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Digital Tools for the Preservation of the Human Fossil Heritage: Ceprano, Saccopastore, and Other Case Studies

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Abstract Computed tomography is presently one of the most powerful analytical tools available to investigate anatomy and morphology in palaeontological contexts. Apart from its important scientific implications, computed tomography must also be viewed as a tool to analyse the conditions of preservation of fossil remains, to plan restoration processes, and to consider fossils in terms of cultural heritage. A densitometric analysis is necessary in order to check the different geological components, the presence of infiltrations within the fossil volume, as well as the extension and presence of fractures and/or weakened surfaces. Furthermore, biomedical imaging allows non-invasive procedures of reconstruction and reproduction of the original morphology of the specimens. Digital anthropology must also be considered in view of the deontological problems associated with fossil record management and with the diffusion of science.

Keywords computed tomography · digital morphology · palaeoanthropology · museology

Introduction

Anthropology and radiological techniques have a long-standing collaboration dating as far back as the beginning of X-ray applications. Egyptology had a pioneering role in the use of plain radiographs, starting in the late 19th century and including its application to the study of mummies and other archaeological remains. This application was followed by palaeoanthropology at the beginning of the successive period [1]. Almost 100 years after

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the first radiological applications, computed tomography (CT) techniques became available to perform axial and complanar radiological scans. This development allowed scholars to obtain serial and undistorted images of the specimens, as well as to reproduce their inner volumes and surfaces. The inclusion of these biomedical diagnostic tools into anatomical and palaeontological frameworks rapidly followed (e.g., [8, 31, 32, 36, 37]). However, the resolution level at the time was not sufficient to compete with other, more traditional morphometric techniques and morphological observations. During the 1990s, technical engineering and informatic facilities enabled a more systematic application of CT in palaeoanthropology by providing a wide availability of dedicated software and the diffusion of expertise (e.g., [9, 25, 39–41]). CT analysis is now widely used to study the inner anatomical structures in fossil hominids, such as endocranial volumes [10–12, 19] and morphology [2, 30, 38], inner ear vestibular structures [24, 28], paranasal sinuses [18, 21], or bone cortical thickness [35]. Presently, CT is easily acknowledged as one of the most important techniques in palaeoanthropology, and computed imaging is presently a fundamental tool in the study of the hominid fossil record (e.g., [14, 15]).

Thus, the applications of CT in morphological studies are now well established. Nevertheless, computed imaging and tomographic analyses must also be considered as a tool to investigate the condition of preservation of the palaeontological remains directly. It is used to plan processes of reconstruction and restoration aimed at providing the best treatment of the fossil record. In fact, specimens are generally recovered in poor condition, fragmented, and rather fragile. After recovery, the fossil tissues are restored using artificial compounds. The fragments are tentatively assembled, with varying results depending upon the personal experience and skill of researchers and curators. The materials used for the reconstruction and preservation (glues, wax, plaster, synthetic compounds, etc.) permeate the fossil matrix more or less superficially, determining an invasive and often irreversible effect. The quality and the integrity of the fossils are clearly biased by these artificial compounds. Apart from the damage *per se*, these approaches are even more dubious considering the never-ending process of reconstruction and reinterpretation associated with any fossil specimen. Such reconstructions and reinterpretations depend upon the improvement of the information available and the historical changes of paradigms and perspectives. Furthermore, the classical methods are merely able to consider the superficial layers of the fossil structure, often ignoring the condition of preservation as well as the anatomical details of its deeper layers. CT and digital imaging are powerful tools that allow researchers to go beyond the external observation, physical handling, and mechanical treatment of the fossil remains. These considerations are particularly important in the special case of palaeoanthropology and in view of the value of the human fossil record.

In the present paper, we describe some applications of CT in palaeoanthropology, employed to perform digital surveys on human fossil specimens. As case studies, we will use data from the late Early Pleistocene calvarium from Ceprano (Italy, 800–900 Ka; [6]), the early Neanderthals Saccopastore 1 and 2 (Rome, Italy, 120 Ka; [16]), the Neolithic skull of Fonterossi (Italy, 6.5 Ka; [5]), and the cranium of the Late Pleistocene skeleton from Nazlet Khater (Egypt, 35 Ka; [4]).

