化石研究会会誌　　Journal of Fossil Research, Vol. 35(1), 6-9(2002)
[Original Report]

The relationship between the tooth size and total body length in the shortfin mako, *Isurus oxyrinchus* (Lamniformes: Lamnidae)

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Abstract

The relationship between the height of tooth crown (CH) and total bodylength (TL) in the modern shortfin mako, *Isurus oxyrinchus* Rafinesque (Lamniformes: Lamnidae) is examined using regression analyses. The results suggest: 1) that an increase in the CH of each tooth through replacement is proportional to the increase in the TL, 2) that the CH can be used to predict the TL, and 3) that distally located teeth develop faster through replacement compared to mesially located teeth. The regression equations presented here can be used to infer lost TL data for modern jaw specimens and possibly for fossil individuals of the taxon.

1. Introduction

The shortfin mako, *Isurus oxyrinchus* Rafinesque (Lamniformes: Lamnidae), that is said to reach 394 cm in total body length (TL), is a common shark found worldwide circumtropically (Compagno, 1984). Jaw specimens of *I. oxyrinchus* are common in museum collections, but most of them lack their TL records. A recent advancement in identifying homologous teeth in most lamniforms (Shimada, 2002) allows an examination of the relationship betweenthe tooth size and TL in *I. oxyrinchus*. The objective of this study is to establish a way to "restore" lost TL data on the basis of dental measurements in *I. oxyrinchus*.

2. Materials and methods

Eleven, non-embryonic jaw samples of *I. oxyrinchus*, each with a known TL, were examined (Appendix). Two are housed in the Natural History Museum of Los Angeles County (LACM), California, and nine are a part of Gordon Hubbell collection (GH: JAWS International, Gainesville, Florida), which has been referred to in several scientific papers (e.g., Gruber and Compagno, 1981; Randall, 1987; Hubbell, 1996; Purdy *et al.*, 2001; Shimada,2002). The height of tooth crown (CH = the maximum vertical enameloid height on the labial side) of 11 upper teeth (A1-A2, I1, and L1-L8) and 10 lower teeth (a1-a2, i1, and l1-l7) in each sample was measured (Appendix; for tooth types, see Fig. 1; for additional dental data of these samples, see Shimada, 2002). Then, the relationship between the CH and TL was examined using regression analysis (least squares method; simple linear regression, $y = a + bx$, where a is the constant and b is the slope of the line; x = CH in mm; y = TL in cm; $\alpha = 0.05$; for statistics, see Zar, 1996). The null hypothesis is: The CH does not predict the TL.

3. Results and discussion

Table 1 lists the results of the regression analyses (see also Fig. 2). All regression lines show a positive correlation, suggesting that an increase in the CH of each tooth through replacement is proportional to the increase in the TL. The slope of the lines generally increases from mesially located teeth to distally located teeth for both upper and lower dental series. This general increase indicates that distally located teeth develop faster through replacement compared to mesially located teeth as an individual shark grows. Despite a rather small sample size, all lines have a high ($r>0.800$) correlation coefficient and a high statistical significance ($p<0.002$), indicating that the

Received October 26, 2001; Accepted February 25, 2002

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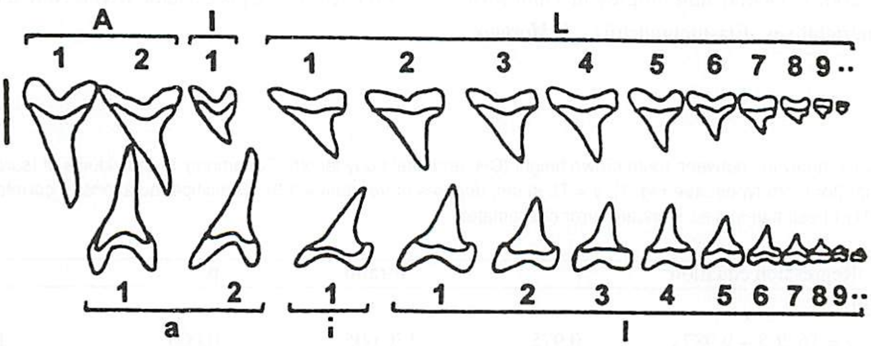

Fig.1. Upper and lower dental series of shortfin mako, *Isurus oxyrinchus* (mesial to the left; labial view; vertical line = position of upper jaw symphysis). Tooth types: A, upper anterior tooth; a, lower anterior tooth;I, upper intermediate tooth; i, lower intermediate tooth; L, upper lateral tooth; l, lower lateral tooth. Illustration modified from Compagno (1984); tooth type identification based on Shimada (2002).

CH of any tooth can be used to predict the TL in *I. oxyrinchus*. Thus, one can use the regression equation(s) to estimate the TL for jaw specimens without TL data.

