AGE DETERMINATION OF PACIFIC COD, *GADUS MACROCEPHALUS*, USING FIVE AGEING METHODS[1]

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ABSTRACT

A comparative study of age determination methods for Pacific cod, *Gadus macrocephalus*, was carried out using dorsal and pectoral fin rays, scales, otoliths, and coracoids. A preliminary validation using the modal length of a strong year class confirmed that sections of dorsal fin rays were the most reliable ageing method. A Monte Carlo method was developed for converting scale ages to dorsal fin-ray ages. An analysis by log-linear model was developed for testing the effects of ageing method and age class on repeatability of age reading.

Scales have been widely used for ageing Pacific cod, *Gadus macrocephalus*, in the North Pacific since Kennedy (1970) developed the method for fish in Hecate Strait, British Columbia. However, Bakkala (1981)[5] found that the scale method may not be an appropriate ageing method since the estimated ages from scales do not appropriately reflect the progress of known year classes in the eastern Bering Sea. Beamish et al. (1978) also found that Kennedy's criteria might not be satisfactory for scales from juvenile Pacific cod in Canadian waters.

Beamish (1981) reported that thin sections of fin rays can be reliably aged and might be more accurate than scale ages when ageing older fish. However, Westrheim and Shaw (1982) encountered difficulties with fin-ray cross sections and reported that fin-ray ages were younger than scale ages. They also discovered false checks on the scales during the first year of life, which fitted the annulus criteria of Kennedy (1970), and validated the scale ageing method for age-1 and -2 Pacific cod. Chilton and Beamish (1982) noted problems associated with scales and fin rays, and recommended a judicious mixture of scale ages, fin-ray ages and length-frequency analysis for ageing Pacific cod in Canadian waters.

In earlier studies, Mosher (1954), Moiseev (1953), and Ketchen (1970) reported that the otolith surface ageing method was not satisfactory for Pacific cod. Ketchen (1970) also had no success with ageing of vertebrae, or opercula. Lai (1985) reported that age determination from the bony tissues in the gillcover, scapula, and cleithrum was not feasible.

This paper reports the results of a comparative study and preliminary validation of age determination methods for Pacific cod in the eastern Bering Sea using dorsal and pectoral fin rays, scales, otoliths and coracoids. In addition, we develop a method to convert scale ages to dorsal fin-ray ages. This age conversion method makes it possible to use existing ages estimated from scales.

MATERIALS AND METHODS

Dorsal and pectoral fin rays, otoliths, and scales were taken from 230 Pacific cod collected from foreign fishing vessels operating in the eastern Bering Sea during September 1983 to March 1984. Among these samples, coracoids were also taken from 101 fish.

Dorsal and pectoral fin-ray sections were prepared using an Isomet low-speed saw (Lai 1985), and the annuli were identified by the criteria of Beamish (1981) and Chilton and Beamish (1982). Scale images were made by acetate plate (Koo 1962) and then read by a microfisch reader. Annuli on scales were identified by the methods de-

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scribed in Westrheim and Shaw (1982). Otoliths must be sectioned with a low-speed electric saw and burnt with care, as they are quite brittle. The interpretation of annuli on break-and-burn surfaces was adapted from that of walleye pollock (Lai and Yeh 1986).

The coracoid is a dermal bone connected to the scapula and radii in the pectoral girdle. A triangular component within the coracoid (Fig. 1) shows alternate opaque (dark) and translucent (light) zones under a binocular microscope and transmitted light, by which annuli can be identified. The center of this structure occasionally contains some checks that are parallel to the annulus; however, their spacing is narrower than that of regular annuli. The age samples were read