Digital Study and Recovery of Fossil Remains

The CT radiographic technique is based on a planar X-ray beam, which tests the densitometric properties of a physical section. X-rays are projected all around the object by using a beam source turning around on a 360° circular trajectory. The attenuation value of each volumetric unit is calculated by integrating the information obtained from all the directions. Each volumetric unit, or voxel, has the surface of the image smaller unit (pixel) and the depth of the slice thickness used in the CT scansion (mm). Using a greyscale, a single value of density is calculated for each voxel as a function of its specific *attenuation*. Attenuation is the property of a volume to decrease the quantity and energy of the X-ray beam, and it is influenced by density and by the molecular composition of the matter included. Generally, the standard densitometric units are called "Hounsfield units" (Hu) and range from −1000 Hu (air density) to 0 Hu (water density), up to a maximum of 3096 Hu. Applications to fossilized tissues require some specific procedures because of the usual biomedical calibration of the scanning machines (see [17, 26, 27] for further details).

Therefore, the densitometric profile is the first set of data available to study the composition of fossil remains. Histograms and curve fitting can be used to report, quantify, and compare the distribution of the densitometric values within the whole object. A graph reporting the frequency of each densitometric value can be called an *attenuation spectrum* and is specific for each sample (Fig. 1). Attenuation spectra can be smooth or not, according to the quality of the digital signal. A single component is expected to show an almost normal distribution of values because of quite gradual differences due to homogeneous variations in density around a mean value. According to this basic framework, each single component represents a different *phase* of the attenuation spectrum. Statistical parameters (mean, standard deviation, range, etc.) of the distribution provide general information on the specimen's structural composition and resistance (X-ray opacity). The presence of two or more densitometric components (phases) will result in multimodal distributions and peaks, which may be more or less distinct. If the components are very different in terms of structure, phases will appear more separated. Conversely, if components share similar densitometric properties, the respective distributions will overlap, hampering a good resolution of the different matrices. Glues and plaster can be very invasive in this sense, and the homogeneity of the attenuation spectrum can be seen as an indication of limited reversibility of the reconstruction process. Geological infiltrations can be often easily localized on the attenuation spectra, both when represented by heavy mineralized compound (high-density peaks) and by infiltrations of less cohering materials (low-density peaks).

A certain bias is represented by the *partial volume effect*. At the interface between different components (including the surface contact between fossil matrix and air), voxels will be associated with values averaged according to the volume occupied by each component. The resulting measure will be intermediate between the two real values, and the bias will be more evident for components with very different densities. The partial volume effect will be quantitatively proportionate to the surface/volume ratio, influenced by the extension of the fossil's external surface plus the extension of pneumatic cavities, diploic structures, and spongious layers. The higher the surface/volume ratio, the more the attenuation spectrum will be biased by the partial volume effect, forming a low-density tail on the densitometric distribution.

The first direct information available in using the attenuation spectrum is then the densitometric composition of the fossil remains. The following step pertains to the study of the physical distribution of the densitometric components. Knowing the general profile of the densitometric properties of the fossil remain, each single slide can be scored to assess where each densitometric component is localized. This can be done either by visual inspection or by using the quantification of the densitometric values. Attenuation spectra can also be computed for single slices, showing how the densitometric profile changes across the fossil volume in a given layer. The densitometric values can be plotted along

