Article id: jbg.2017.3.5.2
Journal of Bioinformatics and Genomics, 2017, 3-5
doi: 10.18454/jbg.2017.3.5.2
Advance Access Publication Date: 13 November 2017

STRUCTURAL BIOINFORMATICS

BIOINFORMATICS MODEL OF THE CARAPACE SCUTE PATTERN OF THE RED-EARED SLIDER *TRACHEMYS SCRIPTA ELEGANS* (WIED-NEUWIED, 1839)

Acknowledgements

The author expresses his profound gratitude to O.F. Chernova (A.N. Severtsov Institute of Ecology and Evolution of the Russian Academy of Sciences) for the academic editing of this article.

Conflict of Interest

None declared.

A.B. Kiladze[1,*]

[1]A.N. Severtsov Institute of Ecology and Evolution of the Russian Academy of Sciences, Laboratory of Morphological Adaptations of Vertebrates, 33 Leninskiy pr., 119071 Moscow, Russia

*To whom correspondence should be addressed.

Associate editor: Giancarlo Castellano

Received on 13 August 2017, revised on 29 August 2017, accepted on 05 October 2017.

Abstract

The scutes located on the carapace of the red-eared slider Trachemys scripta elegans (Wied-Neuwied, 1839) have been modeled. Bioinformatics modeling of carapace's scutes were carried out by utilizing the Voronoi decomposition and Delaunay triangulation method. These two geometric techniques allow the patterns of vertebral and costal scutes to be recreated. The proposed model may have a certain value for taxonomy as well as for estimating the symmetry of the morphological structures, which is important for the purposes of biomimetics.

Keywords: *red-eared slider, carapace, scutes, Voronoi diagram, Delaunay triangulation, symmetry.*

Contact*: andreykiladze@yandex.ru*

1 Introduction

The turtle shell has a long history of studies and is considered in various aspects of biology starting from paleontological and evolutionary reconstructions and ending with molecular genetic studies (Sukhanov, 1964; Zangerl, 1969; Feldman and Parham, 2002; Rieppel, 2013). The shell is a key anatomical structure that forms the habit of turtles and consists of a dorsal carapace and a ventral plastron (Saxena R.K. and Saxena S., 2008). The shell is characterized by adaptive plasticity that manifests in qualitative and quantitative differences in land, freshwater and sea turtles. It is the features of the habitat that predetermine the geometry of the shell and a degree of its dome which can be determined by the angles of carapace curvature in various projections, such as lateral, horizontal and frontal (Kiladze, 2017). The physiological significance of turtle shell is associated with passive protection from predatory animals, thermoregulation, deposition of mineral and fatty substances, as well as water (Cordero, 2017).

Scutes on the shell of the turtles have a geometrically regular shape and a characteristic arrangement. This allows scientists to discuss the natural symmetry of the shell as the scutes are distinguished by a high level of morphological specialization which are associated with adaptations to the environment. There is a high level of individual variability of a mosaic pattern of scutes against the background of their phylogenetically stable pattern (Cherepanov, 2014). The carapace is formed not only by scutes that are separated by furrows, but also by epidermal bumps, or tubercles that can occur in some species. In terms of evolution, the scutes are considered an innovation, while the tubercles are homologous to reptilian scales (Moustakas-Verho and Cherepanov, 2015).

It is important to use visual bioinformatics models to recreate the natural pattern of pholidosis because it aids in providing the solution of taxonomic issues since the configuration of the scutes is of a species-specific nature. In addition, a turtle's shell serves as an excellent example for demonstrating the laws of symmetry in biology. Fundamentals of modeling the surface of a turtle's shell can find their application in biomimetics (Jabbari et al., 2014). Previous attempts were made to study the symmetry and asymmetry of the skin as well as its derivatives in vertebrates, as this would allow us to analyze existing principles and approaches in the field of theoretical and applied biosymmetrics (Chernova and Kiladze, 2014; Kiladze and Chernova, 2014). Scientists from the University of Pisa and Sea Turtle Rescue Centre (Italy) have studied geometric morphometrics and scute patterns of shell of loggerhead turtle (*Caretta caretta*) (Casale et al., 2017).

The purpose of this work is to visualize the geometric features of the mosaic pattern of carapace scutes using the red-eared slider as a study object. The natural habitat of these turtles is the United States, while in Russia red-eared sliders are widely distributed as pets. When these turtle escape into the wild or a new habitat, it acquires the characteristics of an invasive species (Semenov, 2009).

