CHAPTER XXII

CT RECONSTRUCTIONS

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Abstract

The limited number of available fossils and their accessibility are two limiting factors for anthropological studies. Original remains have to be curated in an optimal environment in terms of light, humidity and temperature and direct manipulations need to be limited in order to preserve this patrimony. Imaging techniques constitute an innovative advance for the preservation of unique fossil remains and allow new scientific studies and museographic displays. However, virtual anthropology needs to be considered as an additional tool in our large set of analytical possibilities, with its limits and constraints when working on fossil remains. We describe here the digitisation of the Spy human remains by medical CT equipments. This allowed to preserve the original collections with a digital backup and to initiate new studies developed in this monograph. In this context, the European project "The Neanderthal Tools" (2004-2006) was an important step in terms of collaborative developments of a shared database for imaging datasets of fossil hominids and associated artefacts, as well as of specific tools for anthropological and palaeontological studies.

INTRODUCTION: FROM THE PIONEERS TO THE PROJECT "THE NEANDERTHAL TOOLS"

Computed Tomography has been a tool since the last decades of the 20th century for diagnosis in medical sciences. It has also been more recently applied on ancient human skeletal remains in order to study the taphonomy, the pathology and the morphology of fossil specimens. This imaging approach allows to register, to preserve and to share the fossil "cultural heritage" and opens new perspectives while giving access to internal morphological features. The possibility to probe internal structures increases considerably the available data in order to study the morphological variability and the evolution of fossil hominids.

Historically, the invention of new imaging methodologies has always encouraged rapid applications to the study of fossil hominid remains. Indeed, the discovery of X-rays by Roentgen dates back to 1895 and Gorjanović-Kramberger, who studied the technique with Otto Walkhoff, published the first study based on two-dimensional radiographs on the Krapina fossils in 1902. One year later, Walkhoff published the radiographic study of Belgian fossils including the La Naulette and Spy Neandertal mandibles (Walkhoff, 1903; Figure 1, SF1).

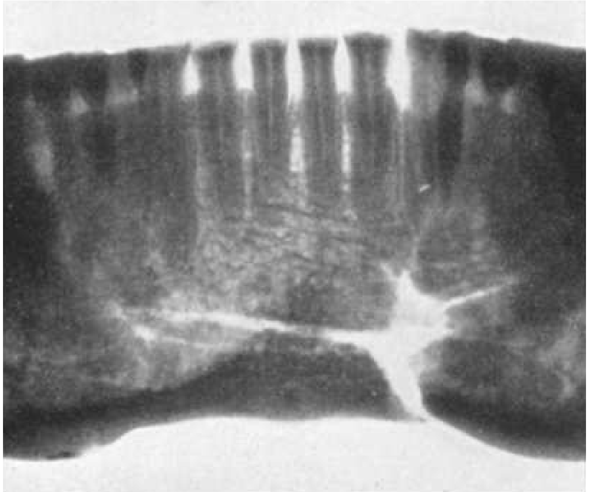


Figure 1. X-ray view of the Spy 3 mandible (after Walkhoff, 1903).

