Quantitative three-dimensional topography in taxonomy applied to the dental morphology of catarrhines

Application quantitative de la topographie tridimensionnelle de la morphologie dentaire à la taxonomie des catarrhiniens

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Abstract This paper presents a new aspect in studies of dental morphology based exclusively on 3D topographical analysis. Our method was applied to a set of 20 unworn upper second molars belonging to seven extant catarrhine genera. From a geometrical analysis of the polygonal grid representing the shape of each tooth, we propose a 3D dataset that provides a detailed characterization of the enamel morphology. In this article, we present a taxonomic application of our method using the example of inclination. Our initial results show intergeneric variation for the selected topographic parameter and its relevance to taxonomic analyses of extinct primates. More generally, our analysis of irregular grid patterns in 3D digital models supplied new parameters and enabled a review of the data classically studied in dental palaeoanthropology, with potential implications for taxonomic, phylogenetic, functional and developmental studies.

Keywords 3D image analysis · Polygonal surface · Dentin · Enamel · Molar · Hominoid · Cercopithecoid

Résumé Nous présentons un nouvel aspect de l’étude de la morphologie dentaire basée exclusivement sur une analyse topographique 3D. Notre méthode a été appliquée à un échantillon de 20 secondes molaires supérieures non usées appartenant à sept genres actuels de catarrhiniens. Au moyen d’une analyse géométrique de maillages polygonaux représentant la forme de la dent, nous proposons un jeu de données 3D permettant de caractériser de manière détaillée la morphologie de la capsule d’émail. Dans ce travail, nous présentons une application taxonomique de notre méthode à travers l’exemple de l’inclinaison. Les résultats préliminaires montrent une variation inter-générique pour le paramètre topographique sélectionné et sa pertinence en termes d’analyse taxonomique chez les primates anciens. Plus généralement, l’analyse du maillage irrégulier des modèles numériques 3D permet d’accéder à de nouveaux paramètres et de revisiter des données classiquement étudiées en paléoanthropologie. Les inférences potentielles sont d’ordre développemental, taxonomique, phylogénétique et fonctionnel.

Mots clés Analyse d’image 3D · Surface polygonale · Dentine · Email · Molaire · Hominoïde · Cercopithécoïde

Introduction

Tooth tissue is of central importance to many fields of investigation including anthropology and palaeoanthropology, as a key to taxonomic identification and phylogenetic or biological inferences (e.g. [1-4]). Like any other organs, teeth - as tools contributing to the digestive process in various diets - are a combination of the phylogenetic inheritance of dental traits and adaptive selection of these traits during evolution. However, unlike most other organs, changes in the shape of teeth after their eruption and during the life history of an individual are driven only by wear and not through remodeling (as with bones). Occlusal tooth morphology thus corresponds to the external surface of the enamel cap (EC) as shaped by tooth wear. Therefore, unworn teeth directly reflect the developmental processes governing morphogenesis and are highly suited to evolutionary investigations. However, distinguishing between the adaptive and phylogenetic significance of dental traits has remained a challenge.

Mammals, and therefore primates, have high intra- and inter-species variability in tooth size and shape. Aspects of
tooth size and shape have been widely considered by researchers over the last century, from detailed descriptions of occlusal morphology to the characterization of the developmental processes underlying tooth shape (e.g. [5]), including quantification of various dimensional aspects of the teeth through a wide range of descriptors (e.g. [1,4,6-9]).

Recent technological advances in capturing the morphology of objects in three dimensions using non-invasive methods (e.g. CT and μCT-scans) and the improvement of image analysis tools have given a new impetus to tooth studies. Researchers are able not only to consider an extensive set of dental features in their analyses, including crown enamel and the enamel-dentine junction as well as root and pulp canals, but also to study these tissues in all three dimensions.

Analytical tools using 3D imagery now make it possible to perform quantitative appraisals and characterizations of both the morphology and properties of dental tissues [e.g., 10-16]. Tooth form and function can thus be accessed through topographical analyses of the occlusal surface using GIS software (e.g. [13,16]).

