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The swordfish, *Xiphias gladius*, is a pelagic migratory species distributed widely from tropical to temperate waters of all Oceans (Nakamura, 1985). In the waters of Taiwan, swordfish are mainly caught by longline fisheries as bycatch and a few by harpoon, gill net, or set net.

Sex ratios and sexual maturity are fundamental biological parameters for incorporation into stock assessments. There has been no study on the reproductive biology for swordfish in the western Pacific since the work of Yabe *et al.* (1959). The objective of this study is to estimate the sex ratios and sexual maturity for swordfish in the waters of Taiwan. The results of this study will be used as biological parameters for further evaluations of this stock.

MATERIALS AND METHODS

Gonad samples of swordfish and the measurements including lower jaw fork length (L_{LJF}), eye fork length (L_{EF}), and round weight (W_R) were collected monthly in Shinkang fish market (Fig .1) during July 1998 to June 2000. Sex of each sample was identified based on the appearance of gonad. Gonads were weighted and then preserved in 10% buffered formalin for later histological analysis and measurement of oocytes. Monthly sex ratios were obtained from Tungkang, Nanfangao and Shinkang fish markets (Fig. 1) from September 1997 to July 2000.

Sex ratio by month and length class (5-cm length interval) was expressed as the proportion of females to total numbers of females and males.

$$sex\ ratio = \frac{numbers\ of\ females}{numbers\ of\ females + numbers\ of\ males} \text{ ---------- (1)}$$

Gonad index (I_G) was calculated following the equation used by other studies (Hinton et al., 1997; Uosaki and Bayliff, 1999; DeMartini et al., 2000):

$$I_G = \frac{\ln(W_G)}{\ln(L_{EF})} \text{ ---------- (2)}$$

where W_G is the gonad weight and L_{EF} is the eye fork length. Notice that the L_{EF} instead of L_{LJF} was used in the equation.

Subsamples taken from fixed gonads were washed, dehydrated in alcohol and xylene, and infiltrated with paraffin. Histological sections of 5~7 μm were cut by using Leica 2055 rotary microtome and stained with Harris's hematoxylin and eosin counterstain (Hunter & Macewicz, 1985). Microscopic slides were examined with a Nikon SE compound microscope at a magnification of 40~400x. Gonadal developmental stages were categorized based on the criteria of DeMartini *et al.* (2000) which were specified by Murphy & Taylor (1990) and de Sylva and Breder (1997). Developmental stages of oocytes were classified into (1) undeveloped stage, (2) developing stage, (3) maturing stage, (4) ripening stage, (5) spawning stage, (6) recently spawned stage and (7) spent or resting stage (Table I). Individuals were designated as mature if the most advanced oocytes were indicative of ≧ class 4 (Table 1).

The length at 50% sexual maturity (L_{50}), e.g. the length at which 50% of individuals sampled were sexually mature, was estimated based on the proportion of mature individuals at each 5 cm length class and the fitted logistic curve (King, 1995) as follows:

$$P = \frac{1}{1 + \exp[r \times (L - L_{50})]} \text{ ---------- (3)}$$

where P is the proportion of mature individuals within a length class; r is the slope of the curve; and L_{50} is the length (L_{LJF}) at 50% sexual maturity. L_{50} and r were estimated by using the nonlinear regression procedure of SAS statistics program.

RESULTS

A total of 208 gonads of female swordfish were collected in Shinkang fish market. The range of body length (L_{LJF}) was 95 to 257 cm (Fig. 2). In addition, L_{LJF} measurements of 551 females and 387 males were collected in Tungkang, Nanfangao and Shinkang fish markets for sex ratio analysis. The range of L_{LJF} was 83 to 290 cm for females and 78 to 243 cm for males, both concentrated in between 95 and 170 cm (Fig. 3).

The total number of female samples was more than that of males. The estimated sex ratio for all samples was 0.59, which was significantly different ($\chi^2 = 28.67$; $P < 0.01$) from the expected 1:1 (sex ratio = 0.5).

Monthly sex ratio exhibited that the proportion of females was higher than males for each month. Especially in the period from February to July and in October, the sex ratios were significantly different from 1:1 (sex ratio = 0.5).