Similarly, Computed Tomography was developed in the early 1970s (e.g. Hounsfield, 1973, 1976). Among the precursory works on fossil material, a study of the temporal bone of the Spy fossils was put forward (Hotton *et al.*, 1976). In spite of the technical limits of the earlier equipment, researchers (e.g. Tate & Cann, 1982; Ward *et al.*, 1982; Wind, 1984; Vannier *et al.*, 1985; Zonneveld & Wind, 1985; Ruff & Leo, 1986) were attracted by the opportunity to get access to the hidden structures of fossils. Since then, this remarkable technological enhancement produced numerous and diverse applications (e.g. Spoor *et al.*, 2000a, 2000b). Some examples of applications in palaeoanthropology (with some selected references) concern the study of the frontal sinuses and their relationship with the face (Seidler *et al.*, 1997; Prossinger *et al.*, 2003), of the morphology of the maxilla and its pneumatisation (Maureille & Bar, 1999; Rae & Koppe, 2000), of temporal bone pneumatisation (Balzeau & Radovčić, 2008), of the bony labyrinth (Hublin *et al.*, 1996; Spoor *et al.*, 2003), of auditory capacities (Martínez *et al.*, 2004), of the teeth (Conroy, 1988; Conroy *et al.*, 1995), of the cranial vault thickness and its internal composition (Weber & Kim, 1999; Balzeau, 2006, 2007), of the endocranial morphology (Balzeau *et al.*, 2005a; Falk *et al.*, 2005), of the mandibular corpus (Daegling, 1989; Zollikofer *et al.*, 1998), and of pathological alterations (Webb, 1990; Bräuer *et al.*, 2003). Moreover, this methodology allows the reconstitution and reconstruction of partial and deformed skulls (e.g. Dean *et al.*, 1993; Thompson & Illerhaus, 1998; Zollikofer *et al.*, 2005). Finally, prototypes can be obtained from the 3D reconstructions (e.g. zur Nedden *et al.*, 1994; Seidler *et al.*, 1997).

The purpose of this paper is to present the applications of CT methodologies used in palaeoanthropology, from the earlier works to the current “state of the art”, illustrated with the Spy fossils. We describe applications in preservation of the collections as well as original applications to scientific studies of fossil hominid remains. In this context, the European project “The Neanderthal Tools” (TNT, 2004-2006; Semal *et al.*, 2004a, 2004b; Macchiarelli *et al.*, 2005; Macchiarelli & Weniger, 2006; ST1, ST2, ST3), a combined RTD- and demonstration project of the 6th framework program of the EU, was an important step in terms of collaborative and sharing developments of a web database for imaging datasets of fossil hominids, as well as of specific tools for anthropological and palaeontological studies.

MATERIAL AND METHODS

All the Neandertal hominid remains unearthed during the different excavations at Spy were CT scanned in the framework of the TNT project. Some CT acquisitions were performed previously in order to evaluate the potential of the technique (Louryan *et al.*, 1995) or after specific requests of researchers (Hublin *et al.*, 1996; Zollikofer & Ponce de León, unpublished).

New CT acquisitions of cranial bones and mandibles were made with a Siemens Volume Zoom in 2002 and 2003 at Erasmus Hospital (ULB) in the framework of the re-study of the Spy collections at the RBINS. During the TNT project, all Spy cranial and infra-cranial Neandertal remains were scanned with a Siemens Sensation 64 barrels scanner in 2005, 2006 and 2007 in Erasmus Hospital (ULB). These data were acquired in order to obtain optimal information for specific analyses of the internal features (see *infra* and in other chapters of this monograph) but also to compute accurate 3D surface objects. The quality of the 2D images was mostly the same between the Siemens Volume Zoom 4 barrels (2002-2003) and the Siemens Sensation 64 barrels (2005-2007) (SF2) but the higher speed of the 64 barrels scanner allowed to compute reconstructions with smaller overlap (0.1-0.3 mm) offering more detailed 3D model reconstructions (Figure 2).

Some extra acquisitions were also made with a Cone Beam CT I-CAT at the Oral Imaging Centre (KUL) with Pr. R. Jacobs. This technology used in orthodontics allows to obtain good data for small bones or portions of large bones with an isometric pixel size of 0.2-0.1 mm. The radiation dose is also lower than with classic medical CT. In some cases like small foot and hand bones, the images are more detailed with the Cone Beam CT but the multi-barrels medical CT scanner is without doubt the best compromise between the time needed for the scanning and the reconstruction and the average quality of our resulting data. We also evaluated several protocols available with the Siemens Sensation 64. The best results were obtained with the “dental” protocol adapted for samples displaying denser tissues like enamel or in our case for fossilised bone.

