

Technical Note: Compatibility of Microtomographic Imaging Systems for Dental Measurements

Anthony J. Olejniczak,^{1*} Paul Tafforeau,^{2,3} Tanya M. Smith,¹ Heiko Temming,¹ and Jean-Jacques Hublin¹

¹Department of Human Evolution, Max Planck Institute for Evolutionary Anthropology, Deutscher Platz 6, D-04103 Leipzig, Germany

²Laboratoire de Géobiologie, Biochronologie et Paléontologie Humaine, UMR CNRS 6046, 40 avenue du Recteur Pineau, F-86022 Poitiers cedex, France

³European Synchrotron Radiation Facility, 6 rue Jules Horowitz, BP 220, 38043 Grenoble Cedex, France

KEY WORDS Microtomographic imaging; enamel thickness; dental measurements; synchrotron radiation; conventional X-ray source

ABSTRACT Modern micro-computed tomography techniques allow the accurate visualization of internal dental structures, and are becoming widely used within (paleo-) anthropological dental studies. There exist several types and name brands of microtomographic systems, however, which have been demonstrated to produce images that vary in resolution and signal-to-noise ratio. As a growing body of dental research using disparate microtomographic techniques is likely to continue accumulating, it is imperative that different systems are compared to ensure that results are comparable and not machine-dependent. In the present study, we compare volume, surface area, and linear measurements recorded on a sample of modern and fossil teeth using four microtomographic systems (three laboratory scanners, and the ID19 beamline of the European Synchrotron Radiation Facility). Results indicate that measurements are compa-

table between systems (within 3%), but that synchrotron radiation is superior to the other systems because its monochromatic X-rays prevent beam hardening and its parallel beam prevents geometric artifacts in the resultant images, making it easier to record measurements and see fine details at the enamel cervix or dentine horn tips. Although the synchrotron produces higher resolution images with less artifacts, results indicate that for gross morphological measurements (e.g., enamel cap volume, intercuspal distances), each of the scanners produces approximately the same measurements. Combining measurements of teeth from multiple microCT systems presupposes that measurements from each system are comparable; the research presented here indicates that this is the case when teeth are not severely diagenetically remineralized. *Am J Phys Anthropol* 134: 130–134, 2007. © 2007 Wiley-Liss, Inc.

Modern laboratory micro-computed tomography (microCT) and third generation synchrotron microCT facilitate the accurate imaging and measurement of internal dental structures, provided teeth have not undergone severe diagenetic remineralization (Chaimanee et al., 2003; Tafforeau, 2004; Olejniczak and Grine, 2006; Tafforeau et al., 2006). Dental studies based on microCT imaging are becoming commonplace in anthropological literature, and several types of microCT systems are utilized in the measurement of recent and fossil primate teeth. Conventional laboratory microCT has been employed to measure enamel thickness and volume, for instance by Kono (2004; Suwa and Kono, 2005), Olejniczak and Grine (2005, 2006; Olejniczak, 2006), Avishai et al. (2004), and Smith et al. (in press). Synchrotron microCT has been used for measurements of enamel thickness and volume by Tafforeau and colleagues (Chaimanee et al., 2003, 2006; Tafforeau, 2004; Macchiarelli et al., 2006; Tafforeau et al., 2006; Smith et al., in press).

The accuracy of both laboratory microCT (Olejniczak and Grine, 2006) and synchrotron microCT (Tafforeau, 2004) were established independently by examining physically produced sections and digital microCT sections from the same specimens. Nonetheless, fundamental differences between techniques lead to differences in image quality (Tafforeau, 2004; Tafforeau et al., 2006), which may result in different measurements. As non-destructive microCT imaging of teeth becomes widespread, it is

essential that measurements taken on images produced by different systems are compared to determine whether combining measurements from multiple microCT systems in analyses is justified in light of potential inter-system variance, or perhaps whether system-specific differences are great enough to preclude comparing measurements.

Five teeth representing primate and reptilian taxa with varying degrees of diagenetic re-mineralization and enamel thickness (Table 1) were scanned using four different microCT systems: a Scanco μ CT 40 (Department of Biomedical Engineering, Stony Brook University), a SkyScan 1172 system and a BIR Actis 300/225 FP system (both housed at the Department of Human Evolu-

Grant sponsors: Max Planck Society, the CNRS, the European Synchrotron Radiation Facility, the European Virtual Anthropology Network; Grant sponsor: "EVAN" Marie Curie Research Training Network; Grant number: MRTN-CT-019564.

