Three-dimensional computer imaging of hominid fossils: a new step in human evolution studies

**Bertrand Mafart, MD, PhD; Gaspard Guipert, DEA;
Marie-Antoinette de Lumley, MD, PhD; Gérard Subsol, PhD**

Radiographic techniques have been used in paleoanthropology and comparative anatomy since the discovery of x-rays, and each leap of medical imaging technology has been accompanied by new applications in both fields. As early as 1906, that is, only 10 years after their discovery by W.K. Roentgen, x-rays were used to study the remains of a Neanderthal hominid found in Croatia.[1] However, the validity of conventional radiography for the study of fossilized human skeletons remains limited because of mineralization or the presence of sedimentary matrix, or both.[2]

The rapid development of medical imaging in the 1980s was quickly followed by applications in the field of paleontology.[3] However, it was the use of computed tomographic (CT) imaging in combination with 3-dimensional (3D) digital technology that paved the way for the revolution in paleoradiology.[4–7] Indeed, CT imaging made it feasible for the first time to analyze and obtain images of the endocranium, sinus cavities and inner ear embedded in soil matrix, which had not been identified on x-ray films,[7,8] enabling restitution of missing pieces, with minimal handling of extremely fragile specimens. In the last 10 years or so, radiologists, computer scientists and paleoanthropologists in the United States and Europe have formed multidisciplinary teams to study hominoid fossils using these virtual techniques. The first virtual paleoanthropology meeting took place in Liège, Belgium, in 2001.[9] Although not devoid of technical and ethical problems, this technology has opened a new era in the study of human fossils.[10,11]

3D CT IMAGING OF FOSSILS

Paleontological studies require high-resolution anatomical reconstruction. The evaluation of virtual and morphometric anatomy should be as accurate as direct examination of the original fossils (Fig. 1). High-definition industrial CT scanners provide such resolution (0.01 mm). Unfortunately, because of the small size of their acquisition chamber, these scanners can only be used for small anatomical specimens.[12,13]

Several factors can hinder the acquisition of CT images of fossil specimens.[14,15] Because of the process of diagenesis during fossilization and the geochemical features of the surrounding sediment, bone density may be greater than in life (> 3500 Hounsfield units [HU]), either uniformly or variably (Fig. 2). Scanning parameters used in clinical settings are usually unsuitable, and specific adjustment is necessary for each specimen.[14]

Cavities within the specimen often contain sediment and air. The density of the sediment matrix is variable and may be either greater than or similar to that of the bone itself. Partial volume effects may be observed at the interface with air. The window setting must be calibrated based on the mean values of the fossilized bone and on threshold effects so as to refine the boundaries between the bone and sediment, on the one hand, and

Mafart, Guipert, de Lumley, Subsol — Antenne du Département de Préhistoire du Muséum National d'Histoire Naturelle, Paris; Mafart — Faculté de Médecine Nord, Marseille, France.

Address for correspondence: Dr. Bertrand Mafart, 160 ave. Jacques Olive, 83000 Toulon, France; fax 33494159827; bmafart@aol.com

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between the bone and air, on the other. In early experience with CT imaging of fossil specimens, manual outlining of each slice was performed to separate the bone from the soil matrix, and then 3D reconstruction was carried out using the outlined sections.[16] Current software and acquisition of fine sections have eliminated the need for manual outlining by allowing automatic delineation of the bone from surrounding sediment using grey scale analysis.[14,17]

Image processing has been greatly simplified by the use of 3D imaging software packages, developed specifically for paleontological applications (e.g., Mimics and Magics). The most common method of 3D imaging is surface rendering, a 3-step process consisting of segmentation, interpolation and illumination by means of 1 or more virtual light sources. The fossil image can be rotated in virtual space, and distances and angles can be measured. In addition to this virtual display, digital 3D data sets provide the basis for the building of stereolithographic models using transparent resin that allows not only the depiction of the outer skull surface but also of internal anatomical details that are not seen in normal fossils.[18]

