Interpretation of non-metric morphological traits of human incisors through their 3D models' analysis

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Key Words: digital odontology, micro-focus computed tomography, dental morphology, incisors, labial convexity

Abstract

Teeth are one of the most frequently studied objects in anthropology and some other scientific disciplines. Our recent works on development of automated measurement techniques for incisors evoked interest to studies of non-metric morphological traits. Such assessments are traditionally made by means of visual analysis in dental anthropological research, including the trait chosen for testing automated algorithms in the current research – incisor labial convexity. 3D models of incisors of Sunghirian adolescents (Sunghir 2 and Sunghir 3) were generated after micro-focus tomographic scanning; teeth with complete morphology included in the study. On the basis of the proposed technique the developed software performs orientation of models, their sectioning, surface and contour analysis, measurements. As a result, two indicators were proposed for digital assessment of incisor labial convexity. Their combined usage showed interesting results for studying the non-metric trait on seven teeth, as well as for morphological studies beyond classical approaches, e.g. when used on lower incisors.

1. Introduction

3D visualisation and image analysis techniques create supportive environment for new methods of research in various scientific disciplines. As for the current paper, it deals with the latest development of fully automated techniques that make a turn from straight metrics to assessment of non-metric morphological traits (though keeping measurements as one of possible approaches). Teeth are one of the most frequently studied objects in anthropology as they provide a wide range of information, which serves for better understanding of evolutionary, ecological, developmental and other processes (Bailey and Hublin, 2007; Zhang et al., 2015; Bermúdez de Castro et al., 2018).

Correspondingly, the methods of research data collection are diverse; they include visual studies of dental morphology, different analytical techniques, visualisation techniques, morphometric assessments etc. Regardless of widespread dynamic technological advances, classical descriptive morphological studies which are based on visual analysis are still keeping their leading role in odontological research today, which is due, to a large extent, to morphological complexity and diversity of teeth. Thus a significant part of anthropological and palaeoanthropological studies represent results of interpretation of detecting specific non-metric morphological traits and, if relevant, scoring teeth according to trait expression degree (Bailey et al., 2013).

Different morphological traits of teeth are grouped in widely recognised systems (e.g. ASUDAS is most commonly and effectively used (Turner et al., 1991; Rathmann et al., 2023)) which provide necessary guidelines for researchers. Another reason for high relevance of visual and descriptive techniques is in existence of different types of teeth within human masticatory system, which is defined as heterodont and includes incisors, canines, premolars and molars. These groups differ in their principal morphology significantly, hence while putting forward new digital analytical techniques corresponding methodological approaches are required for each group of teeth.

Now we focus on incisors attempting to represent formally one of their non-metric morphological traits, which has been described before on the bases of visual studies. It is worth mentioning that incisors are apparently the first group of teeth to be analysed for a non-metric morphological trait – very well-known “shovel-shaped” palatinal (lingual) surface of incisors (see, for instance, works of Hrdlička in early decades of the last century). Studies of incisors take an important part in dental research today in many aspects, such as morphological, metric (or both combined), enamel thickness and other (Xing et al., 2014; Zanolli et al., 2014; Lockey et al., 2017; Benazzi et al., 2014; Denton, 2011). In collaboration with anthropologists, we chose to work with the opposing – vestibular (or also called labial) – surface of incisors and to study its convexity expression degree. The morphological trait has been described in some variety of authorships, which have basic similarities (Nichol et al., 1984; Zubov, 2006 (Figure 1). For instance, the feature we are interested, known as labial convexity, has been described in methods of non-metric odontological research as a trait of upper central incisors having four degrees of vestibular (outer, frontal or facing to lips) surface convexity if any is registered (Scott and Irish, 2017). The trait can be described both, on central and lateral incisors (Turner et al., 1991). As seen on the incisal view (Figure 1), the described trait is observed between boundaries of side (mesial and distal) and vestibular surfaces of teeth. The convexity degree in the central part of the vestibular surface forms the visual effect of the morphological feature being described by means of digital techniques.

Dental anthropological or paleontological research often combines metric and non-metric techniques. Classically measured parameters are bucco-lingual and mesio-distal diameters of tooth crown (Bermúdez de Castro et al, 2018, Zhang et al.,

Publisher's note: Copernicus Publications has not received any payments from Russian or Belarusian institutions for this paper.

