A Preliminary Assessment of the Use of Hard Parts to Age Central Pacific Swordfish, *Xiphias gladius*

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ABSTRACT

We describe the results of preliminary work that contributes to ongoing studies of the age and growth of swordfish, *Xiphias gladius*, in the central Pacific. Multiple hard parts (first dorsal and first anal fin rays, caudal vertebrae, and otolith sagittae) were evaluated for their suitability as ageing structures. Proportional relations were observed between counting-path dimensions of various hard parts (width of fin rays, depth of vertebral cones, and length of sagittae) and eye–fork length of swordfish. Age estimates (counts of presumed annuli) were evaluated within and among tissues and between pairs of readers.

A provisional growth model is presented for swordfish in the Hawaii longline fishery, based on presumed annuli observed in cross sections of the second ray of first anal fins. The validations of annuli on fin rays and sagittae, and of daily growth increments on sagittae, are indicated as key topics for continuing studies. Validation of annuli should include analysis of marginal growth increments on both fin rays and sagittae collected at expanded spatial and temporal scales. Complementary research needs are identified, emphasizing an expanded mark–recapture program to provide specimens needed for conclusive age validation.

Introduction

The age and growth of swordfish, *Xiphias gladius*, stocks in the Atlantic Ocean have received much attention (Ovchinnikov, 1970; Beckett, 1974; Berkeley and Houde, 1983; Radtke and Hurley, 1983; Wilson and Dean, 1983; Prince et al., 1988; Ehrhardt, 1992; Turner[1]), because the status of these stocks has been assessed primarily with age-structured stock assessment models (Megrey, 1989; Miyake and Rey, 1990). Age-structured rather than surplus production models have been used, at least until recently (Cosner et al., 1992; Prager, 1992), because high-quality effort statistics were unavailable for all segments of the fleet. In addition, the size and sex composition of landings varied considerably among different national fleets because of differential targeting.

In the Pacific Ocean, swordfish is not as heavily exploited as in the North Atlantic (Sakagawa, 1990), and Pacific swordfish stocks are presently believed to be under-exploited (Bartoo and Coan, 1990; Skillman, 1990; NOAA, 1993). Yet concern has been raised during recent deliberations of the Western Pacific Fisheries Management Council (WPFMC) that management restrictions in the Atlantic and continued market demand could result in considerable expansion of the Pacific fishery and a rapid decline in Pacific stock (WPFMC[2]).

Dependency on age-structured stock assessment modeling may be expected also in the Pacific because of similar problems with the availability of comprehensive fishing-effort statistics, and differences in fishing strat-

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[1] Turner, S. 1986. Further examination of the marginal increments observed by Berkeley and Houde in cross sections of anal spines from swordfish. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southeast Fisheries Center Swordfish Workshop Working Paper 86/4, 5 p. SEFC, 75 Virginia Beach Dr., Miami, FL 33149.

[2] Western Pacific Fishery Management Council. 1994. Amendment to the fishery management plan for the pelagic fisheries of the Western Pacific Region. Western Pac. Fish. Manage. Counc., 1164 Bishop St., Rm. 1405, Honolulu, HI 96813.

egy between geographically-separated fisheries. The adequacy of age-structured models is of course dependent on accurate and precise estimates of age and growth rates.

Data are generally lacking on growth of Pacific swordfish. Yabe et al. (1959) analyzed the length frequency distribution of swordfish landed in the western North Pacific during 1948–56; and Sakagawa and Bell (1980) estimated the von Bertalanffy growth function (VBGF) *K* from these data. Kume and Joseph (1969) examined length frequency distributions of swordfish from the eastern Pacific. The ages of swordfish from the Mexican fishery have recently been estimated by counting presumed annuli on cross sections of anal fin rays and presumed daily growth increments (DGI's) on otoliths (Castro-Longoria and Sosa-Nishizaki, 1998).

The validation of annuli and DGI's is crucial for any ageing study. To date, only Ehrhardt (1992) and Tserpes and Tsimenides (1995) have been able to provide partial validation of swordfish ages using anal fin rays. Wilson and Dean (1983) verified, but did not validate, counts of DGI's and annuli on cross sections of sagittae from the same swordfish, as did Radtke and Hurley (1983) for counts of DGI's and of external ridges on sagittae. All these comparisons were limited to Atlantic and Mediterranean swordfish. Since neither annuli nor DGI's have been validated for Pacific swordfish, validation of these methods is of the utmost importance in the Pacific, as elsewhere.

Because current knowledge of swordfish growth is insufficient to support age-structured stock assessment, the Honolulu Laboratory of the Southwest Fishery Science Center initiated a program to describe size-at-age relations for swordfish in the central Pacific. In this paper, we report our progress to date in estimating the age of swordfish caught by the Hawaii longline fishery. We first evaluate the basic suitability of various hard parts as ageing structures based on proportionate growth of counting paths on tissues and of fish length, and we evaluate the related issue of variation in tissue preparations among individual fish. We then compare age estimates by the same reader and between age readers, and among different tissues from the same fish. A provisional growth model is next presented, and work in support of age validation is described. Lastly, key topics for future research are identified.

Methods and Materials

Specimen Collection

Hard parts were obtained from swordfish caught north and west of the Hawaiian Islands (Fig. 1) by monofilament longline gear fished from the NOAA research vessel *Townsend Cromwell* on cruises TC-9101 (10 January–15 February 1991), TC-9203 (13 April–7 May 1992), and TC-9303, Leg I (12 March–8 April 1993). We hereafter refer to these three series of collections as 1991, 1992, and 1993, respectively. The longline gear was set around 2000 and retrieved the following morning at 0700. Retrieval of the longline was usually completed by noon. Dead swordfish and some live fish needed for very fresh tissue samples were brought aboard ship. Most viable swordfish were injected with oxytetracycline (~600 mg/fish), marked externally with a stainless steel dart tag (Squire, 1974), and released for use in future age validation studies based on time-marked recaptures.

