Digital Analysis and Processing of 3D Reconstructions of Human Canine Teeth

Armen V. Gaboutchian[1], Vladimir A. Knyaz[2,3], Sergey Vasilyev[4], Anatoly Maximov[3], Dmitri Korost[5], Nikita Stepanov[5], Gohar R. Petrosyan[6] and Samvel V. Apresyan[7]

[1] *Peoples' Friendship University of Russia, 117198, Moscow, Russia*
[2] *Moscow Institute of Physics and Technology (MIPT), Dolgoprudny, Russia*
[3] *State Research Institute of Aviation System (GosNIIAS), 7 Victorenko str., Moscow, 125167, Russia*
[4] *Institute of Ethnology and Anthropology RAS, Moscow, Russia*
[5] *Faculty of Geology, Moscow State University, 119234, Moscow, Russia*
[6] *Schmidt Institute of Physics of the Earth RAS, 123242, Moscow, Russia*
[7] *Peoples Friendship University of Russia, 117198, Moscow, Russia*

Abstract

Today micro-focus tomographic scanning methods are widely used in anthropological and palaeoanthropological research. Facilitating application of non-destructive study techniques, it provides essential, detailed and accurate data in terms of dental morphology. These features become of particular importance in studies of unique findings, such as presented in this paper Upper Palaeolithic Sunghirian samples. A range of techniques are applied to study 3D reconstructions of teeth; some of them are taken directly from traditional methods applied to physical objects, others developed on the bases provided by of digital techniques of image processing and analysis. However the majority of research techniques, especially those based on measurements, require appropriate orientation of the teeth being studied. In this regard it should be noted that human teeth have, different morphology which depends to a great extent on their position in arches; in addition teeth are composed of different tissues. Hence these determining factors influence variety of approaches to image processing. The current paper presents fully automated algorithm for orientation of canines, or more specifically, their coronal part composed of enamel. This provides data for 2D and 3D morphological studies usually related to evolutionary aspects or sexual dimorphism.

Keywords

orientation of teeth, odontometry, 3d image analysis, micro-focus computed tomography, Sunghir

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Ryazan State Radio Engineering University named after V.F. Utkin, Ryazan, Russia
EMAIL: armengaboutchian@mail.ru (A. V. Gaboutchian); knyaz@gosniias.ru (V. A. Knyaz); vasbor1@yandex.ru (S. Vasilyev); anatolym78@gmail.com (A. Maximov); dkorost@mail.ru (D. Korost); stepanov-nikita13@rambler.ru (N. Stepanov); petrosyan-gohar@list.ru (G. R. Petrosyan); dr.apresyan@gmail.com (S. V. Apresyan)
ORCID: 0000-0002-4076-772X (A. V. Gaboutchian); 0000-0002-4466-244X (V. A. Knyaz)

1. Introduction

Dental morphological research plays an important part in natural science. It is most often used for taxonomical and evolutionary studies in palaeontology, anthropology and zoology. This can be explained by two major impacting circumstances. Firstly, and this primarily refers to extinct species, dental remains represent a significant part of study material, being usually the best preserved findings (due to high mineralisation degree if compared to skeletal remains). The other factors is in existence of specific morphological features, which can be described, studied and thereby serve as a source of essential data. Dental morphological study techniques have expanded beyond descriptive approaches and today multiple methods of measurements are applied for research. Measurement techniques are going through a period of robust growth in line with expanding implementation of different imaging techniques and digital image processing. This is not only a more convenient and accurate way of application for traditional measurement techniques but is an impetus for development of new study techniques. Among such we can mention automated odontometric techniques or topographic analysis of enamel thickness.

It should be noted that the majority of odontological studies start with studies of posterior group of teeth (many of extant or extinct species, including Homo, possess heterodont masticatory system, i.e. dental arches consist of morphologically different teeth, such as incisors, canines, premolars and molars). These teeth, in particular molars, have the most variable, interesting and at the same time challenging, in terms of study technique application, morphology. Nevertheless such teeth as canines are of interest as well for, as an example, enamel thickness of sexual dimorphism studies. It is interesting to mention that studies of sexual dimorphism of teeth applied to human remains in anthropological and in forensic odontology are relevant due to controversy of data obtained from skeletal remains of adolescent individuals. And it is exactly the case with Sunghir 3 individual who has been classified as female initially and only genetic analysis have showed that both individuals in the paired Sunghirian burial 2 are male. In connection with planned studies of dental morphology it is these teeth that are presented in the current study.

