APPROACHES TO ORIENTATION OF HIGH RESOLUTION TOMOGRAPHIC 3D RECONSTRUCTION OF TEETH IN METRIC STUDIES

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ABSTRACT:

Metric studies of teeth is a rapidly developing direction in odontological research, which is supported by means of corresponding imaging techniques for obtaining detailed digital reconstructions, and by application of image analysis methods. The current article presents methodological extension of teeth 3D models' orientation tactics, which have been used in measurement techniques in dental, palaeoanthropological and palaeontological studies. Today image analysis has sufficient potential to perform orientation of teeth on the bases of their natural features; at the same time teeth possesses all necessary morphological structures for performing orientation on 3D reconstructions obtained by means of widely used today imaging techniques. Our aim is in providing an approach to orientation of teeth for its further use in morphologically relevant, accurate and applicable for various types of research, measurement techniques. The palaeoanthropological material presented in this paper, on which the proposed technique has been tested, is from territories of European part of Russian Federation and Republic of Armenia; it has been classified as related to the Middle Bronze Age, and is planned to be studied in a wider scope in the future. X-ray micro-focus tomography has been used for obtaining reconstructions of lower molars, which were segmented from semi-mandible 3D models. These teeth were used for setting vertical axis direction by means of surface curvature analysis and calculations based on points' coordinates, which delineate functionally and morphologically important parts of teeth. This approach to accurate and morphologically relevant orientation of the studied teeth uses more than one structure at a time for choosing correct orientation according to aims of research and features of the studied material. This provides the proposed technique necessary potential to be applied for measurements of teeth and studies of their functional changes.

1. INTRODUCTION

This paper presents another stage in development of measurement techniques, which have been applied to digital reconstructions of teeth. Our aim is to propose an efficient approach to measurements, in particular to setting coordinate system, which would be based on dental morphology. This method has a potential be used to measure teeth at their current or ultimate (in case of palaeo-material) conditions as well as for tracking morphological changes, such as caused by dental wear. Discussing issues related to orientation of measured objects, we certainly draw on the experience existing in recognised odontometric methods: starting from manually conducted measurements to latest approaches to 3D models' studies. However the presented here extension of orientations technique differs from originally developed tactics (Gaboutchian et al., 2021a) as well as from well-known measurement techniques (Zubov, 2006, Irish and Scott, 2015). We will focus on some issues in order to clarify why this work has become relevant and possible.

The history of odontological metric techniques' development is closely connected with two key directions of research: measurements of sizes of teeth and measurements of their tissue, especially enamel, thickness. And even at early stages odontometric techniques included instructions on positioning manually operated instruments and teeth in order to obtain parameters correctly. These methods are widely used in our days as well (Berger et al., 2015). However, there are many complicating factors, predominantly related to natural features of dental morphology. For instance, there is a significant degree in variety of sizes and shapes of teeth within an individual (this feature is defined as heterodontia; e.g. human dentition is composed of four different types of teeth: incisors, canines, premolars and molars). Here we can also mention variance of dental morphology, which exists and becomes a matter of studies on teeth within and between biological species. In addition, studied teeth can be found in different conditions: from morphologically intact to all possible degrees of dental wear, they can have cracked or fractured coronal parts and broken roots. These factors make orientation of teeth more difficult hindering reproducibility of measurement results. Therefore many metric studies include intro- and inter-observer errors' analysis (Schwartz and Dean, 2005, Harris and Smith, 2008). Nevertheless, with increase of metric assessments importance in odontological studies, especially in enamel thickness measurements (Grine, 1991, Macho and Thackeray, 1992), procedures of orientation become more elaborated for providing measurement accuracy. Being initially developed for application on physical sections of teeth, orientation protocols were based on such morphological structures as cusp and dentine horn tips, and enamel cervical margin (Martin, 1983, Olejniczak et al., 2013). These approaches were subsequently transferred to studies of 3D reconstructions of teeth with higher degree of accuracy and reliability in localising the above-mentioned structures (Suwa and Kono, 2005, Feeney et al., 2010). Nevertheless sometimes preference can be given to 2D measurements for their usability while apply-

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ing orientation and measurement protocols (Smith et al., 2006). However our experience has showed that dental morphology is described better by methods beyond Euclidian geometric constructions on planes (Gaboutchian et al., 2019).

