GAYANA

ORIGINAL ARTICLE

Individual growth in Jack mackerel (*Trachurus murphyi*) of the Southeastern Pacific Ocean using sagitta otolith weight, daily rings, and annual rings

Crecimiento individual en jurel (*Trachurus murphyi*) del Océano Pacífico Suroriental utilizando el peso del otolito sagittae, anillos diarios y anillos anuales

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ABSTRACT

We estimated the growth of Jack mackerel (*Trachurus murphyi*) using increments of daily growth, otolith weight and annual ring reading in sagittal otoliths. The daily micro-increments were used to fit ring density to the otolith radius (n = 4481) and then to estimate the age of the individual in days. The parameters of the von Bertalannfy growth equation were: maximum theoretical fork length, FL_∞ = 75 cm; individual growth coefficient, K = 0.16 year^{-1}; theoretical age at which fish length is zero, t_0 = −0.19 years. The growth parameters of *T. murphyi* estimated using annual rings reading were: K = 0.10 year^{-1}, FL_∞ = 74.7 cm, t_0 = −0.50 years. The growth parameters estimated using otolith weight were: K = 0.15 year^{-1}, FL_∞ = 75.0 cm, t_0 = −0.48 years. The parameter K estimated with the daily micro-increments was similar to the K estimated using sagittal otolith weights. We constructed a size-age key for *T. murphyi* using otolith weight, OW (milligrams) as a variable was: OW= 0.0323*t-15.197 (r^2 = 0.68). We recommend using otolith weight to estimate age in *T. murphyi* due to this technique is statistically reliable, but also cheap and fast.

Keywords: estimator of the age, growth parameters, otolith weight, *Trachurus*, t (years).

RESUMEN

Se estimó el crecimiento del jurel (*Trachurus murphyi*) usando incrementos de crecimiento diario, peso de otolito y lectura de anillos anuales en otolitos sagitales. Los micro incrementos diarios se utilizaron para ajustar la densidad del anillo al radio del otolito (n = 4481) y luego para estimar la edad del individuo en días. Los parámetros de la ecuación de crecimiento de von Bertalannfy fueron: longitud máxima teórica a la horquilla, FL_∞ = 75 cm; coeficiente de crecimiento individual, K = 0,16 año^{-1}; edad teórica a la que la talla de los peces es cero, t_0 = -0,19 años. Los parámetros de crecimiento de *T. murphyi* estimados usando la lectura de anillos anuales fueron: K = 0,10 año^{-1}, FL_∞ = 74,7 cm, t_0 = -0,50 años. Los parámetros de crecimiento estimados usando el peso del otolito fueron: K = 0,15 año^{-1}, FL_∞ = 75,0 cm, t_0 = -0,48 años. El parámetro K estimado con los microincrementos diarios fue similar al K estimado usando pesos de otolitos sagitales. Se construyó una clave de tamaño-edad para *T. murphyi* usando el peso del otolito, OW (miligramos) como una variable fue: OW= 0,0323*t-15,197 (r^2 = 0,68). Se recomienda usar el peso del otolito para estimar la edad en *T. murphyi*, debido a que esta técnica es estadísticamente confiable, pero también barata y rápida.

Palabras clave: estimador de la edad, parámetros de crecimiento, peso de otolitos, *Trachurus*,t (años).

INTRODUCTION

The Jack mackerel (*Trachurus murphyi* Nichols, 1920) is the main fish resource species of the nearshore fleets of Chile and Peru that operate in the Southeastern Pacific Ocean, in their respective economic exclusion zones (EEZ), as well as the international dragging fleets of China, Russia, Taiwan and others that operate outside the EEZ. The maximum official total landings in Chile occurred in 1995, with 4.96 million tons. By comparison, the total capture of *T. murphyi* in 2017 by all national and international fleets, according with the South Pacific Regional Fisheries Management Organization (SPRFMO 2017), was 303,555 tons, but it increased to 782,000 tons for 2021, corresponding 504,800 tons to the Chilean fleet. The annual quotas of *T. murphyi* are proposed by the Scientific Committee of the SPRFMO and approved by the officials representing the participating countries, usually fishing ministers or vice ministers, or representatives of the Ministries of Foreign Affairs.