Sex ratio fluctuated from 0.4 to 0.7 without significant pattern at L_{LJF} less than 150 cm. Sex ratio increased with L_{LJF} greater than 150 cm and all samples were females (sex ratio = 1) at L_{LJF} larger than 210 cm (Fig. 4). The relationship between sex ratio and L_{LJF} at range from 150 to 210 cm were expressed as

$$\text{Sex ratio} = 2\times10^{-4}\, L_{LJF}^{\;1.5534} \quad (r^2 = 0.8386;\ n = 938)$$

The mean monthly I_G values of female swordfish fluctuated around an $I_G = 1$ (Fig. 5). Except for the period from March to June, mean monthly I_G values were less than 1. For the individual I_G estimates of all female samples collected in the waters of Taiwan, only two (1.508 and 1.382 respectively) were greater than the reproductively active index, $I_G = 1.375$ proposed by Hinton *et al.* (1997).

The results of the two-way analyses of variance did not indicate significant differences in the numbers and diameters of oocytes among three locations within the ovary and between the right and left ovaries of gonads ($P > 0.05$). For the convenience of sampling, the posterior portion was selected for histological analysis, counts and measurements of oocytes in this study.

All the histological sections of gonad samples were observed (Fig. 6) and the sexual maturity stages were determined based on the developmental stages (Table 1). 47 of the total 208 female samples were designated as mature (developmental stage ≧ class 4). The smallest mature female was 135 cm L_{LJF}. Of the 47 mature females, 37 females were in the stage of ripening, 10 were resting, and none was spawning or recently spawned. No hydrated oocytes were observed for all gonad samples including the two whose I_G values were greater than 1.375.

The proportion of mature female for each length class (5-cm interval) was fitted to the logistic curve to estimate the L_{50}:

$$P = \frac{1}{1+\exp[-0.1392\times(L-168.16)]} \quad (r^2 = 0.9863; n = 208)$$

the 95% C.I. for L_{50} was 168.16 ± 1.61 cm (Fig. 7), and the age at maturity was about 5 years (Sun et al., 2002).

DISCUSSION

Except for DeMartini *et al.* (2000), estimates of sex ratio for swordfish in other previous studies were higher than this study. The sex ratio of swordfish caught by the Hawaii-based longline fishery was 0.53 (DeMartini *et al.*, 2000). It was 2.94: 1 (sex ratio = 0.75) for the swordfish caught off the coast of southern California (Weber & Goldberg, 1986); 2.3: 1 (sex ratio = 0.70) for the swordfish caught by Canadian fishery in western North Atlantic (Stone & Porter, 1997); and 2.25: 1 (sex ratio = 0.69) for the swordfish in the eastern Australian AFZ (Young *et al.*, 2000). In this study, the relationship between sex ratio and length showed that the sex ratio fluctuated around 0.5 at length less than 170 cm L_{LJF} (Fig. 4). The number of samples for which the length of specimens was less than 170 cm L_{LJF} was 312 for female and 294 for male, respectively. The sex ratio was 1.06: 1 (sex ratio = 0.51), not significantly different from 1: 1 ($\chi^2 = 0.53$; $P > 0.05$). Since most samples of swordfish caught in the waters of Taiwan were less than 170 cm L_{LJF} (Fig. 2), not surprisingly, the sex ratio of swordfish in Taiwan waters was more close to 0.5.

The estimate of length at sexual maturity has been reported by other methods in previous reproductive researches for swordfish (Table 2). Yabe *et al.* (1959) estimated the body size at sexual maturity as 150~170 cm L_{EF} (or 168~189 cm L_{LJF} according to the relationship between L_{LJF} and L_{EF} in our study) for female swordfish in the western Pacific Ocean by analyzing the relationship between gonad weight and body length. Kume & Joseph (1969) assumed that the eastern Pacific female swordfish was about to spawn when the gonad index was equal to or greater than 3, and the body length was about 170 cm L_{EF} (about 189 cm L_{LJF}). Sosa-Nishizaki's (1990) estimate of length at sexual maturity at about 160 cm L_{EF} (about 178 cm L_{LJF}) for "most individuals" was also inferred from a length-based I_G (DeMartini *et al.*, 2000). In the Straits of Florida and the adjacent waters, Taylor & Murphy (1992) using histological evaluations estimated a L_{50} of 182 cm L_{LJF} for females and 112 cm L_{LJF} for males. In the Mediterranean, de la Serna *et al.* (1996) estimated a L_{50} of 142 cm L_{LJF} for female swordfish by analyzing gonad indices by length-class and validated it with histological method. In the western Atlantic Ocean, Arocha & Lee (1996) estimated that the L_{50} was 179 cm L_{LJF} for female swordfish and 129 cm L_{LJF} for male based on the observation of ovaries with yolked or hydrated oocytes for females and testis with milt for males. DeMartini *et al.* (2000) estimated L_{50} for female and male swordfish caught by Hawaii-based longline fishery based on histological information, the result was 143.6 and 102.0 cm L_{EF}, respectively (equal to 161.8 and 117.3 cm L_{LJF}, respectively). In this study, the L_{50} for female swordfish caught in Taiwan waters was estimated based on histological analysis. The result was similar to those in the western or central Pacific Ocean and was different from those in other areas.