The regression equations may also be used to infer the TL of fossil *I. oxyrinchus* individuals, which are commonly represented only by their teeth (e.g., Purdy *et al.*, 2001). For example, Purdy *et al.* (2001) reported teeth of Pliocene *I. oxyrinchus*, and one of the illustrated teeth was a "first lower anterior tooth" (= "a1"; Purdy *et al.*, 2001, fig. 25b, USNM 312443), which has the CH of 23.5 mm. If their

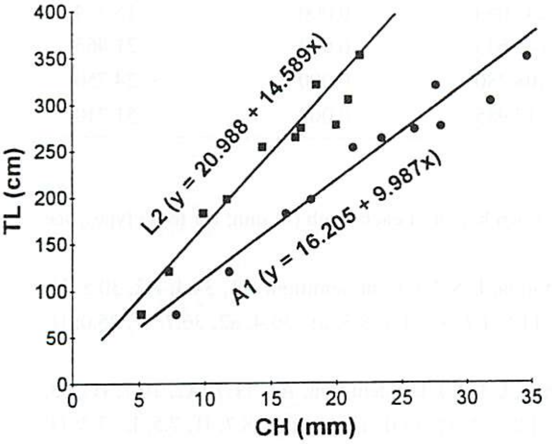

Fig.2. Bivariate scatter with regression line between crown height (CH) and total body length (TL) for the first upper anterior tooth (A1: circle) and second upper lateral tooth (L2: square) in *Isurus oxyrinchus* (n=11; for measurements, see Appendix; for statistics of regression line, see Table 1).

tooth type identification is assumed to be correct, the regression equation for the a1 (y=8.555+9.749x; Table 1) yields the TL of about 238 cm for the fossil individual.

Acknowledgments

I thank the following individuals for their assistance in various ways: D. Bardack, M. Goto, L. Grande, W. S. Greaves, G. and K. Hubbell, R. Plotnick, and T. Poulson, J. Seigel, J. D. Stewart, L. K. Shimada, and H. Yabe.

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Table 1. Regression analyses between tooth crown height (CH) and total body length (TL) among 11 individuals of *Isurus oxyrinchus* (x = CH in mm [for tooth types, see Fig. 1]; y = TL in cm; degrees of freedom = 1,9). Statistical notations: r, correlation coefficient; p, probability of estimates; s.e., standard error of estimates.

x	Regression equation	r	F-ratio	p	s.e.
Upper teeth					
A1	y = 16.205 + 9.987x	0.975	176.605	0.000	19.717
A2	y = 3.693 + 11.463x	0.981	235.966	0.000	17.162
I1	y = 16.422 + 24.341x	0.976	179.613	0.000	19.559
L1	y = 24.069 + 16.404x	0.980	214.064	0.000	17.985
L2	y = 20.988 + 14.589x	0.971	148.828	0.000	21.382
L3	y = 14.972 + 14.920x	0.978	195.617	0.000	18.779
L4	y = 8.125 + 18.392x	0.981	233.930	0.000	17.234
L5	y = 1.210 + 24.199x	0.956	94.904	0.000	26.352
L6	y = 12.698 + 31.502x	0.921	50.569	0.000	34.804
L7	y = 5.221 + 41.165x	0.940	68.340	0.000	30.544
L8	y = 5.468 + 58.758x	0.943	72.295	0.000	29.792
Lower teeth					
a1	y = 8.555 + 9.749x	0.981	225.393	0.000	17.545
a2	y = 3.596 + 9.466x	0.982	238.892	0.000	17.061
i1	y = 20.916 + 14.103x	0.976	181.660	0.000	19.454
l1	y = 24.895 + 14.713x	0.969	140.239	0.000	21.988
l2	y = 34.842 + 15.568x	0.953	89.083	0.000	27.123
l3	y = 22.841 + 18.478x	0.964	116.643	0.000	23.964
l4	y = -15.612 + 26.431x	0.985	297.054	0.000	15.354
l5	y = 6.160 + 29.944x	0.971	147.633	0.000	21.463
l6	y = -16.767 + 43.309x	0.961	108.780	0.000	24.750
l7	y = 58.524 + 41.735x	0.816	17.985	0.002	51.710

Appendix

Examined specimens (with TL, sex, and locality data) and crown height of each tooth (in mm; for tooth types, see Fig. 1; value in parenthesis = estimated measurement).

LACM 32667-1 (351 cm TL; female; caught off California, U.S.A.), right dentition: A1, 34.4; A2, 30.5; I1, 13.5; L1, 20.4; L2, 21.8; L3, 21.8; L4, 18.7; L5, 15.8; L6, 11.5; L7, 8.5; L8, 5.5; a1, 36.4; a2, 36.7; i1, 25.0; l1, 23.9; l2, 22.7; l3, 20.1; l4, 13.9; l5, 12.7; l6, 9.2; l7, 8.2.