The canines, or to be exact, digital reconstructions of their enamel and dentine surfaces, belong to the youngest individual Sunghir 3 (S3) from the Upper Palaeolithic archaeological site of Sunghir. These teeth have low degree of dental wear and are finely preserved. The reconstructions were obtained after micro-focus tomographic scanning and further image processing procedures which will be described below. These reconstructions will serve for new updated morphological description of the mentioned findings.

Nevertheless application of new study techniques applied in odontologial studies, especially those based on measurements (both 2d, or 3d) require a preceding stage of orientation. A new automated algorithm for orientation of canines is presented in the current paper.

2. Related works

Studies of taxonomical affiliation and its evolutionary relevance which are based on dental morphological analysis have passed in recent years through successive stages of methodological improvements. Starting from physical sectioning teeth [1] and analysis of radiographs [2, 3], odontological research has received an impetus for development with introduction of new 3D imaging and reconstruction techniques [4, 5]. Widespread use of micro-focus computed tomography as well as application of synchrotron micro-computed tomography or neutron scanning allow non-destructive, diverse and profound odontological research on wide variety of sample and in different scientific disciplines [6, 7, 8, 9]. The majority of the above-mentioned and similar studies focus on measurements of enamel thickness (which in its turn has its proprietary history of development). Today these measurements are represented by a certain variety of 2D (extensions of physical sectioning) and 3D techniques usually based on topographic analysis [10]. Such study techniques are often combined with other methods applied for dental research such as traditional odontometry [11], geometric morphometrics [12] and non-metric traits description [13].

The majority of study techniques originate from tooth sectioning which requires appropriate and uniform for the studied sample orientation. It is necessary for correct comparisons within the studied material as well as between studies. Many of orientation protocols for molars are based on method suggested in the 1980-s [1], however there is a certain variety of methodological trends. They have been introduced mainly due to more ample opportunities provided by application of 3D reconstructions (e.g. multiplicity of sectioning attempts, which is impossible during physical sectioning) [14, 15]. In their turn, high-resolution tomorgraphic scanning techniques providing access to internal dental morphology (enamel-dentine junction, or outer dentine surface). This facilitates accurate use of new diverse morphological landmarks for orientation purposes [16]. In addition tomographic scanning techniques clearly visualise enamel cervical margin which can also serve for orientation purposes in line with other morphological studies [17, 18]; this refers to fully automated algorithms as well [19].

Canine teeth are often subject to detailed odontological research in line with teeth of other groups, such as molars and premolars. Due to their morphological specificity there are appropriate study techniques [20, 21]. These approaches describe sectioning, 3D analysis and virtual separation of coronal parts of canine teeth from their roots. In some cases measurements on sections are accompanied by preceding reconstruction of contour to compensate dental wear on posterior teeth or canines [22, 23]. We are planning to focus in this paper on automated orientation technique for 3D reconstruction of canine teeth.

3. Materials and methods

3.1. Material

The presented in the current study samples of permanent human canine teeth are from individual Sunghir 3 (S3) from Upper Palaeolithic archaeological site of Sunghir situated

