NATURAL SCIENTIFIC METHODS
IN STUDYING CULTURAL HERITAGE OBJECTS

Automated Morphometric Analysis of 3D Data in Paleoanthropological Research

V. Knyaz[a,b],* and A. Gaboutchian[c]

[a] *Moscow Institute of Physics and Technology (MIPT), Dolgoprudny, 141701 Russia*
[b] *State Research Institute of Aviation System (GosNIIAS), Moscow, 125319 Russia*
[c] *Peoples' Friendship University of Russia, Moscow, 117198 Russia*
*e-mail: knyaz@gosniias.ru

Abstract—Modern methods of non-contact measurements have great potential for paleoanthropological research both for expanding the capabilities of morphometric analysis, and for making unique paleoanthropological materials available to a wider range of researchers. The paper discusses technologies for acquiring three-dimensional data and techniques for their analysis developed for digital paleoanthropological research. New ways of documenting paleoanthropological materials based on novel data types and the advantages of application of new data are discussed.

INTRODUCTION

Most of the information necessary for paleoanthropological research is obtained from geometric measurements of skulls, skeletal bones, and teeth. Measurements and subsequent analysis of linear and angular parameters and shape analysis provide significant evidence for paleoanthropological characteristics of the studied objects. Traditionally, a set of standard anthropological points and measurements is used for morphometric analysis, which reflect the anatomical traits of the studied teeth.

Geometrical measurements are standardized using special mechanical tools. Manual measurements are still widely used in paleoanthropological research. The anthropologist's primary tools are precision mechanical instruments such as rulers and various types of calipers. More sophisticated mechanical instruments can be used, such as a sliding caliper (Martin type), sliding caliper (Eichel type), spreading caliper, Mollison craniophor, and mandibulometer.

In some cases, for example, when measuring teeth (odontometry), measurement reference points are unattainable as it is sometimes impossible to access the required point with a caliper or due to the fragility of the object. Thus, the practice of manual measurement significantly limits the ability to collect statistically reliable data for wide and comprehensive research. Odontological research plays a significant role in the comprehensive study of paleoanthropological materials. These studies are very important because teeth have a whole range of well-studied morphological features that allow evolutionary, taxonomic or historical interpretation. In addition, teeth, as the most highly mineralized structures in the human body, are well preserved. For this reason, odontological material often forms the basis for genetic research, "preserving" nucleotide sequences for longer periods. Along with genetic research, the findings are dated (e.g., by a radiometric method).

To study tooth morphology, visual assessments by experts are mainly used, based on the presence of certain traits and their expression level. Such features are diverse and correspond to the morphological variability of the teeth, which manifests itself, among other issues, in very subtle distinctions identified by experienced experts with appropriate training. Also in odontology, measurement methods are used, which are traditionally carried out with hand instruments [1, 2]. However, the data obtained in the course of random measurements are not sufficient to describe the morphology, but only allow individual parameters of the teeth to be estimated.

The established research model is significantly changed by technologies that allow high-precision 3D models of teeth to be obtained and morphological analysis of these models to be performed. The changes affect not only general aspects related to convenience of information exchange, improving the quality of interaction between specialists, but facilitate accumulation of data, their documentation, systematization, etc. It is fundamentally important to develop new methods of studying teeth: in particular, this paper presents the technique of automated digital odontometry (aDo). The use of different imaging techniques (optical and X-ray) expands the scope of studies.

The use of digital visualization methods for paleo-anthropological studies began almost simultaneously with the appearance of the first visualization systems [3]. Impressive progress and increasing availability of digital systems to obtain and process data on paleoanthropological materials create the prerequisites for the development of new research methods. The ability to study a 3D model, and not the object itself, is useful to preserve valuable material. Another significant advantage of such methods is the repeatability of studies and the possibility to use different methods of data analysis. A detailed review of the use of computed tomography (CT) in paleoanthropology is presented in [4].

