TL) is required. Our TL range estimates from fin, jaw, tooth, and mass regressions from white sharks of known TL varied from 25% to 50%. The TL ranges from fin morphometrics were disappointingly large because the regression CVs were so large. The calculated ranges in TL estimated from jaw and tooth morphometrics were large because white sharks >4 m TL varied more than those of smaller sharks (see Randall, 1973). We did not expect mass, which varies greatly, to reasonably validate TL estimates (see Chapter 9, by Mollet and Cailliet). This was confirmed by the large CV (23%) for the condition factor, M/TL^3 (Table I). The mass of 167 males and 223 females from the Natal Shark Board (see Chapter 32, by Cliff *et al.*) had fewer outliers and, correspondingly, a smaller CV (12%). However, the variations were still too large for precise TL estimation.

More accurate morphometrics would be required to produce smaller TL ranges from body measurements. Body morphometrics >65% TL had CVs smaller than 2.5%, in agreement with the results of Bass *et al.* (1975), and would yield smaller TL ranges. However, if a large fraction of the body of a large white shark can be measured, then TL (or better, PRC) likely could be measured as well.

Fin morphometrics should be taken on fresh material, or the shrinkage of fins should be determined experimentally. The estimate of the fresh pectoral anterior margin (1.128 m, 16.2%) for KANGA was within the limits expected for a 7 m TL white shark. The MALTA pectoral fin measurements were taken on a fin that had dried for 2 years in a bar. The anterior margin (0.938 m, 13.4%, assuming 10% shrinkage) was less than expected (Fig. 1A). A shrinkage of 15% (certainly possible) produced an upper limit of TL at about 7 m. R. Smera (personal communication) observed fin shrinkage of up to 17% and 26% for pectoral and dorsal fin morphometrics, respectively, for a 5.3-m female caught in Cananéia, Brazil (Appendix 1). However, it probably is not valid to compare shrinkages of the fins of a fish prepared by a taxidermist with those of air-dried fins.

The use of improved methods for measurement and the inclusion of more recent data from large white sharks reduced the difference between estimated TL and calculated TL from jaw and tooth

morphometrics. Randall (1973) did not use a confidence band for a new observation, and his data came from small sharks. The variability of upper jaw perimeter and UA1E2 of large white sharks was surprisingly large (Fig. 1D and E). We concur with Ellis and McCosker (1991), who found that tooth size may reach an upper limit in white sharks and may not accurately reflect age or overall size. We conclude that the sizes of the jaw and teeth of KANGA are compatible with the original estimate of 7 m TL, whereas Cappo (1988), following the method of Randall (1973), estimated a TL of 6.4 and 5.8 m from jaw and teeth, respectively. Our TL range calculated from the jaw data for MALTA did not include 7 m. We suggest that the upper range in our data is an underestimate, because we included data from small sharks. If sharks <4 m TL are excluded from the regression, the upper limit becomes indeterminate. The upper jaw perimeter of 1.120 (16%) becomes compatible with a 7-m shark.

The number of bands in the central portion of a vertebra (Cailliet *et al.*, 1985), determined by the proper laboratory techniques (Cailliet *et al.*, 1983b), may provide more precise TL estimates. At least, such measurements should provide an accurate estimate of the age of a large white shark. A visual band count of 15 actually was reported by Abela for a vertebra of uncertain location in the vertebral column of MALTA. This number of bands was much lower than expected, because a 15-year-old white shark should be about 5 m long (Cailliet *et al.*, 1985). This TL would be considerably less than the minimum estimate of 6–6.5 m from photographic evidence (see Chapter 30, by Fergusson). The 5.67–6.00 m TL Gans Bay and 5.36–5.7 m TL North Cape females had 23 and 22 ± 1 bands, respectively (see Chapter 15, by Francis). We suggest that use of the proper techniques would have shown additional bands in the MALTA vertebra.

