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Age and growth of the silky shark *Carcharhinus falciformis* from the Pacific Ocean

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ABSTRACT: The present study estimated the age and growth of the silky shark *Carcharhinus falciformis* in the Pacific Ocean. Samples and biological data were collected from Japanese tuna longline and purse seine fisheries from 1992 to 1999. Vertebra centra were picked from 145 males and 153 females for age determination. The number of annual rings observed for males and females was 0–8 and 0–13, respectively. Combined sex von Bertalanffy growth equations were obtained as follows: $L_t = 216.4(1 - e^{-0.148(t+1.76)})$ where L_t is precaudal length in cm at age t. A mature size for males was considered to be approximately 135–140 cm (precaudal length), with an estimated age of 5–6 years, whereas corresponding values for females were 145–150 cm and 6–7 years, respectively. Birth size ranged from 48 to 60 cm. There was no remarkable difference in growth, birth size and age at maturity between the Pacific and Atlantic Oceans. The life history parameters of the silky shark are approximately the same in both oceans.

KEY WORDS: **age, *Carcharhinus falciformis*, growth, Pacific Ocean, silky shark.**

INTRODUCTION

Sharks are at the apex of the food chain in the ocean. In general, sharks have the following biological characteristics: slow maturity, a small number of embryos and a long gestation time.[1] Some sharks have been regarded as vulnerable to fishing pressure. Although the biological characteristics of coastal sharks are well studied, comparable information for oceanic species is lacking. Therefore, it is very important to collect fundamental biological information on pelagic sharks.

The silky shark *Carcharhinus falciformis* is one of the pelagic species, reaching 3.3 m in total length.[2] This species inhabits tropical to subtropical waters and appears from the surface to a depth of approximately 500 m.[3] The silky shark has the biological characteristic of size segregation. Whereas juveniles occur in offshore nursery areas, adults move to more offshore waters and are isolated from juveniles.[2] Longline and purse seine fisheries incidentally take silky sharks year-round in the Pacific Ocean. The silky shark comprises 2–30% of sharks caught by longline fisheries in the Pacific Ocean.[4] The catch of silky sharks is the largest of several sharks taken by purse seine fisheries in the eastern Pacific Ocean and accounts for 25% of all sharks caught.[5] However, very little is known about the biology of the silky shark. Therefore, the aim of the present study was to examine the age, growth and maturity of silky sharks in the Pacific Ocean.

MATERIALS AND METHODS

Data and samples were collected by Japanese research and training vessels, which belong to the prefectural fisheries experimental stations and fisheries high schools, and by a purse seine fisheries observer program conducted in the Pacific Ocean from 1992 to 1999 (Fig. 1; Table 1).

Vertebrae were collected from 145 males and 153 females (Table 2). After measurement of precaudal length (*PCL*; the distance from the snout to the precaudal pit) to the nearest cm (in the present paper, all length measurements refer to *PCL* unless specified otherwise), vertebral centra were obtained from above the gill slits. Clasper length was measured to the nearest mm. Clasper length was defined as the distance from the insertion of the inner corner of the pelvic fin to the distal tip of the clasper. In order to examine the presence of semen, the sperm sac was squeezed and semen running from the cloaca were observed with the naked eye. The maturity of females was deter-