2 Material and Methods

The carapace surfaces of ten adult red-eared sliders *Trachemys scripta elegans* (Wied-Neuwied, 1839) were examined. Sliders for the research were provided by private terrariophiles. The turtles care and feeding were standard in captivity. Carapaces of the studied turtles were photographed. Simulation of the location and shape of vertebral and costal scutes was performed on a digitized image of the most typical carapace, which did not have visible asymmetry and anomalies of pholidosis. This condition allowed us to consider this carapace as a standard material. The bioinformatics model was based on the Voronoi decomposition and Delaunay triangulation. To create the model, we used Ivan Kuckir's computer program that he posted on the Internet (Kuckir, 2017).

3 Results

The carapace of adult turtles demonstrated different shades of green. The camouflage tones were the most common color, while on a fairly uniform background, yellowish stripes may occur. It was observed that furrows clearly separated each scute. The three most common shapes of the carapace scutes were trapezoidal, pentagonal and hexagonal (Fig. 1).

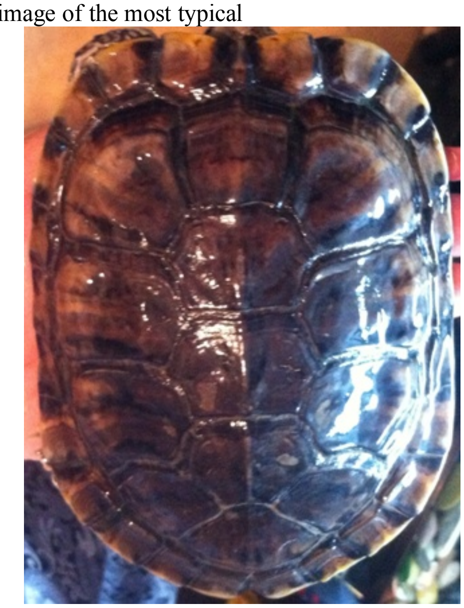

Fig. 1 – The carapace of an adult red-eared slider *Trachemys scripta elegans* (Wied-Neuwied, 1839). Photo by A.B. Kiladze

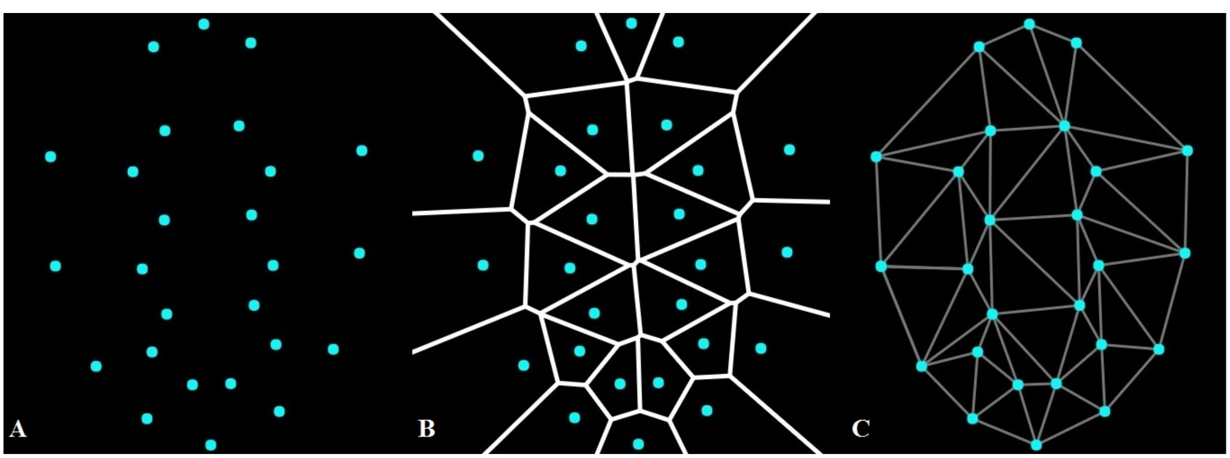

Fig. 2 − Modeling of the carapace scute pattern of the red-eared slider *Trachemys scripta elegans* (Wied-Neuwied, 1839): A − apexes of scutes; B − Voronoi diagram consisting of cells having different areas depending on the arrangement of the scute vertices; C − Delaunay triangulation modeling the shape of scutes

Geometric modeling of the form of vertebral and costal scutes included a number of stages: (1) Plotting of points on the plane, which coincided with the corners of the scutes (Fig. 2A). (2) Construction of the Voronoi diagram. In this context, the distance between the point vertices of the scutes is connected by a positive correlation with the area of the cells: the farther the points from each other, the larger the cell. Conversely, the smaller the distance, the smaller the partition area (Fig. 2B). (3) Modeling, by means of triangular simplices, of the configuration of vertebral and costal scutes using the Delaunay triangulation. The resulting graph is adequate to the real geometric configuration of the scutes and their topography on the carapace (Fig. 2C).