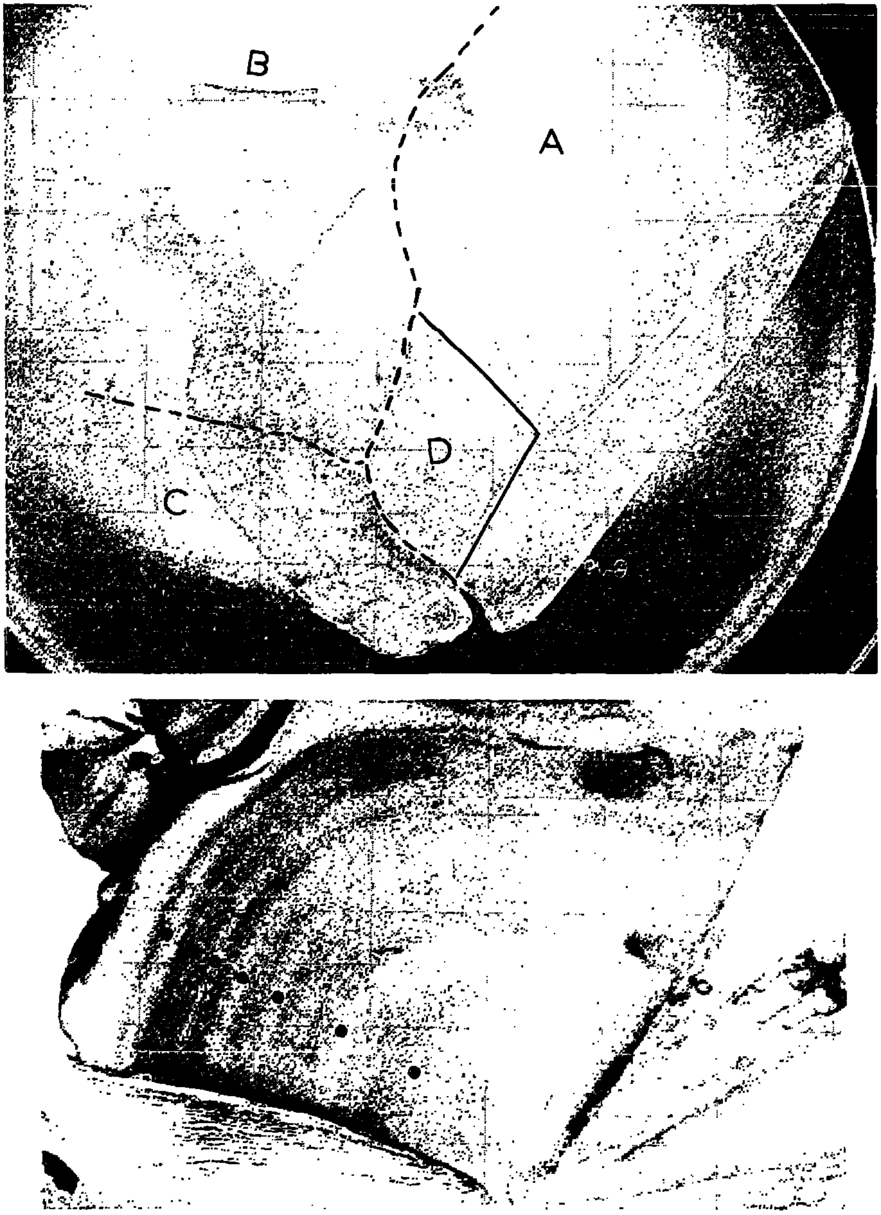

FIGURE 1.—Upper: The pectoral girdle. A, coracoid; B, scalpula; C, radii; D, the portion used for age determination. Lower: Enlarged Part D. ●, translucent zone, counted as an annulus.

twice by the senior author, who had 3 years experience in age determination using all of the ageing methods.

A loglinear model (Fienberg 1981) was used to test the independence of repeatability ($R, k = 1, 2$ corresponding to agreement and disagreement) of age readings corresponding to age-class (A, $j = 1,...,8$ corresponding to age classes given in Table 1) and ageing method (M, $i = 1,...,5$ corresponding to ageing methods in the sequence given in Table 1). See Appendix A for the details of this statistical method. The computer program P4F in BMDP (Dixon 1983) was used for computation and analysis.

TABLE 1.—Observed frequency of agreement between two age readings using different ageing methods. Percent agreement is shown in parentheses.

Method (*M*)	Age (*A*)	Repeatability (*R*)		Total
		Agree	Disagree	
Coracoid	under 2	9 (100)	0	9
	3	1 (50)	1	2
	4	10 (77)	3	13
	5	12 (60)	8	20
	6	18 (67)	9	27
	7	5 (45)	6	11
	8	3 (43)	4	7
	over 9	4 (40)	6	10
Total		62 (63)	37	99
Break-and-burn	under 2	9 (90)	1	10
	3	7 (64)	4	11
	4	8 (73)	3	11
	5	41 (67)	20	61
	6	35 (58)	25	60
	7	14 (39)	22	36
	8	6 (35)	11	17
	over 9	9 (41)	13	22
Total		129 (57)	99	228
Dorsal fin ray	under 2	9 (100)	0	9
	3	2 (67)	1	3
	4	13 (81)	3	16
	5	36 (77)	11	47
	6	40 (82)	9	49
	7	24 (69)	11	35
	8	9 (39)	14	23
	over 9	7 (29)	17	24
Total		140 (68)	66	206
Pectoral fin ray	under 2	8 (100)	0	8
	3	6 (75)	2	8
	4	18 (64)	10	28
	5	36 (68)	17	53
	6	24 (45)	29	53
	7	12 (43)	16	28
	8	10 (45)	12	22
	over 9	3 (25)	9	12
Total		117 (55)	95	212
Scale	under 2	9 (82)	2	11
	3	11 (61)	7	18
	4	60 (74)	21	81
	5	48 (64)	27	75
	6	11 (38)	18	29
	7	1 (11)	8	9
	8	0 (0)	1	1
	over 9	0 (0)	1	1
Total		140 (62)	85	225