It should be mentioned that methods of imaging have a significant impact on potential of techniques which can be applied in odontological research (Knyaz and Zheltov, 2008, Knyaz and Gaboutchian, 2016, Gaboutchian et al., 2021b). Methods which allow visualisation of inner and outer dental morphology are of importance, if compared, for instance, with optical scanning techniques. And today in palaeontology, palaeoanthropology and other disciplines x-ray micro-focus computed tomography satisfies majority study requests (Kono, 2004, Martinón-Torres et al., 2019, Liao et al., 2019). Only more profound studies of enamel micro-structure require application of synchrotron micro-tomography (Smith et al., 2018), and in imaging of fossilised teeth neutron scanners can be used more effectively (Zanolli et al., 2020); combined use of different scanning techniques is possible as well (Xing et al., 2019). Multi-layer 3D reconstructions, which can be obtained through application of the above-mentioned imaging techniques, have truly boosted up advanced research, especially in recent two decades. Such studies as morphometric analysis, enamel thickness measurements, digital odontometry and other directions in odontology are in the list of methods which can provide new data for understanding dental morphology (Westaway et al., 2017). New imaging techniques, in line with expanding the scope of studies, make higher accuracy in measurements or landmark settings more important and, at the same time – feasible. In this connexion, new approaches to procedures of teeth orientation, as an integral part of measurement technique, are proposed in this paper. They are discussed from positions of applicability in odontological research and their relevance to dental morphology.

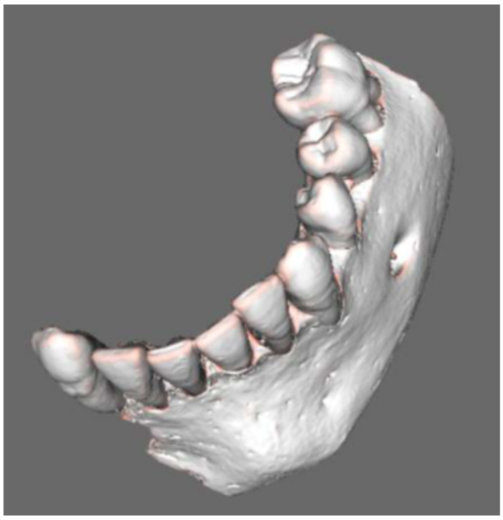
Conventional 3D measurement techniques usually rely on orientation based on geometric constructions of planes according to enamel cervical margin; and it should be noted that there is a number of varieties of the mentioned tactics (Benazzi et al., 2014). However, the cervical part of enamel cap is not always a clearly detected structure due to its frequent chipping on palaeomaterial, and in addition it is not studied enough in terms of its stability. For this reasons search for new methodological approaches to orientation continues in odontological research, and in many respects high-resolution tomographic imaging is one of the main contributing factors in this process. Thus new morphological structures, such as dentine horn tips, have been introduces for plane constructions and subsequent orientation and measurements (Guy et al., 2013).

However the horn tips are frequently subjected to dental wear immediately after complete loss of enamel on cusp tips. Thus we propose different tactics, which are largely based on our experience in implementing automated measurement (including orientation) algorithms. The mentioned approaches use other structures (or to be more precise, their borders), which are morphologically and functionally relevant and thus important in developing new methods of measurements. Here we put forward primarily the occlusal contours on enamel and dentine surfaces, which represent curved closed lines (Gaboutchian et al., 2021a). Even though these structures have been used for orientation purposes, the widely-used approaches are usually based on visual control and plane construction protocols (Skinner et al., 2010). In our works setting these contours is based on surface curvature analysis and subsequent setting of orientation axis direction. In addition enamel cervical margin has been also used in our previously conducted studies for orientation (Gaboutchian et al., 2022).

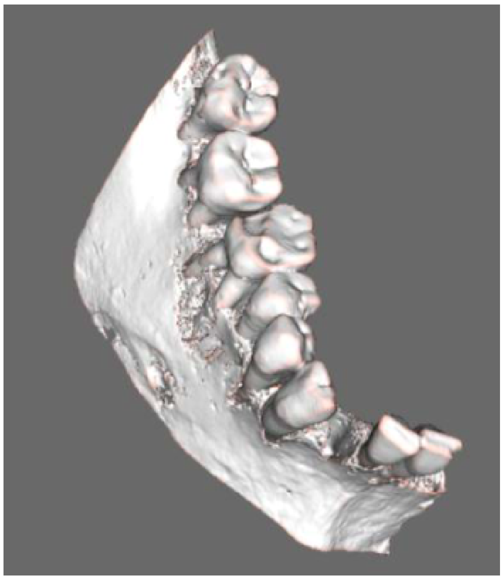
Hence we propose a technique which provides orientation of the studied teeth (their tomographically obtained 3D reconstructions) using more than one morphological structure contour at a time for orientation purposes. This means that results of contour setting on three possible morphological structures: enamel occlusal contour, dentine occlusal contour and enamel cervical margin (Figure 3), can be paired in order to have an accurate and appropriate, in terms of study objectives, orientation.