Currently, odontometry is an integral part of research in various disciplines: physical anthropology of modern man and paleoanthropology, prosthetic dentistry and orthodontics; it is also used in forensic examinations [5−10]. Measurements can be carried out directly on teeth in the oral cavity [11], on plaster models obtained from impressions from the dentition [12] or, for example, on radiographs [13, 14]. However, 3D reconstructions of teeth and dental arches more often become the objects studied. They began to use the techniques adopted for measurements on real dentition, which have already taken a stable position in the diagnosis carried out in orthodontics They allow application of conventional techniques used in various disciplines, such as diagnostic measurement procedures in orthodontics [15−17]. Later, it became possible to combine different methods, thereby expanding research opportunities [18]. In anthropology and paleoanthropology, a tendency can be clearly observed in the combination of digital techniques with geometric morphometry and micro computer tomography (micro-CT) [19−21]. Thus, previously the enamel thickness was measured using X-ray diffraction patterns or from cross-sectioning teeth [22, 23], while at present methods based on a combination of geometric measurements and high-resolution tomographic reconstructions are being actively developed [24−28]. It is noteworthy that more comprehensive studies are being conducted that combine the above approaches [29, 30]. In this study, it is shown that the combination of the method of automated digital odontometry and digital 3D methods can significantly expand the range of data obtained, and it is useful to apply it to morphological studies. Currently, there are many methods for obtaining 3D reconstructions, including optical imaging [31, 32] and stereophotogrammetry, allowing for craniological and odontological studies [33−36]. Several tasks in dental research are solved using dental intraoral scanners [37, 38]. X-ray methods are widely represented by CT [39, 40], cone-beam CT [41, 42], as well as micro-CT [43−47]. Of interest are odontological studies using the Moiré method [48], as well as reconstructions obtained using a piezoelectric digitizer [49]. Particularly noteworthy are 3D reconstructions performed on tomographic sections obtained by neutron scanning of odontological material [50].

MATERIALS AND METHODS

The experimental part of the performed odontometric studies was based on a representative sample of computer 3D models of teeth obtained using various means of non-contact 3D measurements. The 3D models of the object surface were obtained using Evolution plus (Zfx, USA) and S600 Arti Scanner (ZirkonZahn, Germany) dental laboratory scanners, and on an original photogrammetric system developed for odontometric analysis [51, 52]. Optical scanning of unique findings requiring particularly careful handling was performed with intraoral dental scanners with confocal optics and a special lighting source (Trios, 3Shape, Denmark), CEREC Omnicam (Sirona, Germany).

X-ray scanning methods were performed on a PaX-i 3D cone-beam tomographic apparatus (Vatech, South Korea) and Skyscan 1174 (Bruker, Germany) and phoenix v | tome | x m (General Electric, USA) X-ray microtomographs. On a cone-beam tomograph, the reconstruction was carried out with a voxel size of $0.08 \times 0.08 \times 0.08$ mm with a field of view of 50×50 mm with the maximum for the apparatus, manually set values of voltage and current in the tube. The highest resolution with an enlarged field of view of 100×850 mm made it possible to obtain reconstructions with a voxel size of $0.2 \times 0.2 \times 0.2$ mm. The X-ray microtomograph was operated at an applied voltage of 275 kV, which enabled reconstruction of the surface of teeth with a voxel size of 43 μm in each of three dimensions when examining the skull and 10.33 μm when examining individual teeth.

The primary processing of the measurement data to obtain a 3D model of the tooth was performed using standard software (SW) supplied for the scanners used. This software was used to remove artifacts, adjust the optimal level of gray, global and local smoothing, format conversion, and some other procedures. Measuring studies per se were carried out on the obtained 3D models in the specially developed original software.

The presented method of automated digital odontometry (aDo) originates from clinical and experimental research in prosthetic dentistry. It is based on the developed and substantiated interpretation of the morphology of the tooth, which can be presented in the most accessible form on the vestibulo-oral section of the tooth (Fig. 1). Two distinguishable elevations, correspond to the vestibular and oral cusps of the tooth (this division originates from normal human anatomy according to which the closed dentition divides the oral cavity into the vestibulum and the oral parts). However, when describing not the location, but the functions of these cusps, their clear separation becomes not only difficult, but impossible.
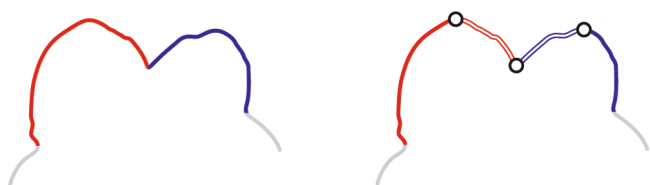
Fig. 1. Anatomical reference points.

Fig. 2. Determination of the occlusal surface and the tooth coordinate system.

Based on the close relationship of function and morphology, in addition to the above-mentioned cusps in the sections, one should distinguish another structure that provides both functional and morphological unity of the tooth, the anatomical occlusal surface. The mentioned cusps and the surface have boundaries set by anatomical landmarks for finding which it is sufficient to consider the geometry of the obtained section. They serve as a basis for further constructions, measurements, and calculations. The parameters obtained (more than 200 at present in each section) broadly, objectively, and variously describe not only the sections, but also under certain conditions (correct orientation and a sufficient number of sections, as well as observing the intervals when obtaining them) the tooth as a whole, its constituent parts: cusps, cuspal slopes, and anatomical occlusal surface.

