Age and growth of the bigeye tuna, *Thunnus obesus,* in the western Pacific Ocean

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Abstract—Bigeye tuna (*Thunnus obesus*) age and growth studies were last conducted in the western Pacific in 1967 and no study has ever attempted to age bigeye tuna from this area by using dorsal spines. The objective of our study was to estimate bigeye tuna age and growth rate in the western Pacific based on counts of growth rings on sections of the first dorsal spine. Length and weight data, and the first dorsal spine from bigeye tuna in the Tungkang (southwest of Taiwan) fish market were collected monthly from February 1997 to January 1998. In total, 1149 specimens were collected. The fork lengths of individuals ranged from 45.6 to 189.2 cm. Cross sections from dorsal spines were taken and examined under a dissecting microscope equipped with an image analysis system. The monthly percentage of specimens having a terminal translucent zone indicated that growth rings formed once a year; therefore, the age of each fish was determined from the number of visible growth rings. Von Bertalanffy growth parameters were estimated for males, females, and both sexes combined. There was no significant difference between males and females. The parameter estimates for the combined sexes were asymptotic length (L_∞) = 208.7 cm, growth coefficient (K) = 0.201/yr, and age at zero length (t_0) = –0.9906 yr.

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Bigeye tuna (*Thunnus obesus* Lowe, 1839) are a commercially important species of tuna inhabiting the warm waters of the Atlantic, Indian, and Pacific oceans. They are found across the entire Pacific between northern Japan and North Island of New Zealand in the west and from 40°N to 30°S in the east (Calkins, 1980; Matsumoto, 1998). Adult bigeye tuna are caught mainly by longlines, but substantial numbers of juveniles are taken by purse seines.

Taiwanese distant water tuna longline fleets have operated throughout these three oceans since the late 1960s targeting albacore. In the early 1980s, the Taiwanese began equipping their longliners with very cold (below –55°C) freezers and deep longlines in the Indian and Atlantic oceans, which allowed them to target bigeye tuna for the lucrative sashimi market in Japan. In the western Pacific, the Taiwanese offshore longline fleets, based in domestic (Tungkang mainly) and foreign fishing ports, have landed more bigeye tuna than in the past.

Growth studies of Pacific bigeye tuna conducted in the 1950s and 1960s were based either on increments between modal points in size-composition data (Iversen, 1955; Shomura and Keala, 1963; Yukinawa and Yabuta, 1963; Kume and Joseph, 1966; Suda and Kume, 1967) or on the number of annual markings (annuli) on scales (Nose et al., 1957; Yukinawa and Yabuta, 1963). Recently, Hampton and Leroy[1] and Matsumoto (1998) presented preliminary results from growth studies based on otolith increment counts. No previous study had aged Pacific and Indian bigeye tuna from dorsal spines, although a few age determination studies existed for Atlantic bigeye tuna (Gaikov et al., 1980; Draganik and Pelczarski, 1984; Delgado de Molina and Santana, 1986; Alves et al., 1998). Accurate age structure of stocks is essential for stock assessment and fishery management. Our study provides estimates of the age and growth rate of bigeye tuna in the western Pacific from growth rings on sections of the first dorsal spine.

Materials and methods

Fork length (in cm), weight (in kg), and sex were determined for bigeye tuna caught by Taiwanese offshore longliners in the fishing area from 23°N to 0°N and 110°E to 140°E (Fig. 1[2]) and sold at the Tungkang fish market between February 1997 and January 1998. In addition, a total of 1149 first dorsal spines were collected. Three cross sections were taken along the length of each spine above the condyle base (Fig. 2A) with a low-speed "ISOMET" saw

[1] Hampton, J., and B. Leroy. 1998. Note on preliminary estimates of bigeye growth from presumed daily increments on otoliths and tagging data. Working paper 18, eleventh meeting of the standing committee on tuna and billfish, Honolulu, Hawaii, USA, 30 May–6 June 1998, 3 p. Oceanic Fisheries Programme, Secretariate of the Pacific Community, B.P.D5, 98848 Noumea, New Caledonia.