Age-structured evaluations are used to estimate the stock of *T. murphyi*, which means that the total capture weight must be transformed into age-specific capture numbers, which is done using age-size keys and the individual growth parameters K (year^{-1}), FL$_\infty$(cm) and t$_0$ (years). The methods used to estimate individual ages of *T. murphyi* have been annual growth ring counts (Pavez & Saa 1978; Aguayo *et al.*

1981; Kochkin 1998) and analysis of modal size progression (Cubillos & Grechina 1998) (Fig. 1). However, estimation of individual age in species of the genus *Trachurus* is complex, since the annual growth increments in the sagittal otoliths are very difficult to interpret (Kochkin 1998; Araya *et al.* 2001; Stewart & Ferrel 2001; Waldrom & Kerstan 2001; Vasconcelos *et al.* 2006), mainly due to the deposition of aragonite, which increases otolith thickness (Green *et al.* 2009).

Pannella (1974) identified micro-rings in sagittal otoliths in fish species of temperate zones of the northwest Atlantic Ocean, including silver hake (*Merluccius bilinearis*), red hake (*Urophycis chuss*), cod (*Gadus morhua*) and winter flounder (*Pseudopleuronectes americanus*), and assumed that these micro-rings were formed daily. Almost 20 years later, Araya *et al.* (2003) showed experimentally that *T. murphyi* produces daily micro-increments of growth in sagittal otoliths. Later, Cisterna & Arancibia (2017) reported that the minimal width of each micro-increment in adult *T. murphyi* is 1.84 µm.

Measuring micro-increments is slow and expensive, thus it is not used massively to determine individual age in fish. An alternative method to estimate fish age, which is rapid and economic, is measuring otolith weight (Pino *et al.* 2004; Lou *et al.* 2005; Pilling *et al.* 2003; Bermejo 2014; Hanson & Stafford 2017), since this increases with the growth in length of the fish. Araya *et al.* (2001) used modal frequency decomposition analysis of sagitta otolith weight to show that there is a
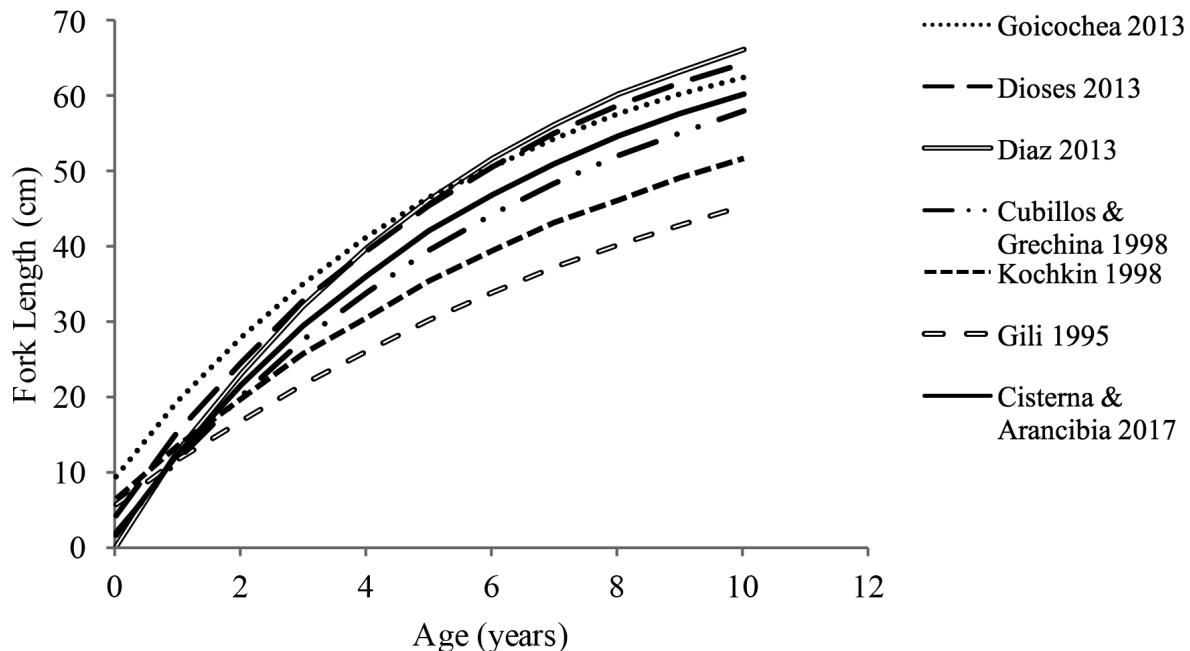