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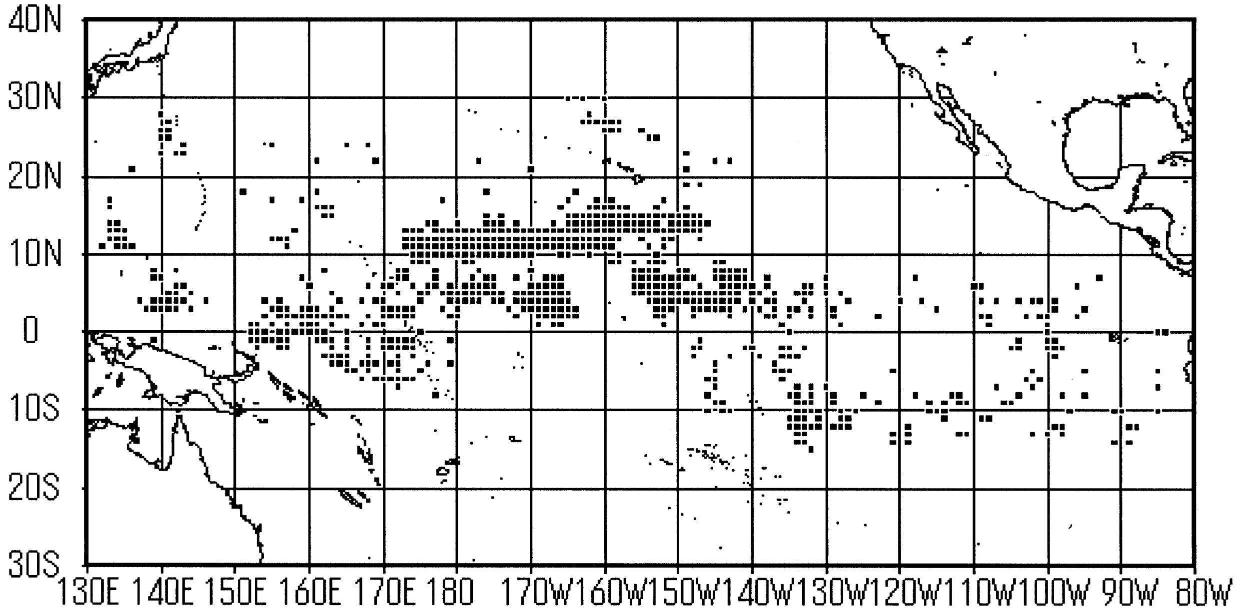

Fig. 1 Locations of sampling during the research cruise.

Table 1 Details of cruises obtaining samples

	Longline fisheries by-catch research	Purse seine fisheries observer program
Period	1992–1999	1995–1999
No. vessels	36	16
No. operations	14 432	350
No. hooks	30 567 842	–
No. catches	6 460	519

Table 2 Number of individuals examined during the cruises

	Total	Longline fisheries by-catch research	Purse seine fisheries observer program
No. males measured	3417	3164	253
No. females measured	3514	3259	255
No. males in which semen observed	15	13	2
No. pregnant females	153	153	
No. embryos	409	409	
No. vertebrae	298	149	149

mined through observations of pregnancy. For pregnant females, the number of embryos was counted according to sex. Embryo length was measured to the nearest mm by random sampling with a limit of five from one litter.

To compare our results with those of previous studies based on total length (*TL*), an equation that converts from *PCL* to *TL* was obtained based on measurements of 84 individuals (*PCL* 48–148 cm), with both sexes combined. The equation between precaudal and fork length (*FL*) was also calculated based on the measurements of 362 individuals (*PCL* 48–184 cm), with both sexes combined. The resulting equations are as follows:

$$TL = 2.08 + 1.32PCL\ (r^2 = 0.990;\ n = 84)$$

$$FL = 1.09 + 1.03PCL\ (r^2 = 0.989;\ n = 362)$$

Vertebral samples were stored at –40°C. After a few months storing, samples were boiled to remove the connective tissue from the centrum surface and then stored in 70% ethanol for > 1 month before processing in the laboratory. Centra were cut into longitudinal sections with a diamond saw and were stained with Alizarin red S. Sections were soaked in the staining solution for approximately 30 min. After staining, sections were washed under running tap water for several minutes and soaked in 100% ethanol.

According to Wilson *et al.*:[6]

> 'An annulus is a concentric zone, band or mark, that is either ridge or valley, or translucent or opaque. A unit passage time (i.e. 1 year) is not inherently implied.'