[2] Yang, R. T., R. F. Chung, and C. L. Chang. 1982. Taiwanese offshore tuna longline fishery. Part I: fishing ground, fishing season, and fishing condition. Spec. Rep. 36, 6 p. [In Chinese with English abstract.] Insitute of Oceanography, National Taiwan University, no. 1, sec 4, Roosevelt Rd, Taipei, 106 Taiwan.

(model no. 11-1280) and diamond wafering blades. Sections ranging from 0.8 to 1.0 mm thick (Fig. 2B) were examined with a dissecting microscope (model: Olympus SZH-ILLD) with transmitted light. Images of the dorsal spine sections were captured by using an image analysis software package, a CCD (charged coupled device) camera, and a high-resolution computer monitor. Translucent rings on the section images were counted by two readers independently. When ring counts disagreed, images were read again by both readers simultaneously, and any questionable spines were discarded.

Spine sections as the structure to estimate age have the advantage of requiring easy sampling and easy reading (the growth rings stand out clearly), and samples are easily stored for future reexamination (Compeán-Jimenez and Bard, 1983). However, early growth rings may be lost in larger specimens because of increased size of the vascularized core in the spine. Accordingly, we estimated the number of lost (obscured) rings from observations of their position and number in spines from young specimens as has been done for little tunny (*Euthynnus alletteratus*) (Cayré and Diouf, 1983), eastern Atlantic bluefin tuna (*Thunnus thynnus*) (Compeán-Jimenez and Bard, 1983), and Pacific blue marlin (*Makaira nigricans*) (Hill et al., 1989).

Age was determined from the translucent rings, assuming that two rings are formed each year—a translucent (light colored) ring formed during the slower growth period and an opaque (dark colored) ring formed during the fast growth period. This assumption was validated by observing a translucent or opaque edge on the dorsal-spine sections and a monthly variation in the number of translucent edges (Antoine et al., 1983).

Distance between the center of the dorsal spine and the outer edge of each annual ring was measured in microns with the software package after calibration against an optical micrometer. The center of the spine was estimated by following Cayré and Diouf (1983) (Fig. 2B). Distances (d_i) were then converted into radii (R_i) by following González-Garcés and Fariña-Perez (1983).

The relationship between fork length (FL) and dorsal spine radius (R) was modeled by a linear equation (Zar, 1999). Fork length was then back-calculated for each ring with the formula (Lee, 1920)

$$FL_i = a + \frac{(FL - a)R_i}{R},$$

where FL_i = predicted fork length of the fish corresponding to age or ring i in cm;

a = ordinate in the origin of the equation $FL = a + bR$;

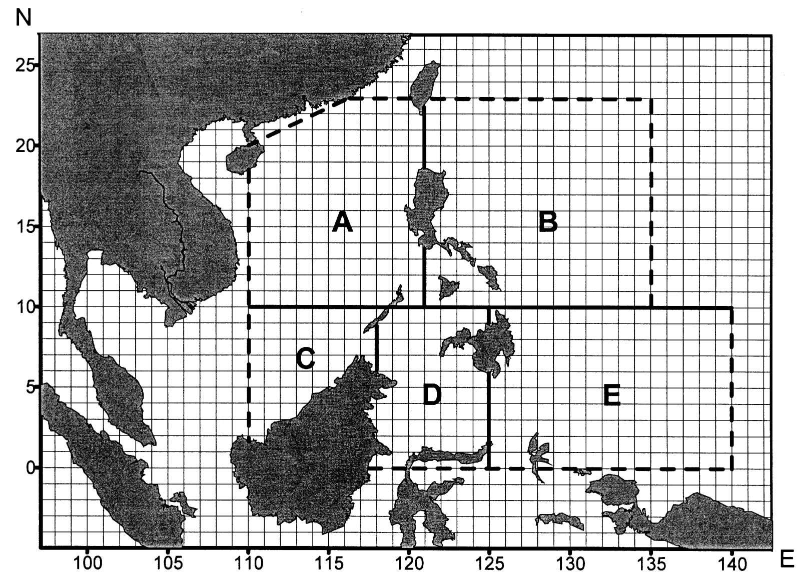

Figure 1

Fishing areas of the Taiwanese offshore tuna longline fishery in the western Pacific Ocean (Yang et al.[2]).