FIGURE 1. Comparison of von Bertalanffy growth curves for *Trachurus murphyi* (different authors and this study). / Comparación de las curvas de crecimiento de von Bertalanffy para *Trachurus murphyi* (diferentes autores y este estudio).

significant relation between these weights and age. These authors also estimated the average annual weight increase to be 8.256 mg year^{-1}.

The objective of this study is to estimate individual growth parameters of *T. murphyi* using three methods in parallel: annual growth rings, daily increments and otolith weight.

MATERIAL AND METHODS

PREPARATION OF THIN SECTIONS
We used thin sections (0.5 mm) of sagittal otoliths to measure daily growth increments of *T. murphyi*, using the technique of Green *et al.* (2009), which was applied by Cisterna & Arancibia (2017) to this species.

MEASUREMENT OF THIN SECTIONS OF OTOLITHS
The otolith micro-increments were observed in an optical microscope as alternately clear and dark concentric rings. According to Green *et al.* (2009), each pair of rings constitutes a daily increment in growth. The procedure for reading these increments is described in Cisterna & Arancibia (2017). We used 400X and 1000X magnification to count the micro-increments. Counts were performed following a radius of the otolith; their structural characteristics (discontinuities and wider increments) were used as markers to facilitate counting.

NUMERICAL INTEGRATION OF DAILY INCREMENTS
The otolith microstructure of adult individuals of *T. murphyi* included areas with clear-cut and easily visible micro-increments and other diffuse areas, which did not allow all daily rings to be counted in some individuals. Thus, to estimate the total number of micro-increments of each otolith we used the numerical integration method proposed by Ralston and Williams (1989) and applied to *T. murphyi* by Araya *et al.* (2001). Otolith growth was calculated using the following expression:

$$\frac{\Delta x}{\Delta increments} = \frac{\Delta x}{\Delta t} \approx \frac{dx}{dt} \qquad (1)$$

where: dx is the length of the segment (μm) at a distance x from the nucleus; dt is the time (days), which is the number of daily increments.

Then dt is treated as a definite integral limited by the nucleus (x=0) and the radius of the otolith, in order to estimate the number of micro-increments in otolith sections where it is not possible to see all the micro-rings. According to Araya

et al. (2001), the analytic expression to estimate the age (in days) using the radius of the otolith is as follows:

$$\frac{dx}{dt} = f(x) = ax(1-bcx)^{1/c} \qquad (2)$$

where: a = 0.144571; b = 0.021913; c = -0.751643; n= 5.787; r^2 = 0.53

The numerical integral defined by Equation 2 was evaluated using the Numerical Integration tool, obtained from Numerical Analysis and Applications (www.hvks.com). The age in days estimated for each fish was transformed to years by dividing the number of micro-increments by 365.

The parameters FL_∞ (cm), K (year^{-1}) and t_0 (years) were estimated using the TableCurve 2D software. Since it was not possible to sample individuals of *T. murphyi* with fork length greater than 64 cm, we used FL_∞= 75 cm, based on Kochkin (1998), who obtained this value of FL_∞ using annual rings in entire otoliths and longitudinal sections.

PREPARATION FOR OTOLITH WEIGHING
We assumed that the annual increase in otolith mass was 8.256 mg year^{-1}, according to Araya *et al.* (2001). We used 187 (left) sagitta otoliths of individuals of *T. murphyi* to count micro-increments. We recorded the weight of 75 whole otoliths in an analytic balance (precision 0.0001 g). Otoliths were first cleaned with distilled water and dried at constant temperature (30 °C) in a Binder model ED-53 oven for 24 h.