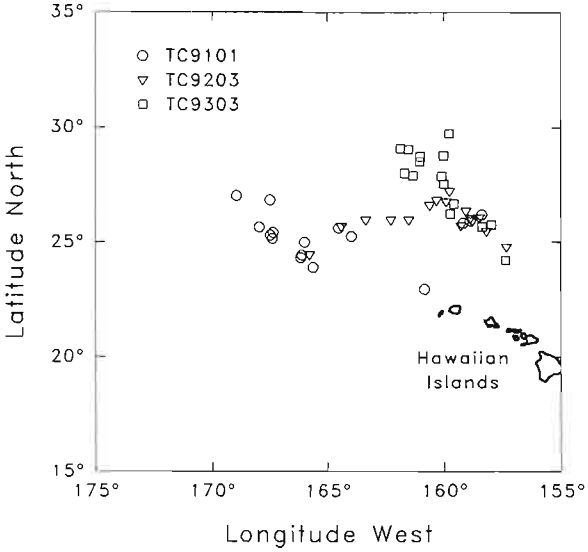

Figure 1
Location of longline sets on *Townsend Cromwell* cruises TC-9101, TC-9203, and TC-9303.

For fish brought aboard ship, eye–fork length (EFL, the distance from posterior edge of orbit to fork of tail) was measured to the nearest 0.1 cm. Sex was assessed macroscopically while dressing the fish, and gonad samples were collected and fixed in 10% formalin (seawater-buffered). Sex was later re-evaluated by microscopic examination of standard histological preparations (Harris' hematoxylin stain, eosin counterstain). Several tissues were collected and frozen for processing and subsequent estimation of age at the Honolulu Laboratory. Fin rays and otoliths were taken in part because prior studies (Berkeley and Houde, 1983; Radtke and Hurley, 1983; Wilson and Dean, 1983) suggested their potential usefulness in ageing swordfish. Future availability was also a criterion in the selection of tissues. The caudal peduncle containing terminal vertebrae, for example, can be easily collected from landed car-

Table 1

Number of counts made by each of three readers on various tissues (one specimen of each) used to age swordfish, for each of the three (1991, 1992, and 1993) series of collections. D1, D2, D3 = dorsal fin rays 1–3; A1, A2, A3 = anal fin rays 1–3.

	Counts by reader and year								
	Reader A			Reader B			Reader C		
	1991	1992	1993	1991	1992	1993	1991	1992	1993
Rays									
D1	1	3	1	1	4	3	1	1	1
D2	1	3	1	1	4	3	1	1	1
D3	1	3	1	1	4	3	1	1	1
A1	1	3	1	1	4	3	1	1	1
A2	1	3	1	1	4	3	1	1	1
A3	1	3	1	1	4	3	1	1	1
Vertebrae		1	1		1	1			1
Sagittae									
Rostral ridges		3	1		4	3			
Postrostral bands		3	1						
Daily growth increments	10			10	10	10			

casses. The skull, with otoliths, and the anterior portions of the first dorsal and first anal fins can be collected by observers or by fishers during onboard processing.

Preparation and Examination of Specimens

The counting of presumed annual marks (hereafter referred to as annuli) was done by three readers with different types and levels of experience. Reader A had the most experience at reading material from different species and tissues. Reader B read greater numbers of specimens for this study, except for vertebrae and band counts on the postrostrum of otolith sagittae (described below). Reader C, experienced in using a computerized optical image analyzer to age hard parts, used an image analyzer to count annuli. The number of counts made on each tissue type by each of the three readers is summarized in Table 1. All repeat counts of presumed annuli on fin rays, and of ridges and bands on sagittae, were made a month apart without knowledge of fish size or of previous counts on that part, to assure independence among readings.

Rays—Because the terminology of swordfish fin morphology is obscure, we first define our usage. The first dorsal (hereafter called dorsal) and first anal (anal) fins of swordfish have both unbranched and branched rays. The first two or three rays in these fins are unbranched, have right and left sides joined by a medial suture, and have an opened gap in their bases (Fig. 2). These structures thus match Summerfelt and Hall's (1987) definition of soft rays, even though the unbranched rays of swordfish have been variously called spines, spiny rays, or spinous rays. None of the dorsal or anal fin rays of swordfish appear to be segmented.

The rays of dorsal and anal fins were separated from their fins, cleaned of tissue, and dried in a dehydrator at about 52°C for 24–48 h. For each fin ray collected in 1993, length was measured to the nearest mm along its convex cephalad surface from a proximal point on its base to its distal tip (Fig. 2) using a fabric measuring tape. After cross sections were cut from the ray (described below), the distance between base of the ray and the point at which the ray was cut was also measured. For 1992 and 1993 specimens, ray widths were measured to the nearest 0.1 mm with a dial caliper on the proximal side of the point at which the ray was first cut.

Using an Isomet[3] low-speed saw, a first cut was made across the ray proximal to the point at which its left and right sides converged posteriorly (Fig. 2). Then 3–5 sections about 1 mm thick were cut successively toward the ray tip (distal end) so that the first section included the point at which the left and right sides converged. Sections were mounted on a glass microscope slide using a synthetic mounting medium (Flo-texx) and examined without further preparation. Counts of annuli were made using a dissecting microscope at 12× magnification with reflected light against a black background.