This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLVIII-2-W9-2025-93-2025

	Upper incisors			
	central right	central left	lateral right	lateral left
Sunghir 2	+	+	+ *	+
Sunghir 3	crack	+	+	+
	Lower incisors			
	central right	central left	lateral right	lateral left
Sunghir 2	chipping	chipping	scan imperf.	+*
Sunghir 3	wear	chipping	+	crack

Table 1. List of Sunghirian adolescents’ incisors, taken into consideration in this study.

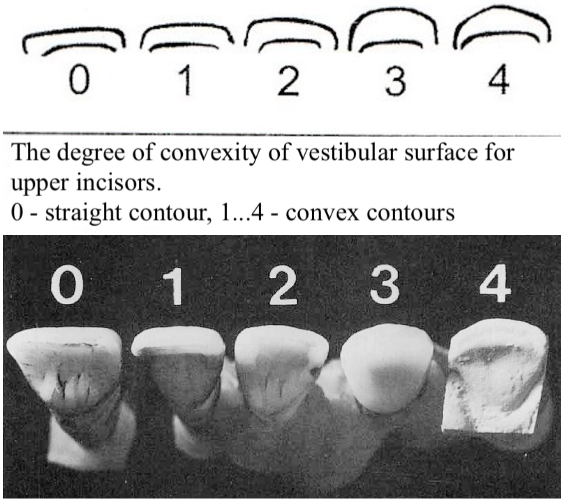

Figure 1. Guidelines for classifying vestibular surface convexity degree on incisors (from Zubov, 2006 – upper, and Nichol et al., 1984 – bottom)

2015). Though diversity of measuring techniques in dental studies is far beyond the mentioned above (Zorba et al., 2011; Knyaz, 2012; El-Zanaty et al., 2008; Kenyhercz et al., 2013; Pilbrow, 2007). In previous works on development of digital automated odontological study techniques we paid attention to measuring teeth; teeth of distal segments of dental arches – molars and premolars – were of primary interest. At the same we have had some successful attempts of describing specific morphological features of molars through metric data (Gaboutchian et al., 2020, Knyaz and Gaboutchian, 2021). Recently fully automated odontometric studies were found to be effective on incisors as well, and as a further extension we propose methodological approaches for studying non-metric traits on incisors. This work, besides its novelty, ensures consistency of the current tendency of growing interaction between traditional study techniques (with their elaborated methodology of conducting research) and methods of 3D imaging and image analysis, which have a high potential to perform and to develop.

2. Materials

A range of recent works on development of fully automated metric and non-metric study techniques for dental anthropological research, including the current one, have been closely connected with materials from the Upper Palaeolithic archaeological site of Sunghir, which is situated in Vladimir Oblast’ of Russian Federation. While choosing sample of teeth, incisors with complete morphology were of primary interest. Therefore teeth of two adolescent boys (Sunghir 2 and Sunghir 3 individuals), fully formed in frontal part and not worn out yet, met the requirements. These unique findings were discovered in a paired burial in 1957 during excavations held by O. Bader (Bader, 1959). The individuals’ ages and morphological features of their teeth, preservation degree and dating of the Sunghirian materials make them very interesting objects for studying as well.

Some of incisors were excluded from the studied sample for objective criteria, such as cracks dividing enamel into two parts, broken or worn out coronal parts and scanning imperfections. The teeth included are presented in Table 1. It is interesting to mention the Sunghir 2 upper right lateral incisor (Figure 2) as possessing unusual additional protuberance of enamel, and this tooth was analysed in our previously conducted metric studies after “trimming” its model. Nevertheless it was temporarily excluded from the current work (together with lower left lateral incisor of Sunghir 2 individual) for some technical issues and we will report on their labial convexity degree in upcoming works (both marked by asterisk in Table 1).