According to the results of the gonad index estimation and the histological observation of ovaries in this study, there was no hydrated oocyte in our samples, and I_G values of all samples except two were below the reproductively active index, I_G = 1.375. This phenomenon indicated that swordfish are reproductively inactive in the waters of Taiwan.

Acknowledgements

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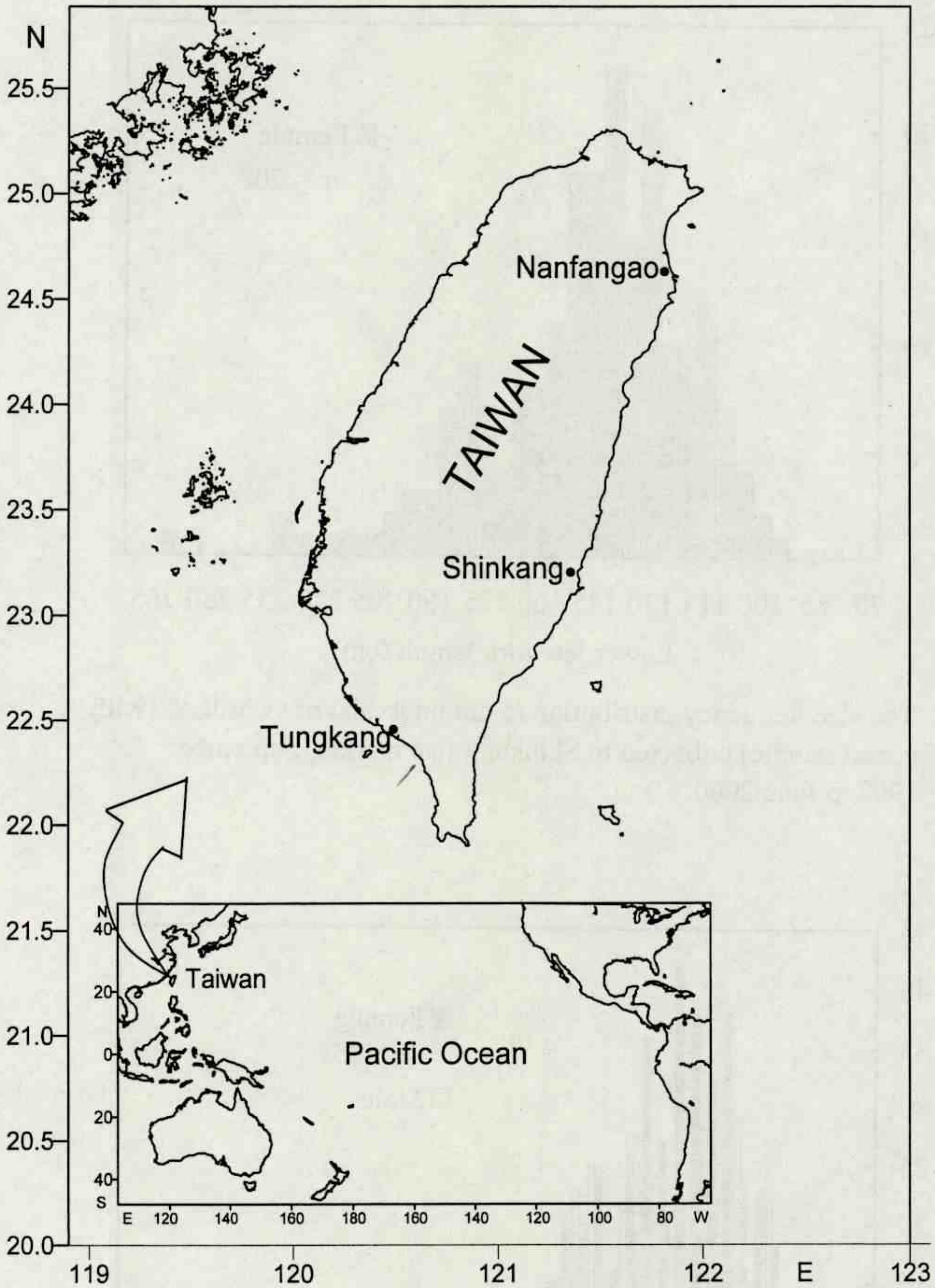