*Correspondence to: Anthony J. Olejniczak, Department of Human Evolution, Max Planck Institute for Evolutionary Anthropology, Deutscher Platz 6, D-04103 Leipzig, Germany.
E-mail: olejniczak@eva.mpg.de

Received 20 October 2006; accepted 19 February 2007

DOI 10.1002/ajpa.20615

Published online 14 May 2007 in Wiley InterScience (www.interscience.wiley.com).

TABLE 1. Specimens scanned by multiple mCT systems

Taxon	Tooth type	Notes
<i>Pongo pygmaeus</i>	Maxillary Molar	ca. 130 Kya
<i>Homo sapiens</i>	Mandibular Molar	Recent
<i>Alligator mississippiensis</i>	Caniniform Tooth	Recent
<i>Diademodon tetragonus</i>	Molariform Tooth	ca. 180 Mya
<i>Gavial</i> sp.	Caniniform Tooth	ca. 17 Mya

tion, Max Planck Institute for Evolutionary Anthropology), and the ID19 beamline (European Synchrotron Radiation Facility). The emphasis of this research is not on statistical comparisons between systems, rather the goal was to evaluate the quality of images produced by each system and the percentage difference in measurements of the same objects between systems. As such, a small and diachronically diverse sample is adequate for

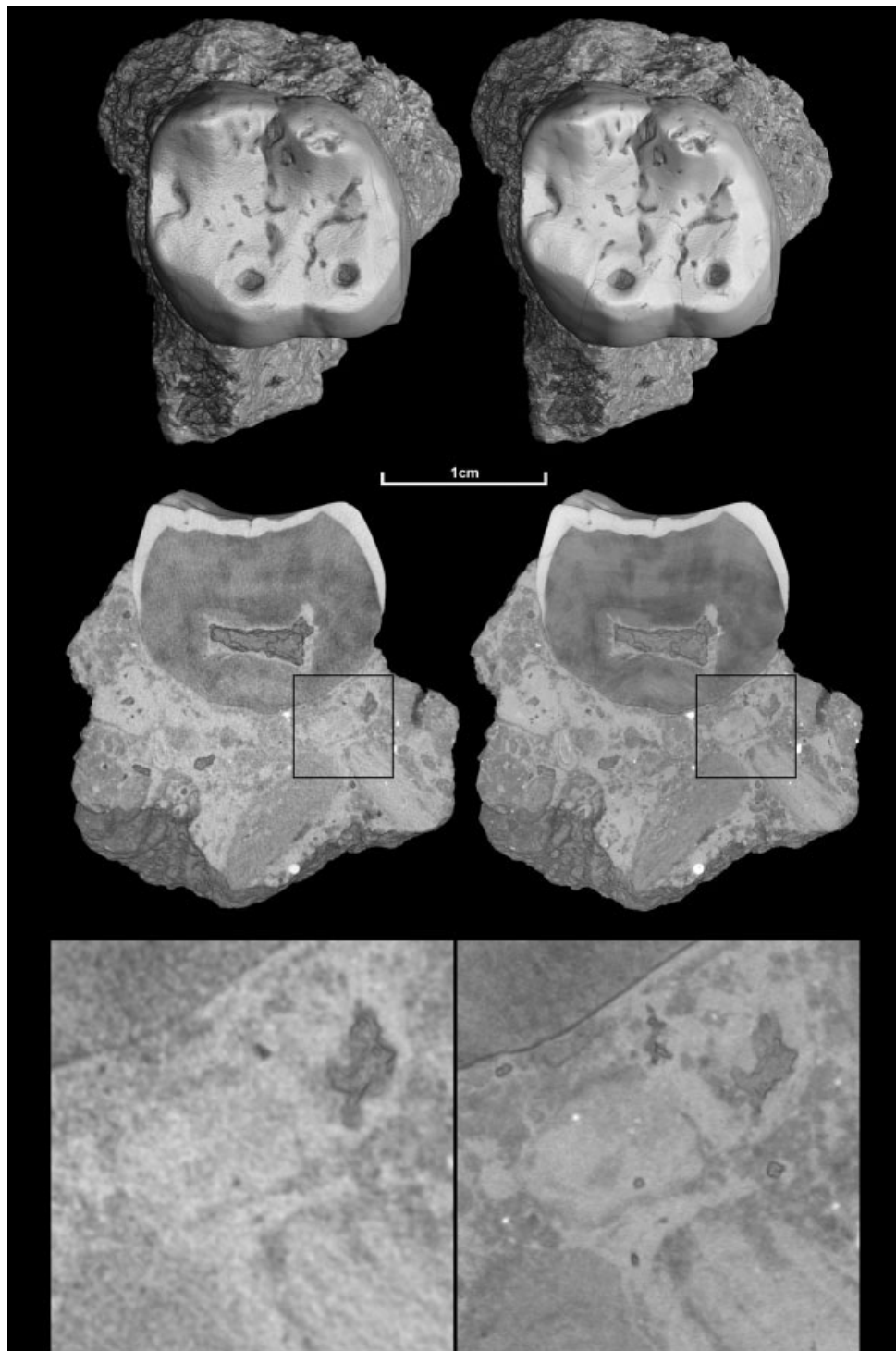


Fig. 1. Comparison of synchrotron microCT (right) and laboratory microCT (left) volume models and cross-sections. The synchrotron model has fewer occlusal artifacts and presents finer details, and in cross-section the synchrotron images appear sharper, of similar quality to a physical section. The laboratory microCT section appears noisier and with less distinct features. For the same voxel size, the synchrotron exhibits a higher resolution than the laboratory microCT.

TABLE 2. Linear measurements recorded for each tooth

Measurement	Definition
<i>Alligator</i>	Length of the entire tooth
	Distance between apical-most points at the tooth base
<i>Homo</i>	Width at mid-point of pulp chamber
	Length
<i>Gavial</i>	Breadth
	Buccal enamel cusp tip distance
	Circumference at 1 mm apical to cusp tip
<i>Diademodon</i> ^a	Circumference at 2 mm apical to cusp tip
	Circumference at 3 mm apical to cusp tip
	Length
<i>Pongo</i>	Breadth at 1/3 length apical to cusp tip
	Breadth at 2/3 length apical to cusp tip
	Length
	Breadth
	Distance between two buccal cusp tips

^a These measurements are of root dentine, not enamel.

evaluation; a larger sample would facilitate testing for statistical differences.

