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RESEARCH ARTICLE

Lateral osteoderms of the Nile crocodile *Crocodylus niloticus*

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The article shows morphometry of large and small lateral osteoderms on the Nile crocodile body, which forms into arc-like lines. Length of large lateral osteoderms is 2.52 times greater than small lateral osteoderms, width of large lateral osteoderms is 2.20 times greater than small lateral osteoderms, and area of large lateral osteoderms is 5.59 times greater than small lateral osteoderms. Configuration index (length to width ratio) is similar in large (2.03 ± 0.06) and small (1.92 ± 0.17) lateral osteoderms, but scale range of this factor is less significant in large lateral osteoderms (1.67–2.50), than in small lateral osteoderms (1.00–3.00).

Keywords: Nile crocodile *Crocodylus niloticus*; Osteoderms; Lateral areas; Topography; Sizes, Configuration; Bioinformatic model

Introduction

Osteoderms are cancellous osseous structures, lying in the dermis thickness, forms modular system of the skin skeleton covering dorsal and lateral area of body and tail of crocodiles (Chernova & Kiladze, 2019). It is obvious that the ordered pattern of osteoderms is associated with the physiological characteristics of crocodiles, as bone structures of dermis, which forms natural armor of body surface, and provide for a protective function due to a number of physical properties (Grigg & Gans, 1993; Vickaryous & Sire, 2009; Clarac et al., 2017). The structure of a separate osteoderm is characterized by a high degree of vascularisation (Clarac et al., 2015, 2017, 2018), for this reason osteoderms are involved in the absorption or heat radiation in the process of thermoregulation, behavioral manifestations of which are basking (breathing with an open mouth), searching for shadows, and also moving from the reservoir to the land and conversely (Cott, 1961; Modha, 1968; Spotilia et al., 1977; Kofron, 1993; Grigg & Gans, 1993; Seebacher & Grigg, 1997; Seebacher et al., 1999, 2005; Downs et al., 2008; Vickaryous & Sire, 2009; Kiladze, 2018a,b). The purpose of the present study is to analyze of location, ratio of linear and area parameters, as well as configuration of lateral osteoderms of the Nile crocodile.

Material and methods

We studied some individuals and one skeleton of the Nile crocodile *Crocodylus niloticus* Laurenti, 1768 (Crocodylidae, Crocodylia) (hereinafter the crocodile), presented in the exhibition of Crocodile farm in the Djerba Explore Park (i. Djerba, Tunisia). Osteoderms on the crocodile body and the skeleton were photographed and described. To study the features of their topography, we used the geometric principle of partition by Voronoi and Delaunay, as well as the program by Ivan Kuckir (http://blog.ivank.net/voronoi-diagram-in-javascript.html) freely posted on the Internet (Kuckir, 2019). Linear and area ratios, and also the calculation of the configuration index (k=L/H, where L is length; H is width), osteoderms were determined not by absolute values, but by relative values taken from photographs. The results were processed by methods of variation statistics with use of a computer program Statistica 10 (StatSoft, USA).

Results

We observed that osteoderms fall into a certain order: dorsal cords rectilinear, but in the lateral areas, they form into arc-like lines, characterized by specific flexure (Figure 1). Osteoderms are quite large and little variable in morphometric parameters in the central parts of the crocodile body but there are two size groups of osteoderms in the lateral area: (i) unvaried large and (ii) more variable small, rather randomly scattered in the terminal areas of the body. We earlier found that average value of the intervals between the osteoderms lines is equal 2/5 approximately of the width of their lines, and the variability of these distances varies from 6/100 (in the center of the back) to 7/5 (in the lateral region) (Kiladze, 2018b).