Annuli were defined as alternating pairs of opaque and translucent bands. These concentric bands ran continuously and in parallel along the lateral circumference of the sectioned ray from the anterior to poste-

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[3] Reference to trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

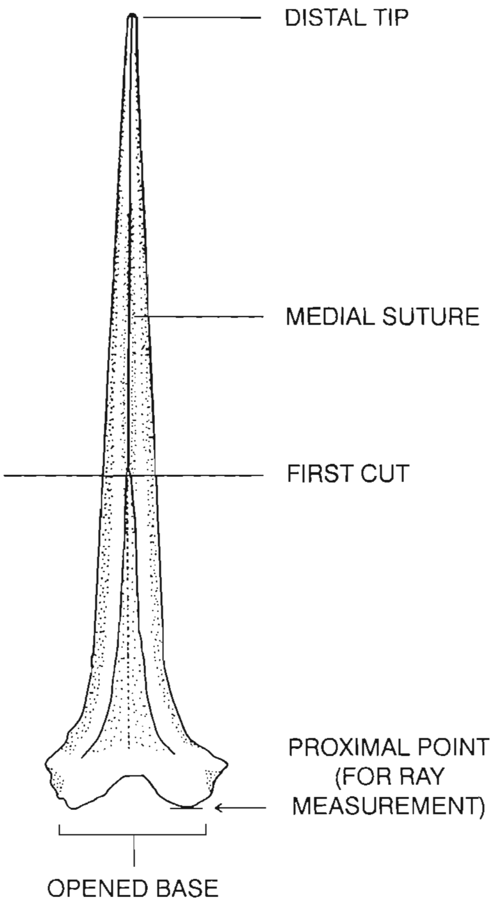

Figure 2
Truncated caudad view of a curved swordfish fin ray, illustrating position at which ray was first cut for cross sections used in ageing. Also indicated are the proximal and distal points between which the length of ray was measured along its cephalad surface.

rior side of the medial suture, but were absent along the relatively flat-sided medial suture (Berkeley and Houde, 1983; Tsimenides and Tserpes, 1989, Fig. 1). It was assumed that one pair of bands had formed each year. Multiple bands sometimes occurred, but could be distinguished from true annuli, in that the opaque bands of neighboring annuli remained distinct from one another around the entire lateral circumference of the section, including the region of the medial suture. Conversely, multiple bands converged on one another near the suture; they were counted as a single annulus. Another type of opaque band ("false check") sometimes occurred, but was not counted. False checks did not extend to the region of the medial suture and usually varied greatly in band width. An opaque band at the edge was scored as a "plus" growth and not a year mark.

Vertebrae—Flesh around the 23rd and 24th (caudal) vertebrae was removed, and vertebrae were separated with a knife. Vertebral annuli were defined as concentric alternating pairs of opaque and translucent bands within cartilaginous tissue on the anterior and posterior cones of vertebral centra. Annuli were counted once by unaided eye before vertebrae were processed further. The vertebrae were then boiled, all remaining soft tissue was removed, and they were dried in a dehydrator at 52°C for 24–48 h. Both anterior and posterior depths of cones (perpendicular distance from the open end of the cone to the apex) were measured to the nearest 0.1 mm using a dial caliper.

Otoliths—The semicircular canals, located lateral to the spinal cord's foramen in the skull, were extracted using watchmaker's forceps. Using a dissecting microscope at 6×, the sagitta (largest of the three otoliths) was teased out of the sacculus with size 00 insect pins. The sagitta was then cleaned of tissue under 25× magnification using pins and a fine-tip brush, and stored in 75% EtOH.

Length of sagittae was measured by placing complete sagittae, antirostrum side down, in the well of a culture slide. The ventral profile was viewed through a video camera mounted on a dissecting microscope and its length measured with an image processor. End-to-end line segments were measured along the middle of the profile, from the tip of the rostrum to tip of the postrostrum (Fig. 3).

Sagittae were further prepared in one of two ways. A sagitta for which DGI's were to be enumerated (Radtke and Hurley, 1983; Wilson and Dean, 1983) was glued onto a microscope slide, sulcus (medial) side down. The exposed surface of the rostrum was sanded lightly with 600-grit silicon carbide paper with frequent inspections until DGI's became visible in the sagittal plane from the core to the distal tip of the rostrum. The sagitta was then mounted in Euparal under a cover slide. All apparent DGI's were enumerated from the core to the tip of the rostrum using a compound microscope at 600× with transmitted light. In a preliminary comparison of counts of DGI's on the rostrum, antirostrum, and postrostrum of sagittae, DGI counts on the rostrum were always highest. We assumed that these highest counts were most representative and thereafter counted DGI's on the rostrum only. After a number of practice counts, we decided on using the average of ten consecutive counts to estimate specimen age. DGI counts were divided by 365 to convert to years.