In the present study, the centrum surface was observed using a dissecting microscope with lighting from the side, which gave contrast to the surface structure. This is a very similar procedure to that used by Francis and Maolagáin,[7] but was developed independently. Concentric structures were observed on the surface of the centrum. Those structures were composed of convex and concave parts. The centrum radius was defined from the focus to the edge of the centrum. The radius of each ring was measured from the focus to the end of the convex structure. Measurements were taken to the nearest 0.01 mm using a microscope (Fig. 2). Marginal increment rate analysis was also performed to examine the seasonal cycle of ring formation. The birthday of silky sharks was assumed and age was estimated by the number of rings plus the number of days from the birthday to the day fished. The parameters of von Bertalanffy growth function were estimated by the non-linear least squares method,[8,9] with solver add-in of Microsoft Excel 97 (Microsoft, Redmond, Washington, USA).

RESULTS

Reproduction

Bodyweight (*BW*) increased exponentially with *PCL* (Fig. 3). Because no significant difference was found between sexes ($F = 0.16$, $P > 0.05$, d.f. = 320), the relationship was obtained with data from both sexes combined. The equation obtained was as follows:

$$BW = 0.0000273PCL^{2.86}\ (r^2 = 0.953;\ n = 322)$$

Clasper length increased rapidly between 120 and 140 cm (Fig. 4). The smallest-size shark having semen was 126 cm. The number of males having semen increased markedly from approximately 130 cm. Males over 130 cm seemed to have become mature.

The length–frequency distribution of females was compared with that of pregnant females to estimate the mature size (Fig. 5). Pregnant females occurred in the 115–215 cm range (Fig. 5). The number of pregnant females increased from approximately 140 cm, with a mode of 145–160 cm. The size frequency of pregnant females was unimodal. Longline gear selectivity is considered to be sigmoidal and that for silky sharks seems to reach its plateau at approximately 110–115 cm (Fig. 5). Because the increase in the number of pregnant females started after the peak of selectivity to overall females, this increase in pregnant females is considered to indicate maturity. Therefore, the female size of maturity is considered to be approximately 145–150 cm.

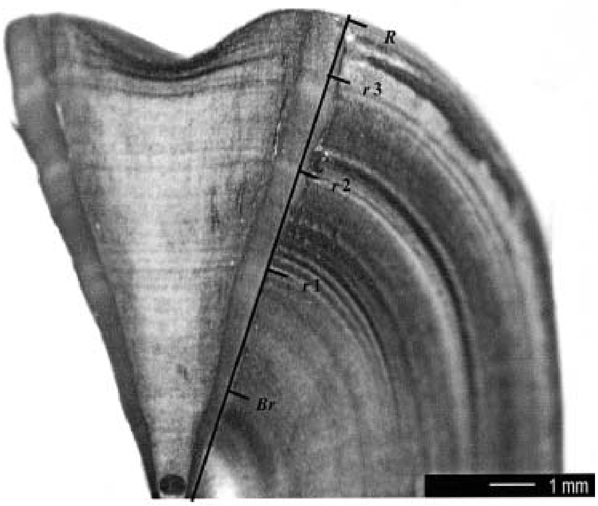

Fig. 2 Vertebral centra stained with Alizarin red S obtained from a 146 cm (precaudal length) female silky shark with a birth ring and three growth rings. R, centrum radius; Br, birth ring; r1–r3, growth rings.

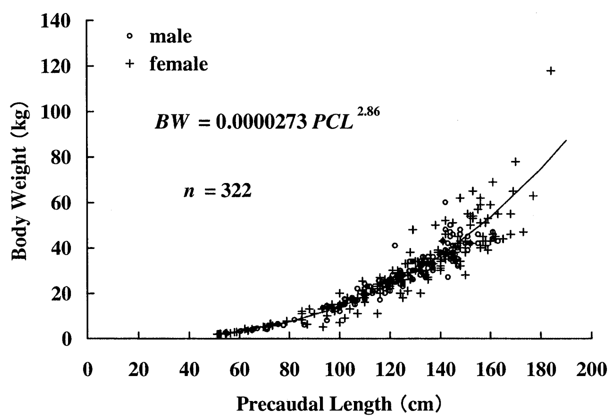

Fig. 3 Relationship between precaudal length and bodyweight of the silky shark.