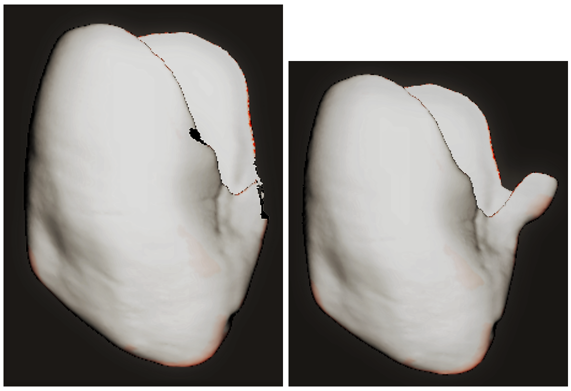

Figure 2. Sunghirian lateral incisor before (left) and after (fight) “trimming” enamel extension (the image is mirrored)

High scientific significance of the studied material required scanning of complete skulls – teeth couldn’t be removed from their sockets to be scanned separately. This is one of the main factors that determined the choice of the tomographic device which could fit a skull-sized object. Actually this approach brought to some insignificant loss of possibly obtainable resolution, nevertheless tomographic scanner Phoenix v—tome—x m (Waygate Technologies) showed decent results and necessary reconstructions of teeth were generated. The two skulls were scanned separately, then their mandibles together; 400 μA current at tube at 275 kV and 250 ms exposure allowed to obtain 3D models with up to 43 μm side size of an isometric voxel. Images related to each tooth were picked from the entire stack, then segmentation based on thresholding and generation of 3D images was performed on Avizo 9.01 software (Thermo Fisher Scientific). After some smoothing, simplifying and format changes enamel models of the incisors with necessary characteristics were ready for further analysis and studies.

Starting the process of development of algorithms for automated non-metric morphological studies we have had ex-

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perience of development automated odontometric software (albeit for molars and premolars) and the software itself (≪O3DO≫ software, reg. Nr. RU 2019665315). During recent works automated odontometric methods were successfully applied to incisors (Gaboutchian et al., 2024), and some parts of this technique, namely those related to spatial orientation of coordinate system, became useful in the current work as well.

3. Methods

Orientation was performed according to such morphological features which are common for all groups of teeth and for incisors, in particular. The first landmark for constructing coordinate system (its "zero" point) was found according to enamel cervical margin. This structure can be visualised after 3D reconstruction following x-ray (or some other, e.g. neutron) tomographic scanning (the latter has become an indispensable visualisation method in many studies (Yi et al., 2020; Guy et al., 2013; Garcia-Campos et al., 2018)).

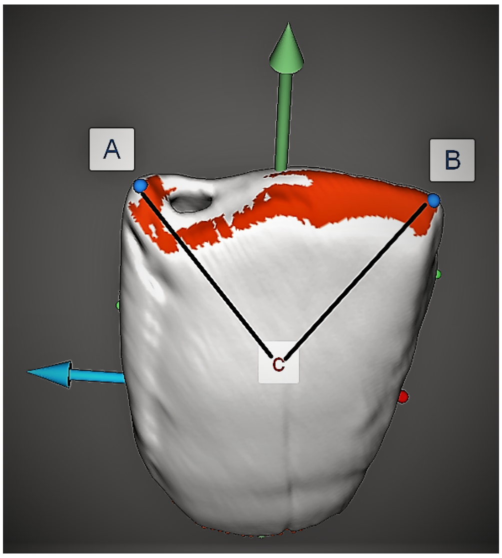

Figure 3. Schematically localized landmarks for setting spatial orientation of tooth coordinate system for an incisor (A and B – crown incisal corners, C – centre of mass of crown cervical margin).

So the vertical axis starts from the centre of mass of the mentioned above margin. We have used this landmark successfully for orientation of molars and premolars as well, as all teeth possess this margin – its formation terminates shaping of enamel cap. Then the proposed algorithm localises landmarks in corners of incisors' crown. Incisors possess a specific functional part – their cutting (incisive) edge. It is prone to changes caused by wear; in addition, its shape is variable on different teeth. The edge itself is therefore too unstable and difficult to be described formally for using as a landmark for orientation. Hence we chose landmarks that limit the cutting edge on both sides. The vertical axis direction defines the bisector of the angle with vertex in the centre of mass of enamel cervical margin and sides running through crown incisive edges' angular landmarks. The three mentioned landmarks are used for constructing a plane that actually completes necessary requirements for orientating the coordinate system on incisors (Figure 3).