External ridges have been observed on the proximal surface of sagittae rostrums for northwest Atlantic (Radtke and Hurley, 1983), but not southwest Atlantic (Wilson and Dean, 1983) swordfish. We additionally observed alternating pairs of opaque and translucent

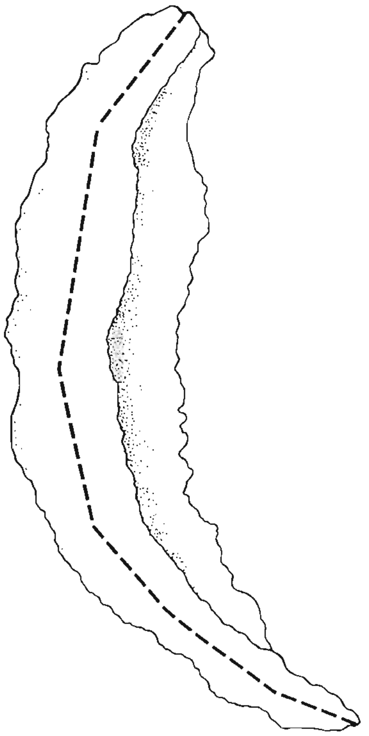

Figure 3
Diagrammatic curved ventral profile of a swordfish sagitta. Dashed line represents a series of end-to-end straight line segments drawn by an image processor and used to estimate total length of the sagitta.

bands on the postrostrums of sagittae (heretofore unreported for swordfish); these also may represent annual marks. A sagitta for which rostral ridges and postrostral bands were to be enumerated was mounted on a microscope slide, sulcus side up, in Euparal without any processing. Ridges and bands were counted using a dissecting microscope at 25× with reflected light.

Data Analysis

Tissue–EFL Relations—Proportionality between EFL and the growth axis of hard parts used for ageing was evaluated by product-moment correlation. The relation between width of fin rays and EFL was examined-for males and females separately. Depth of vertebral cones was related to EFL for the sexes combined because sex is indeterminable for fish in the landed catch. The relation between sagitta length and EFL also was examined for the sexes combined because the number of intact otoliths available for measurement was small.

Position of Sections—Preliminary observations suggested much variability among fin rays and individual fish in the location at which the left and right sides of rays joined at their medial suture. Hence, unavoidable variation existed in the position at which fin ray sections were cut. To evaluate the extent of this variation, we expressed the distance between the base of the ray and its first cut as a percentage of the total length of the ray, and compared coefficients of variation (CV = SD/mean × 100%) among the six different rays.

Precision of Readers—The precision of ages estimated by each of two readers (A and B) was evaluated as average percent error (APE, Beamish and Fournier, 1981). APE values were calculated for repeat counts of annuli on fin ray cross sections, for bands on postrostrums of sagittae, and for rostral ridges on sagittae of all 1992 specimens. Although Reader B made four readings of the hard parts, only B's last three readings were used so that B's APE's would be comparable to Reader A's APE's which were based on three readings.

Comparisons among Readers—To compare counts of annuli among readers, the count of one reader was regressed on a second reader's count for the same tissue using ordinary least squares. Data included all six different rays from the three collection series. The significance of each pairwise comparison was evaluated by Student's *t* test of whether the regression slope equaled zero (i.e. whether reader counts were related). The equivalence of counts between readers was similarly tested by hypothesizing slope = 1. Only the last of the repeat counts by Readers A and B, and Reader C's single count, were used. Comparisons were made for all three pairwise reader combinations. Analogous comparisons among readers were made for counts on vertebrae.

Comparisons among Tissues—To evaluate whether the counts made on the six different rays equivalently estimated age, we used Friedman's two-way ANOVA by ranks (Daniel, 1978). This test analyzed the difference in counts (responses) among rays (treatments) for each swordfish (block). The null hypothesis tested was that counts were equal among rays, within fish. These data consisted of the last series of repeat counts by Reader A for 1992 and 1993 specimens.

Age–Length Relation—Reader A's last series of counts for second anal rays of 1992 specimens, and A's single count of second anal rays from 1993, were used to calculate VBGF parameters. Nonlinear regression using Marquardt's algorithm and Statgraphics version 5.0 (Statistical Graphics Corp., 1991) was used to obtain least squares estimates of parameters. Parameters were estimated by sex and for all fish pooled.

Results

Proportionality of Tissues and EFL

In general, all tissues that we examined satisfied the minimum requirement of proportionality between counting path of hard part and body size of fish. Correlations between width of ray at point of cut and EFL were significant for all six different rays (Table 2). Relation between depth of vertebral centrum and EFL were also significant (Table 3), as was that between EFL and length of sagitta (r=0.69, N=25, P<0.001).

Location of Sections on Rays

The distance from the base at which the left and right sides of the ray converged (relative to length of the ray) decreased from the first to the third ray for dorsal and anal fins (Table 4). The third rays of dorsal and anal fins were the least variable (Table 4).

Precision of Readers

The APE's of repeat counts of annuli for the six different fin rays, for external ridges on the rostrums of sagittae, and for bands on the postrostrums of sagittae were calculated for Readers A and B (Table 5). Values were consistently less for Reader A than for Reader B. Counts of ridges on the rostrum and of bands on the postrostrum were less precise than counts of annuli on rays. Values for the second ray of dorsal and anal fins were less than for other rays (Table 5).

Comparisons between Readers

When we employed Student's t test to compare counts of annuli by different readers for the 6 different fin rays pooled, all regressions were significant, indicating that readings by different readers were related (Table 6). However, each of the regressions had a slope significantly different from 1, indicating a significant difference within each pair of readers (Table 6). Reader counts on specific rays were therefore examined to identify where disagreements occurred. Differences were significant for the first ray of both dorsal and anal fins, but never significant for the second ray of either fin for any pairwise reader comparison (Table 7).

Results of reader comparisons were variably conclusive for the other hard parts examined. All regressions of counts on vertebrae by different readers were significant, but all differences in counts between readers also were significant (Table 8). Only five sagittae were read by both Readers A and B, and the mean difference in counts between readers did not significantly differ from zero (t=1.413, d.f.=4, P=0.23).