Finding landmarks on the contours of the teeth and measuring their coordinates in a manual mode is a very routine and time-consuming process, which serves as a source of measurement errors that distort the research result. Therefore, for carrying out multiple measurements, methods and algorithms have been developed that make it possible to perform morphometric analysis in an automatic mode, starting with the procedure for orienting the tooth model to a standard anatomical position and ending with the search for anatomical landmarks in the sections and measurements of the specified parameters.

The measurement procedure is performed in stages and includes:

—Orientation and determination of the tooth coordinate system (Fig. 2): finding the contour of the anatomical occlusal surface based on the analysis of the curvature of the tooth surface; determination of the mesio-distal (anteroposterior) axis of the tooth; determination of the tooth coordinate system; and determination of a set of tooth sections.

—Morphometric analysis of the tooth: finding anatomical landmarks (cusps, cuspal slopes); calculation of a set of morphometric parameters based on anatomical landmarks; and statistical analysis of measurements.

Algorithms for processing data of a 3D model of a tooth are shown in Fig. 3.

A number of unique paleoanthropological samples were studied using the aDo method, including the
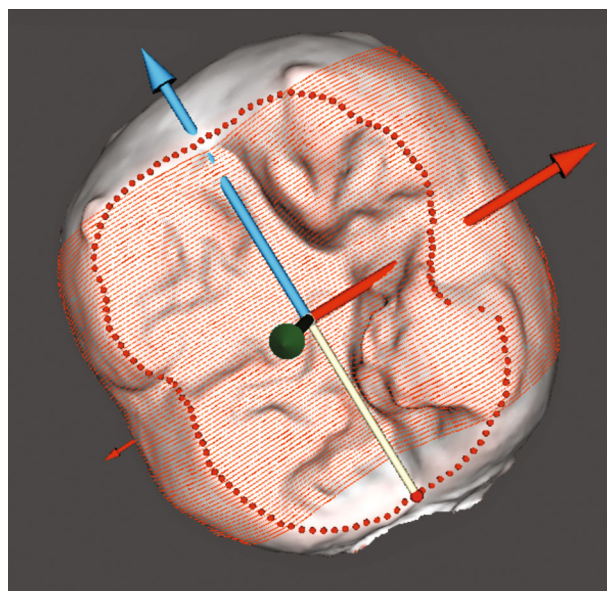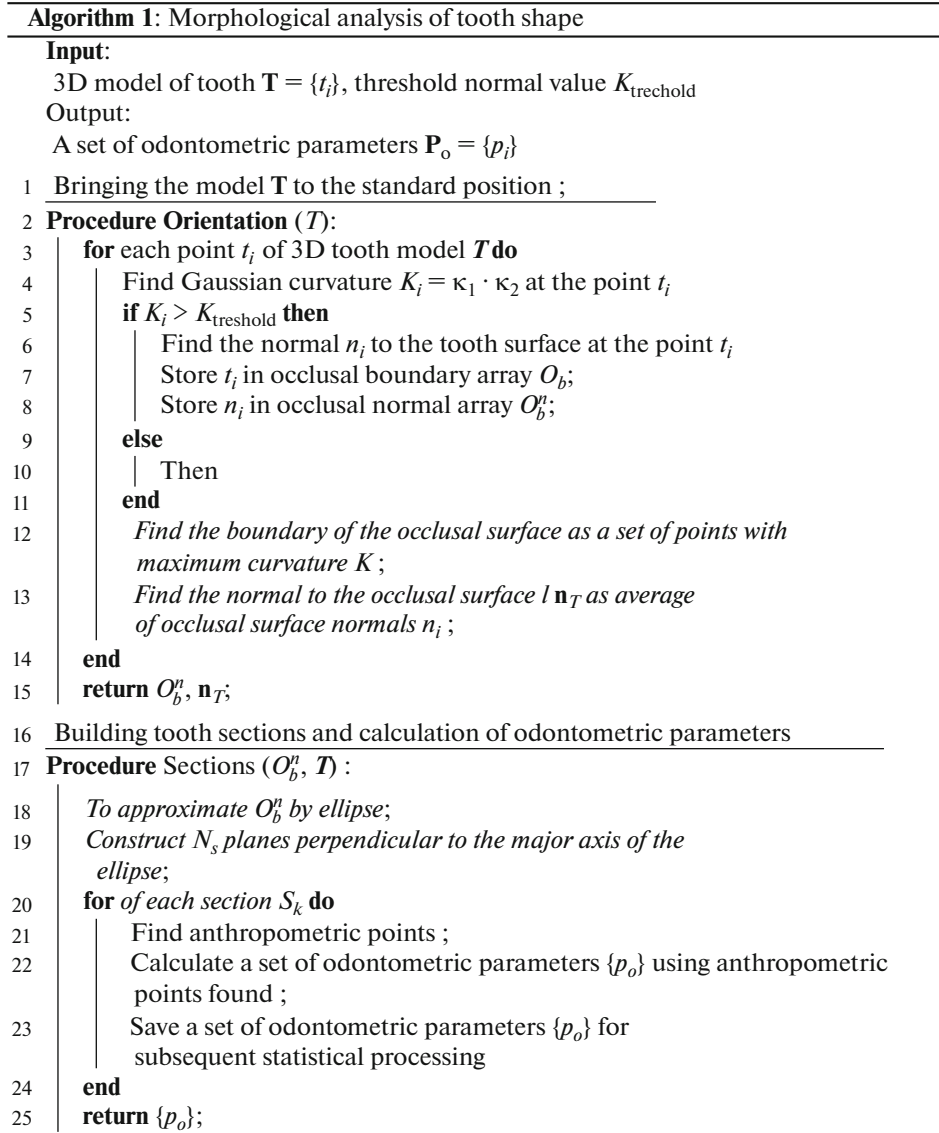
Upper Paleolithic findings from Sunghir (individual C2) (Fig. 4), a sample from Chernovaya (series VIII, individual K8 B7.2), individual teeth from burials at Fofanovo (this archaeological site contains burials dating from the Neolithic to the Bronze Age), material from Burial 4 of the Bronze Age archaeological site of Shengavit located in the Republic of Armenia, as well as a number of specimens dating back to the early and late Middle Ages.