A series of 30-45 parallel planes "slice" models of incisor's enamel perpendicularly to their vertical axis. This allows to obtain contours of teeth in 2D mode, which are analysed for the morphological feature of interest. According to the guidelines for visual analysis and scoring of incisor's labial convexity trait, the sections located at the distance of approximately one third of crown height from the incisive edge are taken into consideration. The number of sections to be analysed is limited to 5-7 in this area, and depends on the tooth height. The contours depicted on sections are analysed in terms of their curvature. This step, in combination with orientation, provides data for localising vestibular (labial) surface of incisors (Figure 4).

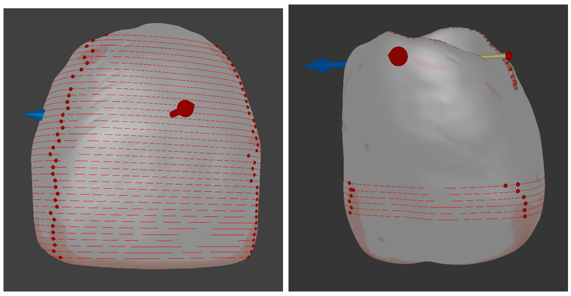

Figure 4. Sectioned (completely – left or locally – right) models of incisor; red dots delineate vestibuar (labial) surface.

Labial convexity estimation can be performed in two different ways. However scoring procedure is a matter of discussion with dental anthropologists as there is no translation system currently, which would directly connect visual and digital techniques.

One of the labial convexity analysis approaches is based on defining contour curvature degree within the borders of labial portion (segment) of the contour. Here two sub-divisions are possible, and the algorithm can work with the contour itself or with an approximated line (as the contour on some teeth is not uniformly convex and data can be therefore distorted) (Figure 5).

Figure 5. Contours of teeth with marked areas of vestibular (labial) curvature analysis application, localised on the contour (grey dots on upper figure - a) or on the approximated line (lower figure - b).

	Upper incisors							
	central right		central left		lateral right		lateral left	
Sunghir 2	0.07	0.10	0.08	0.11	—	—	0.14	0.15
Sunghir 3	—	—	0.08	0.11	0.12	0.13	0.13	0.15
	Lower incisors							
	central right		central left		lateral right		lateral left	
Sunghir 2	—	—	—	—	—	—	—	—
Sunghir 3	—	—	—	—	0.13	0.12	—	—

Table 2. Labial convexity degree analysis results for seven Sunghirian incisors.

The other approach is based on geometric constructions within the limits of labial surface convex contour representing a segment. Labial convexity degree is a ratio of segment height to its width (Figure 6).

Figure 6. Contour with marked width (w) and height (h) of vestibular (labial) contour segment.

4. Results and discussion

The current work is being conducted on incisors of the Sunghirian adolescents, and so 3D models of their well-preserved enamel caps were chosen studies. Expression degree of labial convexity trait is informative in dental anthropology for detecting morphological features which can be classified as archaic or of African origin (Zubov, 2006). The discussed trait of the upper central, as well as lateral, incisors, can be also attributed to Homo heidelbergensis and Neanderthals when expressed markedly (Irish and Scott, 2015). There are also approaches to measurements of labial convexity, which can be interpreted trough angles on enamel-dentine junctions of 3D models of incisors (Denton, 2011).

We used previously developed software, which performs fully automated measurements on coronal parts of teeth, and added some new features upgrading this version for studying vestibular surface convexity on incisors. Our approach to analysing this morphological trait was made on sections, which were obtained by using earlier developed orientation algorithms (Gaboutchian et al., 2024). A series of sections running across the tooth crown model with equal intervals were built perpendicularly to the vertical orientation axis. Sets of sections providing a complete closed incisor contour in the area between the middle and incisal thirds of coronal parts were chosen for further analysis. This limitation comes from classical visual methods, however digital automated methods can measure convexity along the entire height of tooth crown.

Results of application of fully automated algorithms for exploring labial convexity degree on incisors are presented in Table 2. Left cells in columns represent data that is obtained by vestibular (labial) surface curvature analysis technique (Figure 5b). Bold figures on the right side of columns are parameters obtained from geometric constructions on vestibular surfaces on incisors (Figure 6). Being of different origin, both techniques are consistently similarity in showing relative labial convexity on incisors and hence are both useful in assessments of the non-metric trait being analysed. Nevertheless some other approaches to measurements should be proposed as well for more comprehensive analysis taking into consideration similarity and difference of corresponding results in right and left cells for left lateral incisors of the two studied individuals (highlighted yellow cells in Table 2).