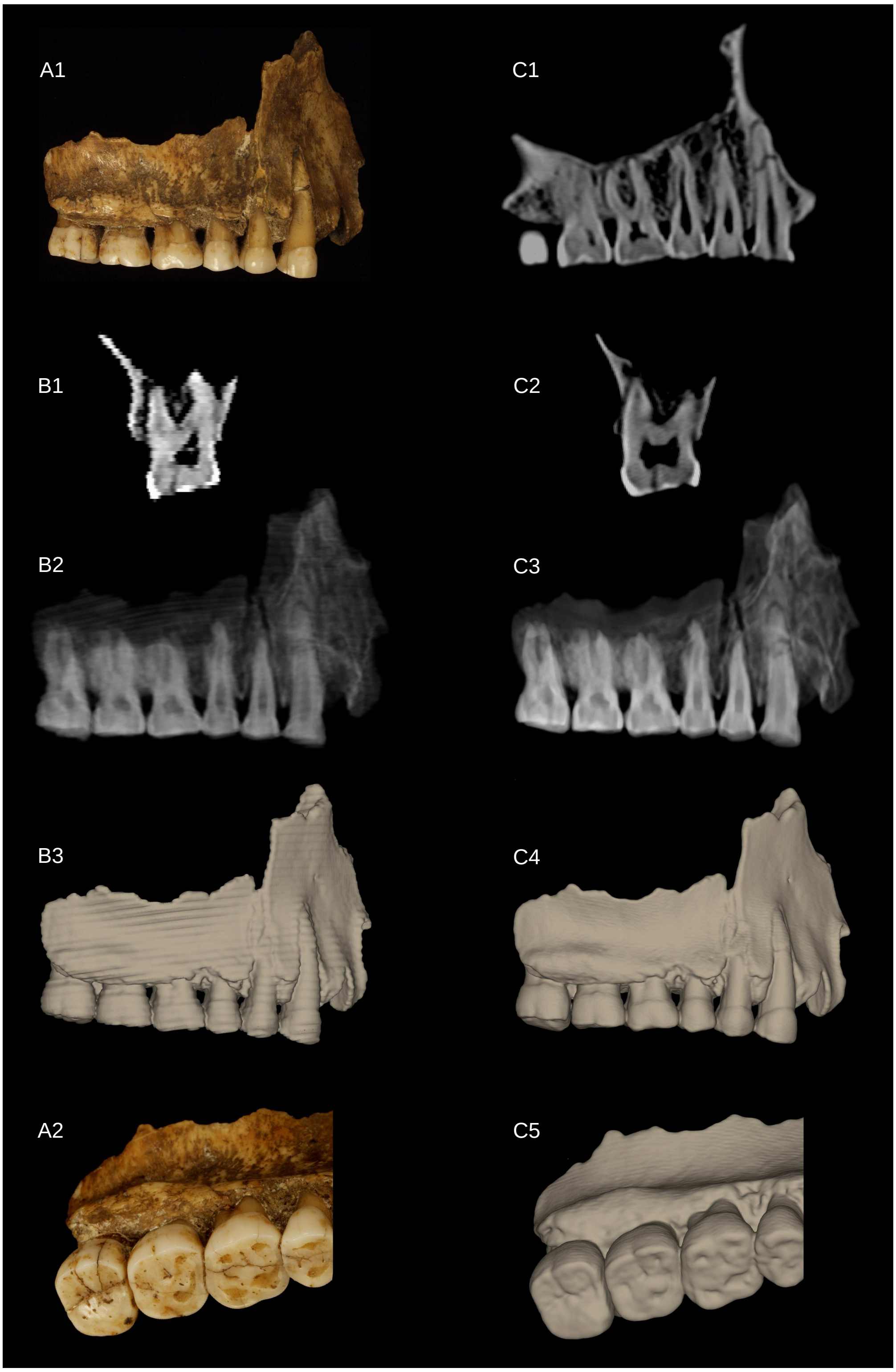


Figure 2. Comparison of scanning results between the Siemens Volume Zoom 4 barrels (VZ, 2003) and the Siemens Sensation 64 barrels (S, 2005). Technical parameters are given in ST1. A1: Right view of the Spy 2A right maxilla; A2: Oblique detailed view of the P4-M3; B1: VZ-bucco-lingual slice in the M1; B2: VZ-computed X-ray view of Spy 2A; B3: VZ-3D surface model; C1: S-antero-posterior slice; C2: S-bucco-lingual slice in the M1; C3: S-computed X-ray view of Spy 2A; C4: S-3D surface model; C5: S-detailed 3D surface model of the P4-M3 (Images: P. Semal, RBINS).

