Age and growth analysis of swordfish (*Xiphias gladius*) in the Indian Ocean based on the specimens collected by Taiwanese observer program

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Introduction

Anal fin ray has been commonly used as the hard part for age determination of swordfish in the Atlantic Ocean and Pacific Ocean (e.g. Barkeley and Houde, 1983; Ehrhardt et al., 1996; Sun et al., 2002; DeMartini et al., 2007). The results of previous studies indicated that the annuli in fin ray sections are formed once a year. In addition, sexually dimorphic growth has also been observed for swordfish in the Atlantic Ocean and Pacific Ocean. In this study, therefore, we attempted to determine the age of swordfish in the Indian Ocean and to estimate the sex-specific growth parameters based on the specimens of anal fin ray collected by Taiwanese observer program deployed in the tuna longline fleet in the Indian Ocean.

Methods and materials

The age determination was based on the annuli on the cross sections of the second rays of the first anal fin. The anal fin specimens and fish measurements, including sampling date, sampling location, length (lower jaw fork length; LJFL), weight (round weight; RW) and sex, were collected from May 2007 to April 2008. All of specimens were collected in the area with the longitude of 35°E-95°E and the latitude of 15°S-10°N (Fig. 1). According to the sub-area definition of IOTC (2009) for swordfish, we also attempted to the divided the specimens into eastern and western sub-groups by around 70°E for examining the spatial difference in growth.

In total, 1152 fish measurements and 983 anal fin specimens were collected. The cross sections with thickness of 0.7 mm were cut from the fin rays at the location based on the standard protocol (Ehrhardt et al., 1996; Sun et al. 2002) using a low-speed saw. The sections were examined under a dissecting microscope (OLYMPUS SZX7) with transmitted light. The images of sections were captured and measured using the image analysis software (Motic Images Plus 2.0) in combination with the CCD camera system (Moticam 2300).

The relationship between ray radius and LJFL was determined by using a power function, $L = aS^b$ (Ehrhardt et. al., 1996) and the individual length-at-age was back-calculated by the following formula (Ehrhardt et al., 1996):

$$L_n = \left(\frac{S_n}{S}\right)^b L$$

where L is the LJFL of capture, L_n is the LJFL when band n formed, S is the ray radius, and S_n is the distance from focus to band n (Fig. 2).

The von Bertalanffy growth function was then fitted to individual back-calculated length-at-age for males and females, respectively. The von Bertalanffy growth function is

$$L_t = L_\infty(1 - e^{-K(t-t_0)})$$

where L_t is the LJFL at age t, L_∞ is the asymptotic length, K is the growth coefficients, and t_0 is the hypothetical age at length zero.

The parameters of length-weight relationship and von Bertalanffy growth function were estimated using nonlinear least-squares estimation function of R (version 2.11.1, 2010). The sex-specific length-weight relationship and von Bertalanffy growth function were examined by likelihood ratio test (Kimura, 1980).

Results and discussion

Fig. 3 shows the length-frequency distributions for males and females. The lengths of specimens ranged from 60 to 260 cm for both sexes. However, females concentrated between 130 and 170 cm with wider range, while males concentrated between 130 and 150 cm and the proportion of male individuals decreased at the length larger than 160 cm.

The length-weight relationships were not statistically different between sexes for entire Indian Ocean ($\chi^2 = 2.75$, p = 0.43) and for western sub-group ($\chi^2 = 0.55$, p = 0.91), while they were statistically different between sexes for eastern sub-group ($\chi^2 = 13.32$, p ≈ 0.01). In addition, the length-weight relationships were not statistically different between sub-groups for females ($\chi^2 = 4.07$, p = 0.25), while they were significant different between sub-groups for males ($\chi^2 = 16.70$, p < 0.01). Since the sample sizes for males and for eastern sub-group was much less than those for females and western sub-group, the length-weight relationship was estimated by pooling male and female data (524 males and 628 female) (Fig. 4) and the relationship is

$$RW = 9.133 \times 10^{-6} LJFL^{3.012}$$

A total of 834 specimens can be used for age determination (about 85% of total specimens) and the monthly sample sizes were listed in Table 1. Excluding the sections without ring (age 0 group; 32 males and 24 males), the ages of 341 males and 437 females were successfully determined. The sex-specific proportions of specimens by 10-cm LJFL interval and by age-group are listed in Table 2 and 3. The relationships between ray radius and LJFL for males and females are shown in Fig. 5. The parameters of von Bertalanffy growth function were estimated by fitting to the sex-specific back-calculated lengths-at-age. The growth functions were statistically different between males and females ($\chi^2 = 20.53$, p < 0.01) (Fig. 5), and the estimated von Bertalanffy growth function for males and females are

Male: $L_t = 234.002(1 - e^{-0.169(t+2.181)})$

Female: $L_t = 274.855(1 - e^{-0.138(t+1.998)})$

The sex-specific back-calculated lengths-at-age and von Bertalanffy growth curves

are shown in Fig. 6.