An analysis of variance (ANOVA) model with repeated measures (Winer 1971) was used to examine variability in age readings due to the methods. The ANOVA model was

$$X_{ijn} = \mu + \pi_n + M_i + (M\pi)_{in} + R_j + (R\pi)_{jn} + (MR\pi)_{ijn} + \epsilon_{ijn}$$

where, X_{ijn} is the observed age of the nth fish by the ith ageing method and jth reading,

$i = 1, 2, 3, 4, 5$ indicates ageing methods in the sequence shown in Table 1,
$j = 1, 2$ indicates the first and second age readings,
$n = 1,...,N$ indicates number of fish,

μ is the grand mean,
π is the effect between subjects (individual fish),
M is the effect of ageing method,
R is the effect of reading,
$(M\pi)$, $(R\pi)$, and $(MR\pi)$ are the two- and three-factor interactions of effects M, R, and π, and
ϵ is the random error.

Readings from coracoids were not included in the analysis because of the small sample size. Specimens with missing values were also excluded from this analysis. The Q-statistic (Snedecor and Cochran 1967) was used to test the differences between the mean ages between readings and between ageing methods.

Validation of age determination was carried out by comparing the mean lengths at age estimated from the five ageing methods to the modal lengths of the 1977 year class. The progression of this year class could be traced by examining the length-frequency distributions for 1978 to 1983.

Because existing age data files for Pacific cod at the Northwest and Alaska Fisheries Center (NWAFC) were derived from scales, it is important to explore whether or not the scale age data can be used for stock assessment. A simulation study was carried out to convert a scale age-length key to a dorsal fin-ray age-length key, since the dorsal fin-ray method provides more accurate ages.

Age-length keys, derived from scales collected in 1979 and 1980 NWAFC demersal trawl surveys in the eastern Bering Sea, and length-frequency distributions obtained from these surveys were used as basic data to be converted. The classification probabilities for fin rays vs. scales were constructed from 966 age readings on dorsal fin rays and scales from the same fish collected in 1983-84 (Table 2). Each fish in the 1979 and 1980 scale age-length key was assigned a "pseudo" dorsal fin-ray age, which was a random variate generated from the subprogram GGDA in IMSL (International Mathematical and Statistical Library). The GGDA subroutine used the prior probability density in Table 2 corresponding to the scale age and length group to which the fish belongs. This was done 30 times to create 30 converted age-length keys each for 1979 and 1980. Then, mean lengths at age were determined from each converted age-length key, and age compositions were estimated by the method described in Lai (1987). These simulated results were compared with those from length-frequency analysis (Lai 1985).

RESULTS

Table 1 shows that the age readings from dorsal fin rays had the highest percent agreement (68%), followed by coracoids (63%), scales (62%), otoliths (57%), and pectoral fin rays (55%). Furthermore, the percent agreement for the major age classes in the fishery (ages 4-7) were much higher than for the other methods. To confirm this result, a log-linear model was fitted to the data in Table 1.

Table 3 shows that the best log-linear model (Appendix A) was

$$\theta_{ijk} = \log(m_{ijk}) = \mu + \lambda_i^M + \lambda_j^A + \lambda_k^R + \lambda_{ik}^{MR} + \lambda_{jk}^{AR} + \lambda_{ij}^{MA} \quad (2)$$

TABLE 2.—Observed classification probability for age readings from scales and dorsal fin-rays.

Scale age	Length (cm)	Dorsal fin-ray age														Total
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	
1	20-29	1.0														20
1	30-39		1.0													6
2	30-39		1.0													8
2	40-49			0.750	0.250											8
3	30-39		1.0													2
3	40-49			0.333	0.667											3
3	50-59				0.188	0.375	0.375	0.063								32
3	60-69				0.087	0.565	0.174	0.130	0.043							23
4	40-49				0.133	0.467	0.400									15
4	50-59				0.604	0.264	0.094	0.038								53
4	60-69				0.066	0.377	0.221	0.197	0.098	0.041						122
4	70-79					0.153	0.350	0.190	0.065	0.058	0.066	0.051	0.036	0.029		137
4	80-89						0.348	0.217	0.174	0.130	0.043	0.087				23
5	50-59				0.143	0.857										14
5	60-69				0.043	0.391	0.239	0.196	0.109	0.022						92
5	70-79				0.005	0.095	0.264	0.206	0.180	0.116	0.069	0.048	0.016			189
5	80-89						0.154	0.128	0.205	0.256	0.154	0.077	0.026			39
5	90-99										0.500	0.500				2
6	60-69							0.611	0.222	0.167						18
6	70-79				0.017	0.083	0.333	0.233	0.167	0.117	0.033	0.017				60
6	80-89						0.188	0.344	0.156	0.125	0.125	0.063				32
6	90-99							0.059	0.412	0.176	0.118	0.118	0.118			17
6	100-109										0.500	0.500				4
7	70-79						0.333	0.111	0.333	0.111					0.111	9
7	80-89						0.182			0.545		0.182		0.090		11
7	90-99							0.063	0.187	0.250	0.187	0.063	0.250			16
8	80-89									0.400	0.200	0.400				5
8	90-99									0.333		0.167	0.333	0.167		6