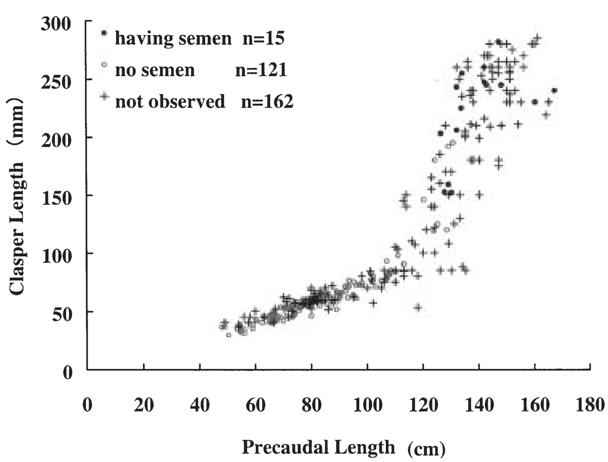

Fig. 4 Relationship between precaudal length and clasper length for 298 silky sharks.

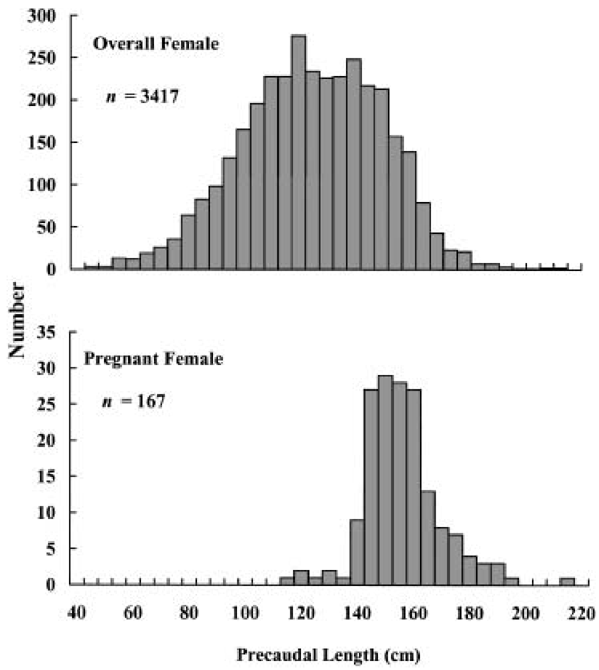

Fig. 5 The length–frequency distribution of females overall and pregnant females specifically.

The size distribution of embryos and neonates overlapped in the range 48–60 cm (Fig. 6). Therefore, birth size should be in the range of 48–60 cm. The size distribution of neonates and embryos according to season was also examined to estimate the parturition period. The smallest embryo was observed in May–July. Large embryos (> 50 cm) were observed from May–December. Although our data on the size distribution of embryos do not show an apparent parturition period, many full-term embryos were observed from May to July. Therefore, these results may suggest that the ripe season of parturition occurs from May to July.

The range in litter size of 153 pregnant females was 1–16, with an average of 6.2. The sex ratio of embryos was 1 : 1.06 for males : females for each pregnant female and the 1 : 1 sex ratio was not rejected statistically(973 individuals; $\chi^2 = 70.18$, d.f. = 149, $P > 0.05$). Litter size tended to increase with the PCL of the mother, but there was considerable variation (Fig. 7). The linear regression equation for the relationship between litter size and mother's PCL was:

$$y = 0.098x - 8.600 \ (r^2 = 0.256;\ n = 153)$$

where x is the mother's PCL and y is litter size.