The results of spatial comparisons revealed that the growth functions were statistically different between eastern and western sub-groups for both sexes (χ^2 = 13.78, p < 0.01 for male; χ^2 = 10.82, p = 0.01 for female). The sex- and area-specific back-calculated lengths-at-age and von Bertalanffy growth curves are shown in Figs. 7 and 8. However, the growth estimations might be confounded due to the bias in sampling procedure. For instance, only two anal fin specimens for eastern sub-group were collected during February to June and sampled fishes might grow with different environmental condition. In addition, spawning of swordfish in the Indian Ocean might occur in different spawning grounds (Poisson and Fauvel, 2009). Therefore, more investigations are needed for understanding the population structure of swordfish in the Indian Ocean.

Wihtin sub-group, the growth functions were also statistically different between males and females (χ^2 = 11.66, p < 0.01 for eastern sub-group; χ^2 = 16.18, p < 0.01 for western sub-group). As the results for the swordfish in other oceans, the female swordfish in the Indian Ocean would grow faster than males and reach larger body length. The sex-specific parameters of von Bertalanffy growth function for eastern and western sub-groups were listed Table 4.

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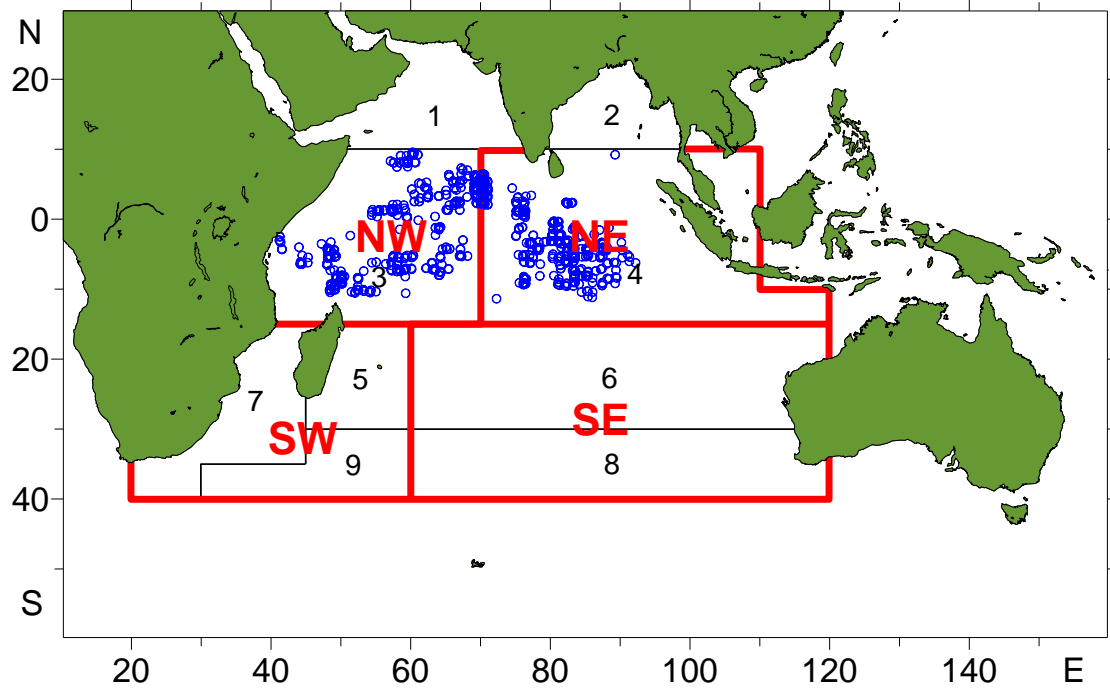
Fig. 1. Distribution of swordfish specimens collected by Taiwanese observer program deployed in the Indian Ocean during 2007-2008.
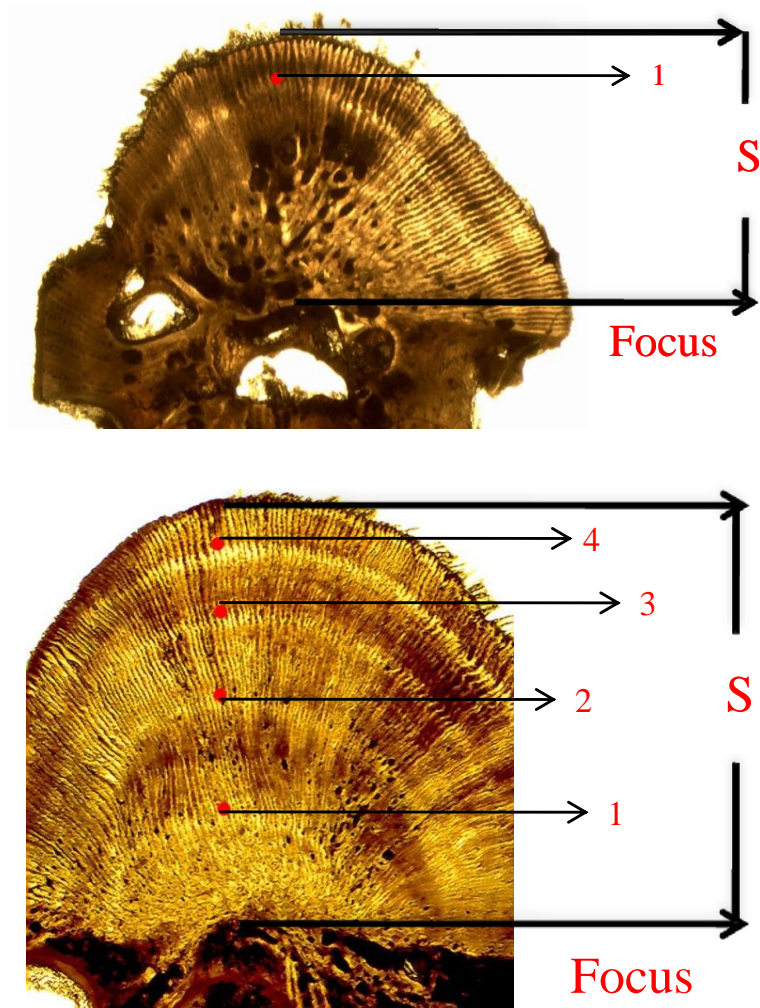
Fig. 2. Illustrations for sections of the second ray of the first anal fin based on swordfish specimens collected by Taiwanese observer program deployed in the Indian Ocean.
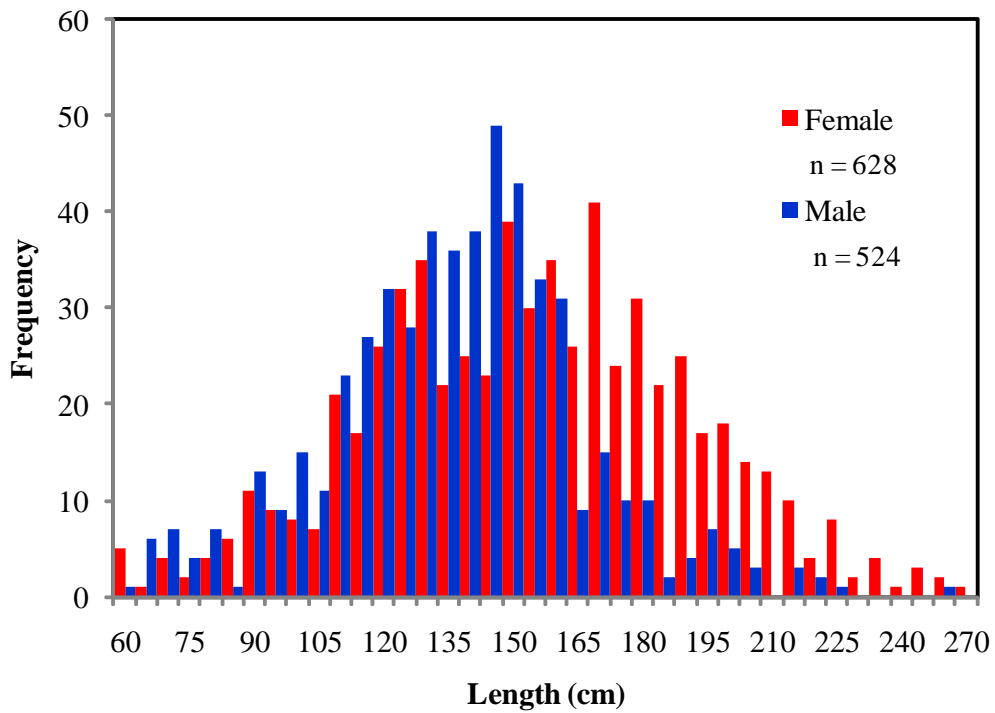
Fig. 3. Length (LJFL)-frequency by 5-cm interval based on swordfish specimens collected by Taiwanese observer program deployed in the Indian Ocean
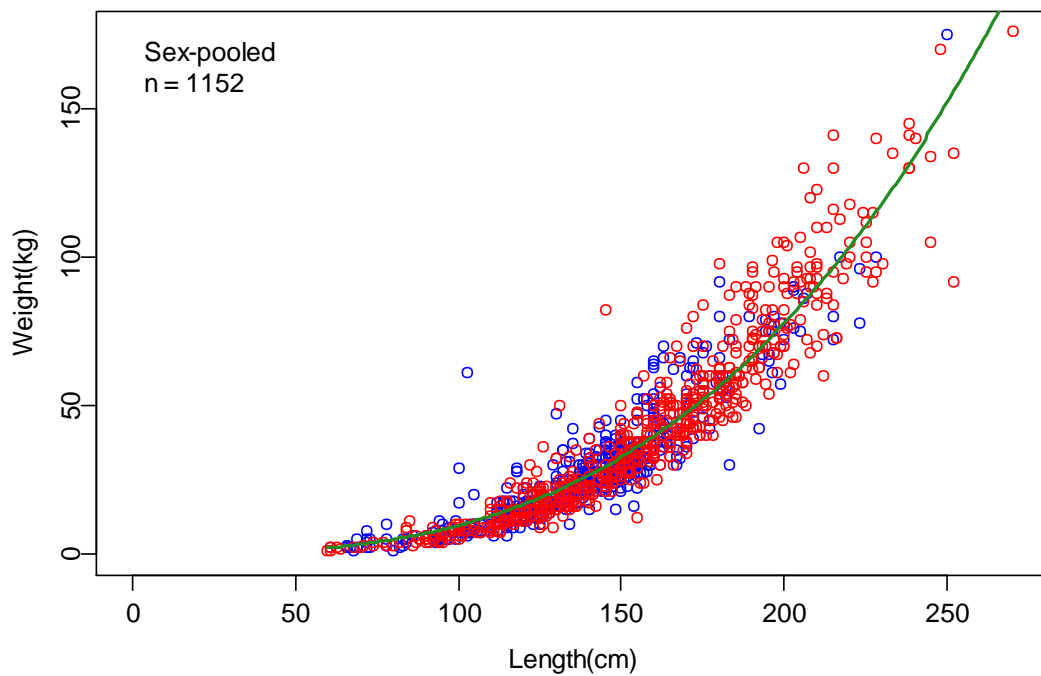

