

Supplementary Information

1. Deriving values of scaling exponents of surface area versus body mass (b_A) by applying Euclidean geometry to additional dimensional measurements in the study species

Given a lack of strong systematic variation in mass-density during ontogeny, relative to size increase (Hirst 2012; Hirst et al 2014), we assume that during ontogeny mass (M) \propto Volume (V). Values of b_L were calculated from length measurements along the long body axis, or from the diameter of oblate medusal forms, which all grew proportionately more by radial increase rather than by bell height increase (Hirst 2012).

Shape shifting or ‘classic geometric dissimilitude’ requires a minimum of three length scales, l_1, l_2, l_3 , to define the general shape changes of three-dimensional objects (Okie 2013), which can be described thus:

$$l_2 \propto l_1^\theta \text{ and}$$

$$l_3 \propto l_1^\beta, \quad [1]$$

where l_1 is the measured body length, and $\beta \leq \theta \leq 1$. Isomorphic growth yields $\beta = \theta = 1$; sheet-like or planar growth with equal increase in just two dimensions, resulting in shape ‘flattening’, yields $\beta = 0$, and $\theta = 1$; and pure body-length elongation yields $\beta = \theta = 0$.

$$\text{As } M \propto V \propto l_1 l_2 l_3 \propto l_1^{(\theta + \beta + 1)}$$

$$b_L = \theta + \beta + 1 \quad [2]$$

Using dimensional analysis, Okie (2013) showed that as aspect ratios (l_1/l_3) increase with increasing size, scaling of surface area, A , on volume, V , converges on:

$$A \propto V^{(\theta+1)/(\theta+\beta+1)} \quad [3]$$

Hence, at the limit of growth to maximum aspect ratio, achieved from minimum initial values of l_2 and l_3 ,

$$b_A = (\theta + 1)/(\theta + \beta + 1) \quad [4]$$

Using equations 2 and 4, and the changing values of θ and β when growth changes from isomorphy to pure elongation and to pure two-dimensional or planar growth, Hirst et al (2014) derived three boundaries that contain the complete set of predicted b_A values when $b_L \leq 3$, and using a similar approach to derive boundaries for growth that yields $b_L \geq 3$. These boundaries are shown in Fig. 1 of the text.

Extending this derivation, it is straightforward to narrow down the range of predicted values of b_A to a single number. Thus, if we have an estimate of how l_2 (e.g., body width) scales with l_1 (i.e., a value for θ), Equation 2 can be substituted into the denominator of Equation 4 to get

$$b_A = (\theta + 1)/b_L$$

This method is used to predict values of b_A from the following data plus b_L values in Table 1 (also see SI section 2).

Key to data:

l_1/l_2 = body length to width ratio

θ = scaling exponent obtained as slope in least squares regression of $\log_{10} l_2$ vs. $\log_{10} l_1$, which are on the Y and X axes, respectively (except in one case for the veliger larvae of *Mytilus edulis*, where $\theta = 1$ based on a regression of l_1 vs. l_2 ; see below).

Error terms (\pm) = 95% confidence intervals

r^2 = coefficient of determination

n = sample size

Calculated values are in bold.

<u>Species</u>	<u>Measurements and calculation of b_A</u>	<u>Source</u>
<i>Beroe ovata</i>	Newly hatched larvae (0.4mm L): $l_1/l_2 = 1.25$	Svetlichny et al. (2004)
	Juveniles (1-2cm L) $l_1/l_2 = 1.34$ $\theta = 0.95$, $b_A = 0.67$	
	Adults $\theta = 0.939 \pm 0.044$; $r^2 = 0.997$; n = 10 (each sample point = midpoint of range given in Table 1 of source; based on measurements of 58 animals); $l_1 = 19-120.5\text{mm}$; $l_2 = 17.25-96.5\text{mm}$ $b_L = 2.16$ (average of values in Table 1; also see SI section 2) $b_A = 0.90$	Shiganova et al. (2007)
<i>Aurelia aurita</i>	Radial diameter used for both ephyrae & medusae. Therefore, we can assume that $l_1 = l_2$, and $\theta = 1$, and $b_A = 0.64$ for ephyrae and $b_A = 0.77$ for medusae	Båmstedt et al. (1999) McHenry & Jed (2003) Hirst & Lucas (1998)
<i>Crassostrea gigas</i>	$\theta =$ scaling exponent for velar length vs. shell length in veliger larvae = 1.01 (high food: $r^2 = 0.87$; n = 30) and 1.01 (low food: $r^2 = 0.92$, n = 37); velar length is assumed to be l_2 , because it is essentially perpendicular to shell length (l_1). $b_A = 0.95$	Strathmann et al. (1993)
<i>Mytilus edulis</i>	Veliger larvae $\theta = 1$; $r^2 = 0.974$; n = 1616; $l_1 = \sim 140-300\mu\text{m}$; $l_2 = \sim 100-260\mu\text{m}$ $b_A = 0.57$	Pechenik et al. (1990)