Fig. 1. The fishing ports in Taiwan where the gonad samples of swordfish and the measurements for sex ratio analysis were collected in this study.

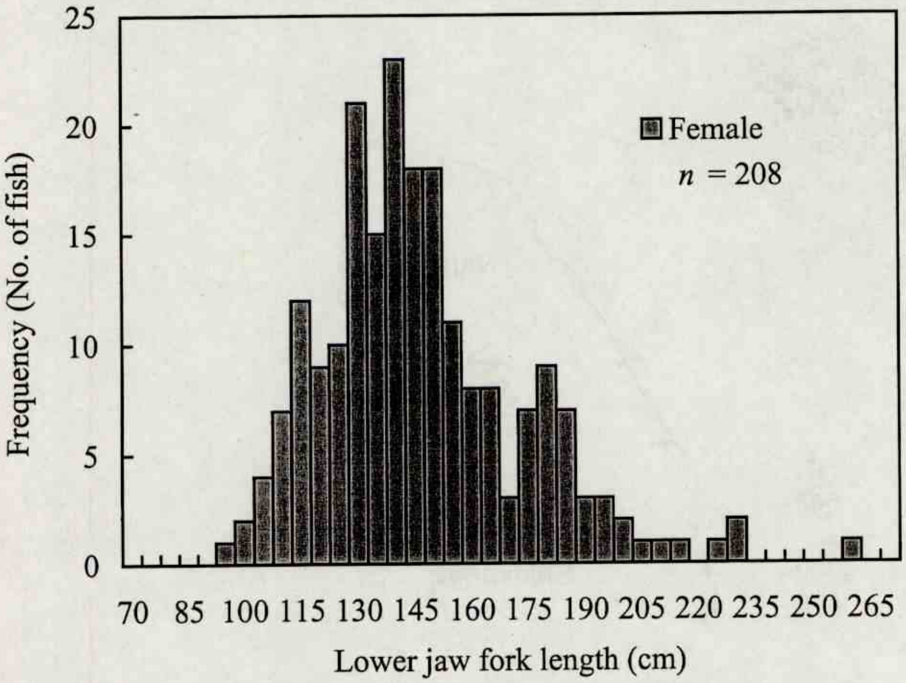

Fig. 2. The size frequency distribution (5 cm intervals) of swordfish (with gonad sample) collected in Shinkang fish market, September 1997 to June 2000.