Fig. 4. Length (LJFJ)-weight (round weight) relationship based on swordfish specimens collected by Taiwanese observer program deployed in the Indian Ocean
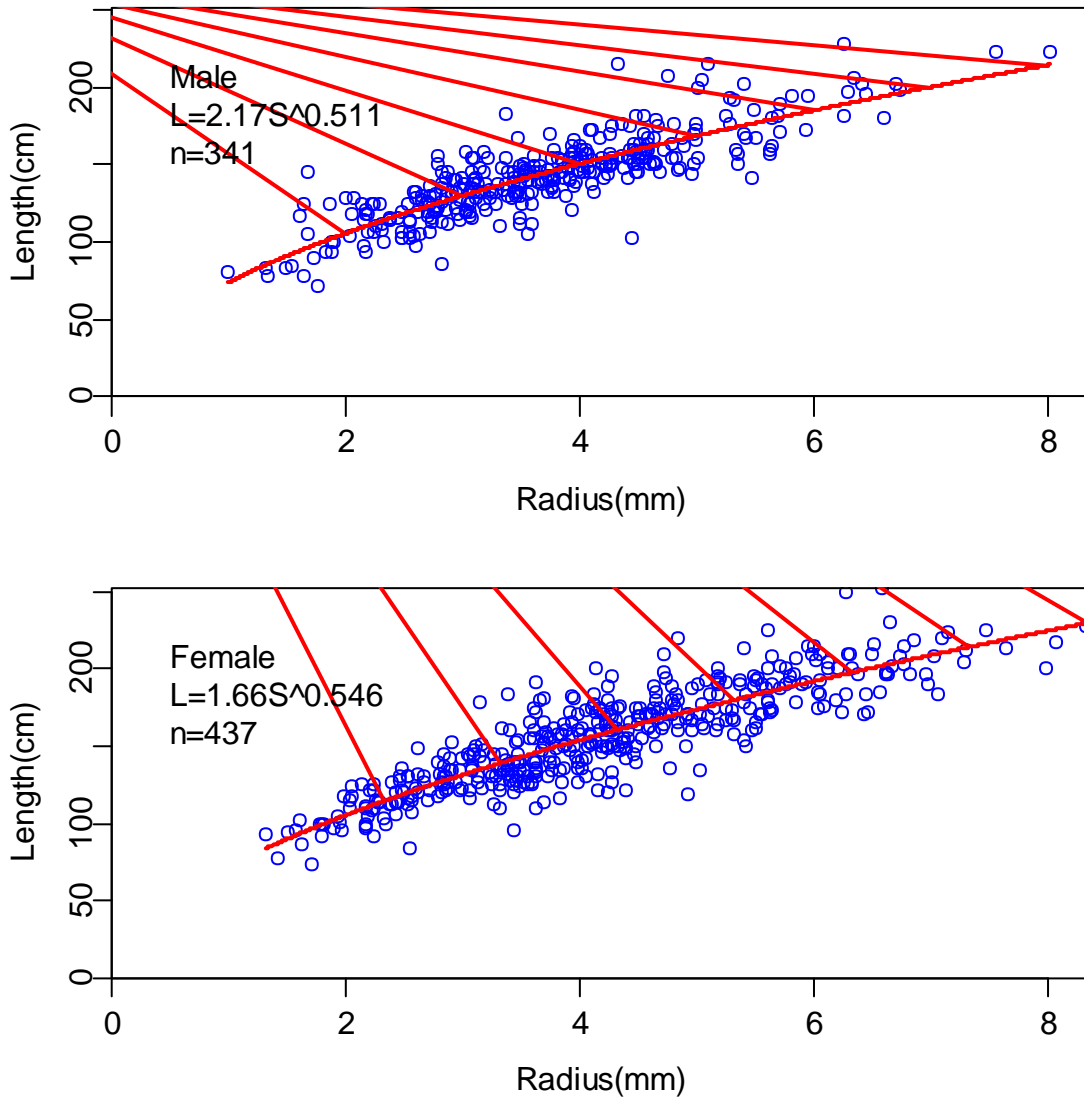
Fig. 5. Relationship between ray radius and length (LJFL) based o swordfish
specimens collected by Taiwanese observer program deployed in the Indian Ocean.