RESULTS AND DISCUSSION

An odontometric technique has been developed and substantiated, which makes it possible to obtain, quickly and automatically, a wide range of parameters objectively characterizing not only the physical dimensions of teeth, but also allowing description of their morphological traits. The data were obtained from samples with complex features, such as curved (bent) cusp tips of the molar in individual C2 from Sunghir, described as an archaic trait in [1]. An odontometric comparison of the mentioned molars with each other (right and left), as well as with samples with a lesser or complete absence of this trait, was carried out. As a result of the analysis, a set of parameters was revealed that obviously reflect visually detectable differences [53]. A number of groups can be distinguished in the obtained measurement data. Thus, the linear parameters on the Sunghir molars in the vestibulo-oral direction are generally similar, except for the relatively massive oral cusps on the right molar (tooth 1.7 according to the dentistry tooth numbering system) 6.57 mm in size (the oral cusps are strongly inclined). A more detailed examination of the results

---

Algorithm 1: Morphological analysis of tooth shape

Input:

3D model of tooth $\mathbf{T} = \{t_i\}$, threshold normal value K_{trechold}

Output:

A set of odontometric parameters $\mathbf{P}_o = \{p_i\}$

---

1   Bringing the model $\mathbf{T}$ to the standard position ;

2   **Procedure Orientation** (T):

3   **for** each point t_i of 3D tooth model $\boldsymbol{T}$ **do**

4   Find Gaussian curvature $K_i = \kappa_1 \cdot \kappa_2$ at the point t_i

5   **if** $K_i > K_{\text{treshold}}$ **then**

6   Find the normal n_i to the tooth surface at the point t_i

7   Store t_i in occlusal boundary array O_b;

8   Store n_i in occlusal normal array O_b^n;

9   **else**

10   Then

11   **end**

12   *Find the boundary of the occlusal surface as a set of points with maximum curvature K ;*

13   *Find the normal to the occlusal surface l $\mathbf{n}_T$ as average of occlusal surface normals n_i ;*

14   **end**

15   **return** O_b^n, $\mathbf{n}_T$;

---

16   Building tooth sections and calculation of odontometric parameters

---

17   **Procedure** Sections (O_b^n, $\boldsymbol{T}$) :

18   *To approximate O_b^n by ellipse*;

19   *Construct N_s planes perpendicular to the major axis of the ellipse*;

20   **for** *of each section S_k* **do**

21   Find anthropometric points ;

22   Calculate a set of odontometric parameters $\{p_o\}$ using anthropometric points found ;

23   Save a set of odontometric parameters $\{p_o\}$ for subsequent statistical processing

24   **end**

25   **return** $\{p_o\}$;

Fig. 3. Algorithms for automated odontometric analysis.

