

## Relationships between the length of select head bones and body size for some Hawaiian parrotfishes (subfamily Scarinae)

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Animal remains can be used to reconstruct patterns of resource use in dietary analysis and archaeology, and to reconstruct ancient environments in geology and paleontology. Estimating the body size of fishes from these remains is desirable, but rarely accomplished because the relationships between the size of a fish and its durable anatomical structures (e.g., bones) are largely unknown (Longenecker, 2008).

Parrotfishes form an important part of the diet of the critically endangered, endemic, Hawaiian monk seal diet (Goodman-Lowe, 1998; Longenecker *et al.*, 2006; Longenecker, 2010; Cahoon, 2011) and are a prominent fish component of Hawaiian archaeological deposits (Pearson *et al.*, 1971; Kirch, 1979, 1982; Goto, 1984; O'Day, 2001). Equations that allow total body size to be estimated from the size of parrotfish remains will help inform conservation decisions for an apparently food-limited marine mammal and lead to better understanding of prehistoric patterns of human resource exploitation in Hawai'i.

Here we present the results of regression analyses examining the relationship between the dimensions of select head bones and the total length and total body weight of Hawaiian scarine parrotfish specimens. The bones analyzed are those that have proven useful for identifying parrotfish remains (Longenecker *et al.*, 2006; Longenecker, 2010; Cahoon, 2011) and yield the highest estimates of minimum number of individuals in regurgitate and fecal samples of the Hawaiian monk seal and archaeological material from Nu'alolo Kai, Kaua'i (K1) and Wai'ahukini, Hawai'i (HA-B22-248, HA-B22-64). Axes chosen for measurement are those that are likely to persist after consumption and elimination, or deposition and excavation.

### Materials and Methods

Thawed, previously frozen specimens of the parrotfishes *Chlorurus perspicillatus* (Steindachner, 1879), *C. spilurus* (Valenciennes, 1840) (formerly *C. Sordidus* (Forsskål, 1775)), and *Scarus dubius* Bennet, 1828 (nomenclature of Randall, 2007) collected from the Northwestern Hawaiian Islands in 2009 were measured (total, fork, and standard lengths) and weighed with a precision of 0.1 cm and 0.1 g, respectively. Heads, including the pharyngeal jaws, were removed, wrapped in aluminum foil, and exposed to low heat (~93°C) for 24 h to denature connective tissue. Oral and pharyngeal jaw bones were isolated, cleaned with stiff-bristled brushes, rinsed in fresh water, and air-dried at ~93°C.

Dimensions of these bones were measured with digital calipers. Images of the bones examined and axes measured are presented in Figures 1–14 (oral jaw bone terminology from Rojo, 1991; pharyngeal jaw bone terminology from Gobalet, 1989; all images from a 126 mm standard length specimen of *Chlorurus perspicillatus*). Regression analysis was used to describe the relationship between bone size and total length and total body weight.

Regression equations were constructed for all species individually, for all *Chlorurus* data combined, and for all species combined. For paired bones (premaxilla, maxilla, dentary, angular, maxilla, upper pharyngeal jaw), axes of both bones were measured and axis-length-to-total-length regressions for all species combined were compared with analysis of covariance. The mean of measurements from right and left bones from a single individual was used in regression analyses when no significant difference was detected between sides, otherwise side-specific equations were generated (e.g., premaxilla axis "A").

### Results and Discussion

Standard length can be modeled as a linear function of all bone axis lengths (Table 1) and total body weight can be predicted using a 2-parameter power function of all bone axis lengths (Table 2). Equations for all axes are listed from more- to less-inclusive taxonomic groups. The relationships for all data combined are based on members of the parrotfish subfamily Scarinae, represented in Hawai'i by the genera *Chlorurus* and *Scarus*. These equations should not be used for remains of *Calotomus*, which belong to the Sparisomatinae and have noticeably different dimensions of jaw bone axes.

These groupings serve three purposes. First, equations can be used to predict the size of a fish from remains larger or smaller than those used in the analyses. Although linear relationships with high coefficients of determination, such as many of those in Table 1, might reasonably be used for extrapolation, doing so with curvilinear relationships (Table 2) is likely to provide unrealistic estimates. Using a relationship for a higher taxon, based on a wider size range of individuals, may help avoid the need for extrapolation. Second, although molecular techniques make species-level identification of fish remains feasible, bones are more easily assigned to higher taxa. The groupings provide reasonable predictions of fish size when a species-level identification of parrotfish remains is not feasible. The more-general higher-taxa regressions should be used in such cases. Third, these groups also provide predictions for species not included in the analysis. With seven parrotfishes known from Hawai'i, the equations presented here represent a portion of the work necessary for detailed reconstruction of parrotfish assemblages. In the interim, these higher-taxa relationships may suffice for predicting the size of the remaining two Hawaiian members of the subfamily Scarinae (*Scarus psittacus* and *Scarus rubroviolaceus*).