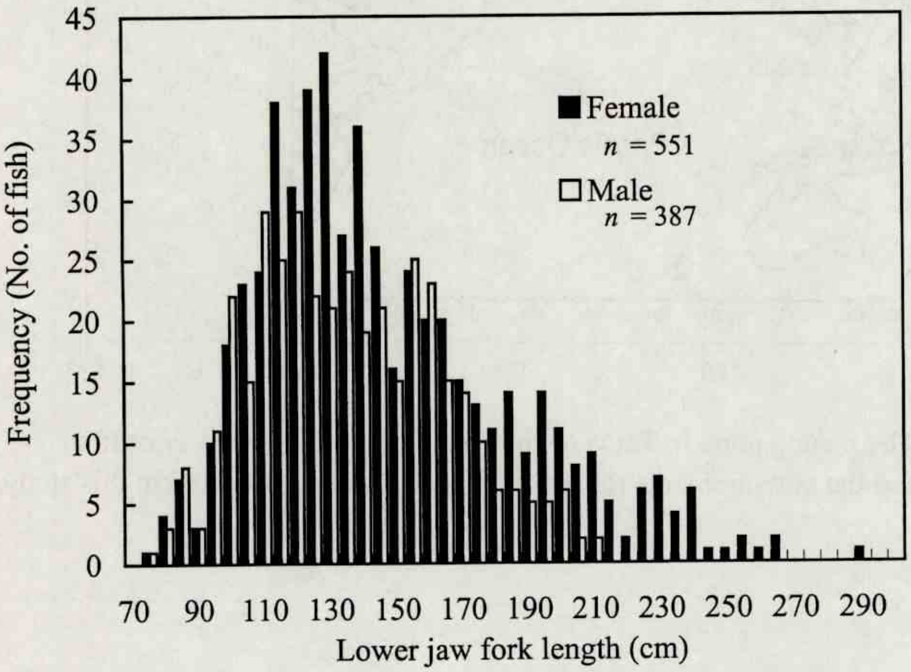

Fig. 3. The size frequency distribution (5 cm intervals) of swordfish collected in Tungkang, Nanfangao and Shinkang fish markets, September 1997 to June 2000.

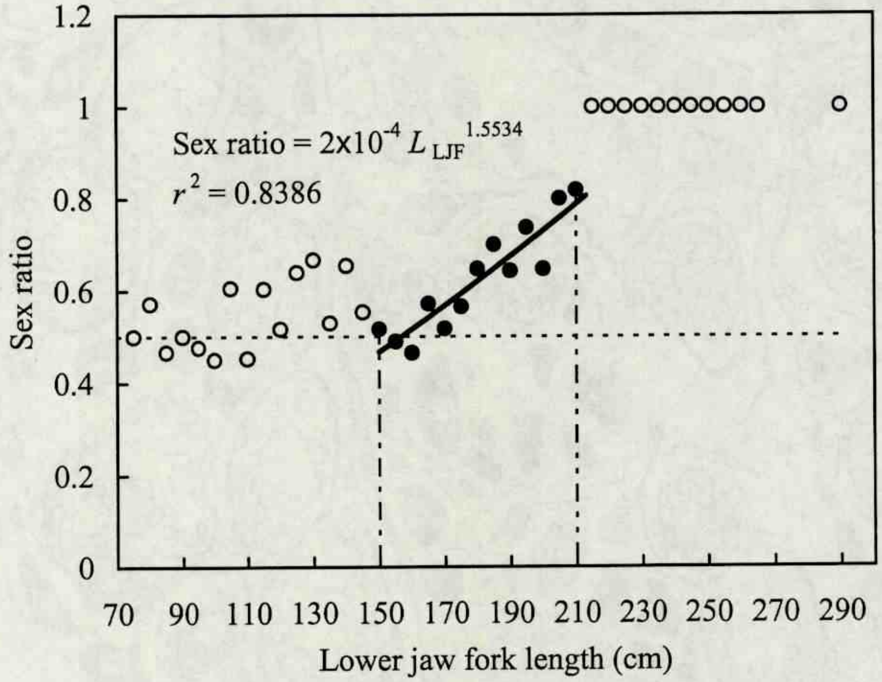

Fig. 4. Relationship between sex ratio and lower jaw fork length (L_{LJF}, 5-cm classes) for swordfish collected from Tungkang, Nanfangao and Shinkang fish markets, September 1997 to June 2000.

