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SHORT NOTE

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

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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 CCL_{ridge}, 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 CCL_{offset}, 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 CCL_{offset}) (Fig. 1). Here, we quantified the typical variation between these two measures of CCL. We also developed a globally-applicable correction factor based on CCL_{ridge} and CCL_{offset} 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 CCL_{offset} and CCL_{ridge} 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 CCL_{offset} 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 CCL_{offset} and CCL_{ridge} 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 ($F_{3,\,234}$=0.82, p=0.48) or intercepts ($F_{3,\,234}$=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_{offset}=0.984 x CCL_{ridge} + 0.157

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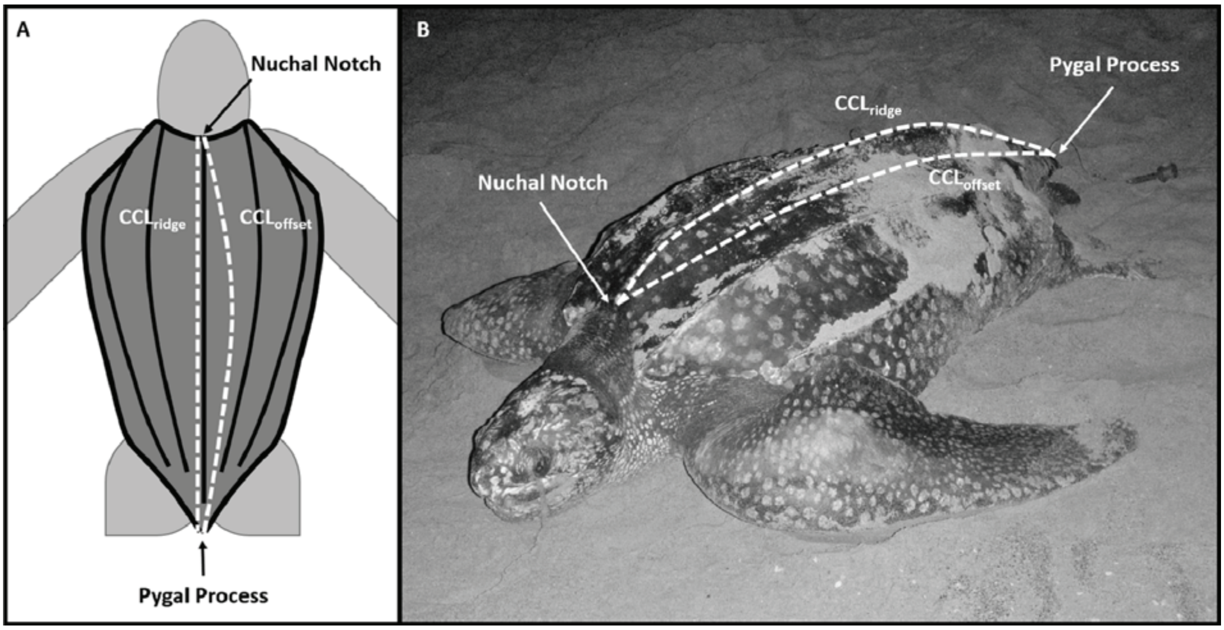

Fig. 1. A schematic (A) and a photo (B) depicting the two methods used to measure curved carapace length (CCL) in leatherback turtles. The two methods: CCL_{ridge} and CCL_{offset}, are illustrated by dotted white lines and measure from the nuchal notch to the pygal process; however, CCL_{ridge} involves measuring the carapace along the vertebral ridge, while CCL_{offset} involves measuring the carapace to the side of the vertebral ridge with the tape measure being allowed to follow its 'natural' position along the contours of the shell.

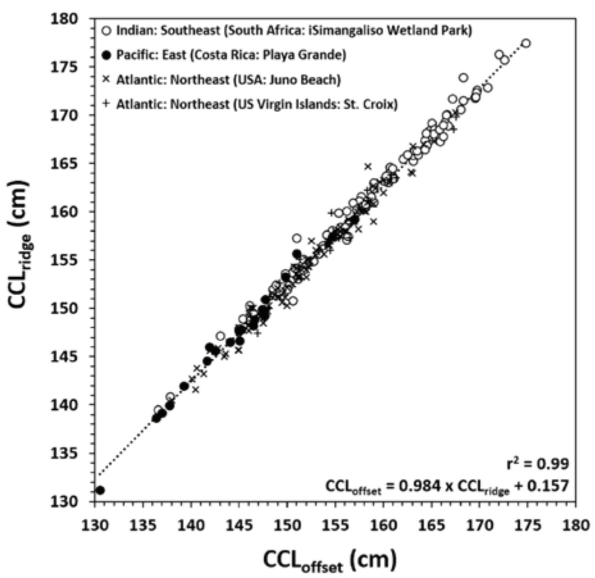

Fig. 2. Comparision of two different methods for measuring curved carapace length (CCL_{offset} and CCL_{ridge}) in leatherback turtles nesting at different locations. White circles represent turtles encountered in Playa Grande on the Pacific coast of Costa Rica. Black circles represent turtles encounted in the iSimangaliso Wetland Park on the Indian Ocean coast of South Africa. Diagonal crosses represent turtles encountered on Juno Beach on the Atlantic coast of the USA. Plus signs represent turtles encountered on St. Croix (US Virgin Islands) in the Caribbean. The dashed line represents the linear regression for these combined datasets. The equation of this line and the r^2 values are also shown.