3D CT IMAGING IN PALEONTOLOGICAL RESEARCH

Study of brain evolution using human fossil specimens

Increasing complexity of brain structures is a cardinal feature of human evolution. Cranial volume and the imprint pattern of brain convolutions are important data for the study of this process. Until recently, because of the state of conservation of fossils or the presence of intracranial rock matrix, the only way to study the interior skull morphology was to create an endocranial cast called an endocast. Using 3D CT imaging, an *Australopithecus* skull from the Makapansgat site, South Africa, was reanalyzed. Values for its endocranial capacity were found to be lower than previous estimates.[16] Since then, cranial volume estimates of fossils have been systematically reassembled using 1-mm sections. 3D imaging has been used to reconstruct the missing parts of these skulls by comparison with direct measurement (Fig. 3).[19,20]

Study of facial sinuses and the inner ear

Little was known about pneumatization of the frontal and maxillary sinuses in nonhuman primates and hominoid fossils because of researchers' reluctance to break up skull specimens. 3D imaging (Fig. 4)[21] has made this destructive approach obsolete. Using this method, the development of the frontal sinus and its relation with the postorbital bar in fossils preceding *Homo sapiens* has been analyzed.[22] Findings show that maxillary sinus size correlates well with craniofacial size in all primates and in humans.[23] The phyletic position of some fossil primates has been accurately defined by studying the ethmofrontal sinus measurement.[24]

The relation of verticalization of the head with acquisition of a permanent upright 2-legged posture, morphological evolution of the skull and morphology of the inner ear is complex.[25–27] Visualization of these intraosseous structures has been feasible only since the advent of CT imaging. Analysis of 3D reconstructions provides new evidence supporting speciation.[27–29]

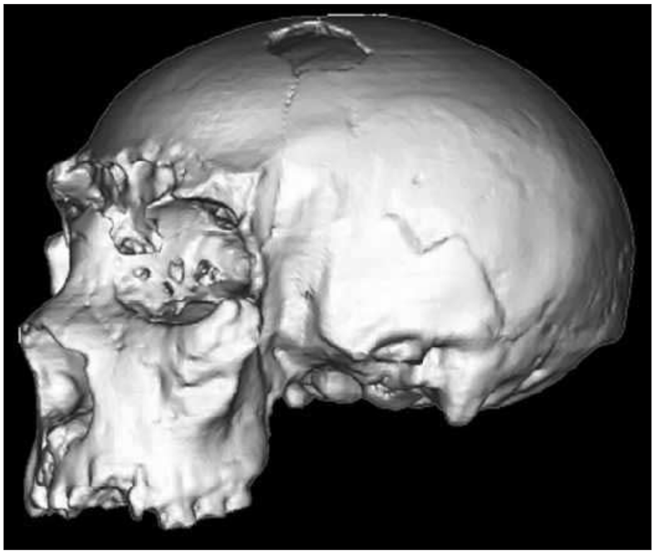

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FIG. 1: Complete virtual reproduction of the Saccopastore 1 skull, Italy (ca. 120 000 BC). This specimen is housed in the Museum of Anthropology "Guiseppe Sergi," Department of Animal and Human Biology, University of Rome "La Sapienza," Rome, Italy.

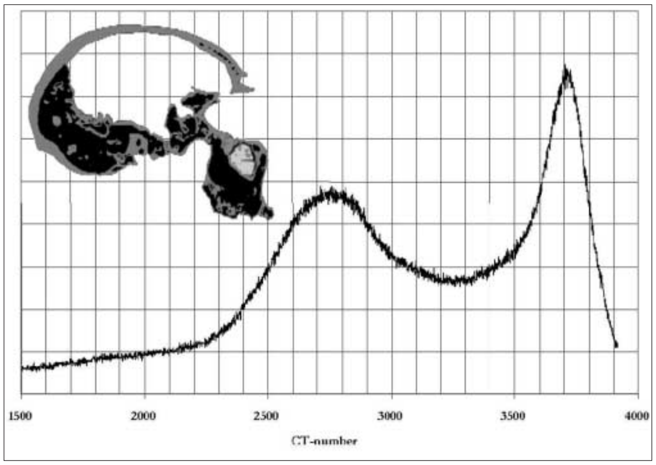

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FIG. 2: Attenuation spectrum (pixels per computed tomography [CT] numbers) of Saccopastore 1 shows a bimodal distribution of density; the left peak (phase 1) corresponds to the fossilized bone and the right peak (phase 2) to the stone matrix.