Table 2

Correlation (r) between swordfish eye-fork length (EFL) and cross section width of the first, second, and third rays of the first dorsal (D1, D2, D3) and first anal (A1, A2, A3) fins.

	Dorsal fin rays			Anal fin rays		
	D1	D2	D3	A1	A2	A3
Males						
r	0.614	0.694	0.740	0.891	0.665	0.725
N	26	29	29	19	27	26
P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Females						
r	0.866	0.942	0.967	0.843	0.891	0.940
N	30	34	33	21	30	31
P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Table 3

Correlation (r) between swordfish eye-fork length (EFL) and the depth of vertebral cones for anterior and posterior faces of the 23rd (V23) and 24th (V24) vertebrae.

	V23		V24	
	Anterior	Posterior	Anterior	Posterior
r	0.959	0.920	0.965	0.894
N	48	48	69	70
P	<0.0001	<0.0001	<0.0001	<0.0001

Comparisons of Tissues

Reader A's last counts of annuli clearly differed among the 6 different rays (Friedman's two-way ANOVA, χ^2=34.8, d.f.=5, P<0.001). Counts ranked lowest for the first ray of dorsal and anal fins (average rank = 3.11) and highest for the second ray of the anal fin (average rank = 3.88), but this apparent maximal contrast was not significant (Friedman's a posteriori multiple comparison test; $P \approx 0.10$; Daniel, 1978, p. 231). Mean counts ranged from a minimum of 2.62 for the first ray of the dorsal fin to a maximum of 3.26 for the second ray of the anal fin.

Reader B's average DGI counts on sagittae of 1992 and 1993 specimens were converted to years for comparison with annuli in rays and vertebrae from the same fish (Table 9). Estimated ages based on DGI's and on

Table 4

Summary statistics for relative position of the first cross section of fin rays for swordfish specimens collected in 1993. Coefficient of variation, CV = (SD/mean) × 100%.

	Dorsal fin rays			Anal fin rays		
	D1	D2	D3	A1	A2	A3
Relative position (%)						
CV	16.7	22.4	18.2	23.7	29.4	19.2
Mean	35.4	25.9	17.6	33.3	22.1	18.2
SD	5.9	5.8	3.2	7.9	6.5	3.5
Maximum	48.0	38.5	25.0	59.5	42.3	26.6
Minimum	22.0	15.3	10.7	15.4	11.9	11.0
Ray length (cm)						
Maximum	16.0	39.0	54.5	10.7	36.0	36.5
Minimum	3.3	6.9	19.5	2.8	8.5	13.0
No. rays measured	41	42	42	41	42	40

Table 5

Precision of repeat counts (APE = average percent error) for individual specimens of swordfish collected in 1992. N = number of specimens.

	Reader A		Reader B	
	N	APE	*N*	APE
Dorsal fin rays				
D1	29	12.18	29	22.20
D2	28	5.97	28	16.98
D3	29	10.39	29	27.01
Anal fin rays				
A1	29	9.76	29	21.22
A2	30	9.06	30	17.58
A3	26	7.25	26	15.28
Sagittae				
Ridges	29	20.62	7	77.36
Postrostral bands	28	14.45		

annuli generally agreed among the 12 relatively small and young fish for which comparison was possible (r=0.89, P<0.001), although DGI's appeared somewhat under-counted (Table 9).

Provisional Growth Model

A provisional estimate of the VBGF equation for central North Pacific swordfish with sexes combined was

$$L_t = 321\,[1 - e^{-0.14(t+1.3)}]$$

Growth curves fit to EFL-at-age for males and females broadly overlapped, at least for ages 4 or less; seven of nine fish aged 6 and older were females (Fig. 4).

Table 6

Comparisons between readers of counts of presumed annuli on all six different swordfish rays.

Readers	*N*	Regression coefficient	SE	Test of H_0: slope = 1	
				t	*P*
A vs B	502	0.913	0.0162	5.34	<0.001
A vs C	353	0.891	0.0129	8.43	<0.001
B vs C	345	0.890	0.0179	6.14	<0.001

Validation

A total of only 28 apparently viable swordfish were caught on the 1991 (10 fish), 1992 (9), and 1993 (9) cruises; each was injected with oxytetracycline, tagged, and released. None of these marked fish has been recaptured as of October 1995.[4]

Discussion

Tissue–EFL Proportionality and Variability

All hard parts that we evaluated for ageing swordfish grow proportionally with body size. Berkeley and Houde (1983) and Tsimenides and Tserpes (1989) similarly observed proportionality between the width of second anal fin rays and body length of swordfish. Our findings of proportionality between sagitta length and body length, though, seem to be the first to date for any billfish. This should not be surprising, as our study is

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[4] Nor as of September 1998.

Table 7

Comparisons between readers of counts of presumed annuli on each of six different swordfish fin rays. D = dorsal, A = anal.

					Test for H_0: slope = 1	
Readers	Ray	*N*	Regression coefficient	SE	*t*	*P*
A vs B	D1	74	0.753	0.0472	5.25	<0.001
	D2	88	1.011	0.0356	–0.32	>0.5
	D3	87	1.059	0.0348	–1.68	>0.1
	A1	76	0.740	0.0492	5.28	<0.001
	A2	95	1.033	0.0371	–0.88	>0.2
	A3	82	1.000	0.0307	<0.001	>0.9
A vs C	D1	50	1.128	0.0268	–4.78	<0.001
	D2	65	1.042	0.0366	–1.16	>0.2
	D3	56	1.115	0.0299	–3.85	<0.001
	A1	43	1.106	0.0310	–3.42	<0.001
	A2	77	0.927	0.0402	1.82	>0.05
	A3	62	1.045	0.0344	–1.30	>0.2
B vs C	D1	50	0.653	0.0533	6.50	<0.001
	D2	65	0.962	0.0281	1.37	>0.1
	D3	54	0.950	0.0356	1.41	>0.1
	A1	42	0.713	0.0522	5.49	<0.001
	A2	73	1.052	0.0407	–1.28	>0.2
	A3	61	0.877	0.0383	3.21	<0.001

Table 8

Comparisons between readers of counts of presumed annuli on swordfish vertebrae.