It is problematic to extrapolate beyond the range of the available data. The ratio-on-size regression results showed that KANGA and MALTA could have been 7 m TL, as reported by Riseley and Abela, respectively, and that our methods and data were not adequate for a reasonably precise TL validation. The use of a ratio-on-size instead of a size-on-size regression has been questioned by many (e.g., Simpson *et al.*, 1960; Sokal and Rohlf, 1981), but we suggest ratio-on-size to be the more appropriate for length validation of large white sharks. The ratio-on-size data used in morphometrics should be considered as a transformation, because all the measured data are divided by the same number (i.e., TL). We suggest that ratio-on-size is not prone to type II errors (see McArdle, 1988) and agree that, because of large type II errors, size-on-size could be particularly inappropriate for the determination of TL ranges. However, we found that size-on-size regressions produced very small type II errors (0.1–0.2 m); Mollet and Cailliet (Chapter 9) further discuss the advantages of the ratio-on-size compared to the size-on-size regression. The TL ranges from the condition factor (a mass/TL^3 ratio) versus TL regression were very similar to those from a GM power regression (log *W* versus log TL). Indeed, it is true that the size-on-size regressions would yield narrower 95% confidence bands for large TL and wider ones for small TL compared to those of the ratio-on-size regression. Along with Simpson *et al.* (1960), Sokal and Rohlf (1969), and Cailliet *et al.* (1986), we suggest that the cautious use of a two-parameter ratio-on-size regression is more appropriate for morphometrics that show large variations or reach an upper absolute limit for large fish. The use of a size-on-size regression requires a three-parameter curve to obtain equally good fits. We found that the ratio-on-size regression, like the log–log transformation, produced more homoscedastic and normal residual distributions for many morphometrics compared to the size-on-size regression. Mollet and Cailliet (Chapter 9) could not substantiate such an improvement, but they used a different set of white shark data comprising only large-scale morphometrics.

Summary

Morphometrics of over 70 white sharks *C. carcharias* were used to validate estimations of TL. The TLs of two large white sharks were estimated from upper jaw perimeter, UA1E2, and pectoral fin size. KANGA was estimated to be 5.3–8.2 m TL, consistent with the >7 m TL estimate of Peter Riseley. MALTA was estimated to be 4.6–7.0 m TL, making the disputed 7 m TL measurement by John Abela possible. None of the additional morphometrics, nor the estimated mass, of MALTA ruled out a TL of 7 m. The most solid TL estimates for KANGA and MALTA are still the original ones provided by Riseley and Abela, respectively. The TL of large white sharks has to be directly measured if a precision range of >0.7 m (10% at TL = 7 m) is required. For these two sharks, the TL range estimates from the 95% confidence band for new observations of upper jaw perimeter, tooth enameloid height, fin morphometrics, and mass from sharks of known TL varied between 25% and 50%. Better definitions for certain morphometrics, to allow for more consistent measurement, and a proper protocol for measuring large white sharks are needed. Such a protocol was presented here.

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APPENDIX 1 General Information for White Sharks Used in this Study

No.[a]	TL (m)	Sex	Location	Date	Collection no.	Reference
1	1.261	M	Los Angeles, California	June 18, 1985	LACM 43804-1	J. Seigel (personal communication)
2	1.290	M	Baja California, Mexico	June 1981		Cailliet *et al.* (1985); this study
3	1.307	M	Newport Pier, California	June 12, 1985	LACM 43805-1	J. Seigel (personal communication)
4	1.321	F	Redondo Beach, California	May 31, 1984	LACM 43638-1	J. Seigel (personal communication)
5	1.400	M	Algoa Bay, South Africa	1950		Smith (1951)
6[b]	1.430	F	North Cape, New Zealand	November 13, 1991		Francis (Chapter 15)
7[b]	1.449	F	North Cape, New Zealand	November 13, 1991		Francis (Chapter 15)
8	1.521	F	Kaipara Harbor, New Zealand	January 19, 1993		Francis (Chapter 15)
9	1.540	M	Bodega Bay, California	September 10, 1984	MBA1, MLML31	This study
10	1.543	F	La Jolla Pier, California	July 21, 1948		Fitch (1949)
11	1.590	M	Los Angeles, California	January 1, 1990	LACM	J. Seigel (personal communication)
12	1.594	F	San Diego, California	November 9, 1955	SIO 55-95f	A. Flechsig (personal communication)
13	1.626	M	La Jolla Pier, California	November 6, 1955	SIO 55-95e	Klimley (1985b)
14	1.629	F	La Jolla Pier, California	October 31, 1955	SIO 55-95b	Klimley (1985b)
15	1.632	M	Southern California	October 31, 1955	SIO 55-95b	Klimley (1985b)
16	1.637	F	Port Hueneme, California	June 1993	LACM	J. Seigel (personal communication)
17	1.696	F	San Diego, California	October 1955	SIO 55-95g	A. Flechsig (personal communication)
18	1.764	F	Los Angeles, California	December 31, 1989	LACM	J. Seigel (personal communication)
19	1.806	F	La Jolla Pier, California	October 30, 1955	SIO 55-95a	Klimley (1985b)
20	1.807	F	San Diego, California	November 12, 1955	SIO 55-95g	A. Flechsig (personal communication)
	1.831	M	Darien, Georgia	January 6, 1994		G. Burgess (personal communication)
21	1.837	F	Los Angeles, California	January 4, 1990	LACM	J. Seigel (personal communication)
22	1.843	F	Santa Monica Bay, California	January 13, 1990	LACM 44842-1	J. Seigel (personal communication)
23	1.877	M	Los Angeles, California	January 23, 1990	LACM	J. Seigel (personal communication)
24	1.877	F	Santa Monica Bay, California	January 13, 1990	LACM	J. Seigel (personal communication)
	1.943	M	Soquel Point, California	August 10, 1959	CAS 26376	W. I. Follett (personal communication)
25	1.960	M	Playa Sur, Mazatlán, Mexico	January 25, 1964		Kato (1965)
	1.967	F	Cape Lookout, North Carolina	April 18, 1974		G. Burgess (personal communication)
26	2.000	F	La Jolla Cove, California	November 4, 1971	SIO 71-196	I. Taylor (personal communication)
27	2.170	F	Puerto Quequén, Argentina	December 11, 1956		Siccardi *et al.* (1981)
	2.184	M	Indian Beach, California	July 30, 1959	CAS 26367	W. I. Follett (personal communication)
28	2.240	M	Puerto Quequén, Argentina	July, 12, 1953		Siccardi *et al.* (1981)
	2.254	M	Stinson Beach, California	November 9, 1959	CAS 26694	W. I. Follett (personal communication)
	2.419	F	Stinson Beach, California	December 27, 1960	CAS 27013	W. I. Follett (personal communication)
29	2.420		Sète, Gulf of Lions, France	1876		Moreau (1881)