The Scanco and SkyScan machines are both cone-beam systems, and are generally similar in design and function with the exception of higher source voltage in the SkyScan machine (~100 kV versus ~70 kV). All scans on the SkyScan machine were performed with an aluminum-copper filter at 100 kV and 100 μ A. The BIR machine is capable of higher source voltage than the other laboratory machines (maximum 225 kV), and it also accommodates larger specimens. All specimens scanned on the BIR scanner were performed at 130 kV, 100 μ A, and with a brass filter.

Unlike conventional X-ray micro-tomography, a third generation synchrotron light source necessitates that specimens are brought to the radiation facility for analysis (whereas some conventional systems are transportable). We employ synchrotron radiation in this study as a "golden standard" against which to assess the accuracy of the other systems. The third generation synchrotron light source we used to perform experiments here has several fundamental differences from the other systems we employed, which are thoroughly recounted by Tafforeau et al. (2006), and only briefly summarized here. Experiments were performed using a beam monochromatized using a double silicon crystal monochromator with an energy bandwidth of $\Delta\lambda/\lambda = 10^{-4}$. 0.5 mm of diamond and 2 mm of aluminum were put in the beam before the monochromator to limit the heat load (these filters have no effect on the monochromaticity of the beam after the silicon crystals). X-ray energy was set to 60 keV depending on the sample size and mineralization. Isotropic voxels were produced for all specimens.

A third generation synchrotron source can produce extremely intense nearly parallel X-ray beams that can be monochromatized, leading to high quality absorption scans without beam hardening effects or geometric artifacts (which are due, respectively, to the polychromatic spectrum and the cone beam geometry used in most laboratory microtomographic systems). Third generation synchrotron sources also have fast scan acquisition times (e.g., the same tooth scanned on the SkyScan and Synchrotron systems took 3.75 and 0.75 h, respectively). Figure 1 illustrates image quality differences between laboratory and synchrotron microCT scans of the *Pongo* molar, recorded with approximately equivalent scan parameters (same voxel size and angular step during the

TABLE 3. Average percent differences between scanners

Specimen	Linear measurements (%)	Surface area measurements (%)	Volume measurements (%)
<i>Alligator</i>	1.16	2.99	0.36
<i>Diademodon</i>	0.75	2.30	2.20
<i>Gavial</i>	6.83	2.50	2.60
<i>Homo</i>	0.45	0.53	0.08
<i>Pongo</i>	1.01	1.22	0.34
Mean % Difference	2.04	1.91	1.12

scan). Three-dimensional rendering was performed using VG Studio Max 1.2.1 software (Volume Graphics, Heidelberg, Germany).