at the level of not only the cusps, but also their slopes, confirmed the difference between the right and left molars on the side where the tops of the cusps are more strongly bent. Thus, right tooth 1.7 is distinguished by the massive oral (3.95 mm) and narrow vestibular (2.62 mm) slopes of the oral cusps compared to left tooth 2.7 (3.39 and 2.75 mm, respectively). The opposite situation is observed on the vestibular cusps of the studied teeth. The vestibular cusps on tooth 2.7 are more massive and have higher values on the outer vestibular slopes, linked to the greater curvature of the vestibular cusps on a tooth in comparison with its antimere. The inner slopes of the cusps of the Sunghir molars have some tendency to shorten on the cusps, which are more strongly bent (2.62 mm on tooth 1.7 and 3.04 mm on tooth 2.7). Compared to the two Sunghir molars, the upper wisdom tooth from Chernovaya is smaller, except for the linear parameter characterizing the vestibulo-oral size of the anatomical occlusal surface, which is 6.11 mm. This completely correlates with its slightly bent cusps and shallow occlusal surface (as a result, the cusps seem to be low). All studied upper molars, which have one or another location and expression level of internal bending of the cusp tips, have large linear parameters in the vestibulo-oral direction in comparison with the lower molar from Fofanovo, with the exception of the size of its vestibular cusp (5.65 mm), which is mainly associated with the elongated outer slope (the length of the contour is 5.32 mm). This observation characterizes some abrasion of the lower tooth in comparison with the upper ones. Note that due to the nature of the relationship between the upper and lower teeth in orthognathy, comparisons of the upper oral and lower vestib-

ular cusps or the upper vestibular with the lower oral ones are correct. The parameters characterizing the contours correspond to the linear horizontal parameters. So, the length of the contour of the tooth from Chernovaya is 17.02 mm and is less than the upper molars from Sunghir, and the latter have rather similar sizes (right tooth 1.7 is 22.70 mm, left tooth 2.7 is 21.67 mm). The significant superiority of the right Sunghir 1.7 in terms of the length of the oral cusp contour (11.51 mm) serves as additional evidence of the prominence of its oral cusps and the pronounced curvature of their tips. The significantly longer oral cusp contour (11.51 mm) of the right Sunghir 1.7 serves as additional evidence of the prominence of its oral cusps and the pronounced curvature of their tips. Moreover, its outer oral slopes have a significantly longer contour than the inner ones (7.83 mm versus 3.69 mm). Similar observations refer to the vestibular cusps of tooth 2.7, which have the largest contour length among the measured teeth (11.54 mm) and the greatest extent of the contour of its outer vestibular slope (7.49 mm), which allows the use of contour length measurements as an effective way to study tooth morphology. It is interesting to observe a different combination of parameters on the tooth from Chernovaya. Along with the aforementioned high linear vestibulo-oral index of its anatomical occlusal surface, the contour of this surface is short, which fully correlates with a small vertical linear parameter (1.66 mm). The presented review of the results obtained is extremely concise. In conclusion, we note a worn tooth from Fofanovo (1.14 mm) has the smallest vertical linear dimension of the anatomical occlusal surface (in contrast to the upper molars). Thus, such a phenomenon as abrasion, which leaves its mark on the morphology of the tooth, can also be described using measurements. Table 1, as an example, shows angular parameters, which are of certain interest, but are not described in this study. In addition, not only the absolute values of odontometric parameters, but also their ratios and proportions are of interest to study.

Despite the fact that the proposed measuring method of aDo needs improvement, including in the direction of analyzing the data obtained, we note its advantage over the method of geometric morphometric analysis that is widely used in odontometry and other disciplines. Geometric morphometric analysis, in contrast to a specialized aDo, is a universal method, however, with the following assumptions. Measurement data invariably characterizes each studied tooth separately, they can be compared on the teeth included in the study group, however, understanding the shape and outlines of the studied samples in geometric morphometric analysis on each sample depends on the samples included in the study group. Morphometric techniques have a strong dependence on the orientation of the samples under study, while the proposed aDo measuring technique uses auto-

Fig. 4. 3D model of the Upper Paleolithic specimen from Sunghir (specimen S2).

mated measuring algorithms. The latter can be combined not only with odontometry of the outer surface of the coronal part of the tooth, but also with the measurement of the enamel thickness (in this technique, the orientation of the tooth and the sectioning plane are extremely important factors that determine the accuracy of the results).