TABLE 3.—Test for the independence of percent agreement (*R*) of age readings correlated to age-class (*A*) and ageing method (*M*).

Model	df	G2	Probability
$\mu + \lambda_i^M + \lambda_j^A + \lambda_k^R + \lambda_{ik}^{MR} + \lambda_{jk}^{AR} + \lambda_{ij}^{MA} + \lambda_{ijk}^{MAR}$	0	0.00	1.0000
$\mu + \lambda_i^M + \lambda_j^A + \lambda_k^R + \lambda_{ik}^{MR} + \lambda_{jk}^{AR} + \lambda_{ij}^{MA}$	28	28.08	0.4603
$\mu + \lambda_i^M + \lambda_j^A + \lambda_k^R + \lambda_{ik}^{MR} + \lambda_{jk}^{AR}$	32	48.87	0.0285
$\mu + \lambda_i^M + \lambda_j^A + \lambda_k^R + \lambda_{jk}^{AR} + \lambda_{ij}^{MA}$	56	241.75	0.0000
$\mu + \lambda_i^M + \lambda_j^A + \lambda_k^R + \lambda_{ik}^{MR} + \lambda_{ij}^{MA}$	35	125.03	0.0000

TABLE 4.—Estimated logit effects corresponding to the loglinear model in Equation (2).

Factor		Logit effect
constant (ω)		0.540
Age (ω_j^A)	≤2	2.204
	age 3	0.240
	age 4	0.676
	age 5	0.278
	age 6	−0.196
	age 7	−0.738
	age 8	−1.064
	over 9	−1.400
Age method (ω_i^M)	Dorsal fin ray	0.568
	Coracoid	0.096
	Otolith	−0.058
	Pectoral fin ray	−0.208
	Scale	−0.398

which implied that percent agreement was correlated to age-class and ageing method, and the estimated age frequencies differed by ageing method. However, these pairwise relationships between any two factors are unrelated to the third.

Because we are interested in the effects of ageing method and age class on repeatability, it is reasonable to look at the ratio between agreement ($k = 1$) and disagreement ($k = 2$) for each combination of ageing method and age class, i.e., m_{ij1}/m_{ij2} for all i and j. The logarithm of this ratio is known as the logit model (Fienberg 1981, chapter 6). The logit model for Equation (2) can be derived as

$$\text{logit}(i,j) = \log\,(m_{ij1}/m_{ij2}) = \omega + \omega_i^M + \omega_j^A \qquad (3)$$

where, the logit effects, $\omega = (\lambda_1^R - \lambda_2^R)$, $\omega_i^M = (\lambda_{i1}^{MR} - \lambda_{i2}^{MR})$, and $\omega_j^A = (\lambda_{j1}^{AR} - \lambda_{j2}^{AR})$. The effects ($\lambda$'s) without factor R in Equation (2) are cancelled out by subtraction in Equation (3). The values of λ's can be obtained from the BMDP program and substituted into Equation (3). The results show that there was a significant declining effect on agreement as age increased (Table 4). This indicated that percent agreement decreased with increasing age. Age determination using coracoids and dorsal fin rays had a positive effect on agreement, which indicated that agreement of these methods was higher than the average of the five methods, but the other ageing methods had a negative effect, i.e., agreement was lower than average.

Table 5 shows that the effect of ageing method was significant for all fish older than age 3. There was no significant difference (5% level) between readings except for ages 5-6. This difference probably resulted from differences between readings for otoliths and pectoral fin rays (Table 6). Mean square (MS) for the ageing method effect increased with age and was the predominant component in the within-subject variation for all age categories. Therefore, variability in age determination was mainly due to ageing method rather than inconsistent annulus interpretation by the reader.

Using the Q-statistic, the mean ages of the two readings were not significantly different except for age group 5-6 using otolith and pectoral fin-ray ageing methods (Table 6). Significant differences between ageing methods were found in all age categories except the youngest. Age readings from dorsal fin rays and pectoral fin rays were not significantly different for fish younger than age 6. Age readings from otoliths and pectoral fin rays were not significantly different for fish older than age 7. Otolith readings were older than other methods for fish younger than age 6 but were younger than dorsal fin-ray readings for fish older than age 7. Scale readings gave consistently younger ages than the other methods.