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_{offset} of 155.0 cm would have a CCL_{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_{ridge} or CCL_{offset} was collected either by consulting the appropriate literature or by contacting the author directly. For studies that had collected CCL_{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

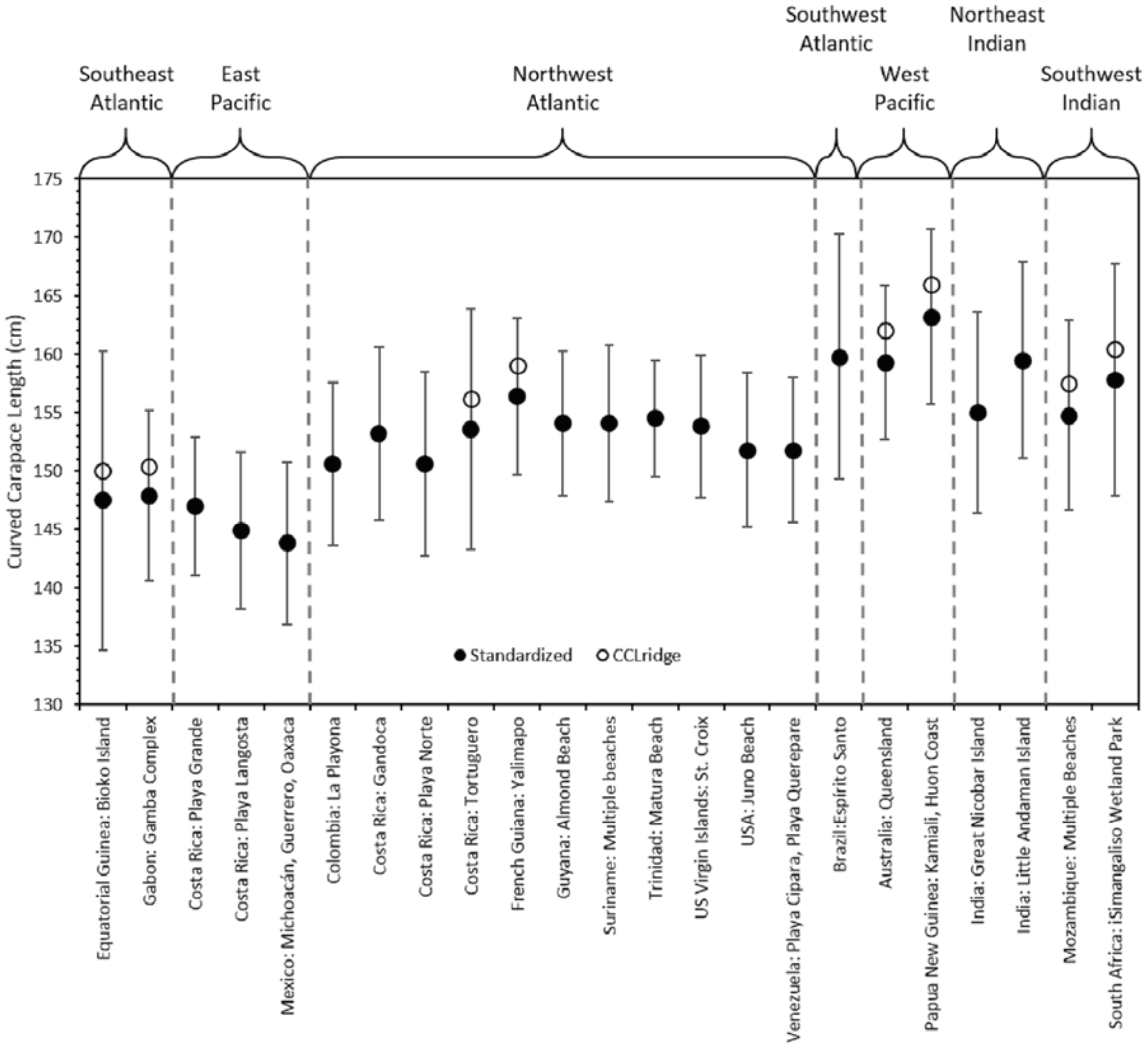

Fig. 3. A global comparison of curved carapace length measurements between major nesting populations of leatherback turtles. Standardised CCL measurements are represented by black circles. Non-standardised CCL_{ridge} measurements are represented by clear circles. Turtles are grouped into Regional Management 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.

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_{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_{offset}.

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Please note that the Appendix for this article is available online via the Herpetological Journal website (http://www.thebhs.org/pubs_journal_online_appendices.html)