The variety of methods used to obtain 3D images made it possible to accumulate a certain experience in their application, taking into account differences of the studied samples. As applied to the aDo method, it can be argued that it is directly dependent on the scanning accuracy and has high requirements for the resolution of 3D reconstructions [54]. In the course of the scanning work, a constantly growing database of digital 3D reconstructions was created. Along with the development of a measuring technique and research, work was carried out to preserve and retrieve data from 3D reconstructions and to restore the lost material. Using the example of a specimen from the Shengavit burial, one of the lost teeth was restored; its 3D reconstruction, obtained in the course of cone-beam tomography, served as material for genetic analysis [55]. Thus, the importance and value of documenting anthropological and paleoanthropological material

Table 1. Odontometric parameters. Absolute values

Tooth	1.7 S2	2.7 S2	2.8 Ch	3.6 F
Linear horizontal parameters, mm				
Tooth	12.71	12.34	10.59	9.89
Oral cusp (OT)	6.57	6.14	5.19	4.24
Oral slope OT	3.95	3.39	2.08	1.24
Vestibular slope OT	2.62	2.75	3.11	3.00
Vestibular cusp (VT)	6.14	6.20	5.40	5.65
Oral slope VT	3.33	3.04	3.00	2.79
Vestibular slope VT	2.80	3.16	2.40	2.86
Anatomical occlusive surface	5.95	5.79	6.11	5.79
Linear vertical parameters, mm				
anatomical occlusive surface	2.25	2.13	1.66	1.14
Contour length, mm				
Tooth	22.70	21.67	17.02	14.92
OT	11.51	10.12	8.45	6.42
Oral slope OT	7.83	6.47	4.76	3.04
Vestibular slope OT	3.69	3.65	3.69	3.38
VT	11.19	11.54	8.57	8.51
Oral slope VT	4.30	4.05	3.83	3.19
Vestibular slope VT	6.89	7.49	4.75	5.32
Anatomical occlusive surface	7.99	7.71	7.52	6.57
Angular parameters, deg				
Tooth	82.8	86.2	90.4	95.6
OT	33.0	34.2	28.2	27.6
Oral slope OT	49.8	52.0	62.1	68.0
Vestibular slope OT	82.2	81.6	97.9	103.9
VT	56.2	54.8	59.9	66.7
Oral slope VT	26.0	26.8	38.0	37.2
Vestibular slope VT	106.0	106.8	122.1	134.7

and creating databases for their digital 3D reconstructions is emphasized. It should be noted that development of automation of digital measuring methods and their implementation has a potential value for the study of teeth closure (occlusiometry) the principles of which have a common morphological basis with odontometry [56, 57].

CONCLUSIONS

Automated digital odontometry has been shown to be effective in studying the size of teeth and their structural parts, as well as in describing the morphology of teeth, which increases the value of using measuring techniques in odontological and anthropological studies. The potential for further development of the method lies in increasing the amount of information supplied by measurements, improving methods for processing and analyzing the data obtained, as well as integrating odontometry with other measuring techniques in anthropology.

FUNDING

REFERENCES

1. A. A. Zubov, *Homo Sungirensis: Upper Palaeolithic Man: Ecological and Evolutionary Aspects of the Investigation* (Nauchnyi Mir, Moscow, 2000), p. 256 [in Russian].

2. A. Zubova, T. Chikisheva, and M. Shunkov, Archaeol. Ethnol. Anthropol. Euras. **45**, 121 (2017). https://doi.org/10.17746/1563-0110.2017.45.1.121-134

3. G. N. Hounsfield, Brit. J. Radiol. **46** (552), 1016 (1973). https://doi.org/10.1259/0007-1285-46-552-1016

4. T. Uldin, Forensic Sci. Res. **2**, 165 (2017). https://doi.org/10.1080/20961790.2017.1369621

5. T. R. Peckmann, C. Logar, C. Garrido Varas, et al., Sci. Justice **56**, 84 (2016). https://doi.org/10.1016/j.scijus.2015.10.002

6. M. Arapovic-Savic, M. Savic, M. Umicevic-Davidovic, et al., Srp. Ark. Celok. Lek. **147**, 74 (2018). https://doi.org/10.2298/SARH180419074A

7. S. E. Bailey, S. Benazzi, L. Buti, et al., Am. J. Phys. Anthropol. **159**, 93 (2016). https://doi.org/10.1002/ajpa.22842

8. L. R. Berger, J. Hawks, D. J. de Ruiter, et al., Lect. Notes. Bus. Inf. P. **4**, 1 (2015). https://doi.org/10.7554/eLife.09560.028

9. J. M. Bermúdez de Castro, M. Martinón-Torres, M. Martínez de Pinillos, et al., Quater. Sci. Rev. **217**, 45 (2019). https://doi.org/10.1016/j.quascirev.2018.04.003