2. MATERIAL AND METHODS

The teeth, which have been used for testing the proposed orientation technique, were picked from a series of mandible fragments and semi-mandibles found in the process of archaeological excavations on territories of Russian Federation and Republic of Armenia (Figure 1). These findings have been classified as related to the Early and Middle Bronze Ages and they are planned to be studied in a wider sample in the near future.



(a) Finding from Fatyanovo culture



(b) Finding from Shengavit settlement

Figure 1: Semi-mandibles with preserved parts of dental arches: Fatyanovo (a), and Shengavit (b).

Thus findings which relate to Fatyanovo culture are from upper Volga region and has similarities with Corded Ware culture, which had been spread over the territories of Central, Northern and Eastern Europe. The other set of samples is from the settlement of Shengavit which is now situated within city limits of Yerevan – capital of the Republic of Armenia. The archaeology of Shengavit has typical traits of Kura-Araxes culture of the Early Bronze Age. It is worth mentioning in addition that recent studies have found common genetic features among the ancient inhabitants of the Great Steppe and Armenia of the aforementioned cultures (Lazaridis et al., 2022). The material in this study represents digitally segmented teeth. These teeth are the first molar from mandible fragment of representative of Fatyanovo culture (Figure 1a). The other semi-mandible is from settlement of Shengavit (Figure 1b), and the second molar was taken from this sample.

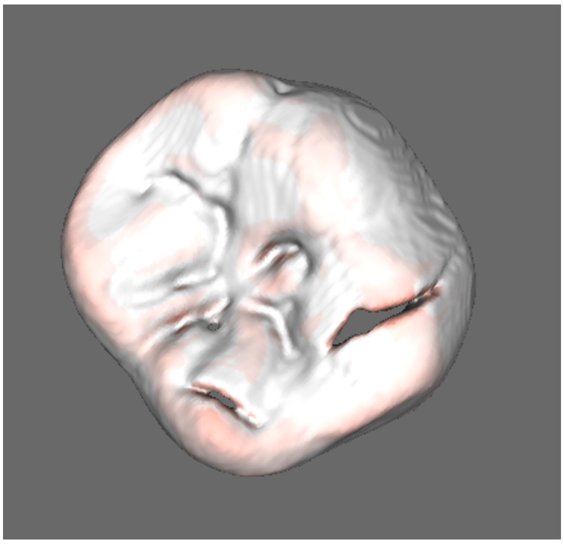
The semi-mandibles were placed in Phoenix v|tome|x m (General Electric) and scanned at 240 kV voltage and 400 μA current, exposition – 250 ms. 3D reconstructions of the semi-mandibles were obtained with voxel isometric side of 0.0978 mm. These models were used for choosing the mentioned above teeth according to their relatively well-preserved morphology, providing necessary conditions for testing proposed approaches to orientation. For reconstruction of 3D models of the teeth, their slices were segmented from the entire semi-mandibles' stacks, and then separate reconstructions of enamel and dentine morpho-histological layers were obtained. (Figure 2 a, b). This allowed to have an immediate access to the morphological structures of the teeth and to define their borders, which were used for orientation.

The models' orientations are performed in the current study according to three contours, which have found in our previously conducted studies by means of automated algorithms. However these teeth, even being one of the best preserved in the current series of samples, due to cracks and worn out surfaces, required some manual corrections of the contours. The three mentioned contours are enamel cervical margin, occlusal surface contour on enamel and occlusal surface contour on dentine (Figure 3), and their clearly defined borders serve for further stages of the orientation. Being initially defined on dentine 3D reconstruction, the contour of occlusal surface on dentine was transferred to inner surface of enamel reconstruction (Figure 3c).