(*continues*)

APPENDIX 1 (*Continued*)

No.[a]	TL (m)	Sex	Location	Date	Collection no.	Reference
30	2.540	F	Gulf of Maine	October 1937		Schroeder (1939)
	2.650	M	Stinson Beach, California	December 28, 1960	CAS 27015	W. I. Follett (personal communication)
	2.673	M	Bolinas Bay, California	November 13, 1959	CAS 26695	W. I. Follett (personal communication)
	2.774	F	Indian Beach, California	July 29, 1959	CAS 26366	W. I. Follett (personal communication)
31	2.830[c]	M	Natal, South Africa	October 1987	DAE-871111-01	This study
32	2.830	M	Puerto Quequén, Argentina	January 29, 1960		Siccardi *et al.* (1981)
33	2.896	F	Vero Beach, Florida	March 27, 1985		G. Hubbell (personal communication)
34	2.935[c]	M	Natal, South Africa	October 1987	DAE-871111-02	This study
	2.959	F	Tomales Bay, California	July 2, 1960	CAS 26781	W. I. Follett (personal communication)
35	3.025[c]	F	Brighton Beach, South Africa	April 1987	NSB-BRI-873	This study
36	3.050	M	Puerto Quequén, Argentina	December 29, 1952		Siccardi *et al.* (1981)
	3.251	M	Seal Rocks, Victoria, Australia	January 19, 1969	RW 376	R. Warneke (personal communication)
	3.270	F	Stinson Beach, California	January 2, 1961	CAS 27014	W. I. Follett (personal communication)
37	3.643	F	Balboa, California	February 1–3, 1960	SIO	C. Limbaugh and R. H. Rosenblatt (personal communication)
	3.750	M	Seal Rocks, Victoria, Australia	November 9, 1969	RW 459	R. Warneke (personal communication)
38	3.790	M	Marathon, Florida	April 23, 1992		J. Castro and G. Hubbell (personal communication)
39	3.826[c]	M	Cape Town, South Africa	August 26, 1987	LJVC-870830	This study
40	3.830		Mediterranean Sea	Before 1865		Duméril (1865)
41	3.870	F	Gulf of Maine	August 24, 1949		Scattergood *et al.* (1951)
42	3.930	M	Monterey Bay, California	September 25, 1978		Cailliet *et al.* (1985); this study
43	4.064	F	Amagansett, New York	October 5, 1964		Pratt *et al.* (1982)
	4.064	F	Seal Rocks, Victoria, Australia	March 4, 1969	RW 383	R. Warneke (personal communication)
44	4.100	M	Cap Bon, Tunisia	May 22, 1956		Postel (1958)
45	4.353	M	Santa Catalina Island, California	May 17, 1985	LACM CCS85-2	J. Seigel (personal communication)
46	4.500	F	Muscongus Bay, Maine	July 20, 1961		Scud (1962)
47	4.510	M	Santa Catalina Island, California	May 17, 1985	LACM CCS85-2	J. Seigel (personal communication)
48	4.570	M	Moriches Inlet, New York	June 29, 1979		Pratt *et al.* (1982)
49	4.572	M	Bornholm Beach, Australia	August 22, 1982	F9682	G. Hubbell (personal communication)
50	4.674		Craig, Alaska	October 1961		Royce (1963)
51	4.700	F	Englewood, Florida	February 1, 1939		Springer (1939), Bigelow and Schroeder (1948)
52	4.712	M	Anacapa Islands, California	April 1985	S41285	G. Hubbell (personal communication)
53	4.750	M	Tossa de Mar, Spain	November 17, 1992	MSP-0492M	I. K. Fergusson (personal communication)
54	4.788	F	Davenport, California	October 6, 1989	MLML #32	This study
55	4.942	F	Point Dume, California	August 30, 1982	LACM 42894	J. Seigel (personal communication); Cailliet *et al.* (1985)
56	4.960[d]	F	San Miguel Island, California	March 18, 1958		Kenyon (1959)
57	5.105	F	Monterey Bay, California	January 23, 1957		Follett (1966)
58	5.200	F	Cap Bon, Tunisia	May 16, 1956		Postel (1958)
	5.234	F	Santa Barbara Island, California	November 8, 1993		C. Winkler (personal communication); J. Seigel (personal communication)
59	5.300	F	Todohokke, Japan	May 30, 1985		Nakano and Nakaya (1987)
60	5.300	F	Cananéia, Brazil	December 8, 1992		Arfelli and Amorim (1993)
61	5.350	F	Egadi Islands, Sicily	May 8, 1987	MSI/0287F	I. K. Fergusson (personal communication)
62	5.360	F	North Cape, New Zealand	November 13, 1991		Francis (Chapter 15)