Fig. 6. Back-calculated lengths-at-age (LJFL) and von Bertalanffy growth curves based on swordfish specimens collected by Taiwanese observer program deployed in the Indian Ocean.

Fig. 7. Back-calculated lengths-at-age (LJFL) and von Bertalanffy growth curves based on swordfish specimens in eastern sub-group collected by Taiwanese observer program deployed in the Indian Ocean.

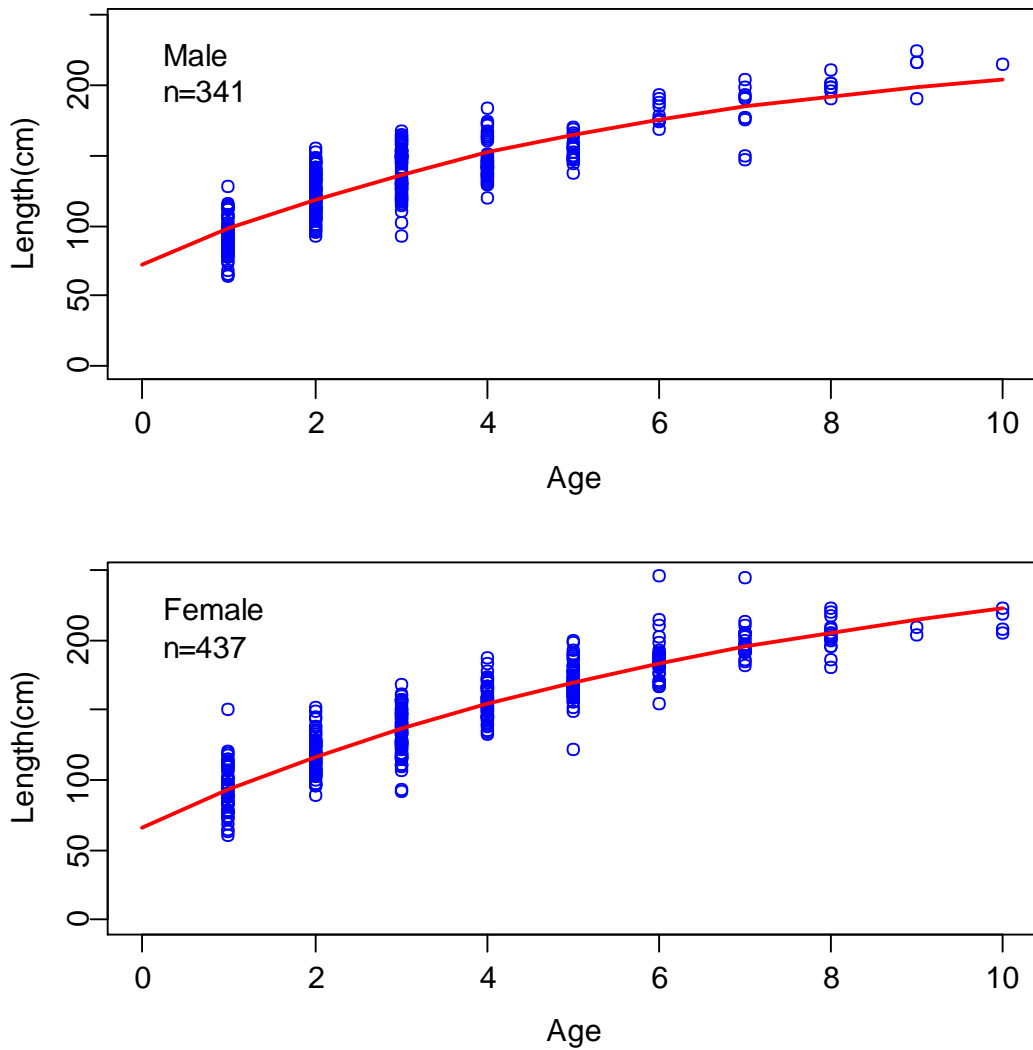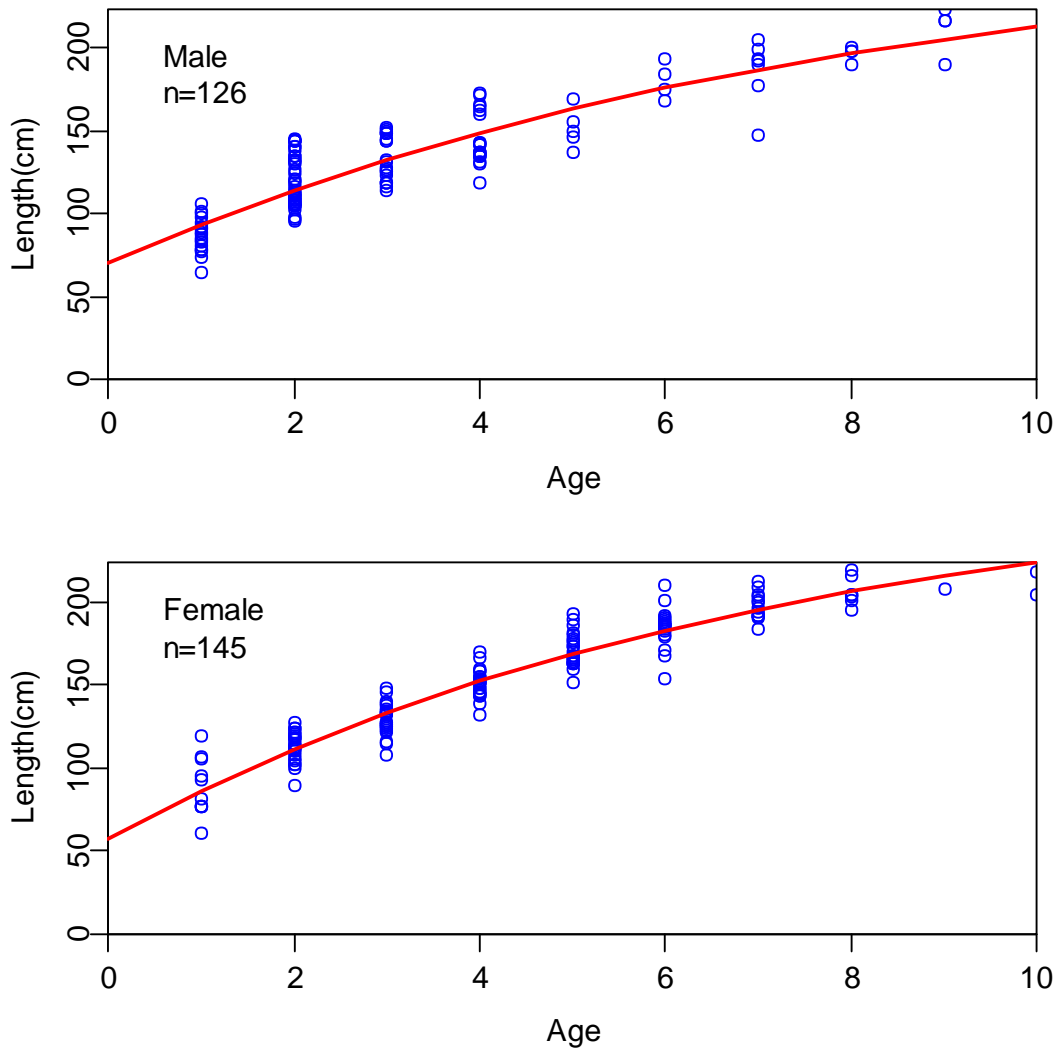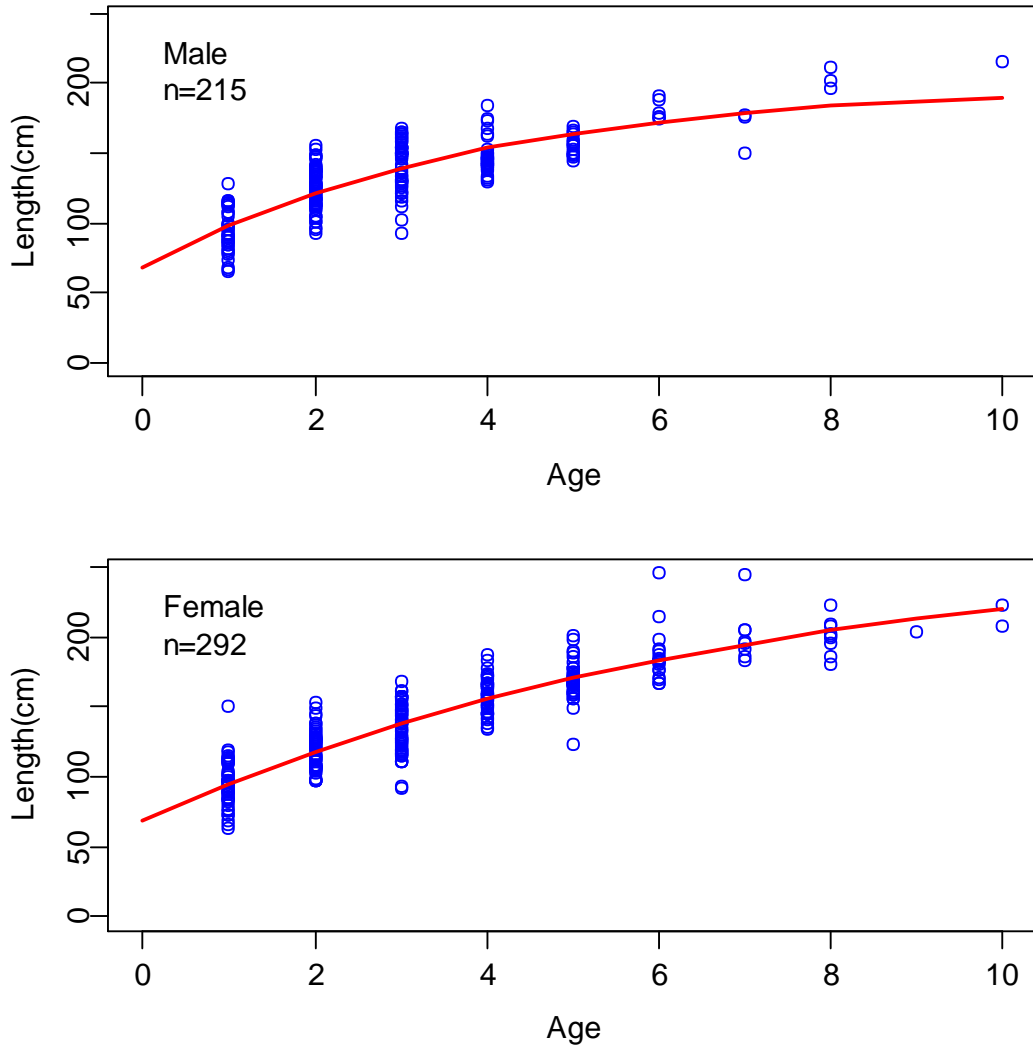Fig. 8. Back-calculated lengths-at-age (LJFL) and von Bertalanffy growth curves based on swordfish specimens in western sub-group collected by Taiwanese observer program deployed in the Indian Ocean.