### Acknowledgments

We thank the following people for their help: members of the ToBo lab at HIMB, especially Z. Szabo and M. Gaither, for their assistance with specimen collection; A. Dow, C. Fumar, and J. Leonard for assistance identifying, measuring, and weighing whole parrotfish specimens; and the Bishop Museum Department of Anthropology, especially R. Gard and T. Jiao, for access to archaeological specimens. This paper is a result of research funded by NOAA Coral Reef Conservation Grant NA09NMF4630123 to R.J. Toonen, T. Hunt, and D. Carlon. Specimen collection and processing were supported by National Marine Sanctuaries NWHICRER-HIMB partnership MOA-2005-008/6882. Images were produced using equipment funded by the National Science Foundation under Grant Number DEB 082868. Manuscript preparation/publication was supported by contract AB133F-06-CN-0139 with the Protected Species Division of the Pacific Islands Fisheries Science Center (NOAA/NMFS).

**Table 1. Regression coefficients for length estimates. Length = a + b(x) where x is the length of the axis measured.**

Bone – Axis (side)/Taxon	n	range (mm)	a	b	r <sup>2</sup>
Premaxilla – A (left)					
<i>Scarinae</i>	44	1.37 – 5.53	63.8681	62.1911	0.79
<i>Chlorurus</i>	34	1.37 – 5.53	41.2404	66.5384	0.82
<i>perspicillatus</i>	12	1.74 – 5.53	79.1995	62.8537	0.93
<i>spilurus</i>	22	1.37 – 4.58	61.8634	54.9123	0.69
<i>Scarus dubius</i>	10	1.41 – 3.52	24.1125	96.4955	0.97
Premaxilla – A (right)					
<i>Scarinae</i>	41	1.00 – 5.23	82.0082	62.1623	0.76
<i>Chlorurus</i>	33	1.26 – 5.23	61.8292	66.1964	0.79
<i>perspicillatus</i>	12	1.70 – 5.23	87.2212	65.2016	0.91
<i>spilurus</i>	21	1.26 – 4.51	88.7079	50.8398	0.61
<i>Scarus dubius</i>	8	1.00 – 3.29	67.3640	86.9705	0.94
Premaxilla – B					
<i>Scarinae</i>	38	1.56 – 6.77	62.5380	53.6031	0.77
<i>Chlorurus</i>	32	1.95 – 6.77	45.2705	56.1224	0.82
<i>perspicillatus</i>	12	2.19 – 6.77	80.6728	52.9736	0.98
<i>spilurus</i>	20	1.95 – 5.41	71.2681	44.3573	0.60
<i>Scarus dubius</i>	6	1.56 – 3.60	14.8120	86.7699	0.90
Maxilla – A					
<i>Scarinae</i>	41	2.36 – 9.07	81.3503	34.1696	0.75
<i>Chlorurus</i>	32	2.55 – 9.07	49.6754	37.9856	0.82
<i>perspicillatus</i>	12	3.04 – 9.07	64.3100	38.5789	0.95
<i>spilurus</i>	20	2.55 – 8.52	75.2878	30.6067	0.66
<i>Scarus dubius</i>	9	2.36 – 4.96	-14.8565	73.3997	0.97
Maxilla – B					
<i>Scarinae</i>	36	3.35 – 14.41	52.7680	24.6936	0.93
<i>Chlorurus</i>	30	3.35 – 14.41	49.9140	24.6055	0.94
<i>perspicillatus</i>	10	5.71 – 14.41	90.9364	21.9810	0.96
<i>spilurus</i>	20	3.35 – 12.19	53.3139	23.2969	0.93
<i>Scarus dubius</i>	6	5.38 – 9.96	-19.4396	37.5507	0.98
Dentary – A					
<i>Scarinae</i>	44	1.21 – 6.66	104.4707	44.5879	0.61
<i>Chlorurus</i>	35	1.83 – 6.66	75.0386	50.0696	0.66
<i>perspicillatus</i>	12	1.83 – 6.66	81.4597	56.0541	0.95
<i>spilurus</i>	23	1.83 – 5.50	111.9210	33.5923	0.42
<i>Scarus dubius</i>	9	1.21 – 3.13	58.0196	85.4702	0.88
Dentary – B					
<i>Scarinae</i>	37	1.21 – 6.05	99.2675	50.5028	0.62
<i>Chlorurus</i>	29	1.53 – 6.05	38.7314	63.6295	0.74
<i>perspicillatus</i>	11	2.25 – 6.05	76.2370	62.2758	0.97
<i>spilurus</i>	18	1.53 – 4.96	69.2207	47.9880	0.58
<i>Scarus dubius</i>	8	1.21 – 2.80	61.7226	97.7943	0.94
Angular – A					
<i>Scarinae</i>	29	4.81 – 14.21	-3.9974	27.7791	0.92
<i>Chlorurus</i>	25	4.81 – 14.21	-5.8451	27.6883	0.95
<i>perspicillatus</i>	7	8.97 – 14.21	59.0253	23.7270	0.99
<i>spilurus</i>	18	4.81 – 13.50	13.0110	24.8532	0.94
<i>Scarus dubius</i>	4	6.22 – 11.59	-30.8961	33.1060	0.99