LACM 39338-1 (121 cm TL; male; caught off California, U.S.A.), left dentition: A1, 11.7; A2, 10.7; I1, 5.3; L1, 6.2; L2, 7.3; L3, 7.5; L4, 6.7; L5, 5.6; L6, 4.6; L7, 3.3; L8, 2.2; a1, 13.0; a2, 13.4; i1, 8.7; l1, 7.5; l2, 7.2; l3, 6.2; l4, 5.4; l5, 4.2; l6, 3.5; l7, 2.6.

GH-Isur1-05 (198 cm TL; male; caught off Florida, U.S.A.), right dentition: A1, 17.9; A2, 17.2; I1, 7.2; L1, 10.2; L2, 11.7; L3, 12.1; L4, 10.3; L5, 8.7; L6, 6.6; L7, 5.3; L8, 3.2; a1, 17.9; a2, 19.6; i1, 11.8; l1, 11.0; l2, 10.0; l3, 9.2; l4, 8.2; l5, 6.6; l6, 5.0; l7, 4.5.

GH-Isur1-06 (254 cm TL; male; caught off Florida, U.S.A.), right dentition: A1, 21.1; A2, 19.6; I1, 9.3; L1, 13.0; L2, 14.4; L3, 14.3; L4, 12.0; L5, 10.0; L6, 7.2; L7, 5.7; L8, 4.7; a1, 22.1; a2, 23.6; i1, 15.5; l1, 13.9; l2, 12.2; l3, 11.1; l4, 9.2; l5, 7.1; l6, 5.5; l7, 4.3.

GH-Isur1-07 (320 cm TL; female; caught off California, U.S.A.), right dentition: A1, 27.4; A2, 25.6; I1, 12.1; L1, 16.4; L2, 18.5; L3, 18.7; L4, 15.5; L5, 11.8; L6, 8.0; L7, 5.8; L8, 4.2; a1, (31.5); a2, 32.1; i1, 19.0; l1, 17.7; l2, 16.6; l3, 14.6; l4, 11.6; l5, 9.5; l6, 7.4; l7, 5.1.

GH-Isur1-08 (264 cm TL; male; caught off Florida, U.S.A.), right dentition: A1, 23.3; A2, 22.0; I1, 10.4; L1, 14.0; L2, 16.9; L3, 16.9; L4, 13.3; L5, 10.6; L6, 8.7; L7, 6.2; L8, 4.3; a1, 26.1; a2, 27.9; i1, 17.8; l1, 16.0; l2, 13.6; l3, 11.6; l4, 10.7; l5, 8.3; l6, 6.1; l7, 3.8.

GH-Isur1-12 (274 cm TL; female; caught off California, U.S.A.), right dentition: A1, 25.8; A2, 22.5; I1, 8.9; L1, 14.9; L2, 17.3; L3, 17.0; L4, 14.3; L5, 11.6; L6, 8.2; L7, 7.0; L8, 4.8; a1, 25.0; a2, 26.8; i1, 16.5; l1, 15.3; l2, 13.0; l3, 13.0; l4, 11.2; l5, 9.3; l6, 6.7; l7, 5.2.

GH-Isur1-14 (183 cm TL; female; caught off Florida, U.S.A.), right dentition: A1, (16.0); A2, 15.8; I1, 7.0; L1, 8.9; L2, 9.9; L3, 11.0; L4, 10.0; L5, 8.4; L6, 5.8; L7, 4.9; L8, 3.4; a1, 17.6; a2, 18.5; i1, 11.0; l1, 11.3; l2, 9.9; l3, 9.3; l4, 7.7; l5, 6.1; l6, 5.0; l7, 3.6.

GH-Isur1-15 (304 cm TL; female; caught off Florida, U.S.A.), right dentition: A1, 31.6; A2, 28.5; I1, 12.6; L1, 18.3; L2, 20.9; L3, 21.0; L4, 17.1; L5, (10.3); L6, (7.2); L7, 7.1; L8, 5.0; a1, 31.8; a2, 34.9; i1, 21.5; l1, 19.7; l2, 17.2; l3, 15.2; l4, 12.6; l5, (9.6); l6, (6.5); l7, 3.7.

GH-Isur1-17 (277 cm TL; male; caught off Florida, U.S.A.), right dentition: A1, 27.8; A2, 25.6; I1, 11.6; L1, 16.9; L2, 20.0; L3, 19.6; L4, 16.0; L5, 11.8; L6, 9.0; L7, 7.0; L8, 5.2; a1, 29.0; a2, 30.0; i1, 18.0; l1, 18.6; l2, 17.1; l3, 13.8; l4, 11.7; l5, 9.0; l6, 7.4; l7, 4.7.

GH-Isur1-18 (76 cm TL; male; caught off Puerto Rico), right dentition: A1, 7.7; A2, 7.2; I1, 2.4; L1, 4.5; L2, 5.2; L3, 4.8; L4, 3.8; L5, 3.2; L6, 2.0; L7, 1.5; L8, 1.1; a1, 8.9; a2, 9.3; i1, 4.8; l1, 4.7; l2, 4.3; l3, 4.2; l4, (3.5); l5, (2.9); l6, (2.5); l7, (1.7).