It is remarkable to notice the difference of results in right and left columns for upper and lower teeth. All results depicted in right cells are higher for upper teeth; the situation is opposite for the lower tooth. Probably the sample is not representative enough to make firm conclusions, but it is highly likely that the mentioned above difference emerges from morphological difference of upper and lower teeth, which is more distinct than the difference between upper central and lateral incisors. These observations also support effectiveness of using both proposed indicators for labial convexity degree analysis and in wider studies of dental morphology.

We possess expert scoring data for two upper central incisors: Sunghir 2 on the right side and Sunghir 3 – on the left (corresponding cells in Table 2 are highlighted in grey). Both are score 1 according to visual estimates. Difference between the digitally obtained indicators is insignificant, and we suppose these parameters (0.07/0.10 and 0.08/0.11) should correspond to score 1. Nevertheless, the lack of ample and variable data doesn’t allow to propose a complete transfer scale for visual and digital scoring techniques; it is a matter further collaboration with odontological experts in studies of more representative sample.

It is worth noting that in the beginning of our study the obtained contours revealed specific areas with maximal curvatures of tooth outline that were situated on distal parts of their coronal parts, namely in the depression and in areas of bending of side surfaces to distal surface (Figure 7). It should be said that these areas are not the ones we were interested in initially (vestibular, or labial, surfaces of incisors are opposite to distal). Improvements of contour curvature analysis procedure enabled locating boundaries between vestibular and side surfaces of incisors and obtaining data on incisors’ vestibular convexity. At the same time our first contour analysis results aroused interest to further studies of distal (palatinal) surfaces of incisors as they possess important morphological traits as well.

Another interesting direction for development of studies of non-metric traits’ expression degree lies in testing the presented in this paper results on 3D images, obtained on different tomographic devices. In these terms we are planning to refer to our earlier published works (Gaboutchian et al., 2020) on digital

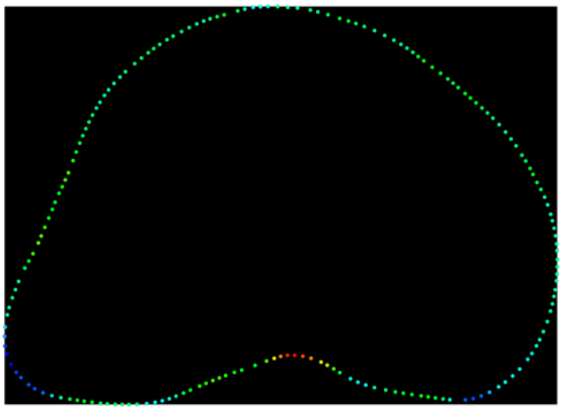

Figure 7. Section contour outline coloured in scale according to curvature degree.

and hard copy reconstructions, which include incisors, obtained on the bases of conventional computed tomographic scanning. The materials are from the Early Bronze archaeological site of Shengavit were found during expeditions held by Dr Hakob Simonyan on the Armenian part, and presented by semi-mandible with complete half of lower dental arch (Figure 8).

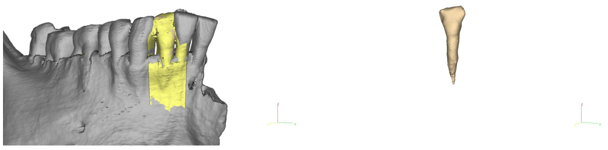

Figure 8. Segmentation of the incisor fragment from the 3D image (left) and the segmented incisor (right); taken from (Gaboutchian et al., 2020b).

5. Conclusion

A fully automated digital technique for labial surface convexity analysis on incisors is presented in the article. Specially developed software performs orientation of 3D tomographically obtained models of incisors, analyses their surface and contour curvatures (in 3D and 2D modes correspondingly) and makes measurements. The proposed objective indicators serve for digital formalised assessment of non-metric morphological trait of incisors, and can be better used together for more detailed analysis of dental morphology of frontal teeth. Development of scoring procedures, corresponding or not to those in visual study techniques, and including other non-metric traits in fully automated techniques are further steps in developing digital analytical odontological methods.

Acknowledgements

We would like to thank Natalya Leybova for inspiring us with her interesting ideas.

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