(*continues*)

APPENDIX 1 (*Continued*)

No.[a]	TL (m)	Sex	Location	Date	Collection no.	Reference
63	5.368	F	Point Vincente, California	September 18, 1985	LACM CCS85-9	J. Seigel (personal communication); G. Hubbel (personal communication)
64	5.474	F	Port Pirie, Australia	January 1984	X11384B	G. Hubbell (personal communication)
65	5.486	F	Malta	1973		J. Abela (personal communication)
66	5.520	F	Dunedin, New Zealand	January 1886		Parker (1887)
67	5.537	F	Israelite Bay, Australia	July 20, 1980	F82380	G. Hubbell (personal communication)
68	5.537	F	Whyalla, Australia	January 1984	X1138C	G. Hubbell (personal communication)
69	5.633	F	Anacapa Islands, California	November 6, 1985	L11985	G. Hubbell (personal communication)
70	5.740	F	Bunbury, Australia	July 2, 1991	H10991	G. Hubbell (personal communication)
71	5.944	F	Ledge Point, Australia	March 22, 1984	H5384	Randall (1987); G. Hubbell (personal communication)
72	5.67–6.00	F	Gans Bay, South Africa	January 17, 1987	LJVC-870303	This study
73	6.096	F	Alberton, PEI, Canada	August 4, 1983	M91683	G. Hubbell (personal communication)
74	6.408	F	Cojímar, Cuba	1945		Guitard and Milera (1974); Randall (1987)
75	~7.0	F	Fifla Farallon, Malta	April 17, 1987	MMA-0187F	Fergusson (Chapter 30); this study
76	>7.0	F	Kangaroo Island, Australia	April 1, 1987		Jury (1987); Cappo (1988)

TL, Total length.
[a]Only numbered individuals were included in the analysis.
[b]Embryo.
[c]TL (actually TOT) was measured with the caudal fin in the depressed position.
[d]TL was calculated from the fork length.

APPENDIX 2 **Measurements of the Jaw and Dentition of White Sharks**

Measurements						General information	
TL (m)	FUJP (m)	DUJP (m)	UA1E2 (mm)	UA1H (mm)	UA1W (mm)	Collection no.	Reference
1.960			15.0		12.0		Kato (1965)
1.975		0.385	17.5				Randall (1973)
1.975		0.410	19.3				Randall (1973)
2.040			20.0				Randall (1973)
2.170			18.0		13.5		Siccardi *et al.* (1981)
2.195		0.433	20.2				Randall (1973)
2.420			21.0		17.0		Siccardi *et al.* (1981)
2.420			22.0	29.0	21.0		Moreau (1881)
2.420		0.487	20.5				Randall (1973)
2.560		0.547	25.5				Randall (1973)
2.675		0.533	24.5				Randall (1973)
2.715		0.530	22.5				Randall (1973)
2.795		0.570	25.2				Randall (1973)
2.830			23.6	33.3	22.3	DAE-871111-01	This study
2.935			28.1	33.5	24.3	DAE-871111-02	This study
3.025			28.1*	35.0	28.0	NSB-BRI-873	This study
3.050			28.0		25.0		Siccardi *et al.* (1981)
3.140		0.618	26.0				Randall (1973)