4 Discussion

The obtained results should be considered in the context of the evaluation of symmetry and asymmetry of natural structures. The Voronoi diagram explains the natural pattern of dragonfly wing (Gawell and Nowak, 2015), scales in some species of fish (Voytekhovsky, 2009), or spotted color in giraffes (Wormser, 2008). In discussing the natural geometry of cutaneous appendages, it must be pointed out that hexagonal symmetry is characteristic of certain features of some animals. For example, it is characteristic of the scales of snakes and also for the location of feather follicles in the African ostrich (Chernova and Kiladze, 2014; Kiladze and Chernova, 2014). All these examples seem to suggest a unified mechanism of morphogenesis, which encompass the development of various organs and tissues. Currently, the alternation of laying skin appendages, as well as the pigmentation in reptiles in ontogenesis, can be explained using the chemical bases of morphogenesis (Turing, 1952), the theory of the formation of biological patterns (Gierer and Meinhardt, 1972) and the physical foundations of biological morphogenesis (Belintsev, 1991).

In practical herpetology, the application of geometric techniques is believed to allow comparative studies of the scute arrangement, to reveal the species-specific features of turtles, which is of great importance in taxonomic work. Considering the regular mosaic of scutes, which is distinguished by a certain symmetry, a natural pattern can be used in systems of the industrial design and biomimetics.

5 Conclusion

In conclusion, it should be noted that the application of the methods of geometric modeling and visualization of morphological elements will allow a wider understanding of the structural architectonics of scutes of a turtle's shell. This would be necessary for solving various biological problems when discussing key theories of the morphogenesis of the skin of vertebrates. The applied aspects of the results obtained can have significant value in the construction of certain technical elements that use as a basis the natural position of scutes on the shell of turtles.

References

Belintsev, B. N. (1991). *Fizicheskie osnovy biologicheskogo formoobfazovaniya* [Physical Foundation of Biological Morphogenesis]. Moscow, USSR: Nauka, Gl. Red. Fiz-Mat. Lit.

Casale, P., Freggi, D., Rigoli, A., Ciccocioppo, A., Luschi, P. (2017). Geometric morphometrics, scute patterns and biometrics of loggerhead turtles (*Caretta caretta*) in the central Mediterranean. *Amphibia-Reptilia*, 38 (2). P. 145–156. doi: 10.1163/15685381-00003096

Cherepanov, G. O. (2014). Patterns of scute development in turtle shell: Symmetry and asymmetry. *Paleontological Journal*, 48. P. 1275−1283. doi: 10.1134/S003103011412 0028

Chernova, O. F., Kiladze, A. B. (2014). Symmetry in topography and microstructure of vertebrate skin derivatives. *Paleontological Journal*, 48. P. 1284−1294. doi: 10.1134/S003103011412003X

Cordero, G. A. (2017). The turtle's shell. *Current Biology*, 27 (5). R168−R169. doi:10.1016/j.cub.2016.12.040

Feldman, C. R., Parham, J. F. (2002). Molecular Phylogenetics of Emydine Turtles: Taxonomic Revision and the Evolution of Shell Kinesis. *Molecular Phylogenetics and Evolution*, 22 (3). P. 388–398. doi: 10.1006/mpev.2001.1070

Gawell, E., Nowak, A. (2015). Voronoi tessellation in shaping the architectural form from flat rod structure. *PhD Interdisciplinary Journal*, 1. P. 47−55.

Gierer, A., Meinhardt, H. (1972). A theory of biological pattern formation. *Kybernetik*. 12 (1). P. 30−39.

Jabbari, E., Kim, D.-H., Lee, L. P., Ghaemmaghami, A., Khademhosseini, A., Eds. (2014). Handbook of Biomimetics and Bioinspiration Biologically-Driven Engineering of Materials, Processes, Devices, and Systems (In 3 Volumes). Singapore: World Scientific Publishing Company.