READING AND MEASUREMENT OF ANNUAL RINGS
Otoliths were hydrated for 1 h to analyze annual growth rings. Observations were made with a Zeiss stereomicroscope model Stemi DV4 using 10X. The sample included 7,610 otoliths of fish collected from 2004 to 2011 off the coast of Chile (range of FL: 18 to 60 cm). However, fish of age 1 were absent in the sample. To avoid bias in the estimation of the intercept of the linear regressions, we forced the regressions through the origin, meaning that t_0 = 0.

COMPARISON OF GROWTH CURVES
We applied the test of coincident curves (Haddom 2001) to compare the growth curves (daily micro-increments, otolith weight and annual rings) of *T. murphyi*.

CONSTRUCTION OF A SIZE-AGE KEY USING WEIGHTS OF *SAGITTA* OTOLITHS
To construct a size-age key we analyzed 1,300 otoliths of juvenile and adult *T. murphyi* (range: 19 to 64 cm FL) which were obtained randomly from Chilean industrial landings

between 1998 and 2016. Each otolith was weighed in a Denver Instrumental analytical balance model AA (precision 0.0001 g). Then the weight of each otolith was transformed to age in days using the following relation:

$$AGE = \frac{OW}{8.256} \qquad (3)$$

where: OW is otolith weight in mg; the constant 8.256 (mg yr^{-1}) is the annual growth rate of *T. murphyi*, according to Araya *et al.* (2003).

RESULTS

We found a high correlation between otolith weight and fork length for *T. murphyi* (r^2=0.90), and a high correlation between otolith weight and fish age (r^2=0.94) (Figs. 2 and 3). The parameters of the von Bertalanffy equation estimated using daily increments, annual increments and otolith weight are shown in Table 1. The growth curves using daily growth increments and otolith weight are clearly superimposed (Fig. 4). There were significant differences between the curve obtained with annual rings and otolith weight (Table 2), and also between the annual ring and daily increment curves. The differences between the curves of otolith weight and daily increments were not significant (Table 2).
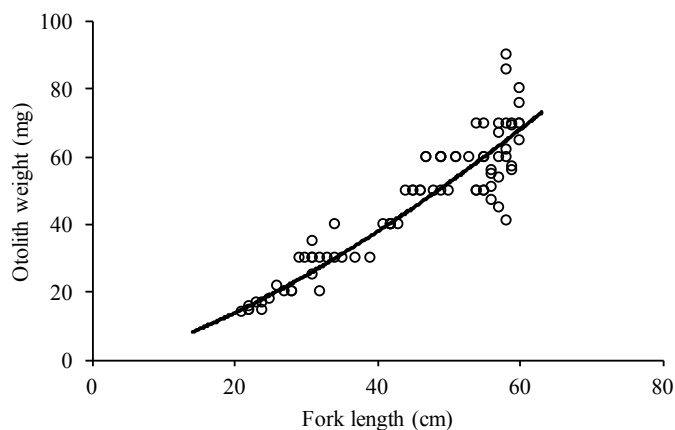
The age-size key obtained using otolith weight is composed of individuals of age 1 to 11 years. The mode was at ages 2 and 3 years (45% of the sample; size range 23 to 39 cm FL), while the least represented age class was 9+ (<2%; size range: 50 to 64 cm FL) (Table 3).
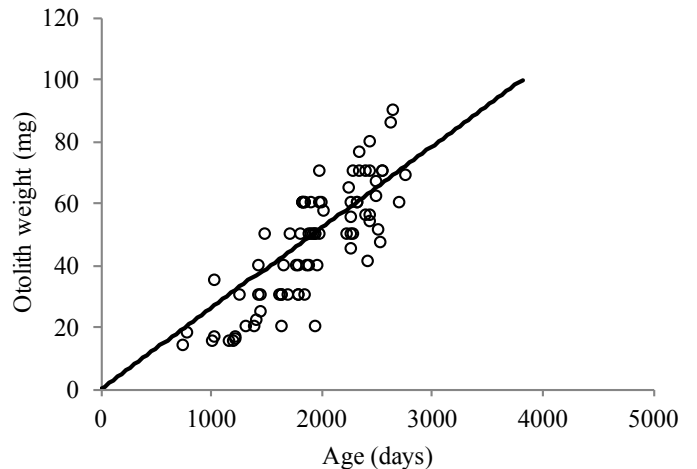

FIGURE 3. Otolith weight (mg) as a function of age in days in *Trachurus murphyi*. OW = otolith weight (mg); t = age (days); OW= 0.0323*t-15.197 (r^2 = 0.68). / Peso del otolito (mg) como una función de la edad en días en *Trachurus murphyi*. OW = peso del otolito (mg); t = edad (días); OW =0,0323*t-15,197 (r^2 = 0,68).