Bakkala and Wespestad (1984) reported that recruitment of the 1977 year class was uniquely strong when compared to its neighboring year classes. The modal length of this year class can be

TABLE 5.—Comparison of ageing variability of Pacific cod by ANOVA.

Dorsal fin-ray age	N		Between subject (π)	Within subject					
				Method (*M*)	*M*π	Reading (*R*)	*R*π	*MR*	*MR*π
1-2	8	SS	14.359	0.297	2.578	0.016	0.109	0.047	1.328
		df	7	3	21	1	7	3	21
		MS	2.051	0.099	0.123	0.016	0.016	0.016	0.063
		F		0.81		1.00		0.25	
3-4	19	SS	52.395	8.967	38.658	0.164	3.711	0.072	7.553
		df	18	3	54	1	18	3	54
		MS	2.911	2.989	0.716	0.164	0.206	0.024	0.140
		F		4.18**		0.80		0.17	
5-6	93	SS	270.495	166.154	273.721	1.840	26.285	1.122	74.253
		df	92	3	276	1	92	3	276
		MS	2.940	55.385	0.992	1.840	0.286	0.374	0.269
		F		55.85**		6.44**		1.39	
7-8	57	SS	217.244	344.018	267.232	0.219	26.031	0.921	56.829
		df	56	3	168	1	56	3	168
		MS	3.879	114.673	1.591	0.219	0.465	0.307	0.338
		F		72.09**		0.47		0.91	
9+	23	SS	339.457	498.283	198.717	0.035	21.652	1.869	53.130
		df	22	3	66	1	22	3	66
		MS	15.430	166.090	3.011	0.348	0.984	0.623	0.805
		F		55.16**		0.35		0.77	

** = significant at 1% level.

TABLE 6.—Tests for differences between mean ages of Pacific cod using various ageing methods. Bracket and underline: not significantly different at 5% level.

Dorsal fin-ray age	N	Reading	Dorsal fin ray	Otolith	Pectoral fin ray	Scale	SD	df
1-2	8	1	1.375]	1.375]	1.375]	1.250]	0.063	7
		2	1.375]	1.475]	1.375]	1.250]		
		Method mean	1.375	1.425	1.375	1.250	0.124	21
3-4	19	1	3.842]	4.211]	3.842]	3.579]	0.147	18
		2	3.847]	4.315]	3.895]	3.579]		
		Method mean	3.895	4.263	3.869	3.579	0.194	54
5-6	93	1	5.505]	5.774	5.430	4.581]	0.078	92
		2	5.588]	5.979	5.591	4.570]		
		Method mean	5.547	5.877	5.511	4.576	0.103	276
7-8	57	1	7.386]	6.561]	6.614]	5.000]	0.128	56
		2	7.316]	6.702]	6.737]	4.982]		
		Method mean	7.351	6.632	6.676	4.991	0.167	168
9+	23	1	10.130]	8.000]	8.304]	5.522]	0.293	22
		2	9.913]	8.261]	8.130]	5.304]		
		Method mean	10.022	8.131	8.217	5.413	0.362	66

traced from the length-frequency distributions from 1978 to 1983 (Fig. 2). Using the method of Macdonald and Pitcher (1979), the mean lengths for ages 1-6 were 22, 35, 43, 52, 61, and 64 cm respectively (Lai 1985) and were very close to the modal length of length-frequency distributions. Figure 2 shows the mean lengths at age estimated from the 1983-84 samples by the five ageing methods and the comparison to the modal lengths. It is apparent that the mean lengths at age estimated from dorsal fin rays were closest to the modal lengths. Also, the variability around mean length at age estimated from dorsal fin rays was generally smaller than for the other methods. We also used the index of variation[6] (IV, Lai

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[6] $IV = 100\% \cdot \sqrt{\Sigma(Y_i - X_i)^2/[(n-1)(\overline{X} + \overline{Y})/2]}$, where X_i is the first age reading, Y_i is the second age reading, n is the sample size, and $\overline{X}$ and $\overline{Y}$ are mean of the X_i and Y_i (Lai 1985). This indicates the degree of variation between the two