A tooth-specific set of linear measurements was recorded on each of the image stacks from the different microCT systems (Table 2). Additional measurements included the volume of enamel and the surface area of enamel. In the case of the *Diademodon* tooth, root dentine was measured in lieu of enamel. All measurements were collected by a single observer (AJO) in order to eliminate interobserver error. All measurements were collected using OsiriX (Rosset et al., 2004), VoxBlast (Vaytek, Inc.), and 3D Slicer (Gering et al., 1999) software. Tissue segmentation protocols differed between specimens, as fossils evince variable levels of diagenetic remineralization, which impacts gray-scale values (Chaimanee et al., 2006; Olejniczak and Grine, 2006; Tafforeau et al., 2006). In all cases, segmentation consisted of one or both of the following filters: the median filter (with a kernel size of three pixels) and the anisotropic diffusion filter. An identical filtering protocol for each tooth was employed, for all scans of that tooth (regardless of which system produced the scans); in this way, the impact of variable filtering protocols on measurements is eliminated. These filters have been demonstrated to greatly enhance tissue boundaries and tissue pixel value homogeneity in dental specimens (Olejniczak, 2006).

The pixel value histogram of each image stack was also recorded to compare the locations of peaks and troughs representing enamel, dentine, mineral matrix (on the *Pongo* tooth), and background noise. Histograms were recorded before any filtering algorithms were applied to the image stacks. Pixel value histograms allow comparisons of the relative ease of tissue segmentation (separating enamel, dentine, and air in digital images produced by scanning, for the purpose of measuring each tissue). Voxel dimensions were kept as close to equal as possible between systems in order to isolate measurement variation due to machine differences rather than voxel size.

The average percent differences for measurements recorded in this study are reported by measurement type in Table 3. Results indicate that measurements taken on all four systems appear to be comparable (less than 3.0% different between machines on average). Volumes are the most stable measurements, with the lowest average percentage difference among systems. Linear measurements and surface areas both show measurement differences of ~2%.

Despite the relative similarity of measurements across systems, there is a notably sharper quality of images produced by synchrotron scanning, whereby images are produced with fewer artifacts and with more distinct tissues (e.g., Fig. 1; see also Tafforeau, 2004 and Tafforeau