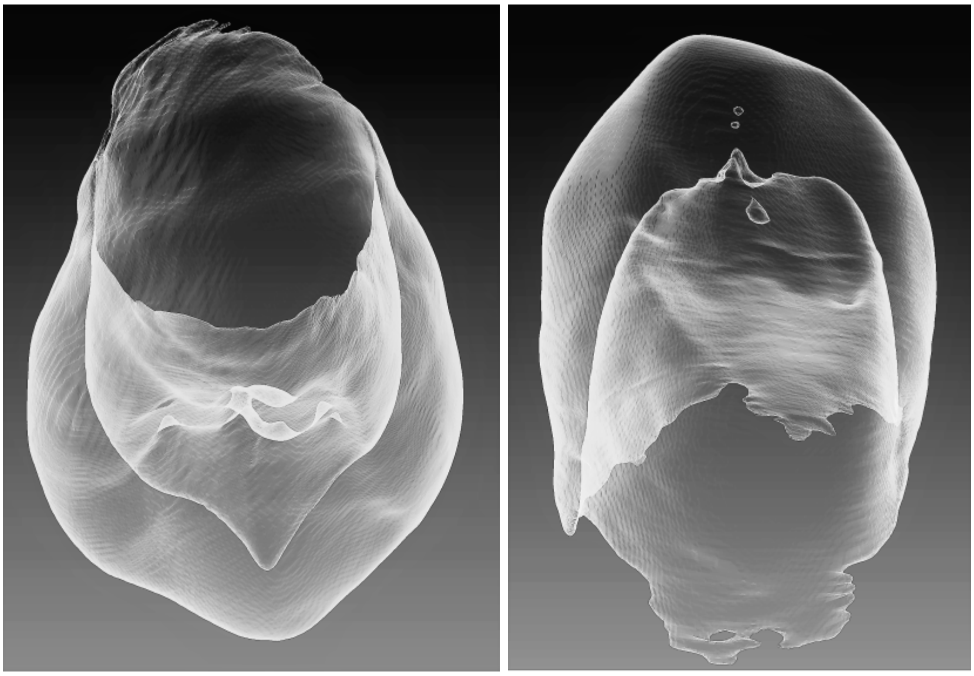

Figure 1: 3D reconstructions of Sunghir 3 canine enamel caps: a) upper right (on the left), and b) lower right (on the right)

in Vladimir Oblast', Russian Federation (Figure 1a,b). Skulls from the burial 2: Sunghir 2 and Sunghir 3, had been described for the first time by T.A. Trophimova [24], and have been dated to 28-29 thousand years [25].

Detailed odontological study has been conducted by Alexandr A. Zubov [26]. According to S3 denture this individuals is younger than Sunghir 2. This is supported by incomplete set of permanent teeth; there are deciduous teeth present at their close to natural loss stage; the first premolars are in the sockets. The initially conducted odontological study suggested to estimate this individuals' sex as female and age at death in the interval between 9 and 11 years. Nevertheless, later conducted genetic analysis clarified that both individuals were male [27]. In general, odontological features of the Sunghirian individuals 2 and 3 were characterised as archaic and macrodont (if compared to average modern human population), as well as corresponding to typical Upper Palaeolithic European population. According to a range of other morphological features the individuals can be referred to representatives of the Western odontological branch [26, 28].

3.2. Micro-focus tomographic scanning and 3D reconstruction

The complete skull of the S3 individual was scanned in Phoenix v|tome|x m (General Electric) scanner at 275 kV applied at tube. The object was placed and oriented to achieve higher accuracy on upper posterior group of teeth providing up to 43 μm voxel size on reconstructed models of separate teeth. The scanning procedure was followed by extraction of images related to each tooth from the entire image stack (through “Magic Wand” function application) and for subsequent 3D reconstruction from .bmp images with 8-bit colour depth. Image processing was performed by Avizo 9.01 software (Thermo Fisher Scientific). In order to obtain separate reconstructions of dentine and enamel and to remove morphologically non-relevant objects (this feature is necessary to have a choice between two alternative approaches orientations) segmentation was performed through setting different thresholding levels according to tissue radiopacity. These procedures were carried out by means of “Grow Selection” and “Shrink Selection” software instruments. 3D model generation was performed along with its surface smoothing (“Unconstrained Smoothing” at level 9 setting) followed by converting the reconstructions obtained to .stl format.

3.3. Orientation algorithm

3D reconstructions were visualised in custom software which performs the following fully automated algorithm for orientation of canine. The enamel marginal edge is detected as a contour represented by points with corresponding coordinate values (it should be noted that enamel marginal edge correspond to edge of coronal portion of outer dentine surface which facilitates some methodological approaches applied to congruent outer dentine and inner enamel surfaces). The marginal edge detection is performed by means of surface curvature analysis. Orientation of canine tooth coronal part is performed along to longitudinal axis, which is set according to two points: one is the centre of “masses” (or, coordinates) of all points lying along the contour of the cervical margin, and the other is the outermost point on the coronal part (Figure 2). Here we use conical, tapered toward the single cusp apex, shape of canine. Insofar as enamel and dentine possess morphological similarity it is possible to use the most apically located point on enamel either on dentine.

The presented orientation allows subsequent analysis of dental morphology. As an example 2D measurements can be performed on the obtained contours of canine enamel cap (Figure 3). Sectioning in the presented case has been performed by radial planes which contain longitudinal axis of canine orientation.

3.4. Orientation of Teeth

Orientation is a significant part of the presented method that influences the results obtained through measurements; it is performed automatically in the suggested odontometric technique. The initial part of tooth orientation is based morphologically on the contour of anatomical occlusal surface and serves for vertical axis alignment. This contour actually is the border between centrally located depression on tooth crown and its outer surfaces. It is defined through surface analysis methods and represents a set of points surrounding the occlusal surface. They set orientation for coordinate system and serve for setting vertical axis inclination, which is marked in green (Figure 2). This process is staged and requires iteration for more accurate settings. We should mention that the use of tomographic imaging allows accurate reconstruction and clear access