(*continues*)

APPENDIX 2 (*Continued*)

Measurements						General information	
TL (m)	FUJP (m)	DUJP (m)	UA1E2 (mm)	UA1H (mm)	UA1W (mm)	Collection no.	Reference
3.310		0.685	29.9				Randall (1973)
3.643			38.0	38.0	36.0		C. Limbaugh and R. H. Rosenblatt (personal communication)
3.710		0.785	31.0				Randall (1973)
3.790		0.790	32.5	41.0	26.0		J. Castro and G. Hubbell (personal communication)
4.075		0.815	35.5				Randall (1973)
4.500			26.0[a]	36.0	29.0		Scud (1962)
4.572		1.120	43.0	54.0		F9682	G. Hubbell (personal communication)
4.674			34.0		37.0		Royce (1963)
4.700			37.0	52.0			Springer (1939)
4.712		1.230	40.0	49.0		S41285	G. Hubbell (personal communication)
4.788	0.838	0.805*				MLML #32	This study
4.825		0.978	43.9				Randall (1973)
4.885		0.938	45.0				Randall (1973)
4.942			34.6*	43.0	33.0	LACM 42894	J. Seigel (personal communication)
4.960			44.2*	55.0	43.1		Kenyon (1959)
5.105			46.0				Follett (1966)
5.110		0.985	44.7				Randall (1973)
5.300	1.065	1.022*	48.3[b]				Arfelli and Amorim (1993); R. Smera (personal communication)
5.360[c]	1.150	1.104*	51.0				Francis (Chapter 15)
5.368	1.220	1.160	47.0	58.0	39.9	LACM CCS85-9	G. Hubbell (personal communication)
5.370		1.055	49.3				Randall (1973)
5.474		1.200	45.0	56.0		X11384B	G. Hubbell (personal communication)
5.486		0.980	47.1[d]	63.8[d]	44.0[d]		J. Abela (personal communication); this study
5.520			40.0		37.0		Parker (1887)
5.537		1.120	40.0	49.5		F82380	G. Hubbell (personal communication)
5.537		1.265	47.0	60.0		X1138C	G. Hubbell (personal communication)
5.633	1.310	1.270	49.0	61.0		L11985	G. Hubbell (personal communication)
5.740		1.128	42.0	56.0		H10991	G. Hubbell (personal communication)
5.944		1.300	51.0	63.0		H5384	Randall (1987); G. Hubbell (personal communication)
5.67–6.00			48.6[b]	62.0	50.0	LJVC-870303	This study
6.096		1.430	47.5	59.0		M91683	G. Hubbell (personal communication)
6.401			44.0	57.0			Guitard and Milera (1974); Randall (1987)
7.010	1.220	1.120	46.9	55.5	38.4		J. Abela (personal communication); this study
7.010	1.297	1.250	51.6				Cappo (1988)

TL, Total length; FUJP, fresh upper jaw perimeter; DUJP, dried upper jaw perimeter; UA1E2, tooth enameloid height; UA1H, tooth total height; UA1W, tooth total width of the larger first upper tooth of white sharks; *, calculated value (see text).

[a]Scud's (1962) results were not included in the final regression analysis because this tooth was likely the third upper.

[b]The left first upper replacement tooth and the right first upper functional tooth were 46 mm.

[c]Used TOT (total length with the caudal fin in the depressed position) = 5.9 m, based on a 5 m precaudal length expected length of a shark, consistent with its 22 vertebrae bands.

[d]Determined from a photograph of John Abela, placing a ruler along the enameloid edge of the tooth.

APPENDIX 3 Protocol for Verification of Large White Shark Records and International Specimen Data Form

A. If you catch a large white shark and cannot release it, bring it in intact to experts so that its size can be verified. If possible, do not cut up the shark. DO NOT REMOVE THE JAWS and DO WATCH THE SHARK before and during the necropsy to prevent spectators from stealing individual teeth or other parts.

B. Call scientists or instructors from local museums, fisheries institutes, universities, or high schools or local physicians to take the measurements or assist the captors in doing so, as well as conducting a necropsy of the captured animal. Also, call in local officials for the purpose of verifying the measurements.