Sagmariasus verreauxi Phyllosoma larvae Jensen et al. (2013b)
 $\theta \approx \mathbf{0.954}$ (high food): based on $b = 1.45$ for
 log l_2 vs. log instar stage, and $b = 1.52$ for
 log l_1 vs. log instar stage
 $\theta \approx \mathbf{0.937}$ (low food): based on $b = 1.48$ for
 log l_2 vs. log instar stage, and $b = 1.58$ for
 log l_1 vs. log instar stage
Mean $\theta = 0.946$
 $b_A = 0.91$

Data sources:

Båmstedt U, Lane J, Martinussen MB. 1999 Bioenergetics of ephyra larvae of the scyphozoan jellyfish *Aurelia aurita* in relation to temperature and salinity. *Mar. Biol.* **135**, 89-98. (doi:10.1007/s002270050605)

Hirst AG, Lucas CH. 1998 Salinity influences body weight quantification in the scyphomedusa *Aurelia aurita*: important implications for body weight determination in gelatinous zooplankton. *Mar. Ecol. Progr. Ser.* **165**, 259-269. (doi:10.3354/meps165259)

Jensen MA, Fitzgibbon QP, Carter CG, Adams LR. 2013b The effect of stocking density on growth, metabolism and ammonia-N excretion during larval ontogeny of the spiny lobster *Sagmariasus verreauxi*. *Aquaculture* **376-379**, 45-53. (doi.org/10.1016/j.aquaculture.2012.10.033)

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Pechenik JA, Eyster LS, Widdows J, Bayne BL. 1990 The influence of food concentration and temperature on growth and morphological differentiation of blue mussel *Mytilus edulis* L. larvae. *J. Exp. Mar. Biol. Ecol.* **136**, 41-64. (doi.org/10.1016/0022-0981(90)90099-X)

Shiganova TA, Christou ED, Siokou-Frangou I. 2007 First recording of the non-native species *Beroe ovata* Mayer 1912 in the Aegean Sea. *Medit. Mar. Sci.* **8**, 5-15. (doi:10.12681/mms.159)

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Other cited references:

Hirst AG. 2012 Intra-specific scaling of mass to length in pelagic animals: Ontogenetic shape change and its implications. *Limnol. Oceanogr.* **57**, 1579-1590. (doi:10.4319/lo.2012.57.5.1579)

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Okie JG. 2013 General models for the spectra of surface area scaling strategies of cells and organisms: fractality, geometric dissimilitude, and internalization. *Am. Nat.* **181**, 421-439. (doi:10.1086/669150)

2. Additional data and sources for Table 1

Shown are ontogenetic scaling exponents from least squares regressions of \log_{10} body mass in relation to \log_{10} body length (b_L) and \log_{10} routine metabolic rate in relation to \log_{10} body mass (b_R) for larvae, juveniles, and (or) adults of the Atlantic ctenophore *Beroe ovata*, moon jellyfish *Aurelia aurita*, Pacific oyster *Crassostrea gigas*, common mussel *Mytilus edulis* and spiny lobster *Sagmariasus verreauxi*; for nauplii, copepodites and adults of the copepod *Mesocyclops brasiliensis*; and for solitary and aggregate life-cycle stages of the salps (pelagic tunicates) *Salpa fusiformis* and *S. thompsoni*. Values of b_L and b_R were taken or calculated from published or unpublished data in the indicated sources. Values of b_A for \log_{10} body surface area in relation to \log_{10} body mass were estimated from b_L values and scaling exponents of width versus length (SI section 1). When data for scaling of width versus length were not available, ranges of potential b_A values are given (based on equations 3.1 and 3.2 in text). Where available, the 95% confidence intervals (CI), coefficient of determination (r^2), sample size (n) and the body length (L), diameter (D) or mass (M) range for each scaling exponent are given.