Reconstruction of fragmented and incomplete fossils

Fossilized hominid skulls are several million years old. During the extremely long taphonomic process that they have undergone, fracture and deformity can occur because of soil movement. Until now, reconstruction has been done manually using various materials (adhesives, plaster, plastic putty) to fill in missing areas. These techniques are not reliable and depend on the quality of the specimen, and serial replication is difficult. Currently, virtual reconstruction guided by computed tomography not only allows testing of every possible configuration but also a comparison with other contemporary fossils to evaluate morphological similarity (Fig. 5, Fig. 6). Virtual reconstruction with the correction of skull defects is also feasible. Rapid prototyping has been used to generate replicas of the various virtual configurations with high accuracy.[13,30,31]

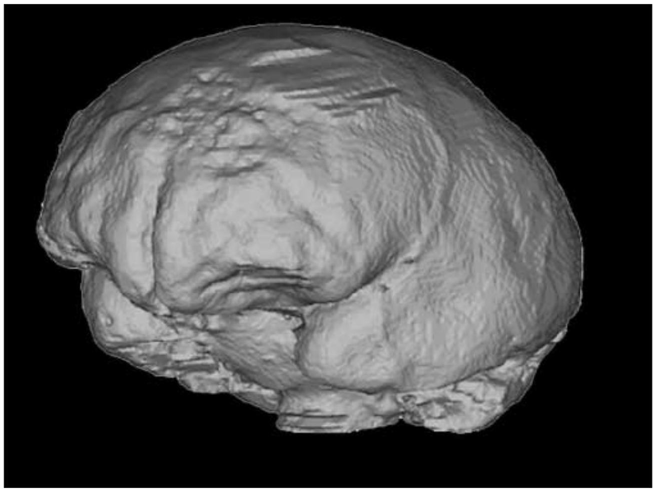

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FIG. 3: Virtual endocast of Saccopastore 1.

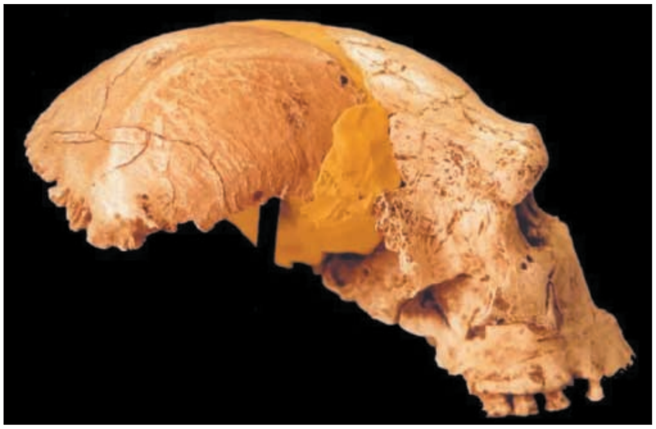

FIG. 5: Lateral view of the Arago XXI skull, France (ca. 450 000 BC). The face and the right parietal bone are preserved. This specimen is housed in the Centre Européen de Recherches Préhistoriques de Tautavel, France.

Skull study in primatology and paleoanthropology

Metric comparison of human fossils has long relied on more or less sophisticated statistical analysis of distance and angle measurements between anatomical landmarks. Recently, geometric morphometry has enabled a more global approach to the analysis of shape differences using techniques such as the Procrustes projection and “thin-plate splines.”[32] However, the use of these methodologies is often limited to 2D analysis of CT images or to a variable number of points extracted from 3D images.[26,33–36] New techniques are now being investigated to evaluate integration of the entire 3D surface of the skull into phylogenic analysis.[37–39] This process is expected to be challenging. Technical image analysis will require highly reliable automatic

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FIG. 4: Virtual reproduction of Saccopastore 1 shows the left maxillary sinus volume.

