Standardising curved carapace length measurements for leatherback turtles, *Dermochelys coriacea*, to investigate global patterns in body size

Nathan J. Robinson1,2, Kelly R. Stewart3,4, Peter H. Dutton3, Ronel Nel5, Frank V. Paladino1,2 & Pilar Santidrián Tomillo2,6

1Department of Biology, Indiana University-Purdue University Fort Wayne, Fort Wayne, Indiana, USA
2The Leatherback Trust, Goldring-Gund Marine Biology Station, Playa Grande, Guanacaste, Costa Rica
3Marine Mammal and Turtle Division, Southwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, La Jolla, California, USA
4The Ocean Foundation, Washington DC, USA
5Department of Zoology, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa
6Population Ecology Group, Institut Mediterrani d’ Estudis Avançats, IMEDEA (CSIC-UIB), Esporles, Mallorca, Spain

There are two commonly utilised, but distinct, methods for measuring carapace length of leatherback turtles (*Dermochelys coriacea*). Either the carapace is measured along the central ridge or to the side of the central ridge. Here, we demonstrate that these two measurements produce differing results. Moreover, we formulate a globally-applicable correction factor to standardise between these two measurements. Standardised curved carapace length measurements from leatherback turtles at nesting sites worldwide generally fit into 3 size categories: small (<150 cm; Atlantic: Southeast and Pacific: East), mid-sized (150-157.5 cm; Atlantic: Northwest), and large (>157.5 cm; Indian: Southwest, Indian: Northeast, and Pacific: West).

**Key words:** correction factor, morphology, marine turtles, nesting, Regional Management Units

Measurements of carapace length are generally used as the universal standard for assessing body size in Testudines. For the largest member of this order, the leatherback turtle (*Dermochelys coriacea*), it is common to measure carapace length using a flexible tape measure to follow the natural curvature of the carapace (Bolten, 1999). However, the distinctive topography of the leatherback’s carapace presents a unique challenge. A leatherback turtle’s carapace is characterised by 7 dorso-longitudinal ridges, which are further elevated by numerous small (<1cm) nodules (Figure 1). Consequently, Curved Carapace Length (CCL) measurements that follow the mid-line of the carapace are strongly affected by the size of these ridges and nodules. This has led to the development of two distinct methods for measuring CCL in leatherback turtles. In one method, termed CCLridge, the carapace is measured along the central (vertebral) dorso-longitudinal ridge from the nuchal notch (the anterior edge at the carapace’s midline) to the posterior tip of the pygal process (caudal peduncle). The second method, termed CCLoffset, is very similar yet the carapace is measured to the side of the ridge, allowing the tape measure to fall into its ‘natural’ position (termed CCLoffset) (Fig. 1). Here, we quantified the typical variation between these two measures of CCL. We also developed a globally-applicable correction factor based on CCLridge and CCLoffset measurements taken from leatherback turtles at four major nesting beaches encompassing the Atlantic, Indian and Pacific Oceans. Lastly, we collated and standardised CCL measurement from nesting populations worldwide to look for global patterns in CCL.

For this study, we collected measurements of CCLoffset and CCLridge from nesting leatherback turtles on Playa Grande on the Pacific coast of Costa Rica (n=21), Juno Beach on the Atlantic coast of the USA (n=101), St. Croix in the Caribbean (n=27), and the iSimangaliso Wetland Park on the Indian Ocean coast of South Africa (n=93). Only the CCLoffset data for St. Croix and Juno Beach have been published previously (see Boulon et al., 1996 and Stewart et al., 2007).