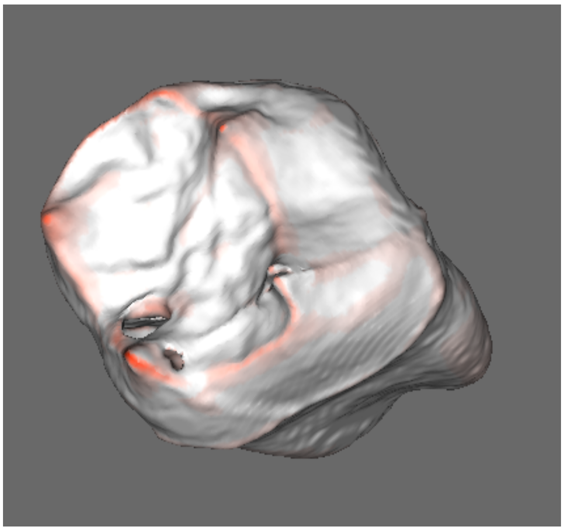
We used a pair of contours for each orientation performed according to the “centre of masses” of their points' coordinates. More specifically the sum on coordinates for all points on each contour was calculated. The vertical axis could be set according to two “centres of masses”. Two alternative orientations were performed. In both proposed orientations for each tooth the contour of enamel cervical margin remained constant serving a starting point for setting orientation axis in vertical direction. The second point for accurate axis positioning was set according to one of the two occlusal surface contours: enamel or dentine.

3. RESULTS AND DISCUSSION

Orientation protocols continue to play an important part in measurements techniques and, even though previously tested approaches to orientation of x-axis on optically scanned teeth, have showed that changes in inclination do influence metrics. And today increasing in number and variety of applied methods studies rely on data obtained by measurements. Thus accuracy starts to play one of the important parts, and many methodological improvements are aimed to achieve its higher levels. To increase accuracy of vertical axis orientation of tooth 3D reconstruction we propose tactics of using two points for setting its direction. Both these points are centre of masses of contours' point which delineate a pair of dental morphological structures. We will focus below on these structures in order to clarify the morphological relevance of the method.



(a) Enamel morpho-histological layer

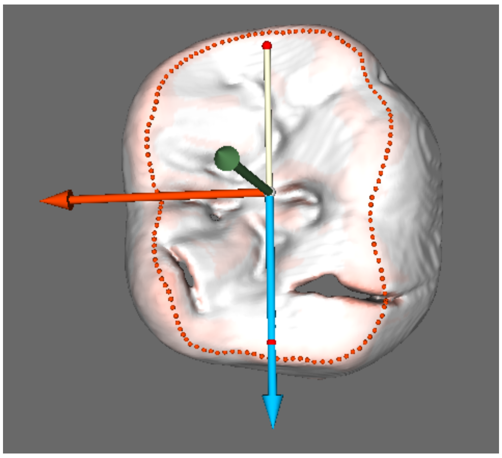


(b) Dentine morpho-histological layer

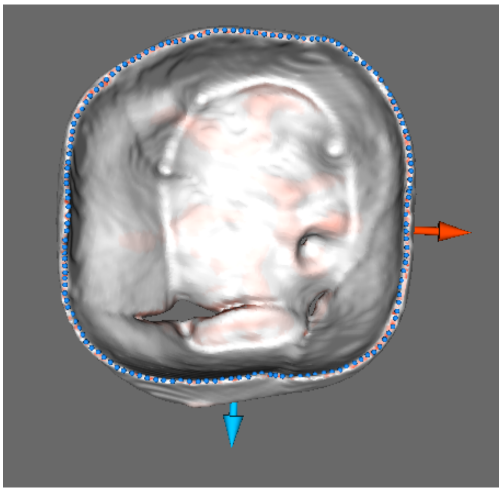
Figure 2: Enamel (a) and dentine (b) reconstructions of lower left first molar from Fatyanovo.

The occlusal surface and its contour are one of the most characteristic and important structures for upper and lower posterior teeth: premolars and molars, in the whole range of their variety. Occlusal surface plays an integrative role in terms of uniting morphological structures within a tooth (e.g., cusps) and functional interaction on opposing teeth. Defining the borders of this structure is based on surface curvature analysis and can be performed, depending on surface features and condition of the studied teeth, in manual or automated modes.