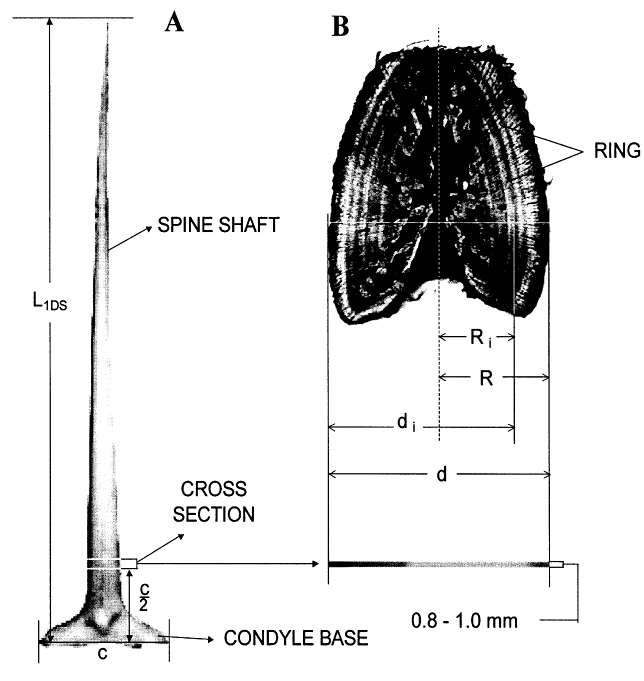

Figure 2

First dorsal spine and the site of cross section (**A**) and the cross section showing annual rings and measurements taken (**B**) for age determination of the western Pacific bigeye tuna (c =width of condyle base; L_{1DS}=length of the first dorsal spine; R=radius of spine; R_I=radius of ring i; d=diameter of spine; d_I=diameter of ring i).

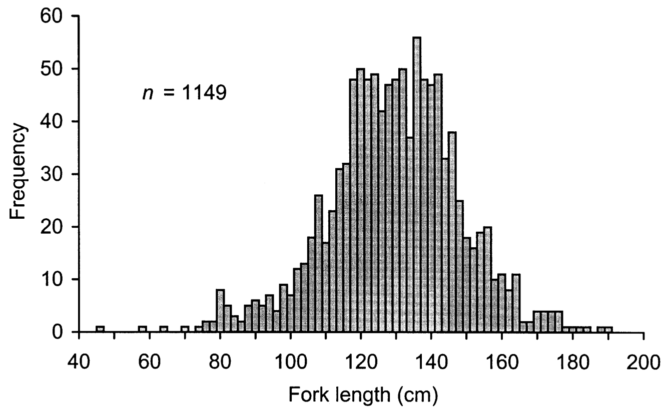

Figure 3
Length-frequency distribution for the western Pacific bigeye tuna sampled at Tungkang fish market from February 1997 to January 1998.

FL = observed fork length of the fish in cm;
R_i = radius of the ring calculated as the average value observed in ring i (Fig. 2B); and
R = dorsal spine radius.

Back-calculated fork lengths were used in Ford-Walford (Gulland, 1983) and nonlinear (Ratkowsky, 1983) methods to fit the von Bertalanffy growth function (VBGF) and to obtain vital parameters by sex. Analysis of the residual sum of squares (ARSS) was employed to compare the VBGF between sexes (Ratkowsky, 1983; Chen et al., 1992).