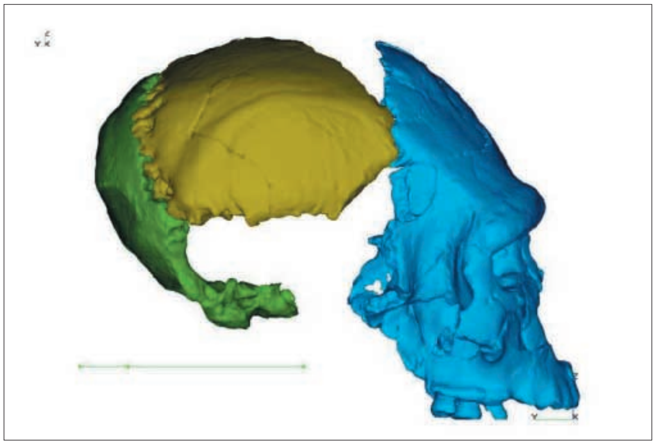

FIG. 6: Hypothetical computer-assisted reconstitution of a European *Homo erectus* skull combining the Arago XXI face after virtual correction of taphonomic changes, the mirror image of the Arago left parietal bone and the Swanscombe skull occipital bone, England (ca. 400 000 BC). This latter specimen is housed in the British Museum, London.

point extraction. Morphometric analysis will require development of computer codes to align homologous cranial structures and quantify their variations and defects in terms of a reduced number of parameters (Fig. 7, Fig. 8). Analysis of paleoanthropological statistics will require new mathematical tools to model the evolution of anatomical structures and to assist in the differentiation of intraspecies variations from interspecies variations that have significant evolutionary implication. Because of these problems, morphometric analysis of 3D CT images in a global mode, namely, the surface and internal morphology of fossils, is still out of reach. However, it should be emphasized that 3D CT imaging has already allowed comparison of skull ontogenesis between current primates,[40] Neanderthal remains and *Homo sapiens*.[41]

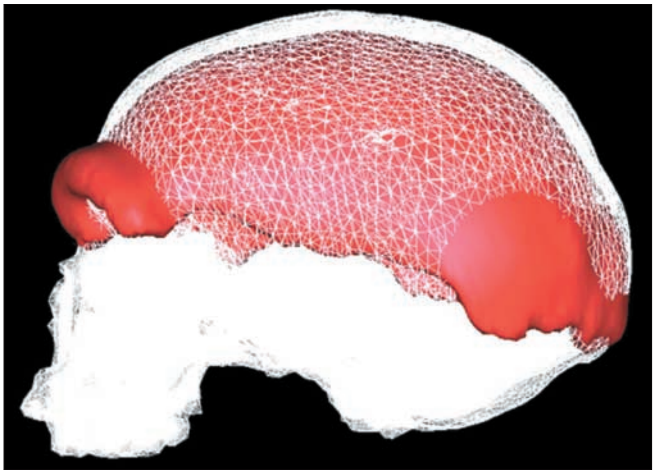

FIG. 7: Comparison of the cranial vault shape of an archaic *Homo sapiens* (Pataud skull, France, which is housed in the Institut de Paléontologie Humaine, Paris) and a *Homo neandertalensis* (Neanderthal, Germany, which is housed in the Rheinisches Landesmuseum, Bonn). The Pataud skull, which is well conserved, is the white image. The Neanderthal cranium, in red, is longer and less high.

OTHER APPLICATIONS FOR 3D CT IMAGING IN PALEOANTHROPOLOGY

Dissemination of scientific knowledge

Dissemination of knowledge to the public is an important responsibility of the scientific community. The study of human evolution lends itself well to scientific popularization, and 3D imaging technology is particularly attractive for the purpose of illustrating the main morphological changes in primates that led to modern humans. Reconstructions using 3D CT images are powerful tools for communication and education (Fig. 9).[42] As this teaching tool is likely to become more popular, 3D imaging will continue to broaden its scope of application from laboratory analysis to other computer-assisted techniques such as 3D display of archeological sites, paleoclimates, extinct wildlife and the paleoenvironment of prehistoric communities.