C. In most places where white sharks are captured, they can be hauled onto piers, placed in the shade, and iced at least until scientists arrive to conduct the necropsy. If lifting the shark out of the water onto a boat or pier, use a sling to lift horizontally. DO NOT tie a rope around the tail and lift vertically, as the animal will be distorted and stretched.

D. Obtain the precise locality data for the shark when captured, including coordinates, as well as capture date, captor, vessel, gear, distance from shore, bottom and capture depth, habitat, and anything else of interest from the fishers that captured the shark, including behavioral notes.

E. Obtain the following basic morphometrics using straight-line measurements between parallels and not over the curve, with standardized methodology (see Fig. A1A and B):
   1. TOT (total length from the snout tip to the extended caudal tip, i.e., with the caudal fin in the depressed position)
   2. TLn (natural total length from the snout tip to the caudal tip, with the caudal fin in the natural position)
   3. FOR (fork length from the snout tip to the notch at the juncture of the upper and lower postventral caudal margins)
   4. PRC (precaudal length from the snout tip to the anterior edge of the bottom of the upper precaudal pit)
   5. HDL (head length from the snout tip to the upper end of the fifth gill slit)
   6. PD1 (predorsal length from the snout tip to the origin of the first dorsal fin)
   7. SVL (snout–vent length from the snout tip to the origin of the vent, (i.e., cloacal aperture)
   8. GIR (girth, or circumference around the body at the posterior end of the pectoral bases)
   9. P1A (pectoral fin anterior margin)
   10. P2A (pelvic fin anterior margin)
   11. CLO (clasper outer length from the pelvic fin base to the clasper tip)
   12. CLI (clasper inner length from the front of the vent to the clasper tip)
   13. CLB (clasper base width, measured across the clasper base)
   14. D1H (first dorsal fin height, perpendicular to the body axis from the base to the apex)
   15. CDM (caudal fin dorsal margin from the upper precaudal pit to the tip of the caudal fin)
   16. CPV (caudal fin preventral margin from the lower precaudal pit to the tip of the lower caudal lobe)

F. Have the local news media or a photographer photograph the following items with a *normal* or short *telephoto* lens, *not* a wide-angle lens, in all cases with a SCALE BAR (meter stick or equivalent) provided in the photo: (1) lateral view of the shark; (2) lateral view of the shark's head; (3) first dorsal fin; (4–5) pectoral fin (state which side), dorsal and ventral surface; (6) abdomen between pectoral and pelvic fins; (7–8) pelvic fin (state which side), dorsal and ventral surface; and (9) caudal fin.

G. If possible sketch or prepare a diagram to note the peculiarities of the shark, including color pattern on the side of the head, fins, flanks, and tail. Note all scratches, bite marks, damage to fins, and other injuries.

H. Weigh the shark AFTER measuring it, but BEFORE cutting into it. Weigh with the stomach contents intact. In many places, sharks can be weighed intact in fish-processing plants. If a truck scale is available, weigh the truck (tare it), load the shark, weigh the truck with the shark, and subtract the former. If the truck scale is some distance from the shark, weigh the shark with the truck's fuel tank at the same level each time, or add or subtract any fuel difference between the two weighings. If it is necessary to dismember the shark to weigh it, carefully keep as much of the body fluids as possible and weigh them, too.

I. Have the total mass and various measurements and a description of the methods used in obtaining them, as well as any photographs taken, validated by local officials (notaries, police, judges, the mayor, etc.) with signed affidavits or notarized statements, with the scientific or medicinal staff, as well as the captors, signing them in public.

J. Examine the animal for stomach content. Weigh and sort ALL contents, looking for the remains of small animals, such as squid beaks, fish otoliths, fish bones, etc., as well as those of large ones. A sieve and water for flushing will help the process. Photograph the intact stomach contents.

K. Note the condition and size of the ovaries, oviducts, and any embryos or fetuses of females, and the testes, epigonal organs, sperm ducts, sperm sacs, and claspers of males. Photograph the process of examining them. In males, check the sperm sacs for spermatophores, and check whether the urogenital duct will project seminal fluid when the sperm sacs are palpitated. In females, check the ovaries for ovarian follicles, and measure a small sample of them. Photograph, weigh, and measure ALL fetuses, and if possible, freeze them for further examination or fix them in 10% formalin solution (1 part concentrated formaldehyde to 9 parts water).