Age and growth

A liner relationship was found between centrum radius (R) and PCL (Fig. 8). Data from both sexes

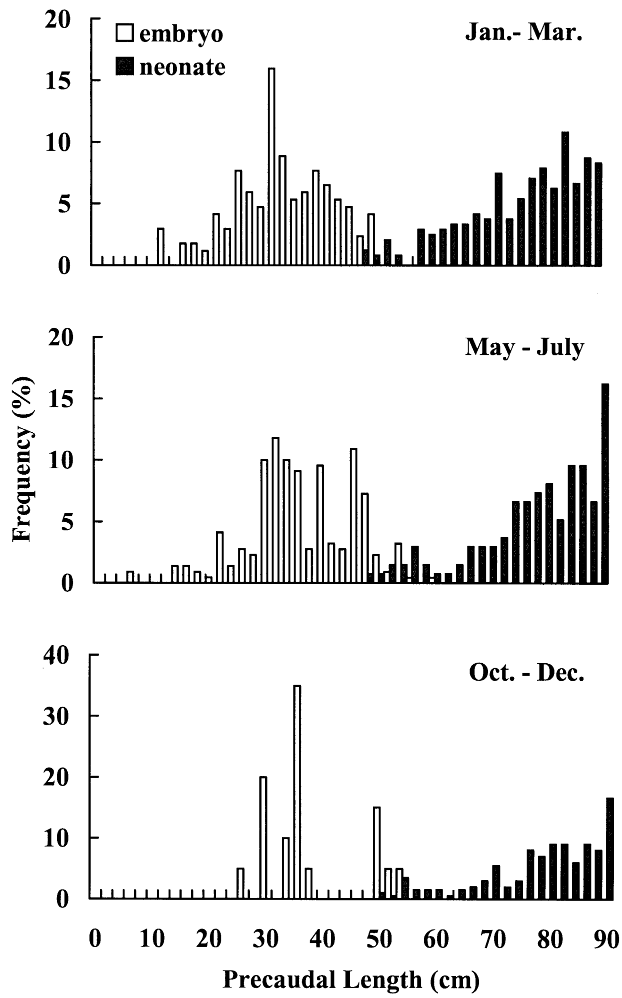

Fig. 6 Seasonal length–frequency distributions of embryos and neonates.

were combined because of no significant difference between the sexes ($F = 1.71$, $P > 0.05$, d.f. = 296). The equation obtained for the relationship between R and PCL was:

$$PCL = 10.93R + 18.94 \ (r^2 = 0.964;\ n = 298)$$

The occurrence of convex structures on the centrum surface reached a prominent peak in May (Fig. 9). We concluded that such structures are formed annually, although the convex and concave structures vary seasonally.

Rings were observed from individuals larger than 50 cm; however, no rings were observed for the smallest neonate (48 cm). It is considered that the first ring is formed just after birth (birth ring). Therefore, the first ring was excluded from the age count. The size by age was back-calculated from mean ring radius observed (Table 3). The birthday of silky sharks was assumed to be June 1 for age

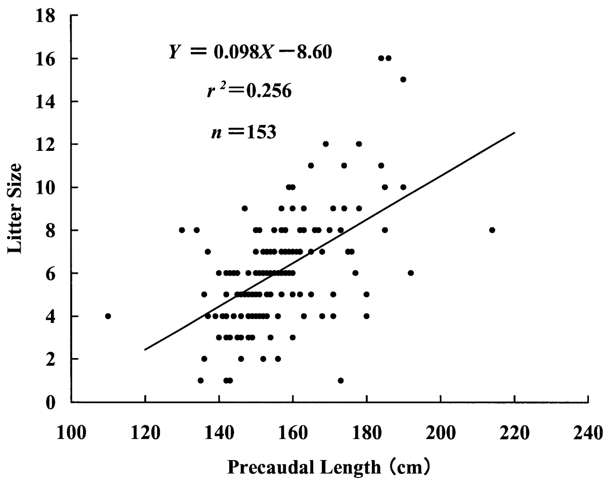

Fig. 7 Relationship between precaudal length of pregnant females and the litter size of silky sharks.