Kiladze, A. B. (2017). *Morfologicheskaya geometriya karapaksa razlichnykh ehkologicheskikh form cherepakh* [Morphological geometry of the carapace of different ecological forms of turtles]. Chernova, O. F., Ed., Moscow: Ru-Science Publishing House.

Kiladze, A. B., Chernova, O. F. (2014). Symmetry and asymmetry of configuration and structure of Vertebrate skin. *Paleontological Journal*. 48. P. 1295−1302. doi: 10.1134/S0031030114120053

Kuckir, I. (2017). Voronoi diagram in JavaScript. Available at: http://blog.ivank.net/voronoi-diagram-in-javascript.html. Accessed on 1 July 2017.

Moustakas-Verho, J. E., Cherepanov, G. O. (2015). The integumental appendages of the turtle shell: an evo-devo perspective. *Journal of Experimental Zoology. Part B: Molecular and Developmental Evolution*, 324 (3). P. 221−229. doi: 10.1002/jez.b.22619

Rieppel, O. (2013). The evolution of the turtle shell. In: Morphology and evolution of turtles. p. 51−62. Brinkman, D.B., Holroyd, P.A., Gardner, J.D., Eds., NY: Springer. doi: 10.1007/978-94-007-4309-0

Saxena, R. K., Saxena, S. (2008). Comparative Anatomy of Vertebrates. Kent: Anshan Limited.

Semenov, D. V. (2009). *Krasnoukhaya cherepakha, Trachemys scripta elegans, kak invazivnaya ugroza (Reptilia; Testudines)* [Slider turtle, *Trachemys scripta elegans*, as invasion threat (Reptilia; Testudines)]. *Russian Journal of Biological Invasions*, 1. P. 36−43.

Sukhanov, V. B. (1964). Subclass Testudinata. In: *Osnovy Paleontologii. Zemnovodnye, Presmykayushchiesya i Ptitsy* [Fundamentals of Paleontology. Amphibians, Reptiles, and Birds]. p. 354–438. Orlov, Yu.A., Ed., Moscow: Nauka.

Turing, A. M. (1952). The chemical basis of morphogenesis. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, 237 (641). P. 37−72. doi:10.1098/rstb.1952.0012

Voytekhovsky, Y. L. (2009). *Geometricheskie motivy v morfologii ryb Tetraodontiformes* [Geometrical motives in the Tetraodontiformes fishes morphology]. *Zhurnal Obshchei Biologii*, 70. P. 257–261.

Wormser, C. (2008). Generalized Voronoi Diagrams and Applications. Computer Science. Unpublished PhD thesis. Universit´e Nice Sophia Antipolis, Nice, France.

Zangerl, R. (1969). The turtle shell. In: Biology of the Reptilia. Vol. 1 (Morphology A). p. 311–339. Gans, C., Ed., London: Academic Press.

БИОИНФОРМАЦИОННАЯ МОДЕЛЬ ПАТТЕРНА РОГОВЫХ ЩИТКОВ КАРАПАКСА КРАСНОУХОЙ ПРЕСНОВОДНОЙ ЧЕРЕПАХИ *TRACHEMYS SCRIPTA ELEGANS* (WIED-NEUWIED, 1839)

Благодарности

Выражается глубочайшая благодарность Черновой О.Ф. (Институт проблем экологии и эволюции им. А.Н. Северцова Российской академии наук ИПЭЭ РАН) за академическое редактирование статьи.

Конфликт интересов

Не указан.

А.Б. Киладзе[1,*]

[1]Институт проблем экологии и эволюции им. А.Н. Северцова Российской академии наук ИПЭЭ РАН, Лаборатория морфологических адаптаций позвоночных, Ленинский проспект 33, 119071 Москва, Россия

*Корреспондирующий автор.

Редактор: Джанкарло Кастельяно

Получена 13 Августа 2017, доработана 29 Августа 2017, принята 05 Сентября 2017.

Аннотация

Смоделирована форма роговых щитков карапакса красноухой пресноводнойчерепахи Trachemys scripta elegans (Wied-Neuwied, 1839). Биоинформационная модель включала разбиение Вороного и триангуляцию Делоне. Это позволило геометрическими методами воссоздать паттерн позвоночных и реберных щитков. Предложенная модель может иметь определенное значение в таксономии, а также для оценки симметричности морфологических структур, что важно для целей биомиметики.

Ключевые слова: *красноухая пресноводная черепаха, карапакс, роговые щитки, диаграмма Вороного, триангуляция Делоне, симметрия.*