L. Count the number of intestinal valves in the valvular intestine. Save any tapeworms or other parasites from the intestine or other body organs for a parasitologist (freeze them or put them in 10% formaldehyde).

M. Weigh (to the nearest gram) the liver, ovaries, or testes, heart, and brain, with the smaller organs weighed on a small sensitive scale.

(*continues*)

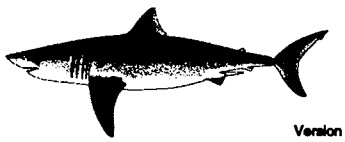
A

IWS SPECIMEN REGISTER NO.: c ____ ____ ____ .

Shark Research Center, South African Museum

WHITE SHARK PROJECT
BASIC DATA

International White Shark Specimen Data Sheet
Carcharodon carcharias (Linnaeus, 1758) Family Lamnidae



Field No.:_____. Accession No.:_____.
Station No.: _____. Catalog No.:_____.
Photos:_____. Radiographs:_____.

MATERIAL SAVED: jaws - tooth sets - cranium - vertebral column - hyobranchial skeleton - fin skeletons and girdles - vertebrae - denticles - entire skeleton - entire shark - other _____.

Locality:_____.
Area: _____.
Province/State: _____ Country: _____.
Latitude: ____ ° ____ ' ____ " N S Collector: _____.
Longitude: ____ ° ____ ' ____ " E W Vessel:_____.
Date: Y: ____M:____D:____. Gear: _____.
Time: _____AM PM. Distance from shore:_____km/m.
Habitat:_____
_____Depth: _____m.
Data from: _____.
Other:

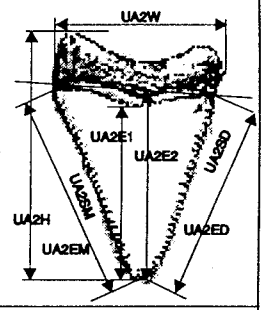
Sex: F M ? Maturation Stage: 1 2 3 4 ? Other: _____.

Basic MORPHOMETRICS:

TOT:_____.	P1A:_____.	Body: _____kg	
TLn:_____.	P2A:_____.	Liver:_____kg	
FOR:_____.	CLO:_____.	Gonads: _____kg	
PRC:_____.	CLI:_____.	Heart:_____gm	
HDL:_____.	CLB:_____.	Brain:_____gm	
PD1:_____.	D1H:_____.		
SVL:_____.	CDM:_____.	SPIRAL Valve #: _____.	
GIR:_____.	CPV:_____.	HEART Valve #: _____.	

WEIGHTS:

Tooth measurements

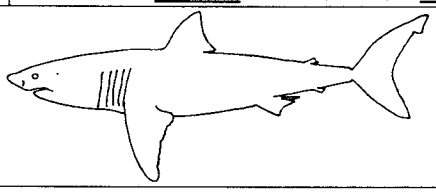


TOOTH COUNTS: UL P____L___I___A___A___I___L___P_____UR
LL P____L___A___A___L___P_____LR

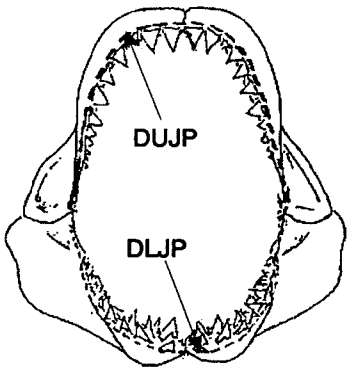
VERTEBRAE:
MP____ LM____
DP____ LD____
DC____ HM____
MP Sample? Y N

TOOTH Measurements/Serration #
UA2H:_____mm UA2ED_____mm
UA2W:_____mm UA2RD_____mm
UA2E1:_____mm
UA2E2:_____mm UA2SM_____#
UA2EM:_____mm UA2SD_____#

COLOR PATTERN:
Axillary spot: y n ?
Black P1 tip: y n ?
Small side spots: y n ?
Caudal base pattern: y n ?
Dorsolateral Color?:



DUJP:_____. DLJP:_____.