<b>Table 1. Regression coefficients for length estimates (continued).</b>					
<b>Bone – Axis (side)/Taxon</b>	<b>n</b>	<b>range (mm)</b>	<b>a</b>	<b>b</b>	<b>r<sup>2</sup></b>
Angular – B					
Scarinae	29	1.70 – 6.60	40.0697	53.6614	0.80
<i>Chlorurus</i>	25	1.70 – 6.60	33.6170	54.0796	0.80
<i>perspicillatus</i>	7	3.75 – 6.43	97.0912	47.9287	0.93
<i>spilurus</i>	18	1.70 – 6.60	64.0733	43.0797	0.72
<i>Scarus dubius</i>	4	2.23 – 4.88	5.3739	72.4764	0.97
Upper Pharyngeal Jaw – A					
Scarinae	35	1.75 – 4.33	-20.7260	87.8946	0.87
<i>Chlorurus</i>	22	1.77 – 4.33	-23.7944	89.2257	0.87
<i>perspicillatus</i>	11	2.13 – 4.33	18.8367	79.6395	0.81
<i>spilurus</i>	11	1.77 – 3.84	-8.2536	77.6601	0.96
<i>Scarus dubius</i>	13	1.75 – 3.44	-7.3854	82.6310	0.90
Upper Pharyngeal Jaw – B					
Scarinae	35	3.88 – 11.03	17.9017	29.6919	0.92
<i>Chlorurus</i>	22	3.88 – 11.03	9.7368	30.4392	0.93
<i>perspicillatus</i>	11	4.73 – 11.03	49.1979	26.7023	0.92
<i>spilurus</i>	11	3.88 – 9.72	7.8577	29.1924	0.96
<i>Scarus dubius</i>	13	4.05 – 9.00	34.8713	27.8649	0.89
Upper Pharyngeal Jaw – C					
Scarinae	39	1.92 – 4.99	-2.7029	69.2349	0.95
<i>Chlorurus</i>	26	1.92 – 4.99	-472.0605	234.5373	0.92
<i>perspicillatus</i>	14	2.29 – 4.99	9.1790	66.7555	0.95
<i>spilurus</i>	12	1.92 – 3.86	-451.9630	231.0588	0.83
<i>Scarus dubius</i>	13	1.96 – 4.24	-316.4140	158.9411	0.72
Upper Pharyngeal Jaw – D					
Scarinae	39	2.39 – 6.17	-0.8470	54.0619	0.95
<i>Chlorurus</i>	26	2.48 – 6.17	-2.8453	54.2308	0.96
<i>perspicillatus</i>	14	2.91 – 6.17	15.0236	50.7321	0.96
<i>spilurus</i>	12	2.48 – 4.94	-26.2678	60.9749	0.92
<i>Scarus dubius</i>	13	2.39 – 5.43	0.4060	54.3868	0.88
Upper Pharyngeal Jaw – E					
Scarinae	39	1.49 – 3.92	1.0139	82.7888	0.90
<i>Chlorurus</i>	26	1.49 – 3.92	-0.5889	85.8921	0.93
<i>perspicillatus</i>	14	1.66 – 3.92	36.0357	75.6251	0.88
<i>spilurus</i>	12	1.49 – 3.40	-4.0370	84.7510	0.93
<i>Scarus dubius</i>	13	1.56 – 3.64	5.7966	76.3027	0.93
Lower Pharyngeal Jaw – A					
Scarinae	40	7.45 – 21.83	12.8485	14.2936	0.94
<i>Chlorurus</i>	27	8.41 – 21.83	11.3948	14.8167	0.97
<i>perspicillatus</i>	15	9.76 – 21.83	8.3607	14.8766	0.97
<i>spilurus</i>	12	8.41 – 17.76	-9.5808	16.8952	0.96
<i>Scarus dubius</i>	13	7.45 – 20.57	21.8879	12.8410	0.91
Lower Pharyngeal Jaw – B					
Scarinae	40	3.36 – 10.62	22.5257	29.3112	0.86
<i>Chlorurus</i>	27	3.56 – 10.62	16.5408	31.6758	0.94
<i>perspicillatus</i>	15	4.32 – 10.62	33.0558	29.9593	0.89
<i>spilurus</i>	12	3.56 – 8.66	22.8518	29.7368	0.93
<i>Scarus dubius</i>	13	3.36 – 9.97	24.3384	26.2671	0.87