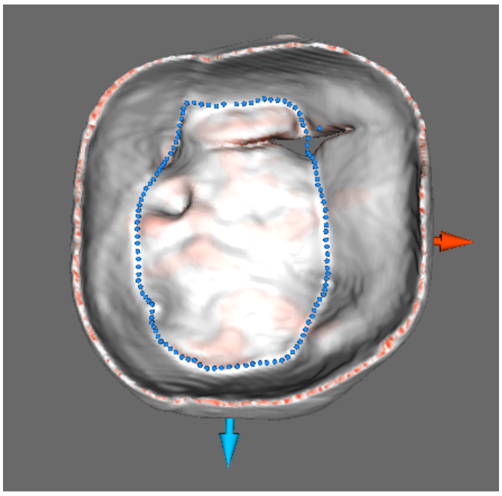
It is important to mention that tomographic scanning techniques give access to internal structures of teeth, and it is interesting that morphology of enamel and dentine surfaces has many common traits, especially since enamel deposition starts from the area of



(a) Enamel



(b) Enamel cervical margin



(c) Dentine

Figure 3: Contours of occlusal surface contour on enamel (a), enamel cervical margin (b) and occlusal surface contour on dentine (c) shown on enamel model).

enamel-dentine junction. Thus the occlusal surface contour can be delineated on dentine as well, and this structure also serves for setting the “centre of masses” for further orientation. The third circular structure is the cervical enamel edge – the place where outer and inner surfaces of enamel merge. It can be clearly defined by means of tomographic scanning technique as segmented enamel cap 3D reconstruction contains that border which has the critical values of surface curvature. It should be also emphasised that no additional constructions (such as plains) are required for correct orientation.

As we have mentioned before accurate vertical axis direction setting requires a pair of “centre of masses” points, and these pairs in the proposed methodological improvement are: a) enamel occlusal surface – cervical enamel edge, and b) dentine occlusal surface – cervical enamel edge (Figure 4). Thus as the “stabile” point the centre of masses of the cervical enamel edge was picked – common for both approaches. This choice was also defined by accuracy requirements, as points distant from each other would give a better result (if compared with another pair: enamel occlusal surface – dentine occlusal surface, which has not been tested now, nevertheless might be useful in studies of enamel cervical margin).

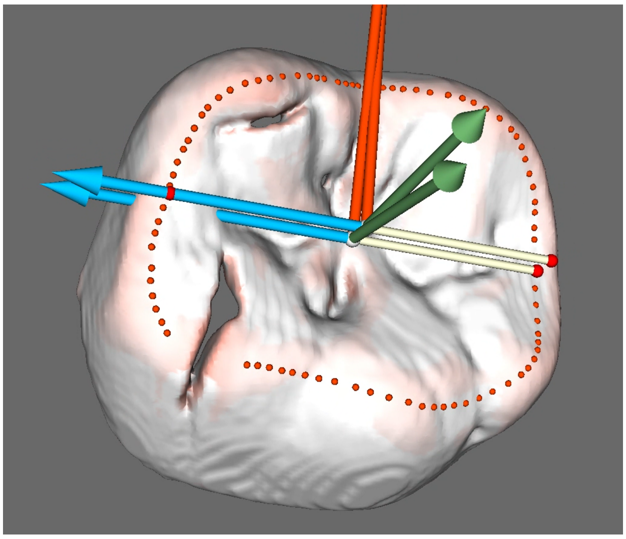


Figure 4: Two coordinate systems set on a tooth.

Nevertheless the mentioned and presented above two pairs give an essential methodological application potential for the proposed orientation technique, which is certainly more significant aspect than inter-point distance. The enamel occlusal surface is the most functionally important part of tooth crown as it interacts with the opposing tooth providing function – chewing. Therefore it is the most rapidly changing surface on the tooth, especially if compared to the surface of dentine, which is involved in the process of dental wear later. It can also be included in the list of factors influencing functional loading of tissues surrounding teeth: periodontium and bone (maxillary and mandibular). Consequently we get to track functional changes which take place on the enamel surface taking dentine as a base surface for comparisons by means of the orientation technique proposed and starting from the orientation stage in measurement technique. Only the task of obtaining a series of images with time intervals should be resolved, which requires application of imaging technique combining sufficient resolution and low exposure rate for in vivo studies.

Such applications can be also used in comparisons of teeth found in different conditions, providing for accumulation of new type of data, which can shed light on new dental morphological features. We should also mention that choosing other pairs of dental morphological structures would allow to study other surfaces and structures (e.g. enamel cervical margin).

We should mention that the studied material is not of a wide sample, and the article presents only methodological development of orientation technique without measurements conducted. But similar material of more semi-mandibles has been scanned in this series (such archaeological sites as Tli, Kokma and others are included). We are planning to segment 3D reconstructions of teeth from these samples for more detailed studies in the near future.

4. CONCLUSIONS

Combination of imaging technique's application with 3D surface analysis allows to improve methodological aspects of metric studies of teeth. The current article presents orientation tactics, which are morphologically relevant and accurate. The proposed method is suitable for measurements of teeth and studying their morphological and functional changes.

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