Facial reconstruction

Facial reconstruction is essential for the identification of human skeletal remains in forensic medicine. The conventional technique consists of sculpting a face onto a skull by reconstructing muscle and skin using clay or substances with similar properties. The same blend of

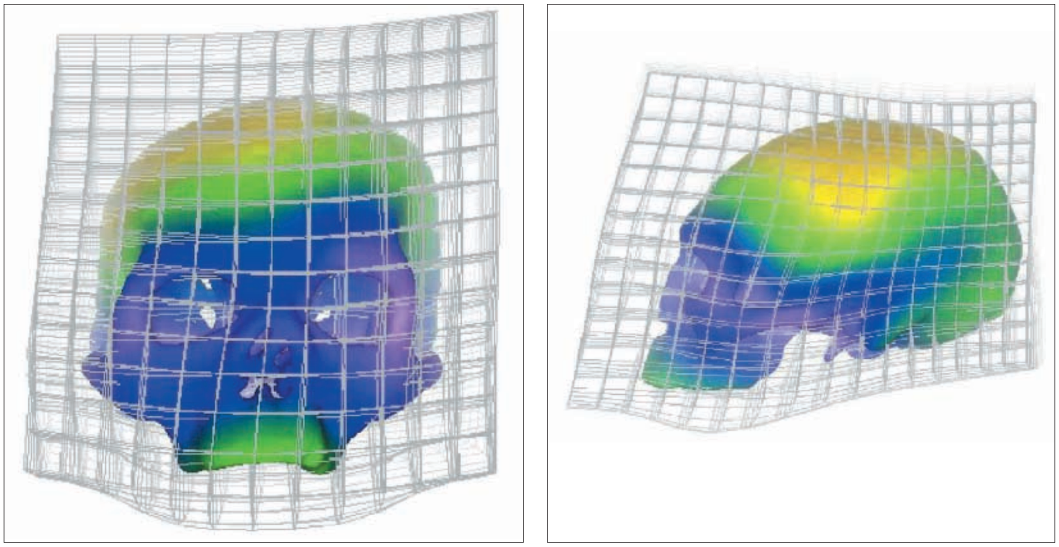

FIG. 8: Frontal (left) and lateral (right) view of a quantitative three-dimensional (3D) display of skull deformity. A comparison between a modern human skull and the Arago skull reconstitution. The 3D CT image of the modern human skull was included in a square matrix for reference. We then computed a 3D transformation based on the feature lines of the Arago skull. This method provides a quantitative overview of the differences between modern humans and *Homo erectus*. The significant frontal dissymetry is the result of taphonomic changes.

science and art has been applied to human fossils in order to obtain a more lifelike representation of the facial features. Average skin and muscle thickness determined from 3D images produced from CT data for living subjects have been used to develop computer software that can automatically generate reconstructed facial features.[43,44] Using this system, it is possible to produce and compare several faces on the same fossil.[45]

WHAT THE FUTURE HOLDS FOR COMPUTER-ASSISTED 3D IMAGING IN PALEOANTHROPOLOGY

The development of imaging technology has facilitated virtual reproduction of fossil specimens using computer-assisted 3D reconstruction. Some investigators have advocated free access to the databases of CT imaging of hominid fossils.[46–48] The Institute for Anthropology of the University of Vienna has made 3D CT data from 4 hominoid fossilized skull specimens available to all researchers. This universal access is beneficial to the entire paleoanthropology community but raises the issue of intellectual property rights. Until recently, imaging studies have been carried out on either cast models or, more rarely, on original specimens stored in museums or scientific institutions, located mainly in Africa in the case of the oldest specimens. Local researchers have been granted exclusive study rights within the framework of scientific partnership programs. Because there is a considerable time lag between the discovery of the fossils and the publication of the specimen, there has been a call for a "glasnost in paleoanthropology."[47] Gerhard Weber has suggested that funding agencies should require open access to fossils after a certain period, either in the form of images on the Web or on CD-ROM.[46]

CONCLUSION

The use of 3D imaging in the study of human evolution has just started. Progress in imaging technology and 3D image processing will provide paleoanthropologists with high-resolution virtual images of hominid fossils. Digital images will be acquired, stored and easily retrieved for analysis. In the very near future, 3D volume rendering and computer-assisted analysis of fossils will become the major tools for paleoanthropology studies.

FIG. 9: Computer-assisted paleoanthropology used as an educational tool to compare *Homo erectus* and *Homo sapiens* skulls.

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