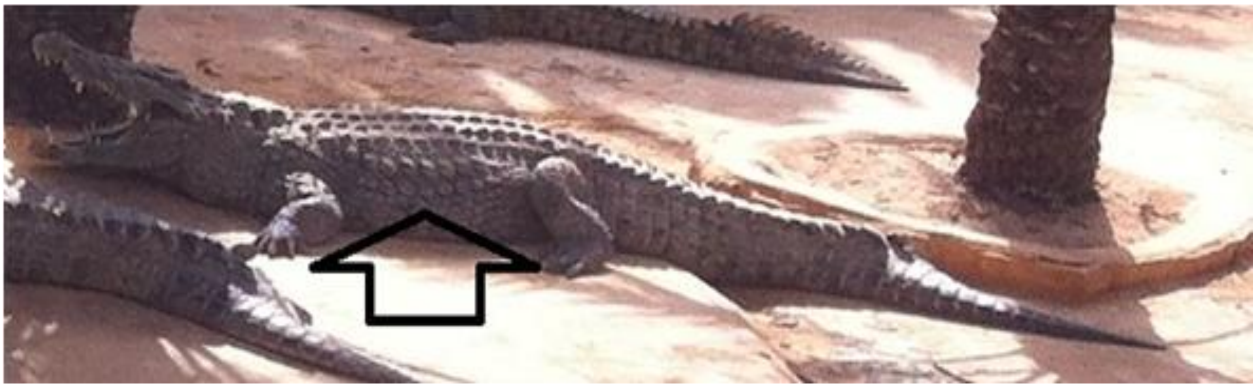

Figure 1. The osteoderms of Nile crocodile *Crocodylus niloticus* form into arc-like lines (arrow). The crocodile is in a state of basking, as evidenced by an open mouth (Kiladze, 2018a). Crocodile farm in the Djerba Explore Park (i. Djerba, Tunisia). Photo by A. B. Kiladze.

A special pattern of the location of lateral osteoderms on the crocodile body surface (Figure 1) is associated with their similar arc-like lines in the lateral parts of the skeleton (Figure 2), here large morphologically developed cellular osteoderms, having a flat shape with a characteristic pointed apex, as well as small bone structures visually resembling a stony placer. Large osteoderms are located closer to the center, and small ones are localized in the terminal part of the lateral area.

Figure 2. The skeleton of the Nile crocodile *Crocodylus niloticus*, having osteoderms on the back and the tail. Osteoderms lines are arcuately curved in the lateral area of the body. Crocodile farm in the Djerba Explore Park (i. Djerba, Tunisia). Note: 1–large lateral osteoderms; 2 –small lateral osteoderms. Photo by A. B. Kiladze.

To define the location character of osteoderms in the lateral area of the body, we made a number of geometric constructions: (i) initial figure (Figure 3A) of osteoderms topography was presented in the form of points (Figure 3B); (ii) the Voronoi diagram reflected the character of the plane splitting into separate modular elements (Figure 3C). We observed that singleton cluster of osteoderms is the larger, the farther from it is the adjacent bone element; (iii) Delaunay triangulation allowed the osteoderms arrangement to be represented in the form of triangular simplexes forming an ordered network of bone structures (Figure 3D).

We compared the averaged linear and areal parameters of osteoderms and found that large osteoderms exceed small ones in length by a factor of 2.52; in width 2.20 times; by area 5.59 times.

The calculated configuration indexes for osteoderms of both types showed approximately the same length excess over the width, but scale range of this factor for small osteoderms is more significant (from 1.00 to 3.00), than for large osteoderms (from 1.67 to 2.50), which affected the calculated statistical parameters (Table 1).

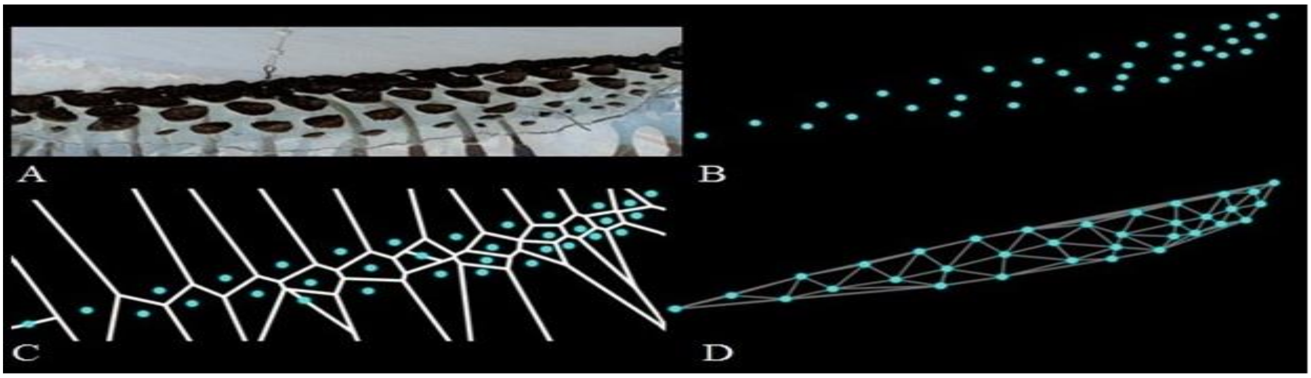

Figure 3. Bioinformatic model of the location of osteoderms in the lateral area of the Nile crocodile *Crocodylus niloticus* skeleton: A–initial location of osteoderms. Photo by A. B. Kiladze; B–point representation of location of osteoderms; C-the Voronoi diagram; D–Delaunay triangulation. Note: for greater clarity, images are shown with inverted colors.