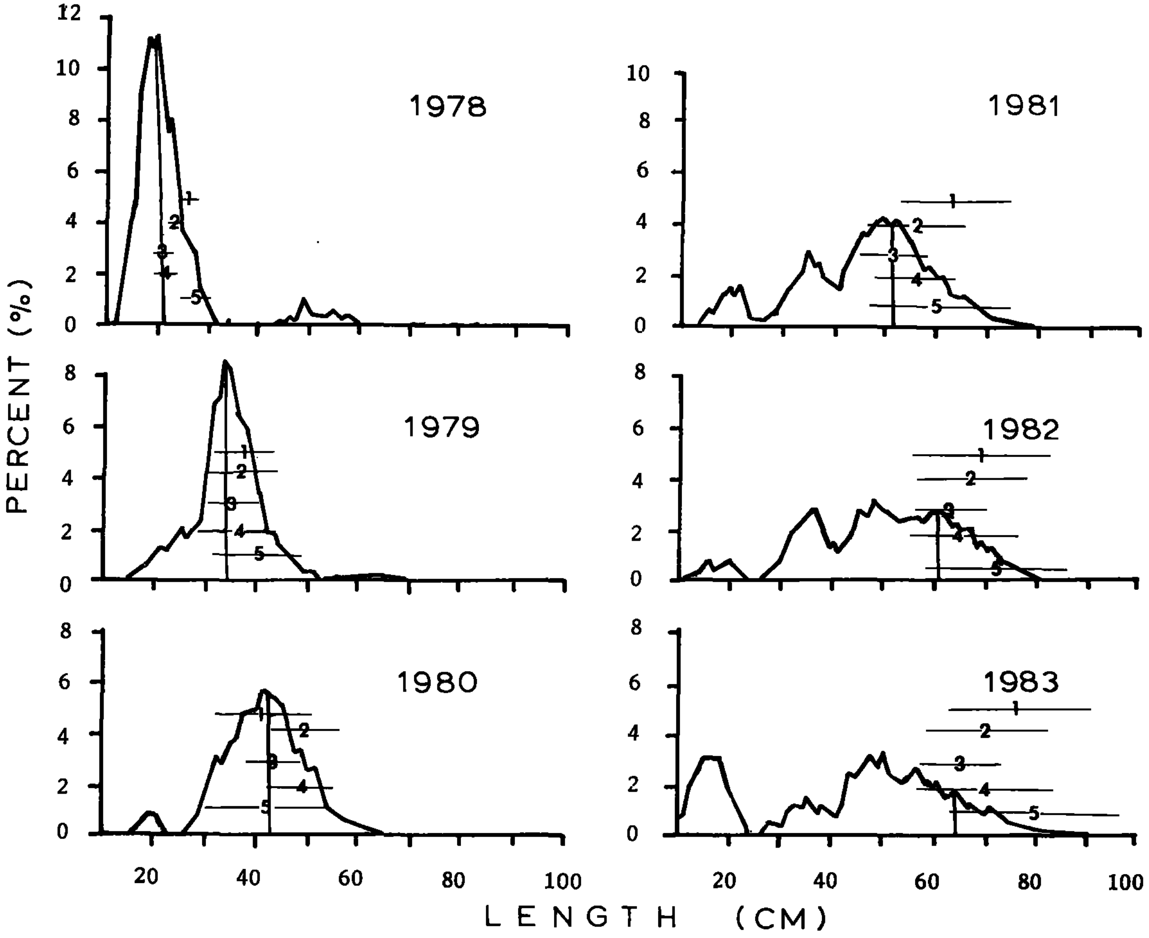

FIGURE 2.—Length-frequency distributions collected from trawl surveys in 1978-83 (after Bakkala and Wespestad 1984). The mode in 1978 represents age-1 Pacific cod of the 1977 year class, and progresses from age 2 to age 6 in the subsequent years. The estimated mean lengths at ages 1-6 estimated from the five ageing methods (1, coracoids; 2, otoliths; 3, dorsal fin rays; 4, pectoral fin rays; and 5, scales) correspond to the age of 1977 year class. Horizontal lines indicate 95% confidence interval around means. Vertical lines indicates the mean length from length-frequency analysis.

1985) to examine the degree of precision. Among the five ageing methods, the IV for dorsal fin rays was the lowest (13%) when compared with other methods (14%, 14%, 15%, and 16% respectively for otoliths, coracoids, scales, and pectoral fin rays).

The accuracy of converting scale ages to dorsal fin-ray ages was also evaluated. Mean length at age and age composition (obtained by using converted dorsal fin-ray ages) were compared with corresponding results from length-frequency analysis (Macdonald and Pitcher 1979). The 95% confidence interval (Fig. 3) for each converted mean length at age in 1979 and 1980 included the corresponding value estimated from the length-frequency analysis. However, the mean lengths at age derived from scales were significantly different from the other two.

The age composition estimated by the scale method showed a monotonic decrease with age in 1979, and the strong 1977 year class (age 2) was not evident (Fig. 4). Nevertheless, length-frequency data from surveys indicated that age-2 fish were dominant in 1979 (Bakkala and Wespestad 1984). The age composition based on converted dorsal fin-ray ages was dominated by age-2 fish and was similar to that estimated from the

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ages being compared taking the age distribution of the sample into account.