FIGURE 2. Otolith weight (mg) as a function of fork length (cm) for *Trachurus murphyi*, OW = otolith weight (mg); FL = fork length (cm); OW = 0.19 FL$^{1.4}$ (r^2=0.90). / Peso del otolito (mg) en función de la longitud de la horquilla (cm) para *Trachurus murphyi*, OW = peso del otolito (mg); FL = longitud de la horquilla (cm); OW = 0,19 FL^{1,4} (r^2 = 0,90).
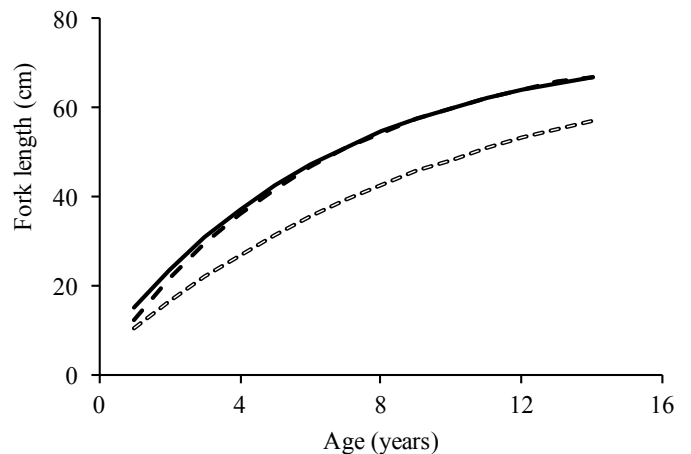
FIGURE 4. von Bertalanffy growth curves of *Trachurus murphyi* fit with the parameter estimations of the three methods used in this study. Solid line: otolith weight; dashed line: daily increments; dashed hollow line: annual rings. / Curvas de crecimiento de von Bertalanffy de *Trachurus murphyi* ajustadas con los parámetros estimados mediante los tres métodos utilizados en este estudio. Línea continua: peso del otolito; línea discontinua: incrementos diarios; línea hueca discontinua: anillos anuales.

TABLE 1. Individual growth parameters of the von Bertalanffy equation in *Trachurus murphyi* using three methods: daily increments, annual rings and otolith weight. / Parámetros de crecimiento individual de la ecuación de von Bertalanffy en *Trachurus murphyi* utilizando tres métodos: incrementos diarios, anillos anuales y peso del otolito.

Method	r^2	Parameters	value	Standard Error	t value	95% Confidence	Limits	p Value
Daily Increments	0.78	FL_∞ (cm)	75.0					
		K (year^{-1})	0.16	0.04	4.26	0.09	0.23	0.00
		t_0 (years)	-0.13	0.17	-2.73	-0.47	0.22	0.01
Annual Rings	0.80	FL_∞ (cm)	74.7	1.6	47.8	71.6	77.1	0.00
		K (year^{-1})	0.1	0.0	22.9	0.1	0.1	0.00
		t_0 (years)	-0.5	0.1	-5.4	-0.7	-0.3	0.00
Otolith Weight	0.98	FL_∞ (cm)	75.0	5.3	14.2	64.5	85.5	0.00
		K (year^{-1})	0.15	0.03	6.12	0.10	0.20	0.00
		t_0 (years)	-0.48	0.25	-1.96	-0.97	0.01	0.05

TABLE 2. Curve comparison test of von Bertalanffy growth curves using analysis of residuals of sum of squares. D.F.= degrees of freedom. / Test para la comparación de curvas de crecimiento de von Bertalanffy utilizando análisis de residuos de suma de cuadrados. D.F. = grados de libertad.