species	stage	b_L ±95% CI (r^2 , n, L, D or M range)	b_A	b_R ±95% CI (r^2 , n, L, D or M range)	sources
<i>Beroe ovata</i>	juveniles	2.92 ¹ (0.99, 21, L=0.4-4.0mm)	0.67 (0.67-0.68)	0.62 ^{1,2} (M=0.021-100mg)	Svetlichny et al. (2004)
	adults	2.47 ¹ (0.96, 102, L=4.0-66mm)	0.80 (0.70-0.81)	0.99 ^{1,3} (M=0.1-55g)	Svetlichny et al. (2004)
	adults	2.23 ¹ (0.98, 22 L=14-120mm)	0.87 (0.72-0.90)	1.04 ⁴ (0.98, 17, M=0.01-0.9g)	Finenko et al. (2001)
	adults	1.78 ¹ (0.79, 43 L=16-162mm)	1.09 ⁵ (0.78-1.00)	0.86 ¹ (0.78, 21, M=8-58g)	Shiganova et al. (2001)
<i>Aurelia aurita</i>	ephyra larvae	3.14 ^{4,6} (0.64, 132, D=3.7-8.8mm)	0.64 ⁷ (0.64-0.66)		Båmstedt et al. (1999)
	ephyra larvae			0.63 ^{4,8} ±0.055 (0.96, 29, M=0.066-12.4mg)	Kinoshita et al. (1997)

	ephyra larvae		0.35⁴ ±0.104 (0.78, 16, M=0.4-7.2mg)	Frandsen & Riisgard (1997): raw data	
	ephyra larvae		1.01⁴ (0.97, 6, M=0.2-0.9mg)	Moller & Riisgard (2007)	
	medusae	2.50 ^{1,9} ±0.23 (0.94, 25, D=30-100mm)	0.80 (0.70-0.80)	McHenry & Jed (2003)	
	medusae	2.72 ^{1,9,10} ±0.11	0.74 (0.68-0.74)	Hirst & Lucas (1998)	
			0.93^{4,8} ±0.07 (0.96, 26, M=12.4-2,100mg)	Kinoshita et al. (1997)	
	medusae		1.11⁴ ±0.104 (0.90, 22, M=11-1,790mg)	Frandsen & Riisgard (1997): raw data	
	medusae		1.01⁴ (0.99, 6, M=25-8,000mg)	Moller & Riisgard (2007)	
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<i>Crassostrea gigas</i>	veliger larvae	2.12 ¹¹ ±0.21 (0.99, 10, L=79-280.7µm)	0.95 (0.74-0.94)	0.96¹¹ (0.97, 10 M=0.069-1.36µg)	Gerdes (1983)
	adults			0.77¹¹ (0.99, 36 M=0.03-1,741mg)	Gerdes (1983)
	adults	2.79 ^{11,12} ±0.14 (L=10-100mm)	0.68-0.72		Gangnery et al. (2003)
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<i>Mytilus edulis</i>	veliger larvae	3.49 ¹¹ (0.99, 32, L=90-410µm)	0.57¹³ (0.57-0.71)		Jespersen & Olsen (1982)
	veliger		0.90¹¹		Hamburger et al. (1983)

	larvae			(0.73, 29, $M \sim -0.02-1\mu\text{g}$)	
	veliger larvae			0.90 ¹¹ (6° C) (n = 31) 0.70 ¹¹ (12° C) (n = 32) 0.59 ¹¹ (18° C) (n = 33)	Sprung (1984) Sprung (1984) Sprung (1984)
	juveniles	2.42 ¹¹ (1.00, 11, $L \sim -0.7-5\text{mm}$)	0.71-0.83		Jespersen & Olsen (1982)
	juveniles			0.89 ¹¹ (0.97, 26, $M \sim -0.001-7\text{mg}$)	Hamburger et al. (1983)
	adults			0.66 ¹¹ (0.97, 21, $M \sim -1.5-500\text{mg}$)	Hamburger et al. (1983)
	adults	3.17 ¹⁴ (n = 69)	0.63-0.68	0.68 ¹⁴ (n = 87)	Zotin & Ozernyuk (2004a, b)
<i>Sagmariasus verreauxi</i> ¹⁵	phyllosoma larvae	2.14 ^{1, 16} ± 0.26 (0.99, 7 ¹⁷ $L = 2.0-35.7\text{mm}$)	0.91 (0.73-0.93)	1.00 ^{1, 16} ± 0.081 (0.995, 7 ¹⁷ $M = 0.63-296\text{mg}$)	Jensen et al. (2013a, b)
	juveniles	2.99 ^{1, 16} ± 0.037 (1.00, 7 ¹⁷ $L = 99-363\text{mm}$)	0.67	0.83 ^{1, 16} ± 0.157 (0.99, 7 ¹⁷ $M = 24.8-1,223\text{g}$)	Jensen et al. (2013a, b)
<i>Mesocyclops brasilianus</i>	nauplii	2.15 ⁴	0.73-0.93	1.08 ^{4, 18} ± 0.20 (n = 30, $M \sim -30-160\text{ng}$)	Epp & Lewis (1979, 1980)
	copepodites & adults	3.12 ^{4, 19}	0.64-0.68	0.56 ^{4, 20} ± 0.078 (n = 88, $M \sim -175-2,500\text{ng}$)	Epp & Lewis (1979, 1980)
<i>Salpa fusiformis</i>	solitary zooids	2.40 ²¹ (0.96, 7, $L = 23-45\text{mm}$)	0.71-0.83	1.15 ²¹ (0.95, 10 $M = 0.6-8.5\text{mg}$)	Cetta et al. (1986)