All surface models (STL) were computed with the Amira® 3.1 or Artecore 1.0 software using the smallest possible downsampling value. For the biggest datasets, the models were computed with the Amira® 3.1 software on a linux Suse 9.1 workstation (4Gb RAM). For smaller models, we used Artecore on a Windows XP with 3 Gb RAM. The STL surface models are available in a public space of the NESPOS database (https://www.nespos.org). The CT datasets are available on request on the NESPOS database and on the MARS database (Semal *et al.*, 2004; http://mars.naturalsciences.be). Files are saved as "via" files. This format is the default format of the Visicore application. Nevertheless, using the data with other software is very easy because the "via" file is just a "zip" compressed folder with the DICOM, TIFF or STL file(s) and an extra XML file with metadata. Renaming the "via" extension in "zip" allows to extract data for other applications.

Details about all of the specimens' CT scanning parameters are given in the supporting tables (ST1, ST2 and ST3).

RESULTS AND DISCUSSION

Applications of imaging methodologies offer important new opportunities for the preservation and the valorisation of fossil hominid remains. All information concerning the dimensions and the morphology of fossils may be recorded. Moreover, this multidisciplinary approach allows "virtual" manipulations and modifications of the fossils which were not possible before. Based on the imaging datasets, the different parts of an object may be individualised, moved, rotated, scaled, restored, deformed, completed… For example, we were able to perform a "virtual cleaning" of the Spy 1 and Spy 10 crania (the neurocranial remains of the Spy I and Spy II adult Neandertals) of all the included non-osseous structures (Figure 3). Indeed, the different cranial fragments were assembled together, probably just after the discovery of these fossils (Fraipont & Lohest, 1887), and some material was used later to fill in and to complete the missing areas in order to reconstitute the global shape of the crania. Direct physical cleaning of the original fossils is not possible because this invasive manipulation would not guaranty the preservation of the integrity of the specimens. On the other hand, all the segmentation procedures on the numeric datasets are reversible and do not cause any damage to the fossils. So, we used the CT datasets and the Amira® 3.1 software to "virtually" dissociate the different elements according to their density and their texture. The method of using global thresholds of CT (Hounsfield) values to separate bone, filling material and air cannot be applied reliably to the Spy CT scans because their density ranges overlap, and part of the plaster would be included as bone, and part of the bone as plaster. Moreover, the exact position of the different interfaces is not always easy to determine. Finally, filling material was used to complete missing parts of the original fossils, but also to consolidate the fossilised bone in some areas. As a result, bone and plaster may be locally mixed together. In this context, it was necessary to identify the boundary between the bone and the filling material by manual segmentation. Adjustment of the settings had to be made each time the attenuation coefficient of one of the elements varies all along the interfaces and on each CT slice. The complete CT datasets, in all orientations, were exploited and each step had to be validated by examination of the original fossils. Based on the segmented data, 3D reconstructions of the crania without their plaster were calculated (Figure 3). Finally, the 3D reconstructions of the "cleaned" crania were used to obtain physical replicas by means of prototyping methodologies (SF3). This work permits to better understand the restoration process made on the Spy 1 and Spy 10 crania at the end of the 19th century. Moreover, these physical replicas of the original fossils will be used to test if some of the original bone fragments rediscovered recently in the collections (see Rougier *et al.*, this volume: chapter XIX) fit on the crania.