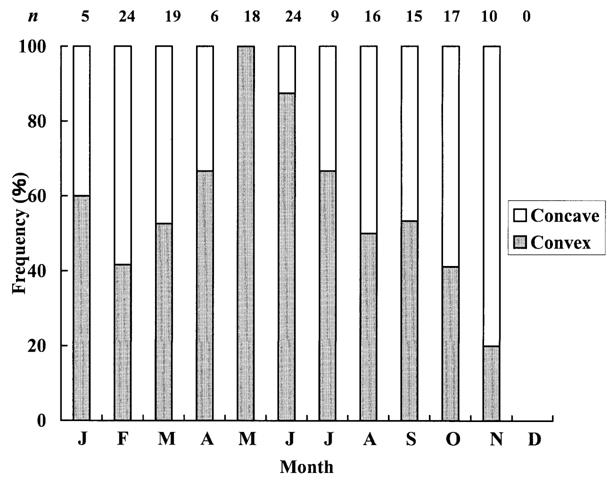

Fig. 9 Seasonality of ring formation on the centrum surface expressed as a proportion of convex and concave structures at the edge of the centrum.

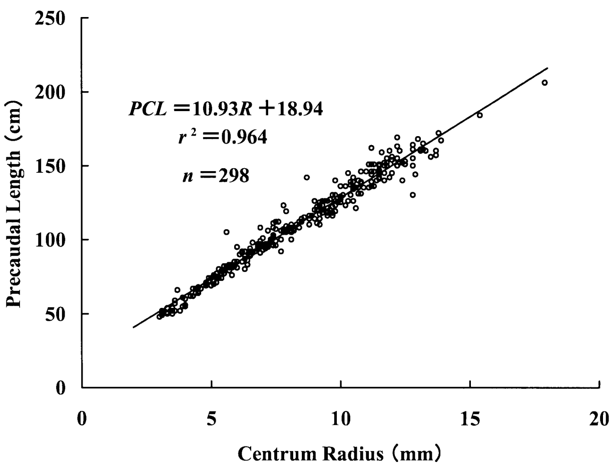

Fig. 8 Relationship between centrum radius and precaudal length of the silky shark.

estimation. Because of no significant difference observed between sexes ($F = 0.00000608$, $P = 0.99$, d.f. = 296), growth parameters were obtained for both sexes combined. The estimated von Bertalanffy growth function for combined sex was as follows:

$$L_t = 216.4(1 - e^{(0.148(t+1.76)})$$

where t is age and L_t is length at age t. The growth curves are shown in Fig. 10.

DISCUSSION

The size of maturity for the silky shark was reported as 202–208 cm (*TL*) from the central Pacific[3] and as 238–250 cm (*TL*) for females and 214 cm (*TL*) for males from the South Pacific Ocean.[10] Springer[11] considered the size of maturity was 221 cm for males and 233 cm for females in the north-west Atlantic Ocean (Table 4). According to Branstetter,[12] the size of maturity of females from the north-western Gulf of Mexico was larger than 225 cm, with an estimated age of 7–9 years, whereas the size of maturity of males was 210–220 cm with an estimated age of 6–7 years. Bonfil *et al.*[13] considered that the size of maturity of females from the Campeche Bank (Gulf of Mexico) was 232–245 cm with an estimated age of > 12 years, whereas the size of maturity of males was 225 cm with an estimated age of 10 years. In the present study, the size of maturity for females was 145–150 cm (*PCL*), with an estimated age of 6–7 years, whereas the size of maturity of males was larger than 130 cm (*PCL*) with an estimated age > 4 years. In terms of TL, maturity sizes are estimated larger than 186 cm for males and 193–200 cm for females. The estimated size of maturity of males is smaller than that reported by previous investigators. The small sample size of males with semen in the present study may have influenced the precision of male maturity estimates. However, male maturity starts from at least 126 cm. The size of maturity of females was close to the observations of Strusburg[3] and Stevens.[10]

In the present study, it is considered that birth size is in the range 48–60 cm *PCL*. As for *TL*, such sizes are estimated to be 65–81 cm (*TL*). The birth sizes of silky sharks have been reported to be 68–84 cm[11] and 76 cm[13] from the Atlantic Ocean (Table 5). The results of the present study are similar to those of the Atlantic Ocean.