Table 1. Sample sizes of anal fin ray used for age determination of swordfish specimens collected by Taiwanese observer program deployed in the Indian Ocean.

Month	Eastern sub-group		Western sub-group		Total
	Female	Male	Female	Male	
1	15	11	28	31	85
2			6	16	22
3	1		12	18	31
4	1		2	4	7
5			15	8	23
6			15	6	21
7	20	24	2		46
8	38	33	29	13	113
9	17	22	38	22	99
10	22	16	64	42	144
11	23	18	67	41	149
12	16	16	30	32	94
Total	153	140	308	233	834

Table 2. The proportions of samples by 10 cm length interval (LJFL) and by age-group based on female swordfish specimens collected by Taiwanese observer program deployed in the Indian Ocean.

Length \ Age	0	1	2	3	4	5	6	7	8	9	10
60	1.00										
70	0.67	0.33									
80	0.71	0.29									
90	0.31	0.56	0.06	0.06							
100	0.08	0.77	0.15								
110	0.12	0.48	0.33	0.06							
120		0.24	0.51	0.24							
130		0.12	0.41	0.47							
140			0.31	0.59	0.10						
150			0.09	0.34	0.50	0.07					
160		0.02	0.04	0.25	0.52	0.15	0.02				
170					0.31	0.60	0.10				
180				0.03	0.10	0.50	0.33		0.03		
190					0.06	0.13	0.50	0.28	0.03		
200						0.11	0.21	0.37	0.32		
210						0.07	0.07	0.29	0.36	0.14	0.07
220							0.17		0.33		0.50
230									1.00		
240											
250							0.50	0.50			

Table 3. The proportions of samples by 10 cm length interval (LJFL) and by age-group based on male swordfish specimens collected by Taiwanese observer program deployed in the Indian Ocean.

Length \ Age	0	1	2	3	4	5	6	7	8	9	10
60	1.00										
70	0.50	0.50									
80	0.38	0.63									
90	0.60	0.40									
100	0.18	0.59	0.14	0.09							
110	0.18	0.33	0.48								
120	0.05	0.16	0.65	0.12	0.02						
130	0.02	0.13	0.34	0.43	0.08						
140		0.03	0.44	0.08	0.41	0.03					
150			0.21	0.38	0.19	0.19		0.04			
160			0.12	0.46	0.23	0.19					
170				0.28	0.33	0.22	0.17				
180					0.20		0.40	0.40			
190							0.43	0.29	0.14	0.14	
200								0.29	0.71		
210									0.50		0.50
220										1.00	

Teble 4. The parameter estimates of von Bertanalffy growth function based on swordfish specimens collected by Taiwanese observer program deployed in the Indian Ocean.

Group	L_∞	K	t_0
Male	234.002	0.169	-2.181
Female	274.855	0.138	-1.998
Eastern sub-group			
Male	270.809	0.125	-2.407
Female	276.518	0.143	-1.613
Western sub-group			
Male	199.887	0.259	-1.629
Female	267.315	0.144	-2.053