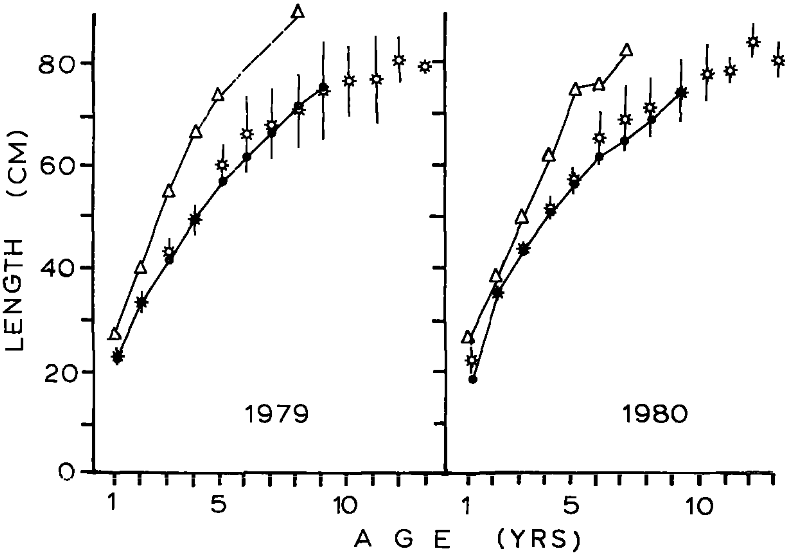

FIGURE 3.—Comparison of mean length at age estimated from scales (—Δ—), converted dorsal fin-ray ages (*), and length-frequency analysis (—●—) for 1979 and 1980. Vertical line indicates the 95% confidence interval from the 30 simulation runs.

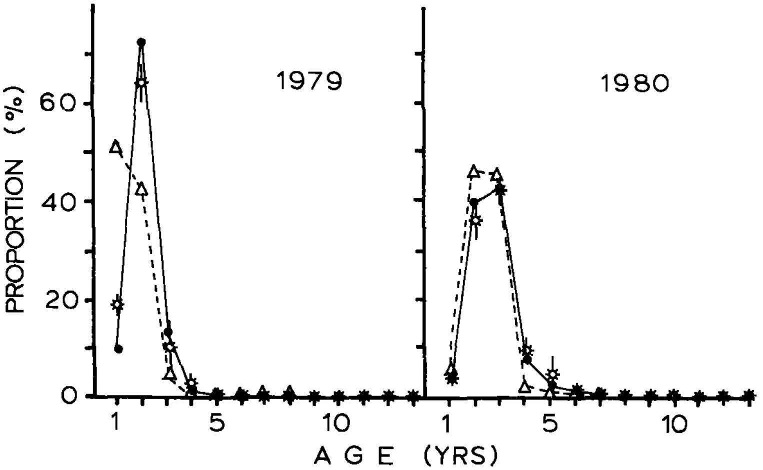

FIGURE 4.—Comparison of age composition estimated from scales (—Δ—), converted dorsal fin-ray ages (*), and length-frequency analysis (—●—). Vertical line indicates 95% confidence interval of the 30 simulation runs.

length-frequency analysis. In 1980, the proportions estimated by using the scale method were somewhat higher than for the other two methods at ages 2 and 3 (Fig. 4), but were lower at ages 4 and 5. Since the classification probabilities and scale age-length keys used in this study were derived independently from different years, the method of age conversion appears to be relatively insensitive to interannual differences in the classification probabilities.

DISCUSSION

Although Westrheim and Shaw (1982) validated the interpretation of the annuli on scales for age groups 1 and 2, this validation was not considered to be sufficient for all age groups. Beamish et al. (1978, figs. 12 and 13) showed that the difference between readers was substantial even in age groups 1 and 2. In our study, we found that age readings from the scale method had low precision, and that scale ages were much younger than those obtained by any other method.

In this study, validation for age groups 1-6 showed that dorsal fin rays gave the most reliable ages for Pacific cod and thus should be used in the future. This method provided estimates of mean length at age that agreed most closely to observed growth of the 1977 year class, and the precision of this method was the highest attained in this study. Another major advantage of this ageing method is that additional fin rays can be taken from fish with a previous history of fin-ray removal to verify the accuracy of age determinations between time of release and recapture.

We used the Monte Carlo method to convert scale ages to dorsal fin-ray ages. The results indicated that the previously collected scale age data can be used in age-dependent methods of stock assessment. Since the 1983-84 classification probabilities used in this study were completely independent of the 1979-80 scale age data, the method appears to be robust with respect to interannual variability in the classification probabilities for Pacific cod. However, application of this method to other species will require caution when the classification probabilities are applied to the data from different years, since interannual variability could be a source of error. Still, any errors that arise will probably be smaller than those produced from an inappropriate ageing method.