Weight was related to fork length by using the power function, and analysis of covariance (ANCOVA) (Steel, 1980; Zar, 1999) was conducted to examine differences between sexes.

Results

Spines from 1149 specimens ranging in size from 45.6 to 189.2 cm FL were examined (Table 1, Fig. 3). There was 90% agreement between the readers' counts of growth rings and second readings improved this agreement to 95.6%, which resulted in discarding 51 specimens from analysis.

The relationship between FL (cm) and weight (kg) is shown in Figure 4. The ANCOVA indicated no significant difference between males and females (P>0.05); thus the FL-W relationship with sexes combined was expressed as

$$W = 3 \cdot 10^{-5} FL^{2.9278} \qquad (r^2=0.97,\ n=856).$$

The relationship of first dorsal spine lengths (L_{1DS}) and FL was (Fig. 5)

Table 1
Sample sizes, ranges of fork lengths (FL, cm), and sampling months and areas of bigeye tuna from the western Pacific Ocean. A, B, C, D, and E denote areas in Figure 1.

Month	Sampling area	Sample size	Minimum FL	Maximum FL
Feb 1997	A	80	70	174.5
Mar 1997	A	104	64	169.5
Apr 1997	B	70	101.3	171
May 1997	B	54	83.8	157.4
Jun 1997	B	71	75.5	162.8
Jul 1997	B, D	131	72.2	165.6
Aug 1997	E	94	78.5	187.7
Sep 1997	E	98	45.6	189.2
Oct 1997	A, C	115	86.5	176.6
Nov 1997	A, C	116	89.6	161.1
Dec 1997	C	123	104.6	162.1
Jan 1998	A	93	88.7	159.1
Total		1149	45.6	189.2

$$FL = 6.9367 L_{1DS} + 6.6667 \qquad (r=0.94,\ n=567).$$

The trend of the monthly percentages of terminal translucent edges (Fig. 6) suggested that the period from February to September was the long period of inhibited growth (translucent edge). From October to November, growth appeared to resume (opaque edge) and later, from December to January, a new translucent edge appeared; indicating the formation of one growth ring per year.

Given the significant linear relationship between the dorsal spine radius and fork length (FL=26.455R + 19.916, r=0.94, n=1098), we used spine measurements to back-

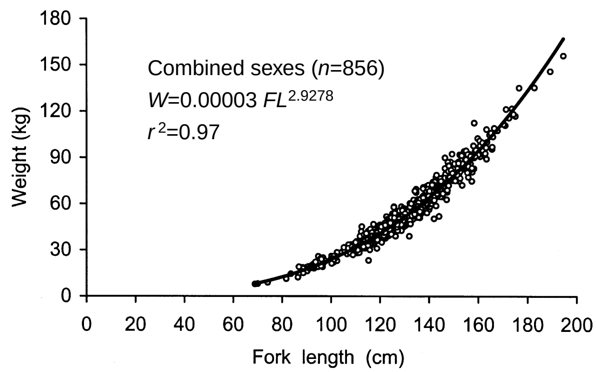

Figure 4

Relationships between weight and fork length of the western Pacific bigeye tuna sampled at Tungkang fish market.

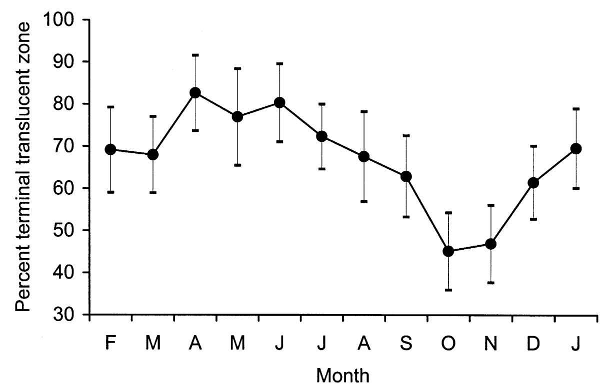

Figure 6

Monthly variation in percentage of the western Pacific bigeye tuna with a terminal translucent zone in dorsal spine sections, February 1997 to January 1998.