				Test H_0: slope = 1	
Readers	*N*	Regression coefficient	SE	*t*	*P*
A vs B	47	0.963	0.0279	1.33	>0.1
A vs C	33	0.937	0.0418	1.50	>0.2
B vs C	14	0.927	0.0564	1.30	>0.2

Table 9

Matched estimates of the number of presumed daily growth increments (DGI's, converted to years) on sagittae and the number of presumed annuli on cross sections of rays and vertebrae of the same swordfish. Counts of annuli agreed across all hard parts examined for these 12 fish.

EFL (cm)	Sex[1]	DGI (yr)	Presumed annuli
76.8	I	0.85	1
80.7	I	0.78	1
82.5	M	0.75	1
88.6	M	0.95	1
95.3	F	0.85	1
105.8	M	1.37	2
107.4	F	1.36	2
107.5	F	1.47	2
116.0	M	1.31	2
140.9	F	1.55	3
141.3	F	1.69	3
165.6	U	2.52	3

[1] F = female, M = male, U = unrecorded, I = immature.

apparently the first to use a series of short straight-line segments to approximate distance along the major axis of a billfish sagitta. The sagitta becomes progressively more curved in large billfish (Radtke and Hurley, 1983), and describing its length by a single straight-line measurement disproportionately underestimates the length of larger sagittae in older fish.

Some potentially useful ageing tissues can be prepared and measured with less variability than others. Among the fin rays that we examined, for example, cuts for cross sections can be most precisely located on the second and third rays of dorsal and anal fins.

Tissue Suitability for Ageing

Additional factors such as reader precision, agreement among readers, and preparation efficiency are also important criteria when choosing tissues to use for ageing. The APE of repeat counts of annuli was consistently lowest for the second ray of both the dorsal and anal fin. Counts made using the second ray of dorsal and anal fins also did not differ between readers, whereas counts clearly differed between readers for other fin rays. On average, counts of annuli did not differ between the second and third rays of either dorsal or anal fins. Second rays typically are the widest and usually have the clearest bands. In general, the preparation of fin ray cross sections and the counting of annuli on ray sections are relatively easy, and fins can be obtained in large quantities because they are discarded as swordfish are dressed at sea. Lastly, the second ray of the first anal fin has precedence in studies of Atlantic and Mediterranean swordfish (Berkeley and Houde, 1983; Prince et al., 1988; Tsimenides and Tserpes, 1989; Ehrhardt, 1992; Tserpes and Tsimenides, 1995; Turner[1]). The second ray of the first anal fin is the most logical choice if fin rays are used to age swordfish, even though there are inevitable complications in using fin ray sections, as there are with other hard parts, for ageing studies. Difficulties in interpreting annuli on swordfish fin rays and other hard parts are discussed in the sections that follow.

Dorsal and Anal Fin Rays—Counts of annuli sometimes varied greatly among the different fin rays of individual fish, especially for large specimens (>165 cm EFL).