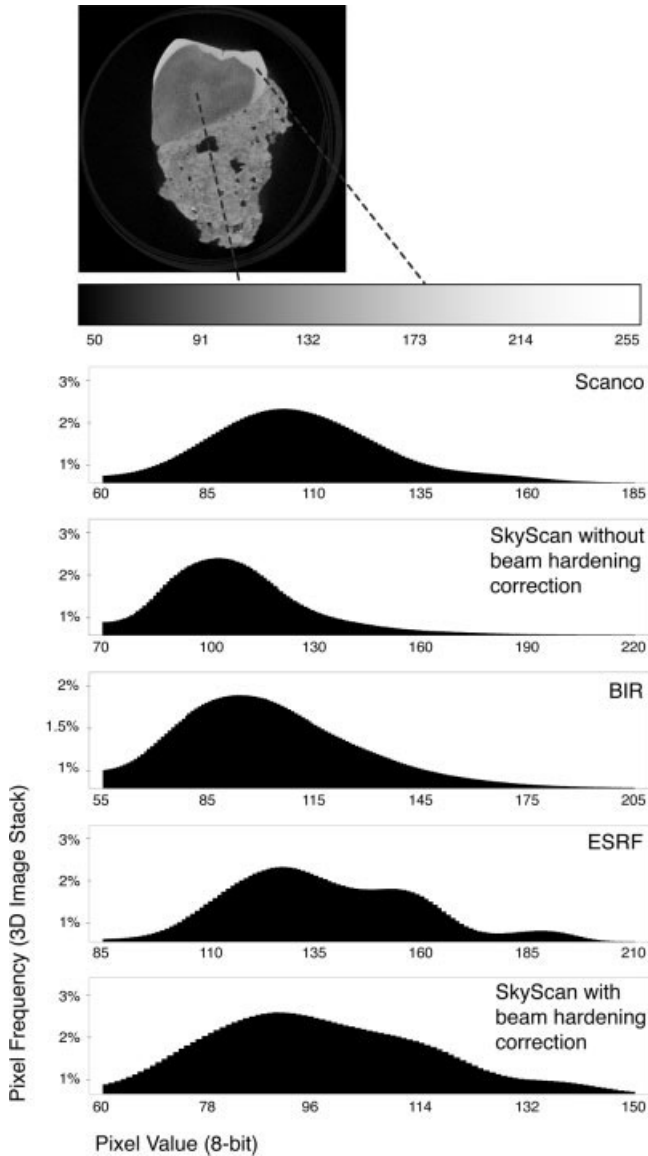


Fig. 2. Pixel value histograms of the *Pongo* specimen from each of the microCT systems on which it was scanned. Only the pixel value range containing the object of interest has been shown in each case. The Scanco system histogram does not show any discrimination between tissues, as is the case in the histograms produced by the BIR system and the SkyScan system (without post-hoc beam-hardening correction filters). The synchrotron shows a separate peak for enamel, as well as two distinct peaks separating dentine from the surrounding matrix. Because of the discrepancy in underlying pixel values, the synchrotron image stack is easier to segment into unique tissues for the purpose of recording measurements. When a beam hardening filter was applied to the SkyScan system's image stack, the histogram improved; this suggests that software solutions to beam hardening may partially improve the relative quality of laboratory microCT scans.

et al., 2006). Voxel value histograms (histograms showing the gray-scale value of all the pixels in a digital image; black is zero and white is 255) demonstrate that the synchrotron produces more distinguishable and homogenous tissue groups than the other scanners. Figure 2 depicts three-dimensional pixel value histograms for the

same specimen (the fossil *Pongo* molar) produced by all four microCT scanners. The Scanco, BIR, and SkyScan systems' histograms show a single, smooth distribution of pixels, indicating that enamel, dentine, and the surrounding matrix have substantially overlapping pixel values. The synchrotron light source, however, produced an image stack with a separate peak of enamel pixels, and even shows a slight difference (in the form of two distinct peaks) between dentine and the surrounding matrix.

The relative lack of tissue separation in the non-synchrotron microCT systems examined here is probably partially due to beam hardening, which is effectively eliminated by the monochromatic beam of the synchrotron. It may also be explained by the synchrotron's higher resolution and signal-to-noise ratio, which result in tissue interfaces (e.g., the enamel-dentine junction) that are not blurred as much as laboratory microCT scans, and less random noise in homogenous areas. To evaluate the beam hardening effect on the resulting histograms, we used a software-based linear gain correction filter (i.e., beam-hardening artifact reduction filter) and reconstructed the fossil *Pongo* molar image stack produced by the SkyScan system a second time. The resultant pixel value histogram demonstrates an improvement in the separation of tissues (see Fig. 2), although the synchrotron light source still produces the greatest tissue distinctions. Moreover, while software solutions to reduce image artifacts may be effective, it is always preferable to record the original scans using optimal parameters as image filters may introduce error, for instance by incorrectly locating the edge of a tissue boundary. That is to say, producing cleaner images by means of equipment modification is always preferable to post-hoc software solutions. Nonetheless, as monochromatic X-ray sources are not commonplace, it is important to note that polychromatic X-ray microCT images may be enhanced to approach the condition produced by the synchrotron light source in terms of pixel value separation of whole teeth.

Clearly separated tissues based on the pixel values in digital images expedite the tedious process of image segmentation, in which unique tissues in each image stack are rendered homogenous in order to facilitate accurate measurement. The synchrotron produces the cleanest images prior to segmentation, making this method of scanning superior to the laboratory scanners in terms of the efficiency of measurements. Nonetheless, the accuracy of tooth crown measurements taken on scans from each of the systems appears to be similar, such that area, linear, and volume measurements of tooth crowns from different scanners may be combined in future analyses. Where fine structures are concerned (e.g., dentine horn tips and cervical enamel), the resolution of the third generation synchrotron would provide a more accurate representation of the true morphology than laboratory scanners. It must be noted, however, that the accessibility of synchrotron scanning is limited; synchrotron radiation facilities are rare, and fossils must be brought to the radiation source. Some conventional microCT scanners are transportable, making it possible to bring the scanner to the specimen.