**Table 2. Regression coefficients for weight estimates. Weight =  $a(x)^b$  where  $x$  is the length of the axis measured.**

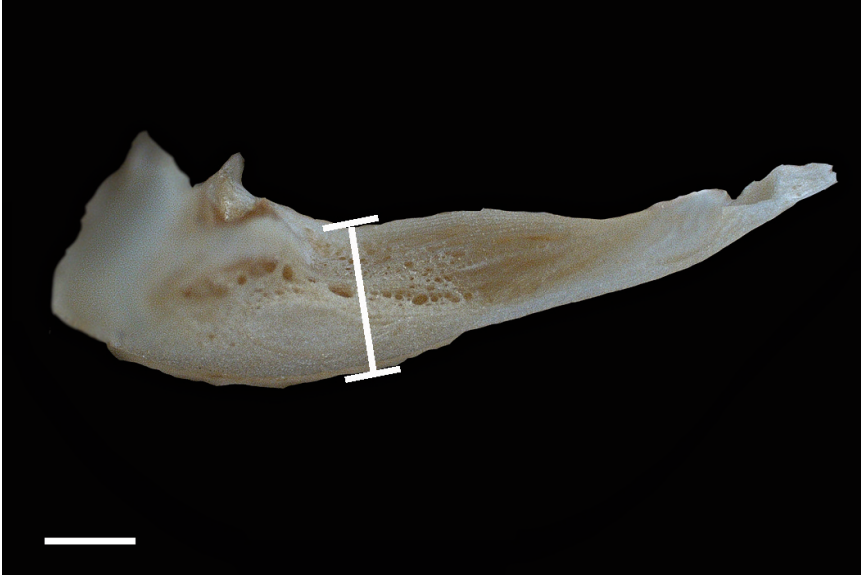
Bone – Axis (side)/Taxon	n	range (mm)	a	b	r <sup>2</sup>
Premaxilla – A (left)					
<i>Scarinae</i>	44	1.37 – 5.53	23.2697	2.4214	0.82
<i>Chlorurus</i>	34	1.37 – 5.53	14.6851	2.7067	0.83
<i>perspicillatus</i>	12	1.74 – 5.53	53.2530	1.9564	0.87
<i>spilurus</i>	22	1.37 – 4.58	14.8484	2.5328	0.72
<i>Scarus dubius</i>	10	1.41 – 3.52	34.7862	2.5735	0.97
Premaxilla – A (right)					
<i>Scarinae</i>	41	1.00 – 5.23	43.3553	2.0954	0.76
<i>Chlorurus</i>	33	1.26 – 5.23	30.5914	2.3192	0.77
<i>perspicillatus</i>	12	1.70 – 5.23	45.6944	1.7779	0.81
<i>spilurus</i>	21	1.26 – 4.51	51.9503	1.6477	0.60
<i>Scarus dubius</i>	8	1.00 – 3.29	54.6344	2.3211	0.97
Premaxilla – B					
<i>Scarinae</i>	38	1.56 – 6.77	14.8559	2.4634	0.85
<i>Chlorurus</i>	32	1.95 – 6.77	8.2015	2.7976	0.89
<i>perspicillatus</i>	12	2.19 – 6.77	26.6599	2.1696	0.98
<i>spilurus</i>	20	1.95 – 5.41	18.4843	2.0999	0.65
<i>Scarus dubius</i>	6	1.56 – 3.60	10.6914	3.2881	0.89
Maxilla – A					
<i>Scarinae</i>	41	2.36 – 9.07	10.6194	2.1706	0.78
<i>Chlorurus</i>	32	2.55 – 9.07	5.1838	2.5081	0.83
<i>perspicillatus</i>	12	3.04 – 9.07	8.1747	2.3520	0.90
<i>spilurus</i>	20	2.55 – 8.52	12.1256	1.9331	0.74
<i>Scarus dubius</i>	9	2.36 – 4.96	3.7359	3.3953	0.99
Maxilla – B					
<i>Scarinae</i>	36	3.35 – 14.41	3.6371	2.1992	0.91
<i>Chlorurus</i>	30	3.35 – 14.41	3.2052	2.2444	0.92
<i>perspicillatus</i>	10	5.71 – 14.41	11.6277	1.7704	0.94
<i>spilurus</i>	20	3.35 – 12.19	3.8454	2.1021	0.93
<i>Scarus dubius</i>	6	5.38 – 9.96	0.2663	3.5126	0.96
Dentary – A					
<i>Scarinae</i>	44	1.21 – 6.66	21.3630	2.2703	0.71
<i>Chlorurus</i>	35	1.83 – 6.66	9.9770	2.7172	0.76
<i>perspicillatus</i>	12	1.83 – 6.66	35.7891	2.0724	0.97
<i>spilurus</i>	23	1.83 – 5.50	27.1425	1.8443	0.50
<i>Scarus dubius</i>	9	1.21 – 3.13	54.0454	2.2024	0.76
Dentary – B					
<i>Scarinae</i>	37	1.21 – 6.05	21.9067	2.3927	0.72
<i>Chlorurus</i>	29	1.53 – 6.05	10.2689	2.8606	0.80
<i>perspicillatus</i>	11	2.25 – 6.05	39.9453	2.1171	0.99
<i>spilurus</i>	18	1.53 – 4.96	18.1491	2.2381	0.58
<i>Scarus dubius</i>	8	1.21 – 2.80	47.8149	2.7166	0.93
Angular – A					
<i>Scarinae</i>	29	4.81 – 14.21	0.5871	2.8713	0.92
<i>Chlorurus</i>	25	4.81 – 14.21	0.4084	3.0061	0.93
<i>perspicillatus</i>	7	8.97 – 14.21	5.7049	2.0269	0.97
<i>spilurus</i>	18	4.81 – 13.50	0.7423	2.6969	0.93
<i>Scarus dubius</i>	4	6.22 – 11.59	0.3671	3.1706	0.99