In this paper we will focus on data that can be retrieved from 3D topographical analyses of the occlusal enamel surface (EC). While our overall goal is to achieve a comprehensive characterization of tooth occlusal morphology using 3D positioning and distributions of topographical (elevation, inclination, orientation) and material (enamel thickness) descriptors of dental features, we report here on an example of three-dimensional tooth characterization from a taxonomic perspective using one topographical parameter: inclination.

We applied our procedure to a set of unworn to slightly worn left upper second molars of catarrhines.

**Data acquisition and analysis**

Our sample consisted of molars from two gibbons (*Hylobates sp.*), four gorillas (*Gorilla gorilla*), three chimpanzees (*Pan troglodytes*), five modern humans (*Homo sapiens*) and six cercopithecoids (two *Cercocetus sp.*, two *Cercopithecus sp.* and two *Papio sp.*). All the specimens belong to the osteological collections of iPHEP/University of Poitiers (19th century) and make up a sample with sufficient taxonomic and morphological diversity to assess our protocols. The molars were scanned using a μ-CT VISCOM X8050 (University of Poitiers Microtomography Centre).

The virtual volumes reconstructed from the microtomographic images were processed by automatic segmentation tools with manual correction, using ©Avizo v7 commercial software. A review of concepts and practices in 3D image segmentation is beyond the scope of this paper, but readers may refer to the abundant literature on this topic [e.g. 17,18].

Once segmentation was complete, the EC was isolated from the dentine material and pulp canals. The EC volume data was converted into a polygonal surface (triangular 3D grid) corresponding to a set of three-dimensional points (nodes) connected by their edges. For analysis purposes and in order to minimize the computational load, each EC was set to an equivalent reduced amount of polygons by decimation. The decimation procedure was done by re-tessellation of the original polyhedral surface with tooth-size standardization of the polygonal unit area (i.e., each surface is made up of polygons of equivalent area, which depends on the tooth size). Following this procedure, all the occlusal EC surfaces together comprised about 22,000 polygons across the sample. Decimation of the original surfaces does not produce any significant alteration of the tooth morphology (Fig. 1) [1,19].

Each surface node and surface triangle is precisely referenced by its Cartesian (x, y, z) coordinates in a virtual 3D space. In order to standardize our result, we chose to orient each molar in its 3D virtual space using a common reference plane and axis. The virtual three-dimensional molar surfaces are aligned to a geometrically constructed plane with no preconceptions as to their biological or functional significance or their future reproducibility in a larger, more heterogeneous sample (i.e., including more disparate taxa and molar morphologies). The only prerequisite, for the sake of convenience, was to have the occlusal surface parallel to the viewer plane (e.g. [20]). First, each molar was aligned to a (xy) plane (reference plane) defined by the tip of the dentine horns at the protocone, paracone and metacone. The z axis was positively oriented from the cervix to the occlusal relief of the tooth. Secondly, each molar was realigned in the reference plane by having its mesial axis, a line joining the tip of the dentine horns at the protocone and paracone, parallel to the x axis of the virtual 3D space. Finally, again for convenience, the lowest point of each molar cervix was set to (x, y, 0) so that crown height is measured on a z-positive scale.

Having oriented all the molars, topographical data were retrieved from EC. The surface geometry of the molar morphology consists of a matrix of 3D point coordinates and their connections. Each triangle of the polygonal surfaces is indexed and can be attached to various signifiers (e.g. enamel thickness at location, elevation, orientation or inclination). Thus, it is possible not only to retrieve individual or average signifier values from the precise location on the molar, but also their entire distribution and all their variations over the whole tooth or a particular region of interest.

**Topographical signifier: inclination**

A standardized vector field was computed from the triangular 3D molar grid, and the matrix of normal vector coordinates at each individual EC triangle was recorded. The vector