



Improving the spatial orientation of human teeth using a virtual 3D approach

Stefano Benazzi^{a,*}, Massimiliano Fantini^b, Francesca De Crescenzo^b, Franco Persiani^b, Giorgio Gruppioni^c

^a Department of Palaeoanthropology and Messel Research, Senckenberg Research Institute, Senckenberganlage 25, D-60325 Frankfurt am Main, Germany

^b Department of Mechanical, Nuclear, Aviation, and Metallurgical Engineering, University of Bologna, Via Fontanelle 40, 47100 Forlì, Italy

^c Department of History and Method for the Conservation of Cultural Heritage, University of Bologna, Vicolo degli Ariani 1, 48100 Ravenna, Italy

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ABSTRACT

Since teeth are resistant to decomposition processes, they provide important and at times unique sources of information about fossil humans. Fortunately, dental remains reflect significant evolutionary changes. These changes make a very important and often exclusive contribution to the definition of new taxa or the attribution of fossil specimens to existing taxa.

The traditional approach to dental morphometric analyses usually focuses on the recording of several measures of the tooth with calipers, especially the two basic crown diameters (buccolingual and mesiodistal). However, since these measures do not adequately represent the complex morphology of the tooth, 2D images and 3D digital models of dental morphology have been used. For both types of analysis, the possibility of correctly comparing homologous teeth depends on the adoption of a common orientation system. The lack of such a system makes it difficult to compare the results of different studies. Here we describe a new method for orienting teeth specifically devised for the upper and lower first molar (M1). Samples of unworn maxillary ($n = 15$) and mandibular ($n = 15$) first molars of modern humans were scanned with a Roland Picza 3D digitizer. The 3D virtual models were used to compare our new orientation method with those proposed in the literature. The new orientation system, which meets a geometric criterion, is based on three points identified on the cervical line and ensures acceptable repeatability of the spatial positioning and orientation independent of the shape and wear of the first molar under investigation. This orientation system is a first step toward the creation of a virtual set of hominid and fossil human first molars, which will allow us to make comparisons via a sophisticated and noninvasive approach. This pilot study also provides guidelines to extend the new methodology to the other types of teeth.

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Introduction

The study of the shape and dimensions of teeth has a long tradition in the field of paleoanthropology (e.g., Keiser, 1990; Moggi Cecchi, 1995; Hillson, 1996; Scott and Turner, 1997; Mallegni, 2001). Because of their physiochemical characteristics, teeth are very well-preserved and they contain fundamental information for evolutionary taxonomy since they reflect interpopulation and interspecific differences in morphology (Guatelli-Steinberg and Irish, 2005; Ullinger et al., 2005) and morphometry (Irish and Guatelli-Steinberg, 2003; Hlusko, 2004; Harris and Lease, 2005). In dental morphometric research, there is a “traditional approach” and a series of “innovative approaches”. The traditional approach is

usually based on the recording of three measures with sliding calipers: the two basic diameters (mesiodistal [MD, length] and buccolingual [BL, width]) and the height of the crown (Moorrees et al., 1957; Goose, 1963; Hillson, 1986). The two diameters at the level of the cervical line and the two diagonals of the crown may also be used (Hillson et al., 2005). However, this approach has significant limitations: first, these measures do not adequately represent the complex morphometry of the tooth; second, when the tooth is worn, at least two dimensions are compromised (crown height and MD length), and the lack of easily identifiable anatomical reference points exposes the measurements to the risk of subjectivity and observer error. Therefore, some researchers have turned to imaging analysis of the occlusal surface by means of a camera (Peretz et al., 1997; Ferrario et al., 1999; Bailey, 2004; Bailey and Lynch, 2005; Harris and Dinh, 2006; Kondo and Townsend, 2006). Since a 2D image has limitations due to the small

* Corresponding author.

E-mail address: sbenazzi@senckenberg.de (S. Benazzi).