**Table 2. Regression coefficients for weight estimates (continued).**

<b>Bone – Axis (side)/Taxon</b>	<b>n</b>	<b>range (mm)</b>	<b>a</b>	<b>b</b>	<b>r<sup>2</sup></b>
Angular – B					
<i>Scarinae</i>	29	1.70 – 6.60	13.7192	2.3867	0.78
<i>Chlorurus</i>	25	1.70 – 6.60	10.1742	2.5459	0.79
<i>perspicillatus</i>	7	3.75 – 6.43	53.5363	1.7137	0.93
<i>spilurus</i>	18	1.70 – 6.60	13.6168	2.2006	0.73
<i>Scarus dubius</i>	4	2.23 – 4.88	15.3422	2.5585	0.97
Upper Pharyngeal Jaw – A					
<i>Scarinae</i>	35	1.75 – 4.33	13.1703	2.8277	0.78
<i>Chlorurus</i>	22	1.77 – 4.33	18.2429	2.6159	0.80
<i>perspicillatus</i>	11	2.13 – 4.33	41.3543	2.0310	0.72
<i>spilurus</i>	11	1.77 – 3.84	5.4490	3.4687	0.99
<i>Scarus dubius</i>	13	1.75 – 3.44	11.3677	2.8017	0.80
Upper Pharyngeal Jaw – B					
<i>Scarinae</i>	35	3.88 – 11.03	1.1265	2.7358	0.94
<i>Chlorurus</i>	22	3.88 – 11.03	1.3627	2.6606	0.96
<i>perspicillatus</i>	11	4.73 – 11.03	3.7875	2.2186	0.93
<i>spilurus</i>	11	3.88 – 9.72	0.4186	3.1854	0.99
<i>Scarus dubius</i>	13	4.05 – 9.00	2.0075	2.4121	0.92
Upper Pharyngeal Jaw – C					
<i>Scarinae</i>	39	1.92 – 4.99	6.5528	2.9831	0.90
<i>Chlorurus</i>	26	1.92 – 4.99	10.1078	2.7149	0.93
<i>perspicillatus</i>	14	2.29 – 4.99	11.2867	2.6303	0.92
<i>spilurus</i>	12	1.92 – 3.86	2.2183	4.0551	0.95
<i>Scarus dubius</i>	13	1.96 – 4.24	6.3516	2.8706	0.74
Upper Pharyngeal Jaw – D					
<i>Scarinae</i>	39	2.39 – 6.17	3.8308	2.8686	0.93
<i>Chlorurus</i>	26	2.48 – 6.17	4.8084	2.7473	0.94
<i>perspicillatus</i>	14	2.91 – 6.17	5.5553	2.6547	0.95
<i>spilurus</i>	12	2.48 – 4.94	0.4697	4.4321	0.97
<i>Scarus dubius</i>	13	2.39 – 5.43	4.8862	2.6431	0.79
Upper Pharyngeal Jaw – E					
<i>Scarinae</i>	39	1.49 – 3.92	9.1431	3.1969	0.83
<i>Chlorurus</i>	26	1.49 – 3.92	16.6609	2.7883	0.90
<i>perspicillatus</i>	14	1.66 – 3.92	28.1701	2.3688	0.83
<i>spilurus</i>	12	1.49 – 3.40	6.8825	3.6158	0.97
<i>Scarus dubius</i>	13	1.56 – 3.64	7.5385	3.1133	0.89
Lower Pharyngeal Jaw – A					
<i>Scarinae</i>	40	7.45 – 21.83	0.0691	2.9937	0.88
<i>Chlorurus</i>	27	8.41 – 21.83	0.1865	2.6882	0.96
<i>perspicillatus</i>	15	9.76 – 21.83	0.1335	2.7935	0.96
<i>spilurus</i>	12	8.41 – 17.76	0.0276	3.4576	0.98
<i>Scarus dubius</i>	13	7.45 – 20.57	0.0875	2.8091	0.90
Lower Pharyngeal Jaw – B					
<i>Scarinae</i>	40	3.36 – 10.62	1.1706	2.7365	0.76
<i>Chlorurus</i>	27	3.56 – 10.62	2.2679	2.5009	0.89
<i>perspicillatus</i>	15	4.32 – 10.62	4.2811	2.2116	0.81
<i>spilurus</i>	12	3.56 – 8.66	0.4647	3.2811	0.96
<i>Scarus dubius</i>	13	3.36 – 9.97	0.6431	2.8360	0.85