Table 3 Back-calculated precaudal lengths corresponding to centrum rings and estimated age

		No. rings													
	n	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Males															
Age (years)															
0	13	57.09													
1	23	55.34	73.92												
2	29	55.12	72.39	90.53											
3	28	55.77	72.61	89.77	108.13										
4	18	56.21	74.14	90.86	108.89	118.49									
5	16	55.45	74.46	91.19	108.78	118.38	138.73								
6	8	55.34	72.82	90.09	109.44	120.13	140.04	148.90							
7	3	55.01	72.50	89.99	107.80	119.15	139.94	150.43	158.84						
8	1	57.20	75.78	89.99	104.19	111.50	133.71	144.64	155.57	166.50					
Mean		55.83	73.58	90.34	107.87	117.53	138.10	147.99	157.20	166.50					
SD		0.82	1.20	0.53	1.89	3.44	2.99	3.00	2.32						
Females															
Age (years)															
0	16	56.53													
1	26	54.35	72.61												
2	31	55.12	73.15	90.97											
3	25	56.32	74.46	91.73	110.10										
4	12	55.45	71.73	87.47	106.60	119.15									
5	17	54.79	73.04	89.33	108.35	119.15	139.72								
6	14	56.65	74.46	90.09	108.68	120.46	140.37	149.88							
7	5	55.66	72.93	92.39	109.22	120.68	140.48	151.19	161.03						
8	2	58.29	74.14	92.17	106.38	115.32	137.53	148.46	158.84	166.50					
9	1	56.10	72.50	86.71	104.19	113.68	134.80	147.91	161.03	168.77	179.61				
13	1	59.38	81.24	100.92	114.03	120.24	139.17	150.10	162.12	170.87	180.70	191.63	201.47	208.03	210.22
Mean		56.23	74.03	91.31	108.44	118.38	138.68	149.51	160.76	169.05	180.16	191.63	201.47	208.03	17.50
SD		1.49	2.69	4.12	2.94	2.76	2.18	1.32	1.38	2.28	0.77				