We modelled the relationship between CCLoffset and CCLridge at each geographic location using a linear least-squares regression. We used two separate ANCOVAs to test for differences in the slope and intercept of the linear regression lines for each geographic location. As there were no statistical differences between the slopes (F2,234=0.82, p=0.48) or intercepts (F2,234=1.94, p=0.13) at any location, we combined the data and calculated a new linear regression line for the combined dataset (Fig. 2). The equation for the combined linear regression was: 

\[ CCL_{\text{offset}} = 0.984 \times CCL_{\text{ridge}} + 0.157 \]
The linear regression fit the data closely ($r^2=0.99$) indicating that this correction factor can be used to standardize CCL measurements with a high-level of accuracy. Using this correction factor a mid-sized leatherback turtle with a CCL$_{\text{offset}}$ of 155.0 cm would have a CCL$_{\text{ridge}}$ of 157.7 cm. This difference of 2.7 cm is small relative to the overall CCL of the animal, but could affect comparisons of average CCL between populations. Indeed, differences of only a few cm in CCL have been used, along with other complimentary data, to argue for ecological differences between leatherback populations worldwide (Saba et al., 2008). To further confirm the potential effect that differences in CCL measurements may play in interpreting global patterns of CCL in leatherback turtles, we applied our correction factor to reported values of CCL for leatherback populations throughout the world.

From the published literature and personal communications, we collated data on CCL from leatherback turtles at 23 nesting locations (Fig. 3, Online Appendix 1). Each location was grouped by its Regional Management Unit (RMU). RMUs are spatially defined assemblages of sea turtles that are used to prioritise conservation efforts and while not necessarily constituting a single population, are predicted to be on independent evolutionary trajectories and represent geographic barriers to gene flow (Wallace et al., 2010). For each location, we determined whether CCL$_{\text{ridge}}$ or CCL$_{\text{offset}}$ was collected either by consulting the appropriate literature or by contacting the author directly. For studies that had collected CCL$_{\text{ridge}}$ measurements, the data were modified using the previously determined correction factor.

Even before standardising CCL measurements, it was clear that there were distinct differences in size between
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Nesting leatherback turtles between RMUs. Specifically, leatherback turtles from the East Pacific RMU appears to be the smallest, while those from the West Pacific RMU are the largest. However, once the correction factor was applied to all locations that had previously only reported CCL\textsubscript{ridge} data some subtle changes were apparent. It appears that the leatherback turtles of Southeast Atlantic RMU are actually of a similar size to the East Pacific RMU. In addition, the leatherback turtles from the West Pacific RMU are not notably larger than those from the Southwest Atlantic or Northeast Indian RMU. Standardised CCL values also reduces some of the variation in mean CCL values between different locations within a single RMU. Specifically, leatherback turtles from Tortuguero in Costa Rica and Yalimapo in French Guiana appeared notably larger than all other populations in the Northwest Atlantic RMU before standardisation; however, after standardisation these populations now fall much closer to the average CCL for the RMU. Overall, it appears that nesting leatherback turtles from different RMUs can be separated into 3 size categories: small (<150 cm; Southeast Atlantic and East Pacific), mid-sized (between 150 and 157.5 cm; Northwest Atlantic), and large (>157.5 cm; Southwest Indian, Northeast Indian, and West Pacific).

We demonstrate a straightforward and reliable correction factor to account for differences between CCL measurements of leatherback turtles. By standardising CCL measurements, we can improve our capacity to observe subtle differences in CCL between populations, even when different measuring techniques are employed. It should be noted, however, that this correction factor is only suitable for nesting leatherback turtles and further investigation is required before it can be shown if this correction factor can also be applied to foraging animals as well as males or juveniles. Interestingly, the carapaces of foraging leatherback turtles can expand to accommodate their increased mass (Davenport et al., 2011) and this may directly alter CCL measurements, especially CCL\textsubscript{offset}. 

Fig. 3. A global comparison of curved carapace length measurements between major nesting populations of leatherback turtles. Standardised CCL measurements are represented by black circles. Non-standardised CCL\textsubscript{ridge} measurements are represented by clear circles. Turtles are grouped into Regional Management Units as defined by Wallace et al. (2010) and indicated by the brackets at the top of the graph. Error bars=± 1 standard deviation. References for each data point are listed in Appendix 1.
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