Sum of squares	162263	521642	Annual rings
D. F.	7607	7682	*vs.*
F estimated	225	1.35	Otolith weight
Sum of squares	162263	542627	Annual rings
D. F.	7607	7816	*vs.*
F estimated	85	1.17	Daily increments
Sum of squares	6905	7697	Daily increments
D. F.	185	281	*vs.*
F estimated	0.22	1.26	Otolith weight

DISCUSSION

The methods used to determine the age of adult individuals of *T. murphyi* have been annual ring counts in entire otoliths, annual ring counts in transverse sections of otoliths (Pavez & Saa 1978; Aguayo *et al.* 1981; Kochkin 1998) and the analysis of modal progression (Cubillos & Grechina 1998). However, the growth parameters of the von Bertalanffy equation reported have varied widely both for *T. murphyi* and for other species of the genus *Trachurus* (Waldrom & Kerstan 2001; Araya *et al.* 2003; Yankova *et al.* 2010; Yankova 2013). This may be due to the choice and use of criteria to interpret the annual rings, i.e. what is understood by an annual ring and how it is identified in otoliths. Waldron & Kerstan (2001) indicated that the otoliths of the genus *Trachurus* are very difficult to interpret, since they have zones of annual growth with not only a translucent and opaque area, but it may contain two or more translucent zones or false rings. These appear similar to annual rings, and thus may be erroneously interpreted as "years of life", leading to overestimation of individual age. For example, Kochkin (1998) worked with annual rings and reported that K=0.11 year^{-1} for *T. murphyi*, which is close similar to K = 0.10 year^{-1} estimated in the present study with the same technique.

TABLE 3. Frequency distribution of lengths at different ages in *Trachurus murphyi* (n=1300). Nomenclature: FL = fork length (cm). / Distribución de frecuencias de longitudes a diferentes edades en *Trachurus murphyi* (n = 1300). Nomenclatura: FL = longitud de la horquilla (cm).

FL (cm)	1	2	3	4	5	6	7	8	9	10	11	Total
						AGE (years)						
19	1											1
20	2											2
21	16											16
22	40											40
23	21	4										25
24	4	2										6
25	8	20	1									29
26	5	27	1									33
27		30	6									36
28		42	18									60
29		29	52	3								84
30		35	47	7								89
31		13	25	3								41
32		9	76									85
33		1	72	11	1							85
34			35	14	2							51
35			20	18	2							40
36			14	15	4							33
37			3	25	5							33
38			4	24	9	1						38
39			3	23	15	3						44
40				12	17	1						30
41				11	17	2	1					31
42				13	13	9	2					37
43				5	13	2	5					25
44				1	15	18	2					36
45				1	12	11	2					26
46					9	14	8					31
47					7	15	5					27
48					5	17	12	6				40
49					5	6	7	4				22
50					3	11	15	3	2			34
51					1	3	7	4	1			16
52						3	6	2	2			13
53						4	1	5		1		11
54							3	2				5
55							8	9				17
56							3	5	3	2		13
57								1		1		2
58								2				2
59								1				1
60									1	2		3
61									1			1
62									1	2		3
63										2		2
64											1	1
n	97	212	377	186	155	120	87	44	11	10	1	1300
%	7.5	16.3	29.0	14.3	11.9	9.2	6.7	3.4	0.8	0.8	0.1	100
FL mean	22.5	28.0	31.8	37.2	42.2	46.3	49.2	52.8	55.1	59.2	64.0	
SD	13.3	14.3	25.7	8.0	5.6	6.0	4.0	2.3	0.8	0.5	0.0	

However, Dioses (2013) estimated K = 0.155 year^{-1} for *T. murphyi* off Peru by using annual rings, which is similar to both K = 0.16 year^{-1} estimated in the present study with daily ring counts, and K = 0.155 year^{-1} with the technique of otolith weight.

Otolith weight has been used to estimate fish age in hoki *Macruronus magellanicus* (Pino *et al.*, 2004), leopard coral trout *Plectroponus leopardus* (Lou *et al.* 2005), sky emperor *Lethrinus mahsena* (Pilling *et al.* 2003) and cod *Gadus morhua* (Bermejo 2014) among other fish species. We recommend using otolith weight to estimate age in *T. murphyi* (Fig. 4) due to this method is statistically reliable, but also cheap and fast.

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