	aggregate zooids	2.78 ²¹ (0.98, 12, L=2-20mm)	0.68-0.72	0.68 ²¹ (0.90, 15, M=0.3-10.1mg)	Cetta et al. (1986)
<i>Salpa thompsoni</i>	solitary zooids	2.28 ^{1, 16, 22} (0.98, 6, L=26-132mm)	0.72-0.88	0.84 ^{1, 16, 22} ±0.16 (0.98, 6, M=0.94-34.9g)	Iguchi & Ikeda (2004)
	aggregate zooids	2.41 ^{1, 16, 22} (0.96, 31, L=12-56mm)	0.71-0.83	0.92 ^{1, 16, 22} ±0.14 (0.89, 25, M=0.26-15.2g)	Iguchi & Ikeda (2004)

¹ Based on wet body mass

² Based on data from several studies all normalized to 20° C. Similar exponents were found at 21° C ($b_R = 0.65$; $r^2 = 0.93$; $n = 25$; M range = 0.021-700mg) and at 26° C ($b_R = 0.58$; $r^2 = 0.96$; $n = 14$; M range = 0.03-100mg)

³ Based on data from several studies all normalized to 20° C. Similar exponents were found at 21° C ($b_R = 1.078$; $r^2 = 0.83$; $n = 51$; M range = 700-55,000mg) and at 26° C ($b_R = 1.044$; $r^2 = 0.93$; $n = 73$; M range = 100-50,000mg)

⁴ Based on dry body mass

⁵ It is not known why this calculated estimate of b_A is higher than the predicted range (in parentheses). Perhaps it is because body-mass density decreased during growth, thus causing b_L to be an underestimate of the scaling slope for body volume in relation to length.

⁶ Based on outermost diameter, including the lappet tips.

⁷ Accurately estimating the body-mass scaling of surface area in ephyra larvae is complicated because their shape changes considerably from being snowflake-like with long radiating projections (lappets) to umbrella-like, with little or no radiating projections [see Fig. 3 in Kinoshita et al. 2007; also see Fig. 1 in Feitl et al. 2009]

⁸ Estimated at 15° C. Similar values were observed at 10° C

⁹ Based on bell diameter

¹⁰ Mean of 12 separate estimates. Mean for 7 dry mass values is similar (2.77).

¹¹ Based on dry soft tissue mass

¹² Mean of 16 separate estimates

¹³ This estimated b_A range is likely underestimated, because it ignores the high surface area of the veliger's nutrient-absorbing, sail-shaped velum (foot) that can extend far beyond the measured shell length used in calculating b_L and b_A (see text)

¹⁴ Based on wet soft tissue mass

¹⁵ Similar results found for dry tissue mass and for standard metabolic rate

¹⁶ Calculated from unpublished raw data.

¹⁷ Each data point is a mean of 4-11 replicate measurements

¹⁸ Pooled from 3 separate estimates at 3 different temperatures (24, 26 and 28° C)

¹⁹ Mean of 2 separate estimates (including males versus females)

²⁰ Pooled from 4 separate estimates at 4 different temperatures (22, 24, 26 and 28° C)

²¹ Based on carbon mass

²² Similar results found for dry mass, carbon mass and ash-free dry mass

Sources:

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3. Sources for data in Table 2

Nauplii b_L :

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