10. L. T. Camardella, H. Breuning, and O. de Vasconcellos Vilella, Dental Press J. Orthod. **22**, 65 (2017). https://doi.org/10.1590/2177-6709.22.1.065-074.oar

11. M. A. Igbemi, E. L. Oghenemavwe, and O. Ch. Ugwa, Eur. J. Biomed. Pharm. Sci. **6** (6), 9 (2019).

12. D. E. O. Eboh, Anat. Cell Biol. **52** (3), 1 (2019). https://doi.org/10.5115/acb.18.221

13. R. Kapila, K. S. Nagesh, A. Iyengar, et al., J. Dent. Res. Dent. Clin. Dent. Prospect. **5** (2), 51 (2011). https://doi.org/10.5681/joddd.2011.011

14. L. K. Nadendla, G. Paramkusam, A. Pokala, et al., Indian J. Dent. Res. **27** (9), 27 (2016). https://doi.org/10.4103/0970-9290.179810

15. D. Naidu and T. J. Freer, Aust. Orthod. J. **29**, 159 (2013).

16. D. Naidu and T. J. Freer, Aust. Orthod. J. **29**, 164 (2013).

17. H. M. El-Zanaty, A. El-Beialy, A. El-Ezz, et al., Am. J. Orthod. Dentofac. **137**, 259 (2008). https://doi.org/10.1016/j.ajodo.2008.04.030

18. S. Talaat, A. Kaboudan, H. Breuning, et al., Am. J. Orthod. Dentofac. **147**, 264 (2015). https://doi.org/10.1016/j.ajodo.2014.07.027

19. S. Benazzi, S. E. Bailey, and F. Mallegni, Am. J. Phys. Anthropol. **152**, 300 (2013). . https://doi.org/10.1002/ajpa.22355

20. G. W. Weber, C. Fornai, A. Gopher, et al., Quatern. Int. **398**, 159 (2016). https://doi.org/10.1016/j.quaint.2015.10.027

21. J. J. Hublin, A. Ben-Ncer, S. E. Bailey, et al., Nature (London, U.K.) **546**, 289 (2017). https://doi.org/10.1038/nature22336

22. L. B. Martin, "The relationships of the later Miocene Hominoidea," PhD Thesis (Univ. College London, London, 1983).

23. G. Schwartz and M. Dean, Am. J. Phys. Anthropol. **128**, 312 (2005). https://doi.org/10.1002/ajpa.20211

24. C. Garcia, M. Martinón-Torres, L. Martín-Francés, et al., C. R. Palevol. **18**, 72 (2018). https://doi.org/10.1016/j.crpv.2018.06.004

25. L. Buti, A. la Cabec, D. Panetta, et al., J. Hum. Evol. **113**, 162 (2017). https://doi.org/10.1016/j.jhevol.2017.08.009

26. F. Guy, V. Lazzari, E. Gilissen, et al., PLoS One **10** (9), e0138802 (2015). https://doi.org/10.1371/journal.pone.0138802

27. C. Margherita, G. Oxilia, V. Barbi, et al., J. Hum. Evol. **113**, 83 (2017). https://doi.org/10.1016/j.jhevol.2017.07.011

28. K. E. Westaway, J. Louys, R. Due Awe, et al., Nature (London, U.K.) **548**, 322 (2017). https://doi.org/10.1038/nature23452

29. A. J. Olejniczak, Ch. C. Gilbert, L. B. Martin, et al., J. Hum. Evol. **53**, 292 (2007). https://doi.org/10.1016/j.jhevol.2007.04.006

30. T. M. Smith, A. J. Olejniczak, J. P. Zermeno, et al., J. Hum. Evol. **62**, 395 (2012). https://doi.org/10.1016/j.jhevol.2011.12.004

31. S. J. Dykes and V. C. Pilbrow, Peer J. **7**, e6990 (2019). https://doi.org/10.7717/peerj.6990

32. A. Gomez-Robles, J. B. Smaers, R. L. Holloway, et al., Proc. Natl. Acad. Sci. U. S. A. **114** (3) (2017). https://doi.org/10.1073/pnas.1608798114

33. V. V. Kniaz, F. Remondino, and V. A. Knyaz, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. **XLII-2/W9**, 403 (2019). https://doi.org/10.5194/isprs-archives-XLII-2-W9-403-2019

34. A. Bertsatos, K. Athanasopoulou, and M. E. Chovalopoulou, Egypt. J. Forensic Sci. **9** (25), 9 (2019). https://doi.org/10.1186/s41935-019-0133-7