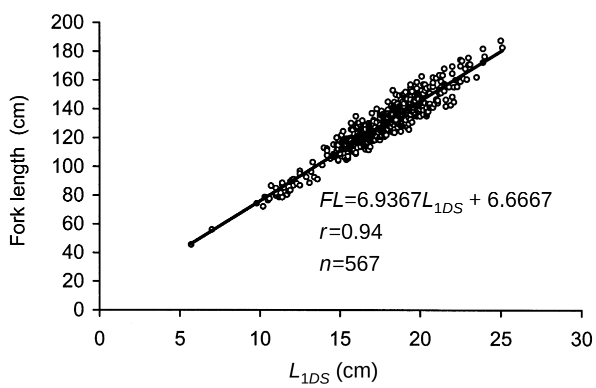

Figure 5

Relationship between fork length and length of the first dorsal spine (L_{1DS}) of the western Pacific bigeye tuna sampled at Tungkang fish market.

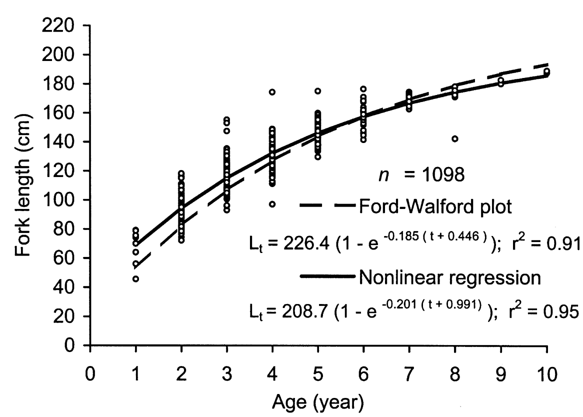

Figure 7

Comparison of the growth curve obtained by the Ford-Walford plot with the growth curve obtained by nonlinear regression method for the western Pacific bigeye tuna.

calculate the fork lengths of previous ages. The mean back-calculated fork lengths for the first 10 years of life for the western Pacific bigeye tuna are given in Table 2.

Parameters of the VBGF estimated by the Ford-Walford method for males, females, and sexes combined are shown in Table 3. Growth was not significantly different between sexes (ARSS, F=1.98; df=3, 452; P>0.05); the pooled growth curve is shown in Figure 7. VBGF parameters computed by nonlinear regression are also shown in Table 3 and Figure 7. Length-at-age of bigeye tuna estimated by nonlinear regression is larger (up to age 6 years) than that estimated by the Ford-Walford method.

Discussion

Available genetic information supports the hypothesis of a single bigeye stock in the Pacific Ocean (Hampton et al., 1998; Grewe and Hampton[3]). Although the fishing area of the Taiwan fleet and thus the sampling area of bigeye tuna used in our study was limited to a small area of the western Pacific, our results may be representative of bigeye tuna throughout the Pacific Ocean.

Monthly variation in percent terminal translucent edges in our study suggested the formation of growth rings once a year. Ehrhardt et al. (1996) attributed the narrow, trans-

[3] Grewe, P. M., and J. Hampton. 1998. An assessment of bigeye (*Thunnus obesus*) population structure in the Pacific Ocean, based on mitochondrial DNA and DNA microsatellite analysis. University of Hawaii, Joint Institute for Marine and Atmosphere Research Contribution 98-320, 29 p. Pelagic Fisheries Research Program, University of Hawaii at Manoa, 1000 Pope Road, Honolulu, HI 96822.

Table 2

Observed and back-calculated mean fork length (FL, cm) at age for the western Pacific bigeye tuna, *Thunnus obesus*. ("—" means there were no data owing to vascularization at core area). Numbers in normal print represent the mean back-calculated fork lengths; numbers in parentheses represent the number of specimens for which the specified ring was readable.