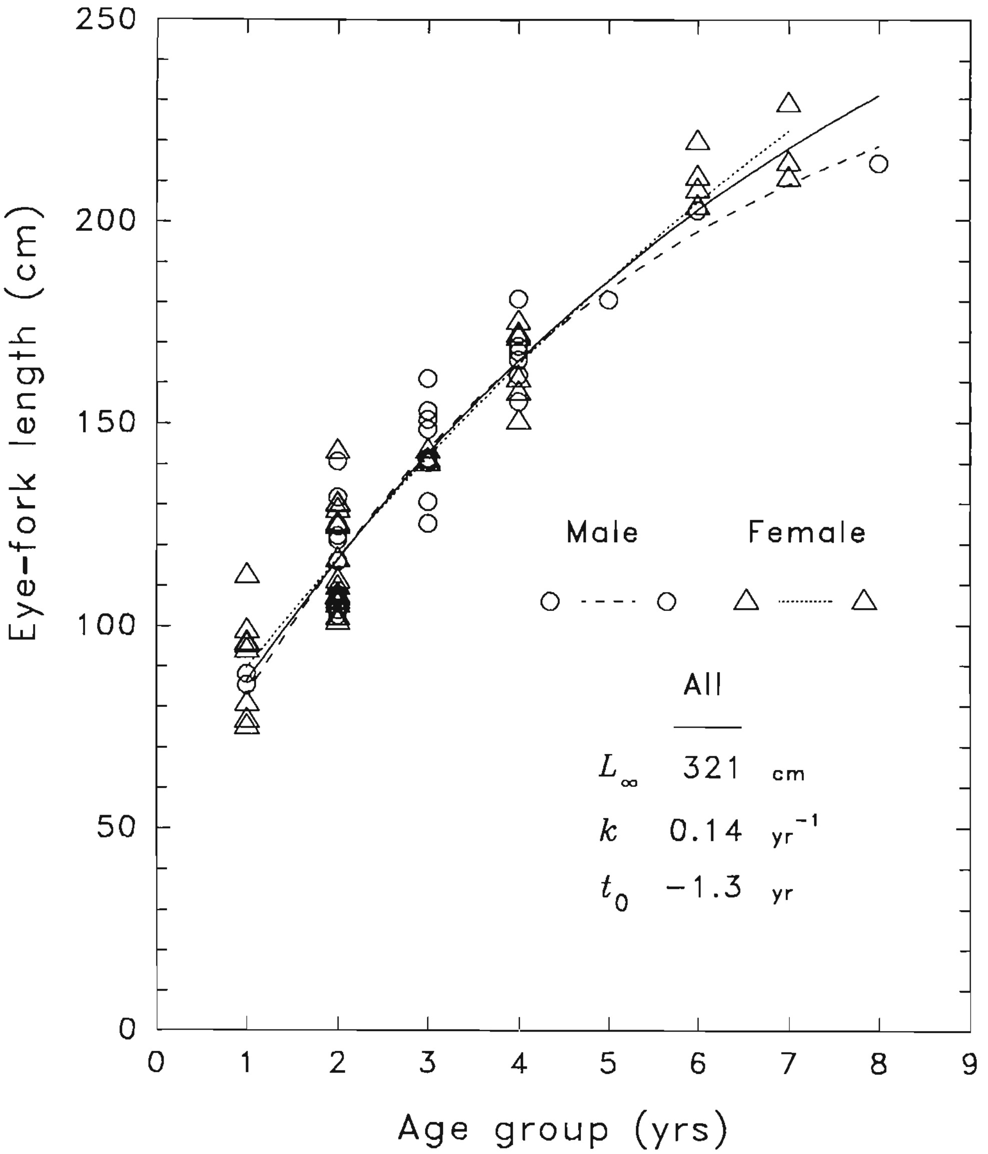

Figure 4

Von Bertalanffy growth curves (VBGF's) for adult male (n=33) and female (n=40) swordfish collected in 1992 and 1993. Provisional estimates of VBGF parameters (L_∞, K, and t_0) are noted for all (n=77) fish, including three immatures and one of undetermined sex. Age estimates were based on presumed annuli counts on cross sections of the second anal ray.

Second rays of dorsal and anal fins sometimes appeared to have more bands than adjacent rays. Higher counts may represent mistaken inclusion of multiple bands or false checks. Berkeley and Houde (1983) and Tsimenides and Tserpes (1989) both observed multiple bands on swordfish fin rays, but (like ourselves) only counted the more prominent bands as annuli.

Loss of early annuli is theoretically a problem whenever living tissues such as fin rays are used to estimate age. Neither Berkeley and Houde (1983) nor Tsimenides and Tserpes (1989) rigorously adjusted their fin ray counts for potential loss of annuli due to internal resorption. Tsimenides and Tserpes (1989) in part elected to use the second anal ray because external wear (erosion) did not seem to be a problem and because the vascularized matrix (core) of the second ray is small. Under-counting can be an important problem if early-formed annuli are missing due to resorption in the core of fin rays; back-calculating the location of resorbed first annuli has been modestly successful for other billfishes (Hill et al., 1989). Loss of the first and second annuli may not be a problem when fin rays are cut (as we have done, Fig. 2) at a moderate distance above the base, thereby potentially minimizing the effects of internal resorption and external wear. The general agreement that we found between DGI's and annuli counts for the same fish (Table 9) suggests that first annuli were present in our ray preparations, although these comparative data were limited to young fish for which resorption and wear may be less or not a problem. Further studies are needed that compare counts of annuli between sections of fin rays cut at various distances above the base and cut at the more conventional location (base) of the same fin ray, particularly for old fish.

Vertebrae—It is possible to obtain a large number of age estimates requiring no tissue preparation by counting bands on vertebral centra of landed swordfish. However, the use of vertebrae for ageing poses several problems. When counts of annuli on centra were compared to counts on rays, higher counts sometimes occurred on vertebrae, suggesting the presence of multiple bands or false checks. Since pairing of adjacent bands does not occur on centra, we had no objective basis for adjusting counts. Counts also sometimes differed between the anterior and posterior cones of the same vertebra. The last pair of bands to form on the cartilaginous faces of centra can easily be damaged or lost when vertebrae are separated with a knife or scalpel. Bands on swordfish vertebrae have previously been investigated by Beckett (1974), with similarly inconclusive results.

Otoliths—The potential of using DGI's on sagittae to estimate swordfish ages has been demonstrated by Radtke and Hurley (1983) and Wilson and Dean (1983). However, several unresolved problems exist. A major difficulty in using otoliths is the care needed to extract and prepare the tiny (1–5 mm long), delicate sagitta. To obtain age estimates, the long fragile rostrum must be extracted and prepared intact. Also, more time is required to count DGI's than to count annuli. Furthermore, increment widths near the tip of the rostrum may be too narrow to be resolved by light microscopy (Campana and Neilson, 1985), requiring scanning electron microscopy. Light microscopic counts of the relatively broad DGI's that form during rapid early growth may be the best way to age larval and young-of-year juvenile swordfish (Megalafonou et al., 1995), however.

The ridges reported by Radtke and Hurley (1983) on the rostrums of sagittae of northwest Atlantic swordfish have now also been observed on sagittae of central Pacific swordfish. Since rostral ridges are surface structures, the angle at which rostrums are viewed affects their counts. Identifying the first and last ridges can be subjective because these ridges are sometimes less developed than others, and an obvious potential bias exists for underestimating ages. Conversely, we observed some specimens for which ridge counts were higher than counts of annuli on other tissues from the same fish. Ridges did not appear to form pairs or groupings on these latter specimens, so there was no obvious basis for objectively adjusting counts. The use of rostral ridges on sagittae for estimating ages of swordfish merits further study.