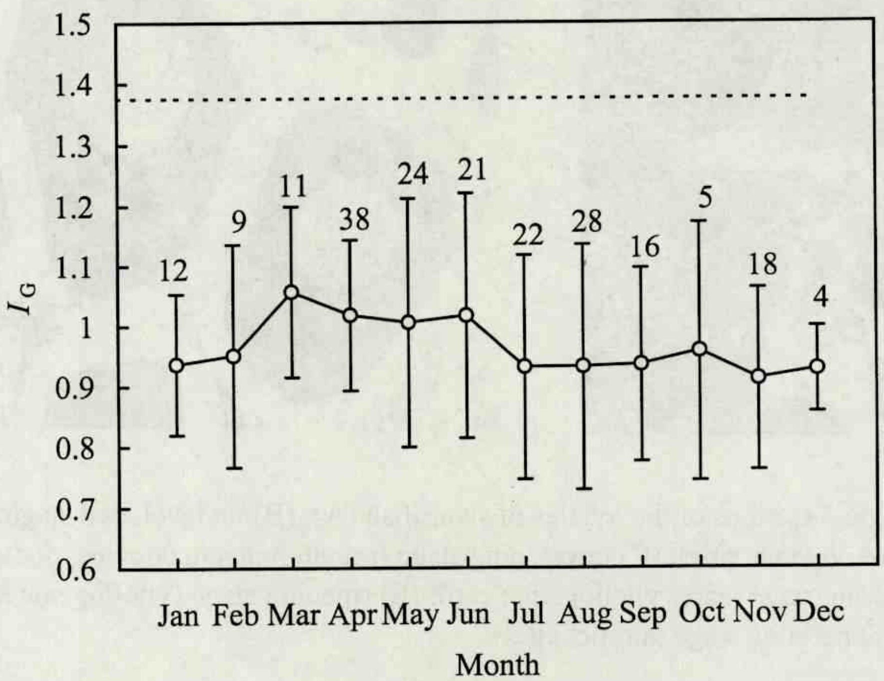

Fig. 5. Monthly variation in mean gonad index of female swordfish collected from Shinkang fish market, July 1998 to June 2000 (Dotted line present the I_G = 1.375; vertical bar is the standard error for each month).