Table 1. Configuration index of large and small osteoderms in the lateral area of the Nile crocodile *Crocodylus niloticus* skeleton.

Type of osteoderms	**Configuration index**			
	M ± m*	**Lim**	**± σ**	**Cv, %**
Large (n=16)	2.03 ± 0.06	1.67—2.50	0.24	11.82
Small (n=18)	1.92 ± 0.17	1.00—3.00	0.71	36.98

***Note:** n is the number of measurements; M ± m is the arithmetic mean with the error of the arithmetic mean; lim-parameter limits; ± σ is the standard deviation; Cv is the coefficient of variation.

We can also demonstrate the variation of configuration index for two types of osteoderms in a graphic form (Figure 4).

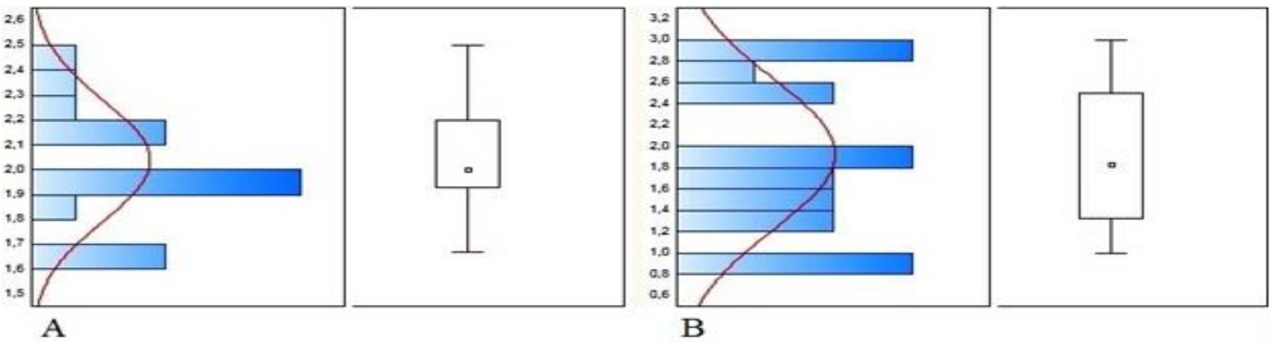

Figure 4. Visualization of the scale range of configuration index for large (A) and small (B) osteoderms in the lateral area of the Nile crocodile *Crocodylus niloticus* skeleton.

The obtained results indicate that in all cases large osteoderms show an excess of length over width, but in some cases small osteoderms show equality of linear values of length and width, and in other cases part of the osteoderms are more elongated, which indicates a three-fold excess of length over width.

Discussion

There are obvious differences in the configuration and relative morphometry of osteoderms, depending on their topography. The dorsal surface of the body, the most susceptible to insolation during the basking of crocodiles (Grigg & Gans, 1993; Downs et al., 2008; Vickaryous & Sire, 2009; Kiladze, 2018a), is covered with tightly-spaced wide lines of large monomorphic osteoderms (Kiladze, 2018b). The lateral surface of the body with arc-like marginal lines of osteoderms, apparently, is not so fully involved in thermoregulation, and that explains the polymorphism of osteoderms (configuration, dimensional characteristics, disunity of rows and adjacent osteoderms). The morphology of osteoderms as modular units of the skin (Chernova & Kiladze, 2019) showed the dependence of physiological heat transfer processes on the heterogeneity of their surface, which increases the surface area of osteoderms by 40%, and their relatively high degree of vascularization, as well (Clarac et al., 2015, 2017, 2018). This recent evidence on complexly structured (ornamented) osteoderms as amended by 3D modeling outcomes allow considering these specific dermal ossification as eco- and physiological adaptation of crocodile to living environment (Clarac et al., 2015, 2017, 2018). An additional point is that dermal ossification neutralize the resulting acidosis and also deposit a certain amount of lactate, which is a product of the exchange of the muscular system (Jackson et al., 2003; Janis et al., 2012).

Conclusion

We presented relative morphometric parameters of osteoderms, which demonstrate features characteristic of the lateral parts of the body of the Nile crocodile: (i) areal segregation, (ii) arc-like flatness of line construction, (iii) diffusive location of small osteoderms, (iiii) polymorphism, which is manifested in the morphometric parameters defining the configuration of the two morphotypes of osteoderms.

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