35. J. D. Irish and G. R. Scott, *A Companion to Dental Anthropology* (Wiley Blackwell, Malden, MA, 2016).

36. L.-O. Morch and J. Luengo, in *Proceedings of the 9th Conference: Jornadas de Jóvenes en Investigación Arqueológica, Santander, June 8–11, 2016.* https://doi.org/10.13140/RG.2.2.34367.51368

37. F. Zhang, K.-J. Suh, and K.-M. Lee, PLoS One **11** (7), e0157713 (2016). https://doi.org/10.1371/journal.pone.0157713

38. A. V. Gabuchyan, N. A. Leibova, S. V. Vasil'ev, et al., in *Proceedings of the International Conference Dedicated to Academicians V. P. Alekseev and T. I. Alekseeva—8th Alekseev's Readings* (NII Muzei Antropol. MGU, Moscow, 2019), p. 43.

39. Y. Zaim, R. Ciochon, J. Polanski, et al., J. Hum. Evol. **61**, 363 (2011). https://doi.org/10.1016/j.jhevol.2011.04.009

40. D. Toneva, S. Nikolova, and I. Georgiev, Acta Morphol. Anthropol. **24**, 55 (2017). https://doi.org/10.1007/978-3-319-49544-6_18

41. J. B. Ferreira, I. O. Christovam, D. S. Alencar, et al., Dentomaxillofac. Rad. **46**, 20160455 (2017). https://doi.org/10.1259/dmfr.20160455

42. H. Yu, T. Yamaguchi, D. Tomita, et al., Angle Orthodont. **88**, 575 (2019). https://doi.org/10.2319/092917-659.1

43. M. Skinner, Ph. Gunz, B. A. Wood, et al., J. Hum. Evol. **55**, 979 (2008). https://doi.org/10.1016/j.jhevol.2008.08.013

44. A. Kato and N. Ohno, Clin. Oral. Invest. **13**, 43 (2008). https://doi.org/10.1007/s00784-008-0198-4

45. M. le Luyer, M. Coquerelle, S. Rottier, et al., PLoS One **11** (7), e0159688 (2016). https://doi.org/10.1371/journal.pone.0159688

46. W. Liao, S. Xing, D. Li, et al., Sci. Rep. **9** (2347), 1 (2019). https://doi.org/10.1038/s41598-019-38818-x

47. R. M. G. Martin, J.-J. Hublin, P. Gunz, et al., J. Hum. Evol. **103**, 20 (2017). https://doi.org/10.1016/j.jhevol.2016.12.004

48. W. Nowaczewska, P. Dabrowski, Ch. Stringer, et al., J. Hum. Evol. **64**, 225 (2013). https://doi.org/10.1016/j.jhevol.2012.12.001

49. S. Benazzi, M. Fantini, F. de Crescenzio, et al., J. Hum. Evol. **56**, 286 (2009). https://doi.org/10.1016/j.jhevol.2008.07.006

50. C. Zanolli, B. Schillinger, O. Kullmer, et al., Front. Ecol. Evol. **8**, 42 (2020).
https://doi.org/10.3389/fevo.2020.00042

51. V. A. Knyaz, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. **XXXIX-B3**, 585 (2012).
https://doi.org/10.5194/isprsarchives-XXXIX-B3-585-2012

52. V. A. Knyaz and A. V. Gaboutchian, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. **XLIX-B3**, 849 (2016).
https://doi.org/10.5194/isprs-archives-XLI-B5-849-2016

53. A. V. Gaboutchian, V. A. Knyaz, N. A. Leybova, et al., Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. **XLIII-B2-2020**, 845 (2020).
https://doi.org/10.5194/isprs-archives-XLIII-B2-2020-845-2020

54. A. V. Gaboutchian and V. A. Knyaz, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. **XLII-2/W18**, 53 (2019).
https://doi.org/10.5194/isprs-archives-XLII-2-W18-53-2019

55. A. V. Gaboutchian, V. A. Knyaz, M. M. Novikov, et al., Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. **XLIII-B2-2020**, 851 (2020).
https://doi.org/10.5194/isprs-archives-XLIII-B2-2020-851-2020

56. A. V. Gabuchyan, "Clinical-experimental study of tooth occlusal surface preparation for prosthetic treatment by fixed prosthesis," Extended Abstract of Cand. Sci. Dissertation (MGMSU, Moscow, 2011).

57. A. V. Gabuchyan, V. A. Knyaz', and G. V. Bol'shakov, Vestn. Antropol., No. 3 (39), 98 (2017).

Translated by S. Nikolaeva