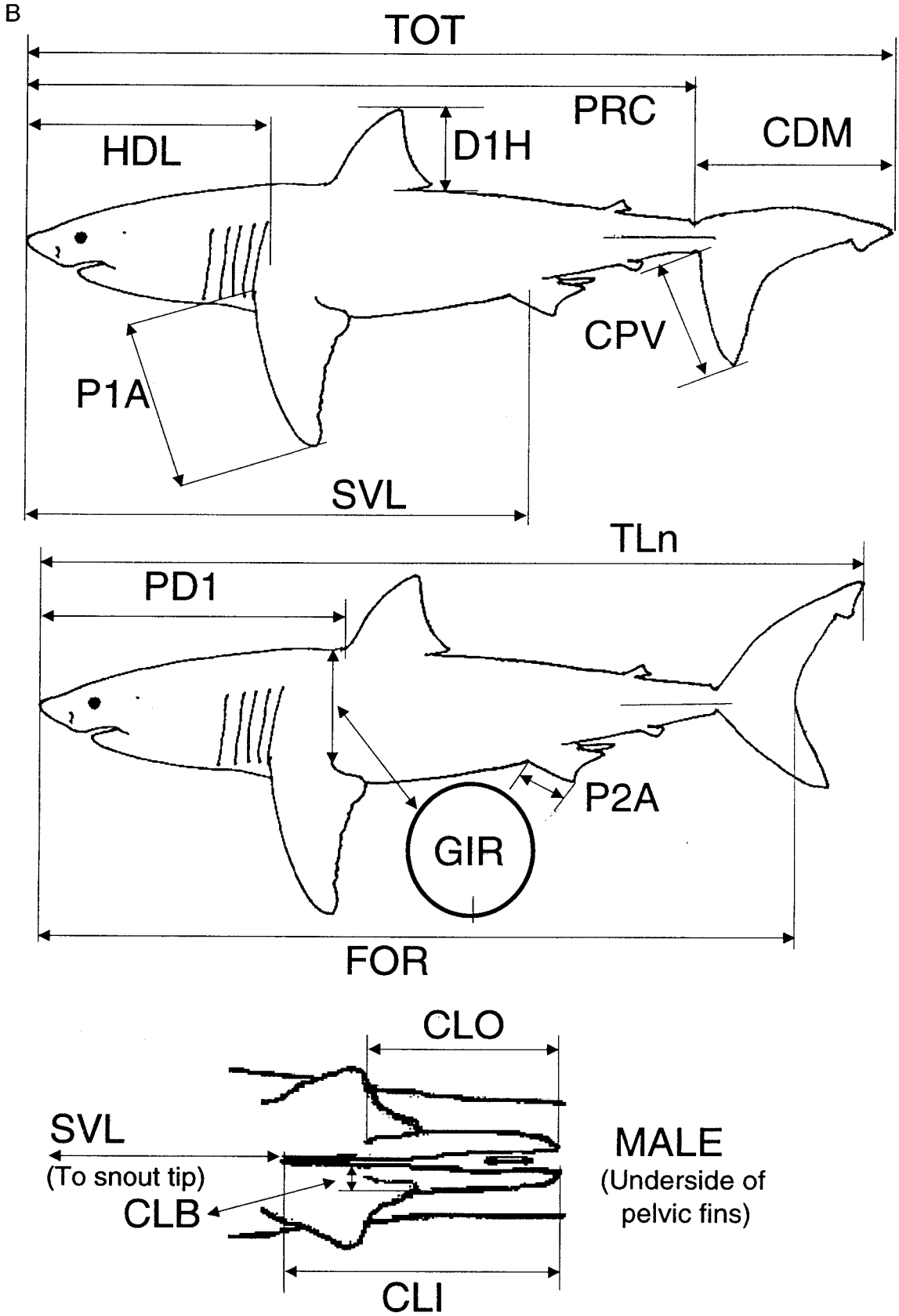


Jaw Measurements
(others optional)

BIOLOGICAL DATA:

OTHER DATA:

B



Basic white shark morphometrics

APPENDIX 3 (*Continued*)

N. Remove the jaws, photograph them intact with a scale bar, measure the upper and lower jaw perimeters fresh according to Fig. A1A, and if possible, repeat the measurements some time later after the jaws are dried. Measure (to the nearest millimeter) the first and second upper anterior functional teeth according to Fig. A1A. Determine the dental formula, and count the tooth rows (see Welton and Farish, 1993). If the functional teeth (first row) are missing or broken, record and measure the replacement teeth in the second row.

O. If possible, remove the entire vertebral column (including caudal vertebrae), and freeze, preserve, or dry intact; properly label sections. Remove vertebrae from below the first dorsal fin if it is not possible to save the whole vertebral column.

P. Send copies of the data, photos, and other information collected on the shark to a shark researcher(s).

Q. Deposit representative material of the shark (i.e., jaws and fins, vertebrae, pelvic fins with claspers for males; dermal denticle samples from the midback under the first dorsal fin) in a natural history museum.

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GREAT WHITE SHARKS

The Biology of Carcharodon carcharias

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