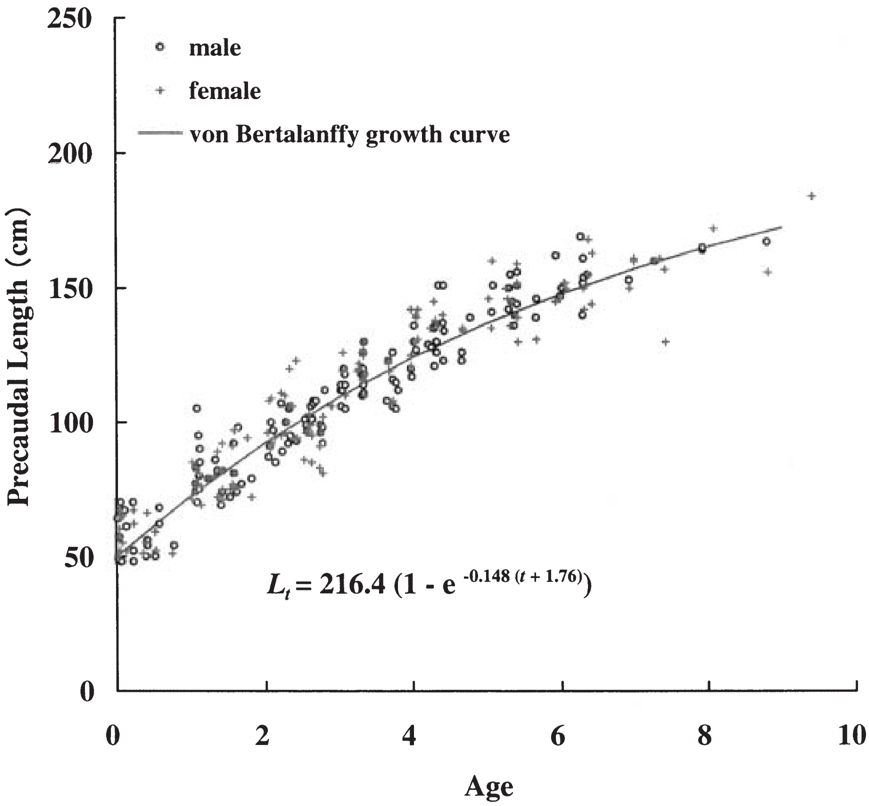

Fig. 10 The von Bertalanffy growth curves for silky sharks based on age determination by vertebra rings.

Table 4 Comparison of size and age at maturity from the present study and reports in the literature

Area	Sex	Maturity size (cm)	Maturity age (years)	Reference
Pacific	Male	200–206	5–6	This study
	Female	186	6–7	
Central Pacific	Male	–		3
	Female	202–208		
Tasman sea	Male	238–250		10
	Female	214		
Atlantic				
Western north Atlantic	Male	221		11
	Female	233		
Northwestern part of Gulf of Mexico	Male	210–220	6–7	12
	Female	225	7–9	
Off the Yucatan peninsula (Gulf of Mexico)	Male	225	10	13
	Female	232–245	12	

A study of silky sharks caught in the Gulf of Mexico suggested 12 month cycle of parturition, with late spring as the parturition period,[12,13] which is in contrast with reports that the silky shark does not have a seasonal parturition period in Indian and Pacific Ocean populations.[3,10,14,15] Although the data on embryo size distribution are not enough on their own to examine the parturition period, the results suggest that the ripe parturition season may occur from May to July. The parturition season of the silky shark is poorly known and further investigations should be conducted in the future.

The observed litter size was in the range 1–16, which is similar to the litter size of 2–12 reported from the Atlantic Ocean.[11] Our results suggest that parturition occurs throughout the year in the Pacific Ocean.

The growth functions in the present study were quite similar between male and female sharks. The growth curve in the present study was similar to

Table 5 Comparison of birth size in the present study with reports in the literature

Area	Birth size (cm)	Litter size	Reference
Pacific	65–81	1–16	This study
Atlantic			
Western north Atlantic	68–84		11
Off the Yucatan peninsula (Gulf of Mexico)	76	2–12	13

the one estimated by Branstetter.[12] In the Atlantic Ocean, Bonfil *et al.*[13] and Branstetter[12] presented two different growth equations. Bonfil *et al.*[13] pointed out that their samples were taken from inshore waters on the continental shelf for grouper and shark fishery grounds, whereas the samples of Branstetter[12] came from swordfish fishing grounds located at offshore deep waters. So, Bonfil *et al.*[13] suggested that the difference in the areas sampled, inshore versus offshore waters, would account for the different growth rates. Our result showed that there was no significant difference in growth in the Pacific Ocean and the Atlantic Ocean. It does not mean that the growth rate of the silky shark is different between inshore and offshore waters. Therefore, interobserver differences may have resulted in different growth curves.

In general, vertebrae sections are most frequently used for the age determination of elasmobranchs. However, there are some differences in the number of rings counted in same-sized species between observers.[17,18] One reason for such differences could be an additional structure existing between regular concave and convex structures on the surface of vertebrae. Such additional structures (rings) cannot be distinguished from rings (annuli) by only observation of the section. Therefore, surface observation of vertebrae was used for counting annuli in the present study. Vertebral surfaces provide more detailed information of structure than do sections and they are easier to prepare and observe. In addition, three-dimensional structures of vertebra surface were easily recognized by light. So, rings were easily distinct from the surface. It is suggested that the observation of the vertebral surface is much better than observation of sections because of more accurate ring counting.

As for the present study, there were no differences in growth rates between the Pacific and Atlantic Oceans. The parturition season, birth length, litter size and female size of maturity were also quite similar to results reported in previous studies. Therefore, the life history of the silky shark is not remarkably different in these two oceans.

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