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**Figure 1.** Axis A of premaxilla (dorsal aspect). Minimum width of posterior to ascending process (jaws of calipers held parallel to ascending process). Scale bar = 1 mm.



**Figure 2.** Axis B of premaxilla (medial aspect, rotated 90° clockwise from its normal anatomical position). Width of ascending process at constriction. Scale bar = 1 mm.

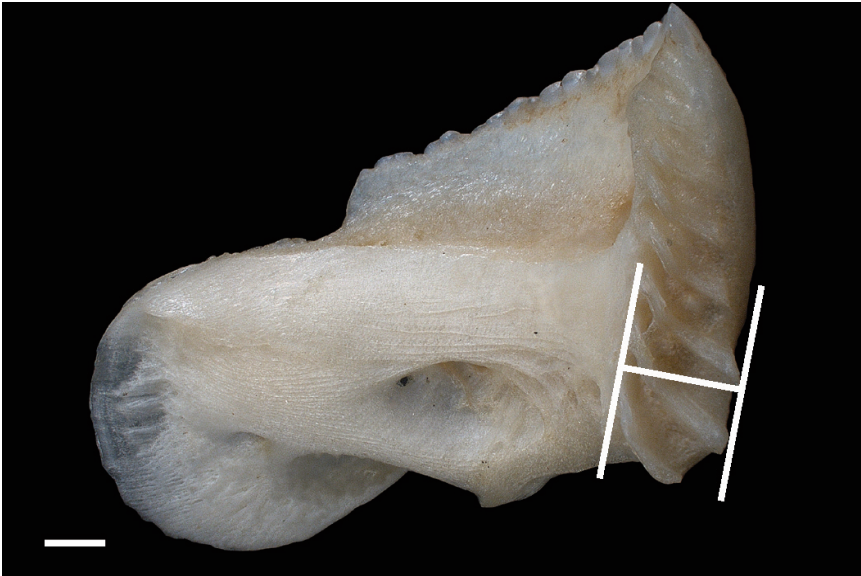




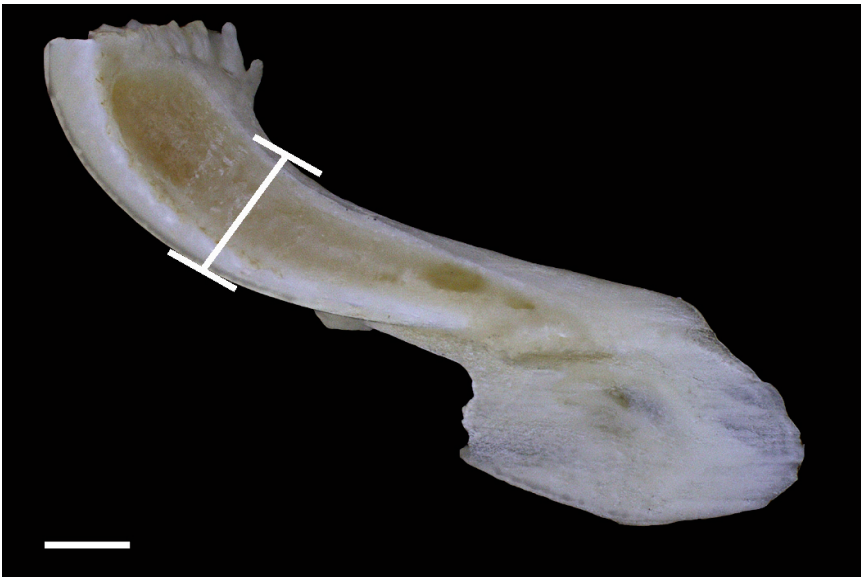
**Figure 3.** Axis A of maxilla (ventral aspect). Shortest distance between indentations on internal and external processes. Scale bar = 1 mm.