Analytical methods, such as those of Pella and Robertson (1979) and Cook (1982), could also be used for converting scale age-length keys to dorsal fin-ray age-length keys. However, these methods are mathematically more complicated and occasionally yield negative values in some of the converted age-length keys (Cook 1982). The method of Hoenig and Heisey (1987)[7] is of particular interest because it avoids negative values by applying an incomplete E-M (estimation and maximization) algorithm to fit a log-linear model to the classification matrix. Nevertheless, this method may not be valid if there is a substantial systematic ageing error (as in our case, dorsal fin-ray ages vs. scale ages) because too many empty cells are in the classification matrix. Alternatively, the method of Barlow (1984) can also be used for this purpose, although the result will be very similar to our Monte Carlo method, as Barlow's method is a deterministic version of our own.

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APPENDIX A.—ANALYSIS BY LOG-LINEAR MODEL

In our study, there are three factors, ageing method (M), age class (A), and repeatability (R). Our sampling model is product-multinomial, using the terminology of Fienberg (1981, Sec. 3-2), since the number of fish being aged is fixed for each ageing method after deleting unreadable or damaged age-structures. The aged fish were cross-classified into corresponding cells denoted by factors A and R (Table 1).

Let y_{ijk} be the observed cell frequency for the ith ageing method, the jth row of age class, and the kth column of repeatability, and let m_{ijk} be the expected value of y_{ijk}. The general log-linear model (called the saturated model because it includes the highest three-factor interaction) for our three-way (5 × 8 × 2) contingency table is

$$\theta_{ijk} = \log(m_{ijk}) = \mu + \lambda_i^M + \lambda_j^A + \lambda_k^R + \lambda_{ik}^{MR} + \lambda_{jk}^{AR} + \lambda_{ij}^{MA} + \lambda_{ijk}^{MAR} \tag{A.1}$$

where, as in the usual analysis of variance model, all effects sum up to zero over any subscript. Let $\bar{\theta}$ be the marginal mean of θ_{ijk} over the subscript which is replaced by "+" to indicate averaging, then the parameters in (Equation A.1) can be written as

$$\begin{aligned}
\mu &= \bar{\theta}_{+++} & \lambda_{ij}^{MA} &= \bar{\theta}_{ij+} - \bar{\theta}_{i++} - \bar{\theta}_{+j+} + \bar{\theta}_{+++} \\
\lambda_i^M &= \bar{\theta}_{i++} - \bar{\theta}_{+++} & \lambda_{ik}^{MR} &= \bar{\theta}_{i+k} - \bar{\theta}_{i++} - \bar{\theta}_{++k} + \bar{\theta}_{+++} \\
\lambda_j^A &= \bar{\theta}_{+j+} - \bar{\theta}_{+++} & \lambda_{jk}^{AR} &= \bar{\theta}_{+jk} - \bar{\theta}_{+j+} - \bar{\theta}_{++k} + \bar{\theta}_{+++} \\
\lambda_k^R &= \bar{\theta}_{++\mathrm{k}} - \bar{\theta}_{+++} & \lambda_{ijk}^{MAR} &= \bar{\theta}_{ijk} - \bar{\theta}_{ij+} - \bar{\theta}_{i+k} + \bar{\theta}_{i++} \\
& & & \quad - \bar{\theta}_{+jk} + \bar{\theta}_{+j+} + \bar{\theta}_{++k} - \bar{\theta}_{+++}.
\end{aligned} \tag{A.2}$$

Log-linear models are "hierachical", i.e., higher-order interaction terms can be included only if related lower-order terms are included. For example, λ^{MAR} is not included unless λ^{AR}, λ^{MR}, and λ^{MA} are all included.

Once all expected cell frequencies (m'_{ijk}) are estimated, the goodness-of-fit for the selected model can be tested using the likelihood ratio test statistic

$$G^2 = 2 \sum_i \sum_j \sum_k y_{ijk} \log\left(\frac{y_{ijk}}{m'_{ijk}}\right) \tag{A.3}$$

which has approximately a χ^2 distribution with degrees of freedom (df) = number of cells − number of parameters (Fienberg 1981, sec. 3-3 and 3-4).

Using the partition property of G^2, we can decide whether an effect or an interaction should be included. In Table 3, for example, H_0: $\lambda^{MAR} = 0$ can be tested by examining $G^2 = 28.08 - 0.00 = 28.08$. This is not significant at the 1% level (referred to a χ^2 distribution with df = 28). Similarly, $G^2 = 20.79$ for H_0: $\lambda^{MA} = 0$, which exceeds the upper 1% tail value of a χ^2 distribution with df = 4, and is rejected. This means that λ^{MAR} will not be included in the model but λ^{MA} will. Hence, our best log-linear model is Equation (2).