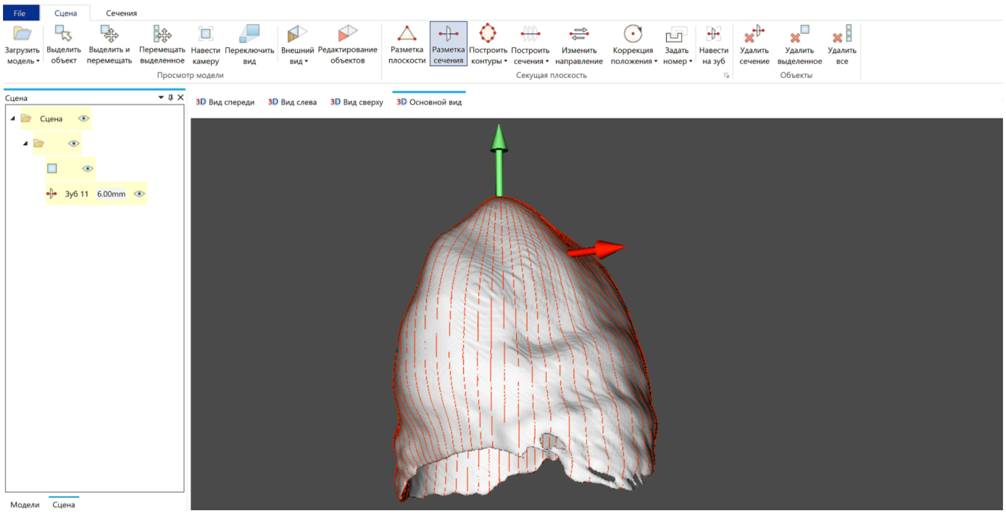

Figure 2: Orientation of canine enamel cap 3D reconstruction

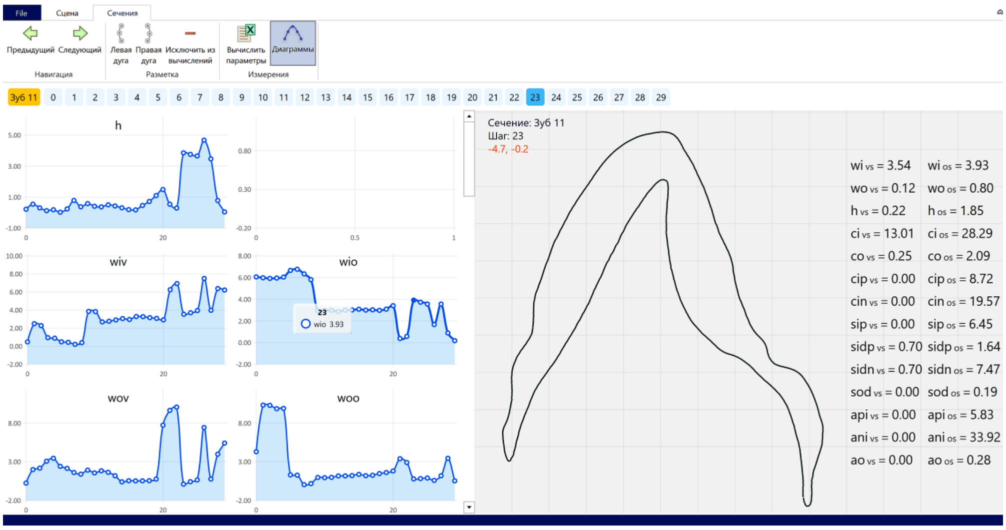

Figure 3: 2D measurements on the obtained contours of canine enamel cap

to morphological structures, which is due to different circumstances can be completely hidden or non-obvious for correct detection. Thus, the edge of cervical enamel has been tested for orientation algorithms in automated digital odontometry in line with occlusal surface contour [19], which we consider a reliable morphological structure as a reference landmark.

The result of the scanning data processing is a 3D model of a tooth $\mathbf{T}$. It is represented in a form of triangulated irregular network (TIN) – a set of coordinates of surface points (nodes) $t_i, 1 = 1, \ldots N$ and a set of corresponding edges $l_j, j = 1, \ldots L$ that connect the nodes into elementary surface element (facet). To perform correct and interpretable morphometric analysis, it is necessary to define a tooth coordinate system that allows for comparing measuring results for teeth of different shape and dimension. As the occlusal surface seems to be the most relevant reference for teeth morphology comparison, it is taken as a basis for the XY plane of the tooth coordinate system.