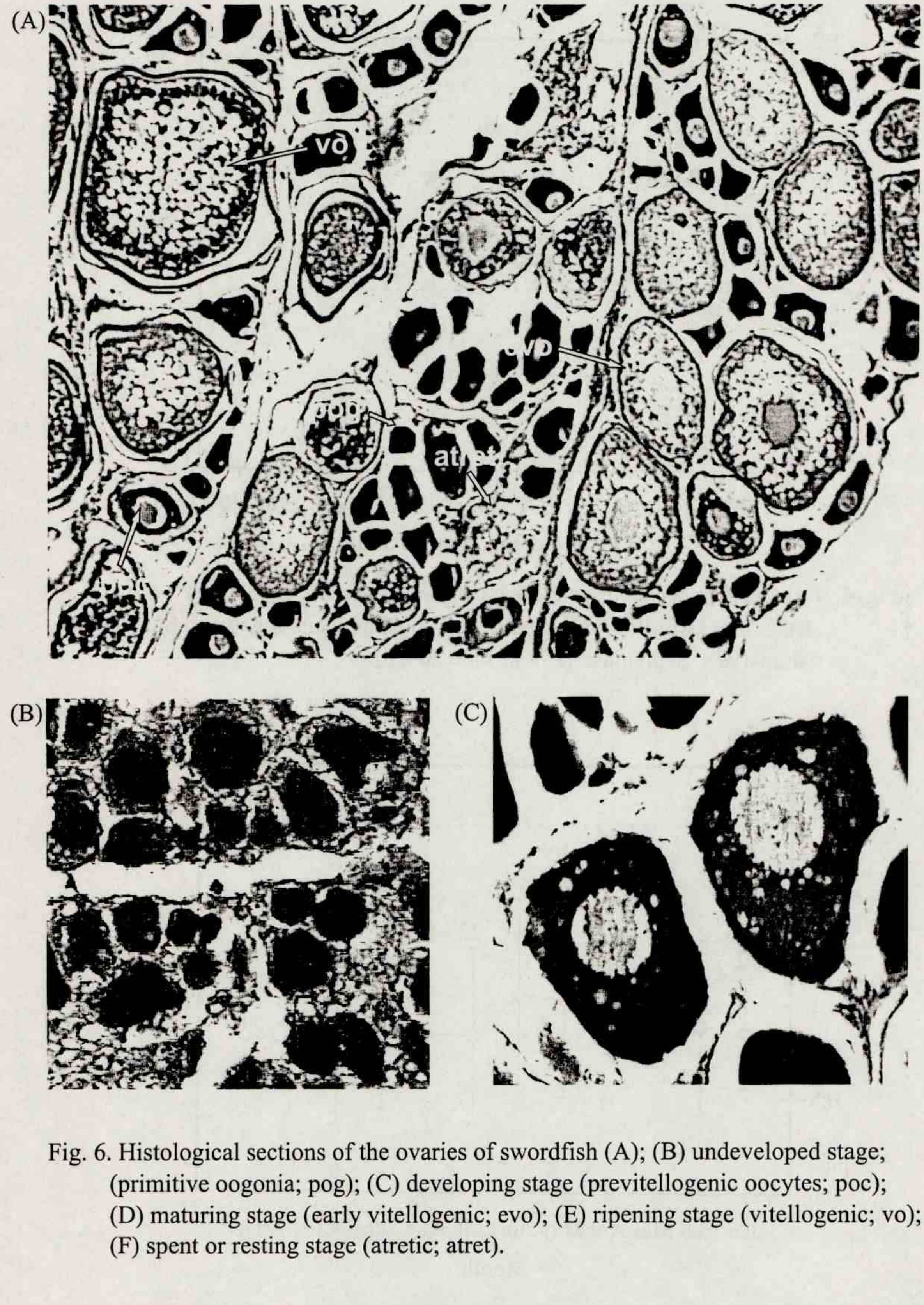

Fig. 6. Histological sections of the ovaries of swordfish (A); (B) undeveloped stage; (primitive oogonia; pog); (C) developing stage (previtellogenic oocytes; poc); (D) maturing stage (early vitellogenic; evo); (E) ripening stage (vitellogenic; vo); (F) spent or resting stage (atretic; atret).

(D)

(E)

(F)

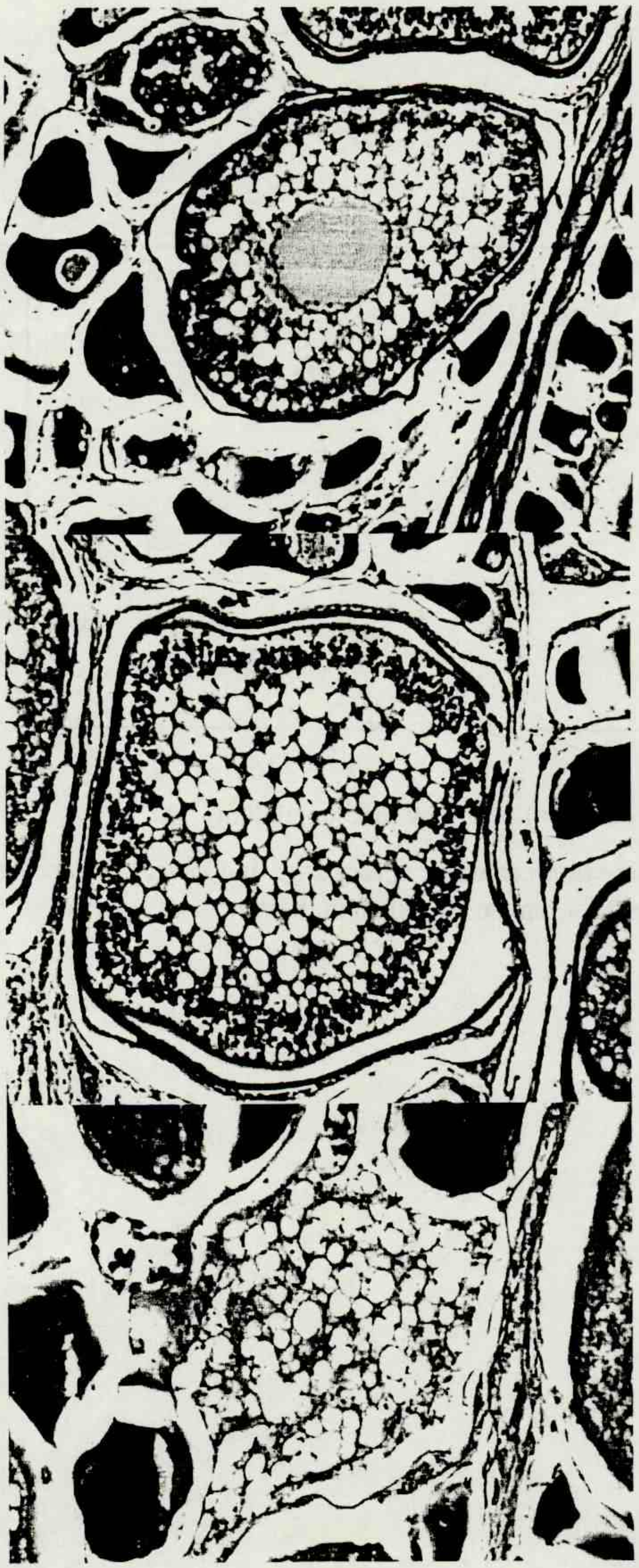

Fig. 6. (continued)