These "virtual" opportunities have another important output for the preservation of the collections. Indeed, the 2D CT datasets and the 3D reconstructions, when correctly used, allow observation and quantification of information similar to those obtained directly on the original fossils. Moreover, the "virtual" objects are permanently available for study. Classic descriptions, metric analyses and approaches in geometric morphometrics can be generated on these data, while preserving the original fossils.

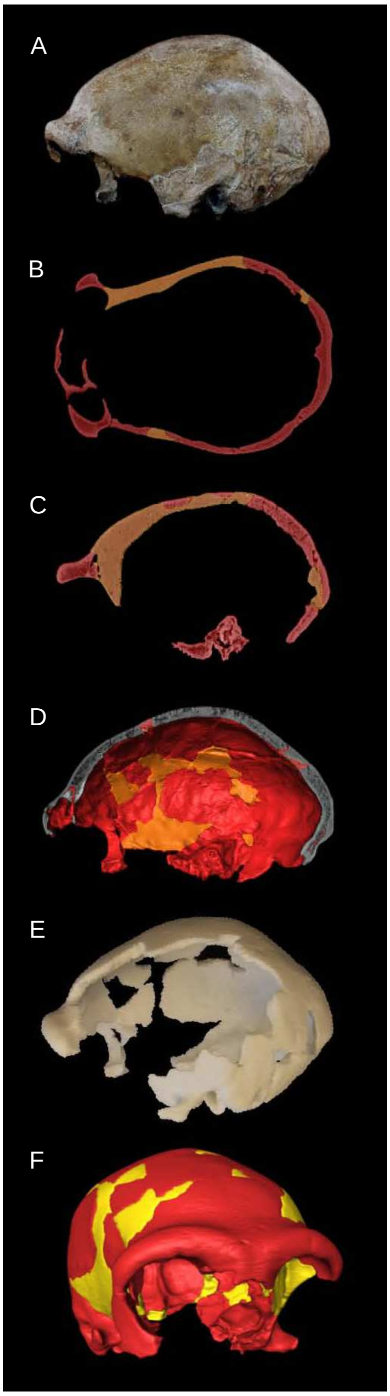
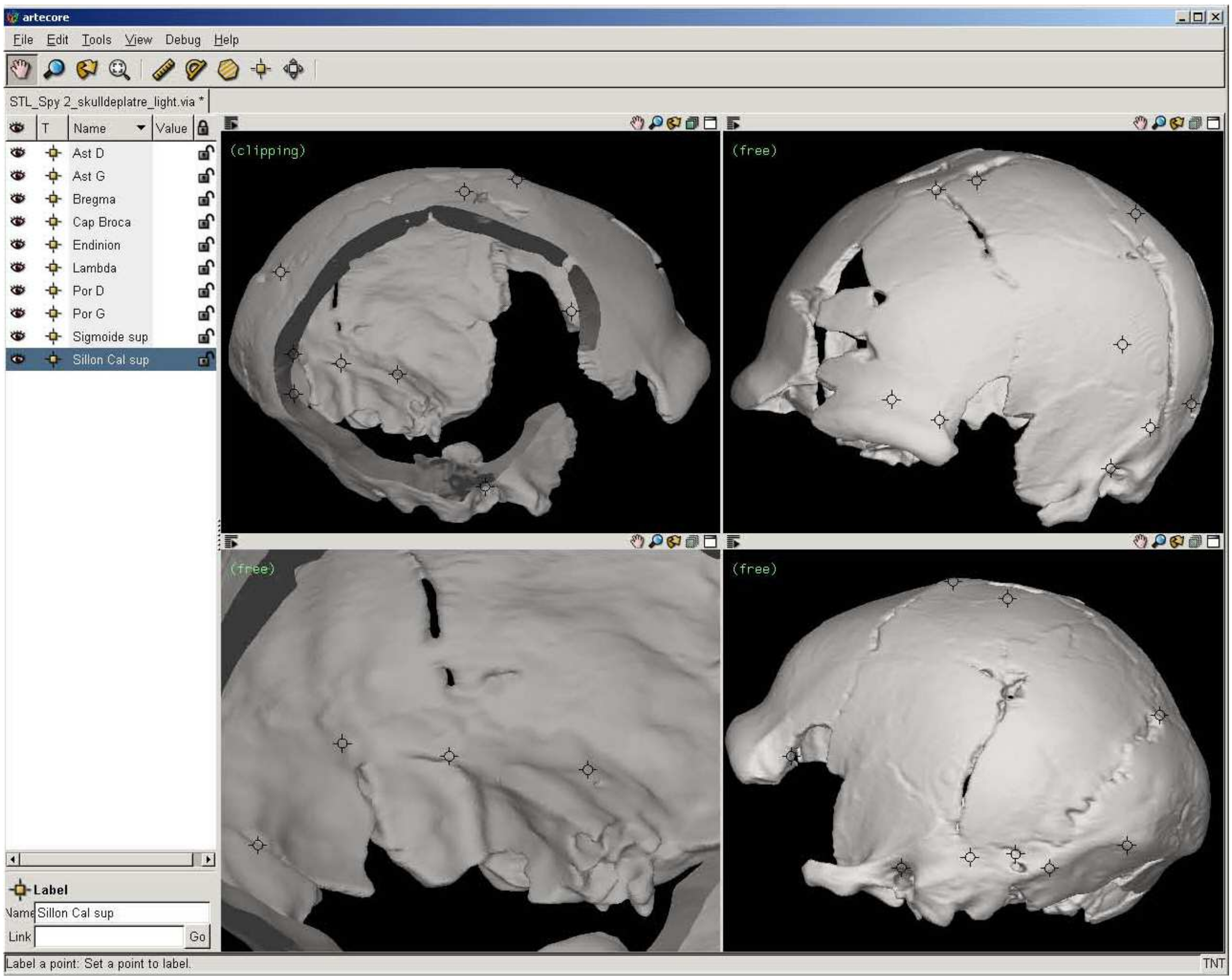