The occlusal surface is an area lying inside the occlusal border O_b that can be defined as a set of tooth surface points having maximal values of Gaussian curvature $K = \kappa_1 \cdot \kappa_2$. Here, κ_1 and κ_2 are principal curvatures of a surface. The XY plane is defined by its normal $\mathbf{n}_T$ that is calculated as an average value of the normals at points of the occlusal border O_b.

The procedure of the tooth system of coordinates determination is presented as Algorithm 1.

Algorithm 1: Tooth system of coordinates determination

Input:
TIN 3D model of a tooth $\mathbf{T} = \{t_i, l_j\}$,
Output:
tooth occlusion surface border array O_b,
tooth occlusion surface normal $\mathbf{n}_T$,

Tooth 3D model $\mathbf{T}$ orientation into the standard position ;
Procedure `Orienting(`$\boldsymbol{T}$`)`**:**
  for *each point t_i of tooth 3D model* $\boldsymbol{T}$ **do**
    Find Gaussian curvature $K_i = \kappa_1 \cdot \kappa_2$ at point t_i
    if $K_i > K_{treshold}$ **then**
      find normal to the tooth surface n_i at point t_i
      save t_i in occlusion border array O_b;
      save n_i in occlusion border normals array O_b^n;
    else
      skip;
  Find the occlusion border O_b as a set of points with maximal curvature K_i ;
  Find tooth occlusal normal $\mathbf{n}_T$ as an average of occlusion surface normals n_i ;
  Define the z-axis in the direction of occlusal normal $\mathbf{n}_T$;
  Find maximal mesio-distal dimension of tooth crown D_md ;
  Define x-axis in the direction of maximal mesio-distal dimension D_md ;
  Define y-axis as perpendicular to the xz-plane;
  return O_b, $\mathbf{n}_T$;

The next stage for orientation is the mesio-distal, or anteroposterior, axis orientation (this axis is marked in two colours: yellow and blue, in order to distinguish its direction easier). It is set perpendicular to the vertical axis and according to the shape of occlusal surface contour.

Additional calibration of mesio-distal axis is performed according to maximal dimen-

Figure 4: Enamel layer reconstruction of the upper left S3 canine with fractured and partially missing coronal part

sions of tooth crown. The third – vestibulo-oral (bucco-lingual, transverse) axis direction – is set as perpendicular to both mentioned above axes; it is marked in red in Figure 2.

Orientation was performed in the current study for the enamel cap reconstruction, which was studied both in terms of its outer and inner morphological features. Algorithms were set to orientate the system of coordinates according to enamel occlusal surface contour. The same orientation was used for measurements on dentin.

4. Results and discussion

The 3d reconstructions, even though they allowed the suggested algorithm to perform, possessed crenulated margins. This is most probably is the result of the scanned object size and its positioning in the scanner: the teeth were scanned within the entire skull which was oriented in order to obtain the closest position of posterior teeth to the rotation axis. We are planning to test reconstruction procedures for the enamel layer of the reconstructions according to dentine layer morphological features. In the current study, in order to avoid significant distortions, we reduced the density of marginal points. These reconstruction techniques might be quite helpful especially for S3 canines as one of the teeth has lost its coronal part portion (Figure 4) and only half of the crown is now preserved.

The presented algorithms allow fully automated orientation of canine enamel cap according to enamel cervical margin and the most apical point of canine. According to the suggested algorithm enamel/dentine cervical margin becomes the most essential morphological structure launching the process described. Here two algorithms have been suggested: both performing on the basis of enamel cervical margin however differing in the apical point selection – one works on outer enamel surface apex and the other on the apex of outer dentine surface (enamel-dentine junction). This is helpful not only in terms of alternative methodological choice. It is more essential when studied samples have been subjected to natural dental wear. In such cases deeper dentine layers might preserve the apical portion of teeth thus facilitating running of the algorithm proposed. Enamel thickness measurement results and detailed odontological and odontometric analysis of the Sunghirian canines are not presented in the current paper.

Nevertheless, if compared to many similar studies, fully automated algorithms provide for objectivity and accuracy of measurements which is essential in metric study techniques; in addition it is important for comparisons of different samples. Many of existing software applications provide coordinate systems for subjective manually operated orientation rather than ready-to-use orientated sample. We should also mention that automated algorithms for canines expand application potential of software previously used for studies of posterior teeth.

Further studies on wider sample of canines in different morphological variety and condition will provide relevant data for algorithm improvements.

5. Conclusion

The algorithm presented in the current paper is based on characteristic features of canine teeth and digital analysis of 3D reconstructed surfaces. It allows to perform orientation of the studied teeth in fully automated mode providing for objectivity and other useful features in odontological research.

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