Age (yr)	*n*	Observed mean FL (cm)	Annulus number I	II	III	IV	V	VI	VII	VIII	IX	X
1	8	67.9	57.0									
			(8)									
2	79	93.7	50.0	80.8								
			(29)	(79)								
3	329	115.3	52.4	85.8	102.9							
			(69)	(265)	(329)							
4	413	131.7	51.9	82.7	107.1	121.2						
				(19)	(162)	(384)	(413)					
5	188	145.9	—	80.9	112.1	122.8	135.8					
				(14)	(77)	(184)	(188)					
6	59	158.4	—	—	115.5	126.6	138.2	149.5				
						(3)	(36)	(58)	(59)			
7	11	169.3	—		119.5	130.1	142.6	152.1	161.8			
					(1)	(5)	(9)	(11)	(11)			
8	6	174.7	—	—	—	123.8	139.6	150.8	161.0	172.1		
						(1)	(5)	(6)	(6)	(6)		
9	3	178.5	—	—	—	121.0	129.2	142.0	154.2	169.2	174.2	
						(1)	(2)	(2)	(3)	(3)	(3)	
10	2	188.5	—	—	—	—	138.2	148.4	162.5	174.1	180.6	186.2
							(1)	(2)	(2)	(2)	(2)	(2)
Total	1098		(125)	(520)	(794)	(640)	(263)	(80)	(22)	(11)	(5)	(2)
Weighted back-calculated mean FL (cm)			52.1	83.9	105.9	122.0	136.6	149.8	160.6	171.7	177.4	186.2
Growth increment (cm)			—	31.9	21.9	16.2	14.6	13.1	10.9	11.1	5.7	8.7

Table 3

Growth parameters obtained by the Ford-Walford plot method and the nonlinear regression method for the bigeye tuna from the western Pacific Ocean.

Parameter	Ford-Walford plot Male	Female	Pooled	Total[1]	Nonlinear regression Total[1]
n	278	180	458	1098	1098
K	0.1789	0.191	0.1842	0.185	0.2011
L_∞	220.6	211.4	216.1	226.4	208.7
t_0	−0.5566	−0.4592	−0.5266	−0.4465	−0.9906

[1] Male, female, and sex-unknown combined.

lucent rings to slower growth periods, whereas the wide, opaque rings were attributed to periods of fast growth. The spawning season of bigeye tuna in the western Pacific is between February and September and peaks from March to June (Sun, et al.[4]), the period that we found to coincide

[4] Sun, C. L., S. L. Chu, and S. Z. Yeh. 1999. Note on reproduction biology of bigeye tuna in the western Pacific. SCTB12/WP/BET-4, 6 p. Twelfth meeting of the standing committee on tuna and billfish; Tahiti, French Polynesia, June 14–23, 1999. Oceanic Fisheries Programme, Secretariate of the Pacific Community, B.P.D5, 98848 Noumea, New Caledonia.

Table 4

Comparisons of estimates of parameters of von Bertalanffy growth function for the Pacific bigeye tuna by various authors. Partly reproduced from Table 10 of Shomura (1966).