Figure 3. Reconstruction of the Spy 1 cranium.
A: Left lateral view of the original specimen;
B and C: CT slices in horizontal and parasagittal orientations and segmentation of bone (in red) and plaster (in orange) with Amira® 3.1;
D: Internal view of the 3D reconstruction of the right part of the fossil; E: Left lateral view of the 3D stereolithographic replica of the bone material without plaster; F: Reconstructed cranium with segmented bone and plaster
(Images: A Balzeau & P. Semal, RBINS).

Finally, the major scientific interest is that this approach offers new analytical possibilities and gives the opportunity to study previously unavailable morphological features. However, the application of CT methodology to anthropology still has some limits. Some are inherent to the methodology like partial volume averaging or limits in spatial resolution (e.g. Spoor & Zonneveld, 1995). Nevertheless, the accuracy and the reproducibility of the measurements and of the landmarks coordinates definition on both the 2D and 3D data have been tested and validated (e.g. Richtsmeier *et al.*, 1995; Coleman & Colbert, 2007; Schoenemann *et al.*, 2007). Settings have to be modified for the acquisition procedure in the case of specimens which are heavily mineralised in order to avoid or to limit imaging artefacts like overflow and beam hardening (e.g. Spoor & Zonneveld, 1994). Occasionally, it is not possible to obtain precise images with information about the internal structures for a fossil with a medical CT scanner. Other limitations are due to the specificities of anthropological studies. Global segmentation permits to obtain easily a 3D reconstruction. However, this model does not necessarily have a definition corresponding to the original spatial resolution of the CT dataset because of the variations of density of the different elements composing the images. Moreover, the user can possibly encounter difficulties to define precise outlines with automatic segmentation procedures. In most cases, it is necessary to use manual segmentation with as many different settings as necessary to accurately isolate the outlines of a structure, particularly when some sediment or some plaster is present or when the different parts of the fossil are characterised by large variations of density. Specific protocols are also needed to study precisely the internal morphology. In this context, the anthropologist needs complementary knowledge and competences in morphology, imaging methodologies and informatics since many software –sometimes very expensive– are necessary for the various applications in anthropology. During the project "The Neanderthal Tools", the Artecore application was developed in order to facilitate anthropological studies based on different types of numeric datasets. Artecore is very easy to use and reads data from CT and μ-CT scanners (DICOM, TIFF and PNG), polygonal models (STL, X3D) and simplified models from 6 digital photographs (PNG and JPEG). The user is able to define landmarks as well as angular, distance and surface measurements (Figure 4). Automatic and totally free manual segmentations are available for CT and µ-CT data to reconstruct 3D models. These procedures were developed to be particularly adapted to the specific needs of anthropological and palaeontological studies. Moreover, multiplanar reformatting of 2D datasets, "virtual" cutting of 3D models and possibilities of animation exportation are also offered. All coordinates and measurements data, as well as information for segmented areas, are readable on the 2D stacks and the 3D reconstructions resulting from the same acquisition and are exportable for analysis with other software, but also for collaborative purpose or as a support for repetitiveness of the study.