**Figure 4.** Axis B of maxilla (medial aspect). Maximum distance along internal process. Scale bar = 1 mm.



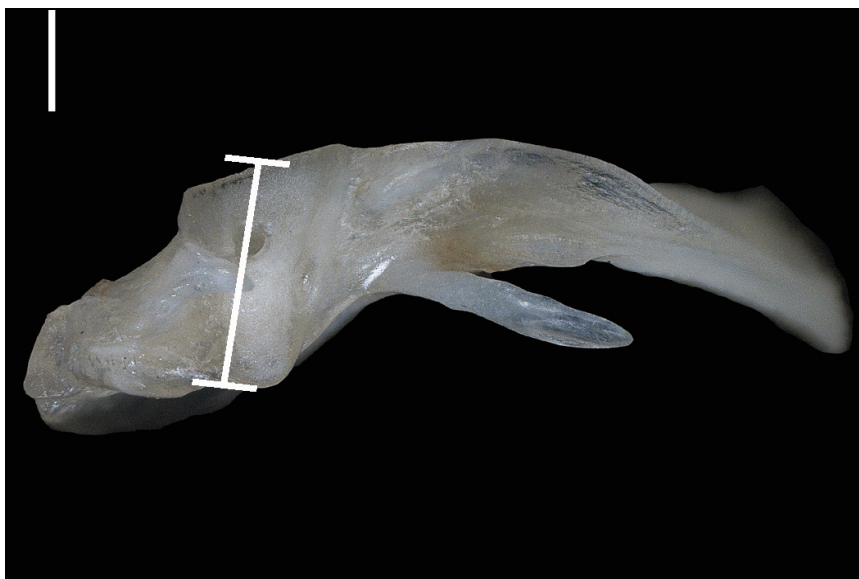
**Figure 5.** Axis A of dentary (lateral aspect). Maximum distance across interdigitating flanges of mandibular symphysis (jaws of calipers held parallel to posterior edge of flanges at their greatest width). Scale bar = 1 mm.



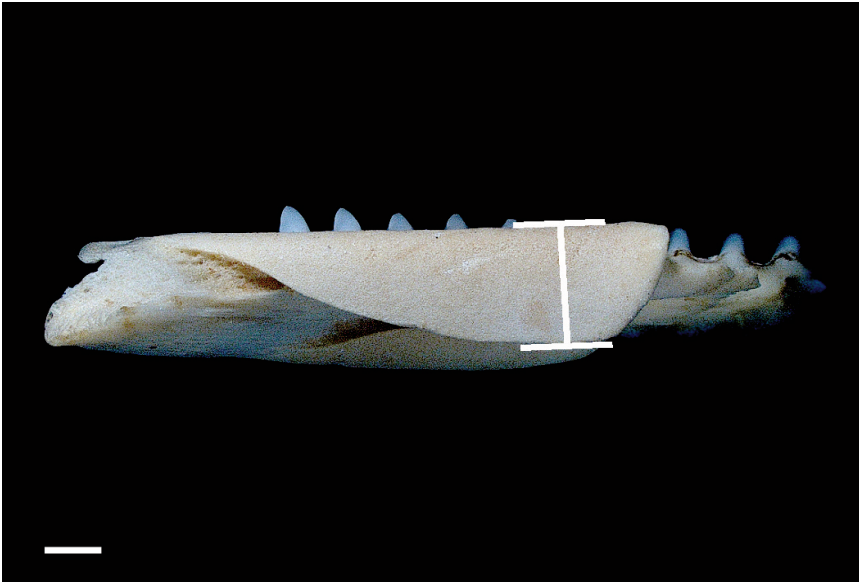
**Figure 6.** Axis B of dentary (dorsal aspect). Shortest width at point of maximum inflection (jaws of calipers held parallel to lateral face of bone). Scale bar = 1 mm.



**Figure 7.** Axis A of angular (medial aspect, right bone). Shortest distance between terminus of anterior process and quadrate facet. Scale bar = 1 mm.