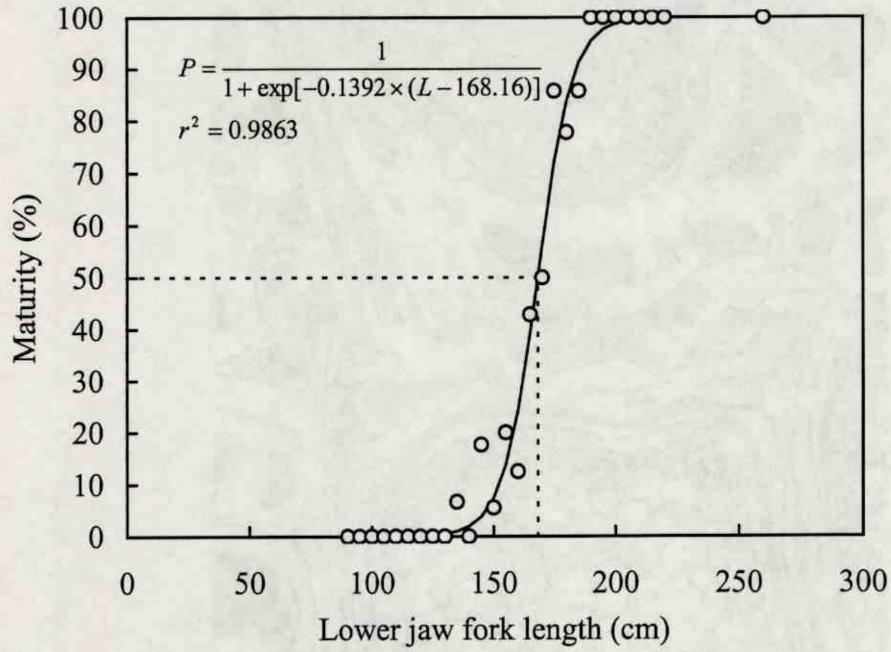

Fig. 7. Relationship between mature percentage and lower jaw fork length (5-cm class) for female swordfish in the waters of Taiwan.

Table 1. Histological criteria for classification of gonadal developmental stages and maturation in female swordfish. The maturity stages are based on the criteria of Murphy and Taylor (1990) and DeMartini et al. (2000).

Maturity stage		Histological appearance of the most advanced gamete stage present in gonads
1	undeveloped	Primitive oogonia only
2	developing	Primary oocytes (basophilic) only present
3	maturing	Early vitellogenesis; beginnings of nucleus breakdown and development of fat inclusions; no chorionic membrane (zona pellucida)
4	ripening	Oocytes well-yolked (completely eosinophilic); nuclear membrane indistinct; prominent chorionic membrane, with fat inclusions distributed throughout cytoplasm
5	spawning	Migratory (eccentric) nucleus, hydrating or hydrated oocytes present
6	recently spawned	Postovulatory follicles present
7	spent or resting	A majority of classes 4-5 yolked oocytes present undergoing α- β-, or later atresia

Table 2. The estimates of body size at sexual maturity reported by various researches on reproductive biology for swordfish.

Area	Investigator(s)	Analysis Method	Body size at sexual maturity (L_{LJF} in cm)	
			Female	Male
Western Pacific Ocean	Yabe *et al.* (1959)	Length-ovary weight relation	168~189*	-
Eastern Pacific Ocean	Kume & Joseph (1969)	I_G analysis	189*	-
North Pacific	Sosa-Nishizaki (1990)	I_G analysis	178*	-
The Straits of Florida and the adjacent waters	Taylor & Murphy (1992)	Histological analysis	182	112
Mediterranean	de la Serna *et al.* (1996)	I_G and histological analysis	142	-
Western Atlantic Ocean	Arocha & Lee (1996)	Observation of ovary with yolked or hydrated oocyte and testis with milt	179	129
Central north Pacific Ocean	DeMartini *et al.* (2000)	Histological analysis	161.8	117.3
Eastern waters of Taiwan	This study	Histological analysis	168.2	**

* L_{LJF} was transferred from L_{EF} in the original paper by using the relationship between L_{LJF} and L_{EF} in our study ($L_{LJF} = 7.7911 + 1.0647\ L_{EF}$).

** Maturities of male samples were determined in this study, but the L_{50} for male could not be estimated because of insufficient specimens.