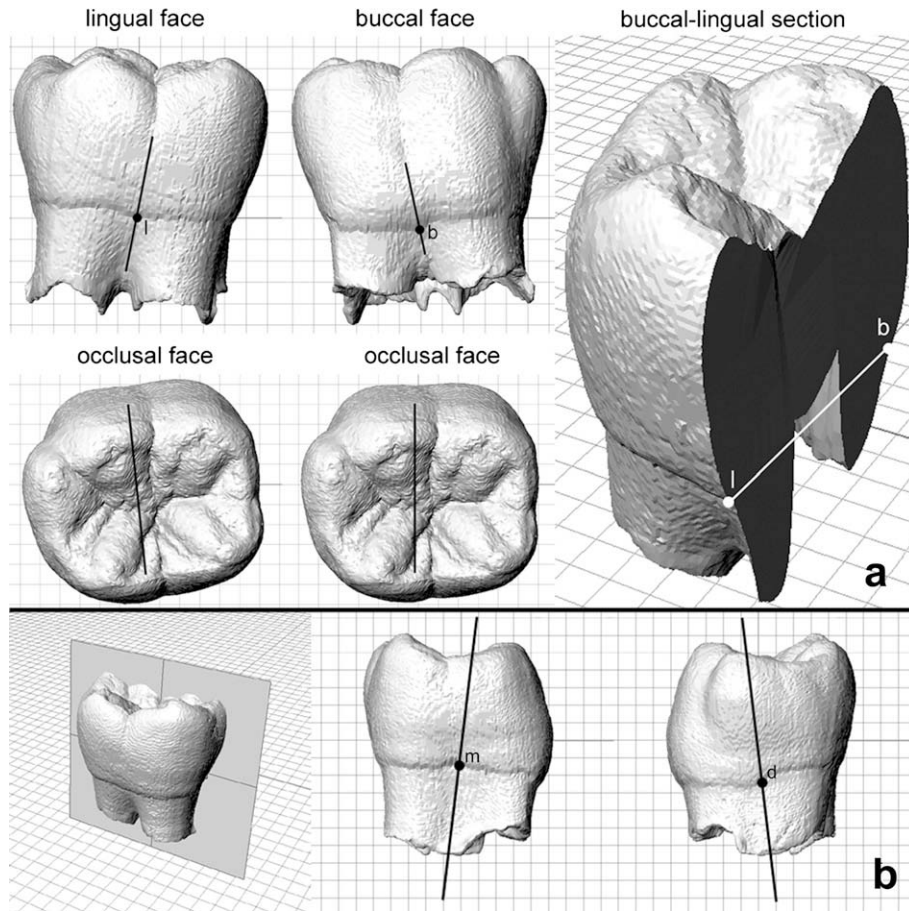


Fig. 1. (a) Preorientation of the tooth. Upper left: identification of the lingual (l) and buccal (b) points on the cervical line by means of the intersection of the cervical line with the line joining the highest point of the bifurcation of the root and the lowest point of the groove dividing the two main lobes of each surface. Lower left: the tooth (occlusal view) is rotated until the projection of the segment joining the two points (l and b) is parallel to the y axis of the Cartesian reference plane. Right: perspective view of the sectioned tooth showing the segment joining the lingual (l) and buccal (b) points. (b) Representation of the plane perpendicular to the preorientation axis and passing through its midpoint for the identification of the mesial (m) and distal (d) points on the cervical line. Left: perspective view; center: mesial tooth side; right: distal tooth side.

number of possible measurements and the necessity of using unworn teeth, several researchers have produced 3D digital models of teeth. Some 3D reconstructions have been carried out by computerized tomography (Schwartz et al., 1998; Alt and Buitrago-Téllez, 2004) or computerized microtomography (Rao et al., 2003; Avishai et al., 2004; McErlain et al., 2004), both of which also allow analysis of the interior of the tooth. Other studies have been based on less expensive techniques that are more easily applied but generate less information, usually only 3D reconstruction of the external dental morphology; these techniques use an electromagnetic digitizer (Zuccotti et al., 1998), confocal laser microscope (Jernvall and Selänne, 1999), or laser scanner (Ungar, 2004). These studies have shown that the 3D approach provides the best results for a complete analysis of the morphology and morphometry of the tooth.

For both 2D imaging analysis and virtual 3D models, the ability to correctly compare homologous teeth depends on the adoption of a common orientation system. This is particularly important in 2D imaging analysis since the occlusal surface of the tooth is photographed after orientation of the tooth. In the 3D approach, the virtual model can be oriented after complete scanning of the tooth. The lack of a conventional standardized-orientation system leaves researchers free to orient the teeth at their own discretion. The consequence is that the results of different studies are not rigorously comparable. In a recent study, Robinson et al. (2002) evaluated the interobserver error in the identification of a series of points on 2D images of the buccal and occlusal surfaces of different

types of teeth. They found that the greatest error was made on occlusal images and that this depended mainly on how the tooth was oriented before photographing. Bailey et al. (2004) quantified the error of different researchers when measuring the area of the base of the cusps of the upper first molar of *Pan* (*P. troglodytes* and *P. paniscus*). They concluded that the error due to orientation was insignificant, but they still recommended that one pay particular attention to the orientation phase when studying teeth by means of 2D images. There remains, however, a fundamental problem: which orientation method should be used as the reference system?

The aim of the present study was to compare different systems for the orientation of teeth in an attempt to identify and standardize the most rigorous and efficacious one for the creation of digital models of teeth. For this purpose, we decided to test a sample of upper and lower first molars of modern humans scanned with a digitizer.

Orientation criteria

Three orientation systems have been used in studies based on 2D imaging analysis: in the first method, the occlusal surface of the tooth is positioned so as to maximize the area of the surface as seen by the camera (Robinson et al., 2002); the second method identifies the plane useful for orientation at the level of the cervical line (Bailey, 2004; Bailey and Lynch, 2005; Martín-Torres et al., 2006); the third method, recently devised by Kondo and Townsend (2006) based on the system proposed by Jernvall and Selänne

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