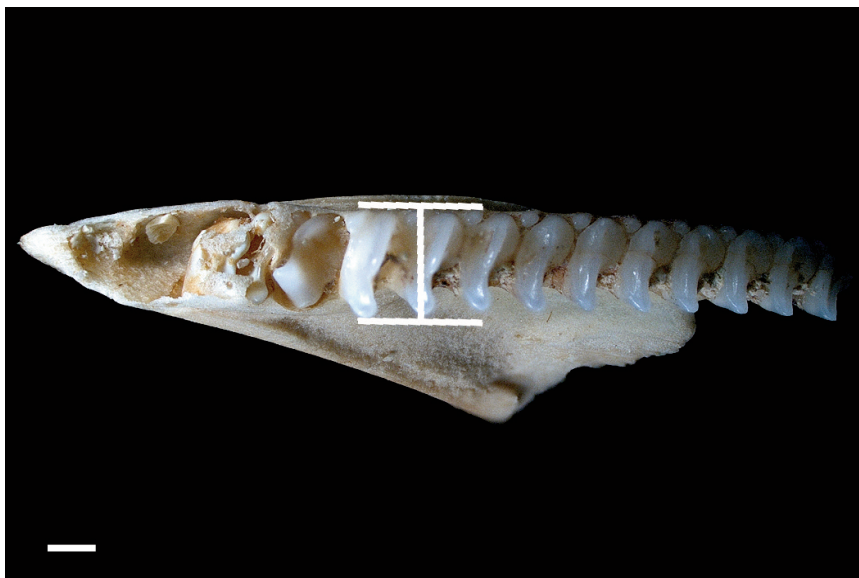
**Figure 8.** Axis B of angular (posterior aspect, right bone, rotated 90° clockwise from its normal anatomical position). Distance across deepest area of quadrate facet. Scale bar = 1 mm.



**Figure 9.** Axis A of upper pharyngeal jaw (dorsal aspect). Greatest width of cranial condyle (jaws of calipers held parallel to medial border). Scale bar = 1 mm.



**Figure 10.** Axis B of upper pharyngeal jaw (lateral aspect). Width between fourth-epibranchial condyle and cranial condyle (jaws of calipers held parallel to articulating face of cranial condyle, with tip of one jaw at posterior end of fourth-epibranchial condyle). Scale bar = 1 mm.



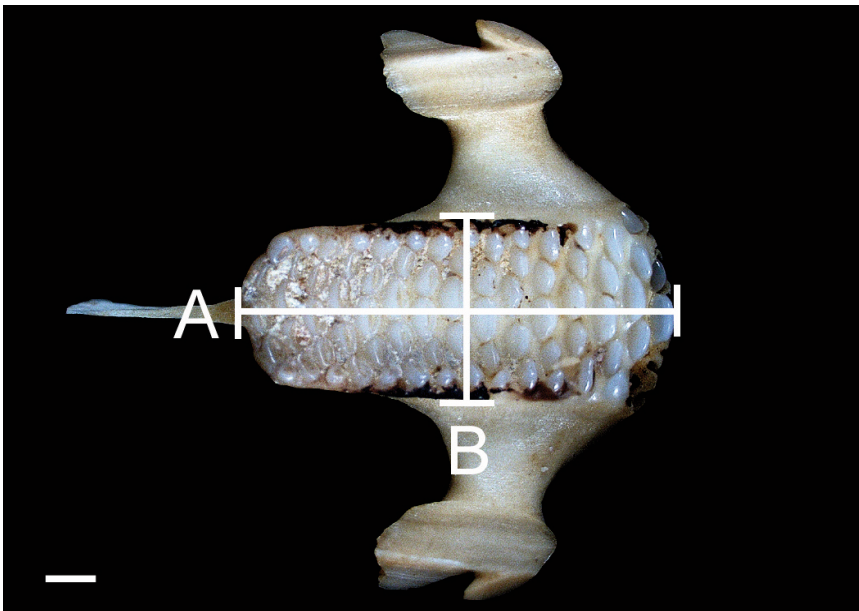
**Figure 11.** Axis C of upper pharyngeal jaw (ventral aspect). Width of anterior-most teeth (jaws of calipers held parallel to lateral edge of teeth). Scale bar = 1 mm.



**Figure 12.** Axis D of upper pharyngeal jaw (posterior aspect). Width at lateral extreme of fourth-epibranchial condyle when medial face of body is held vertically. Scale bar = 1 mm.



**Figure 13.** Axis E of upper pharyngeal jaw (anterior aspect). Width at base of anterior teeth (anterior portion of bone removed for illustrative purpose). Scale bar = 1 mm.



**Figure 14.** Axes of lower pharyngeal jaw (dorsal aspect). A – maximum length of tooth plate; B – maximum width of tooth plate. Scale bar = 1 mm.