Area	Investigator(s)	Method of analysis	Parameters			Size range of fish (cm)	Comments
			L_∞ (cm)	K	t_0		
Pacific-wide, north of 10°S	Nose et al. (1957)	Scales	195.2	0.106	–1.128	Mean observed length for 58–109	Parameters based on mean observed length by age provided by authors
Western North Pacific (north of 2°N and west of 180°)	Yukinawa and Yabuta (1963)	Size frequency	257.5	0.156	–0.107	Modal sizes estimated to be 65–150	Parameters computed from data provided by authors
Pacific (north of 10°S)	Yukinawa and Yabuta (1963)	Scales	215	0.10412	0.0010995	Estimate 51–160	Authors' values; time (*t*) in half-year units
Pacific (north of 10°S)	Yukinawa and Yabuta (1963)	Scales (same basic data as above)	213.1	0.212	0.017		Parameters computed by graphic method from data provided by authors
Central Pacific (Hawaiian Islands)	Shomura and Keala (1963)	Size frequency (males)	196.7	0.267	–0.929		Authors' values
Central Pacific (Hawaiian Islands)	Shomura and Keala (1963)	Size frequency (females)	183.0	0.316	0.718		Authors' values
Eastern Pacific (east of 130°W and between 10°N and 25°S)	Kume and Joseph (1966)	Size frequency	186.95	0.095	2.11	39–209	Authors' values; time (*t*) in quarter-year units
Pacific area	Suda and Kume (1967)	Size frequency	214.8	0.2066	0.0249		
Western Pacific	Hampton and Leroy (1998)	Otolith and tagging	165.3	0.3732	0.3420	25–175	Preliminary
Eastern Pacific	Matsumoto (1998)	Otolith	—	—	—	33.4–57.9	Author estimated only the lengths of 40 and 55 cm at ages of 0.5 and one year, respectively; preliminary.
Western Pacific	This study	Spine	208.7	0.2011	–0.9906	45.6–189.2	

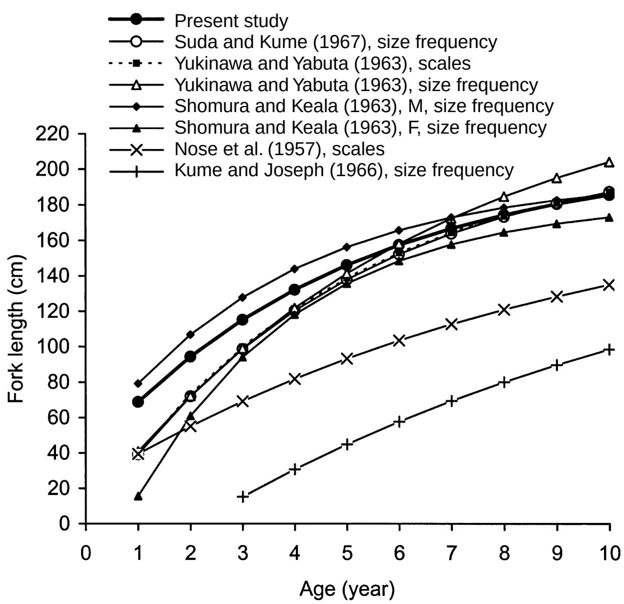

Figure 8

Growth curves of Pacific bigeye tuna estimated by different authors.

with the slow-growth period indicated by the narrow and translucent rings. Similar findings have been reported for skipjack tuna (Antoine et al., 1983), bigeye tuna (Gaikov et al., 1980), and swordfish (Ehrhardt, 1992; Tserpes and Tsimenides, 1995). Our efforts only partially validate fish age; complete validation requires either mark-recapture data or the study of known-age fish in the population (Beamish and McFarlane, 1983; Prince et al., 1995; Tserpes and Tsimenides, 1995).

We estimated the parameters of the VBGF by using the Ford-Walford and nonlinear methods and found that the nonlinear method had a better fit (r^2=0.95) than the Ford-Walford method (r^2=0.91). Comparisons of our VBGF parameters with previous studies (Fig. 8, Table 4) showed similar results to those of Yukinawa and Yabuta (1963) who used scales and to those of Suda and Kume (1967) who also used Pacific samples of bigeye tuna. The values of t_0 differed because different aging techniques were used. Following the suggestion of Gallucci and Quinn (1979), Vaughan and Kanciruk (1982), and Hanumara and Hoenig (1987) that Ford-Walford and other linear methods be replaced by nonlinear fitting techniques; we propose using parameters of VBGF estimated by the nonlinear method (Table 3) for description of age and growth for the western Pacific bigeye tuna.

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