We also observed bands on the postrostrums of sagittae that possibly could be used to estimate age. However, counts of these bands were usually higher than counts on other tissues of the same fish. As with vertebral bands and otolith ridges, these postrostral bands did not appear to form pairs or groupings whose numbers could be objectively adjusted downwards. Postrostral bands on swordfish sagittae appear to be among the least reliable time markers and we discourage their use.

Age Validation

Ehrhardt's (1992) and Tserpes and Tsimenides's (1995) edge analyses of annuli on anal fin rays of Atlantic and Mediterranean swordfish, respectively, remain the only partially successful attempts to date at validating swordfish ages based on a hard part. Wilson and Dean (1983) and Radtke and Hurley (1983) only verified their results when they found agreement between counts from different preparations or tissues. We have similar verification based on a general agreement between estimates from second and third rays from dorsal and anal fins, caudal vertebrae, and otolith ridges and DGI's. To date we have been unable to validate our results, however, because no oxytetracycline-marked fish have been recaptured. Thus far we also lack a comprehensive time series of specimens necessary for an analysis of the seasonal progression of marginal growth increments on ageing structures. Insufficient seasonal samples seriously limited Ehrhardt's (1992) study.

Provisional Growth Model

We are reasonably confident that our estimates of age in whole years for swordfish collected in 1992 and 1993 neither over- nor under-estimate ages by significant fractions of a year. Even though the fin rays used for this analysis were collected during a limited period of the year (March–May), a translucent zone was always present on the edges of ray cross sections of the young-of-year and age-1 fish, indicating completion or near-completion of the last annulus. Some edges of ray cross sections of older fish (≥2 yr) were translucent, but most were partly translucent and opaque or still fully opaque (Uchiyama, unpublished observation). Our current study of fin rays emphasizes the timing and duration of opaque and translucent band formation for most early age groups of central North Pacific swordfish.

Yabe et al. (1959) consistently identified four length modes (73, 102, 128, and 148 cm EFL) for swordfish caught during 1948–56 in the western North Pacific. Our provisional growth curve for swordfish of both sexes in the central North Pacific generally agrees with these length modes, if the second, third and fourth length modes of Yabe et al. (1959) correspond to fish ages 1+ (18 mo), 2+ (30 mo), and 3+ (42 mo). Our curve estimates a length of 74 cm in about 7 mo, 104 cm in 18 mo, 132 cm in 30 mo, and 157 cm in 42 mo (Fig. 4). Our estimate of the VBGF parameter, $K = 0.14$, for the sexes pooled is similar to the $K = 0.124$ estimated by Sakagawa and Bell (1980) using Yabe et al.'s (1959) progression of length modes and $L_\infty = 309$ cm, graphically estimated using Walford's (1946) method. Our growth curve describes an average growth increment of about 28 cm/yr for swordfish between 74 and 157 cm EFL, compared to Yabe et al.'s (1959) estimate of about 25 cm/yr for swordfish of 73–148 cm EFL from the western North Pacific. Using length frequency data for swordfish caught in the eastern Pacific, Kume and Joseph (1969) estimated growth rates of 38 cm/yr for fish of 62–165 cm EFL.

These general agreements between length modes and estimates of the VBGF parameter, K, are limited to only the first several apparent age classes entering their respective fisheries. Clearly, additional data for both small (young-of-year and yearling) and very large (>200 cm EFL) fish are needed to adequately describe the shape of the VBGF growth curve. The von Bertalanffy parameters K and L_∞ are inversely related, and L_∞ is greatly influenced by data that lie near and on the asymptote of the curve (Southward and Chapman, 1965).

Kume and Joseph (1969) further concluded that females grow faster and larger than males among eastern Pacific swordfish. Also, based on size frequency distributions, female swordfish in the eastern Atlantic appear to grow faster and larger than males (Beckett, 1974). The hard-part ageing studies of Berkeley and Houde (1983), Radtke and Hurley (1983), and Wilson and Dean (1983) all suggest or indicate faster growth rates for female swordfish in the western Atlantic, as did analogous studies by Tsimenides and Tserpes (1989) and Megalofonou et al. (1991) of swordfish of the Mediterranean and Aegean Seas. Our data likewise suggest that male growth starts decelerating earlier, perhaps because males mature at smaller sizes or younger ages in the Pacific as well as the Atlantic (Taylor and Murphy, 1992; Arocha et al., 1994). Greater numbers of large (>165 cm EFL) specimens of both sexes are needed before we can adequately evaluate possible sexual dimorphism in the growth and mortality rates of Pacific swordfish.

Research Needs

Since the end of summer 1993, observers have been placed aboard commercial longline vessels operating from Honolulu, and these observers have collected anal fins and otoliths for our ageing studies. These samples will enable us to expand our studies over a broader geographical area and obtain greater numbers of large fish. In addition, better seasonal coverage should result than can be accomplished with our single research vessel.

A larger-scale tagging program with a more efficient system for tagging and recovering tagged fish is necessary for validation. Greater involvement of the fishing industry, other U.S. agencies, and foreign investigators would vastly improve the chances of recapturing time-marked fish. On research cruises, we have learned how to select and handle swordfish during the tag application process to maximize apparent viability, and these findings need to be implemented on observer and cooperating fishermen cruises. A more accurate method for estimating size of fish at the time of tag release also still needs to be developed.

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