As the use of microCT in dental research becomes increasingly prevalent, future studies (especially meta-analyses, wherein multiple data-sets are combined) will likely contain data produced by multiple microCT systems. Combining measurements of teeth from multiple

microCT systems presupposes that measurements from each system are comparable; the research presented here indicates that this is the case (within 3%) when gross morphological measurements are taken (e.g., enamel volume and intercuspal distances), and when teeth are not severely diagenetically remineralized.

ACKNOWLEDGMENTS

For access to specimens we thank R. Ciochon and F. Grine. Scanning assistance in Stony Brook was provided by F. Grine, S. Judex, and S. Xu. M. Skinner and R. Feeney graciously provided critical feedback on the original manuscript.

LITERATURE CITED

- Avishai G, Müller R, Gabet Y, Bab I, Zilberman U, Smith P. 2004. New approach to quantifying developmental variation in the dentition using serial microtomographic imaging. *Microsc Res Tech* 65:263–269.
- Chaimanee Y, Jolly D, Benammi M, Tafforeau P, Duzer D, Moussa I, Jaeger JJ. 2003. A Middle Miocene hominoid from Thailand and orangutan origins. *Nature* 422:61–65.
- Chaimanee Y, Yamee C, Tian P, Khaowiset K, Marandat B, Tafforeau P, Nemoz C, Jaeger J-J. 2006. *Khoratpithecus piriyai*, a late Miocene hominoid of Thailand. *Am J Phys Anthropol* 131:311–314.
- Gering D, Nabavi A, Kikinis R, Eric W, Grimson L, Hata N, Everett P, Jolesz F, and Wells III W. 1999. An integrated visualization system for surgical planning and guidance using image fusion and interventional imaging. In: *Proceeding of Medical Image Computing and Computer-Assisted Intervention (MICCAI)*, Cambridge: England, p 809–819.
- Kono R. 2004. Molar enamel thickness and distribution patterns in extant great apes and humans: new insights based on a 3-dimensional whole crown perspective. *Anthropol Sci* 112:121–146.
- Macchiarelli R, Bondioli L, Debénath A, Mazurier A, Tournepiche J-F, Birch W, Dean C. 2006. How Neanderthal molar teeth grew. *Nature* 444:748–751.
- Olejniczak AJ. 2006. Micro-computed tomography of the post-canine dentition. Ph.D. dissertation, Stony Brook University.
- Olejniczak AJ, Grine FE. 2005. High-resolution measurement of Neanderthal tooth enamel thickness by micro-focal computed tomography. *S Afr J Sci* 101:219–220.
- Olejniczak AJ, Grine FE. 2006. Assessment of the accuracy of dental enamel thickness measurements using microfocal X-ray computed tomography. *Anat Rec A* 288:263–275.
- Rosset A, Spadola L, Ratib O. 2004. OsiriX: an open-source software for navigating in multidimensional DICOM images. *J Digit Imaging* 17:205–216.
- Suwa G, Kono R. 2005. A micro-CT based study of linear enamel thickness in the mesial cusp section of human molars: reevaluation of methodology and assessment of within-tooth, serial, and individual variation. *Anthropol Sci* 113:273–289.
- Smith TM, Olejniczak AJ, Tafforeau P, Reid DJ, Grine FG, and Hublin J-J. Molar crown thickness, volume, and development in South African Middle Stone Age humans. *S Afr J Sci*, in press.
- Tafforeau P. 2004. Phylogenetic and functional aspects of tooth enamel microstructure and three-dimensional structure of modern and fossil primate molars. Ph.D. dissertation, Université de Montpellier II.
- Tafforeau P, Boistel R, Boller E, Bravin A, Brunet M, Chaimanee Y, Cloetens P, Feist M, Horszowska J, Jaeger J-J, Kay RF, Lazzari V, Marivaux L, Nel A, Nemoz C, Thibault X, Vignaud P, Zabler S. 2006. Applications of X-ray synchrotron microtomography for non-destructive 3D studies of paleontological specimens. *Appl Phys A* 83:195–202.