The Spy fossils were CT scanned on many occasions since the 1990s to perform different scientific analyses and/or to test technical developments (e.g. Louryan *et al.*, 1995; Balzeau *et al.*, 2005b; Bouchneb *et al.*, 2005; Mazurier *et al.*, 2005; ST4). Moreover, all recent applications are detailed in this monograph. Indeed, imaging methodologies are now a complementary tool for palaeoanthropological studies. It has allowed observation and quantification of internal features to complete the set of available information to discuss the laterality, the asymmetry and the attribution of the Spy remains (Rougier *et al.*, this volume: chapter XIX) and to analyse original features. In this volume, it is the case for the internal cranial anatomy of Spy I and Spy II (Balzeau, this volume: chapter XXIV-2) and for the Spy bony



- Ast D
- Ast G
- Bregma
- Cap Broca
- Endinion
- Lambda
- Por D
- Por G
- Sigmoide sup
- Sillon Cal sup

Name: Sillon Cal sup

Label a point: Set a point to label.

Figure 4. Definition of some anatomical landmarks on the Spy 10 STL model.
The model was produced with Amira® 3.1 by manual segmentation of the bone and plaster,
and visualised with Artecore 1.0 (Image: A. Balzeau, RBINS).

labyrinths (Crevecoeur *et al.*, this volume: chapter XXIV-4). CT and µ-CT have been used to study the "virtual dentition" of the Spy VI child (Bayle & Macchiarelli, this volume: chapter XX-3) and of Spy I and Spy II (Bayle *et al.*, this volume: chapter XXV-2). Applications to the post-cranial skeleton are also detailed, particularly for the internal structure of the humeri (Volpato & Macchiarelli, this volume: chapter XXVI-2) and of the femurs and tibia (Volpato *et al.*, this volume: chapter XXIX-2), as well as for the cross-sectional geometric properties of the long bone diaphyses (Hambücken, this volume: chapter XXVI-1; Shackelford, this volume: chapter XXIX-1). Finally, 3D models of the lower limb bones have been used to simulate the possible bipedal locomotion of the Spy individuals and to reconstitute the Spy motion pattern (Chapman *et al.*, this volume: chapter XXXII).

CONCLUSIONS

Imaging methodologies open new perspectives for the preservation and the scientific studies of fossil specimens. We have produced numerous and diverse applications in the framework of the anthropological reassessment of the Spy collections. However, this approach has to be considered as an additional tool in our large set of analytical possibilities. This application needs specific protocols, both for the acquisition procedures and the data treatment, in order to allow accurate and repetitive observation and quantification of the morphology of fossil hominid remains. In this context, the NESPOS database and the Artecore software developed during the project "The Neanderthal Tools" facilitate the sharing of information about the Neandertals as well as scientific analyses and collaborations.

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