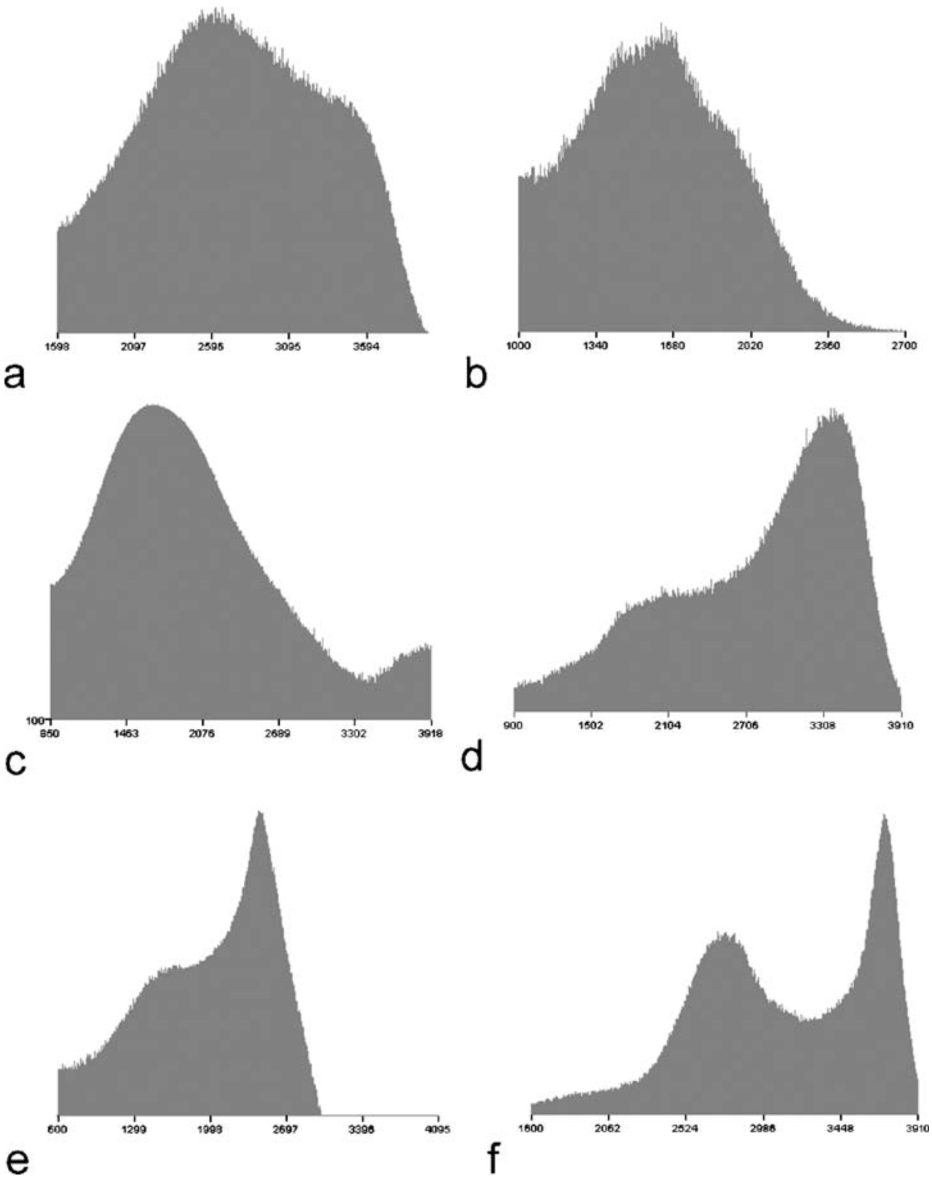

Figure 1 Attenuation spectra showing different levels of overlapping between fossil and geological matrices. The *x*-axis reports the densitometric values in attenuation coefficients (Hounsfield units), while the *y*-axis represents the abundance of pixels (often expressed in logarithms); therefore, the abundance of each phase is proportional to the surface covered by the graph in correspondence to each range of densitometric values. The sequence is ordered as a seriation ranging from more overlapped to more separated phases and relative peaks: (a) fresh bone (vault); (b) Saccopastore 2; (c) Fonterossi; (d) Ceprano; (e) Nazlet Khater; (f) Saccopastore 1.

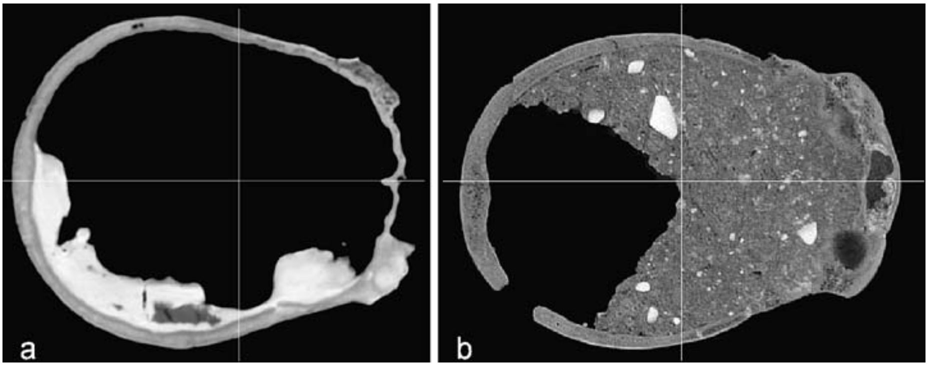

Figure 2 Transversal tomographic sections of Saccopastore 1 (a) and Fonterossi (b). In both cases, the endocranial cavity is partially filled with geological matrices. However, in the former, the fossil and geological matrices can be separated easily, while in the latter, the boundary between the endocranial table and the concreted sediments is less clear. The dense objects in the endocranial cavity of Fonterossi are stones.

defined linear transects as well, focusing on the specific transition between different anatomical areas. The densitometric profile will quantify the differences between each component according to the greyscale, suggesting the degree of separation between the different matrices (Fig. 2). Through automatic filters and semi-automatic segmentation algorithms, it is possible to represent the volumetric localization of the different phases (Fig. 3). It is worth noting that the resolution of the matrices does not strictly depend upon the age of the fossils. The densitometric composition and distribution are related to the conditions of the fossilization process and to the taphonomic history of the palaeontological

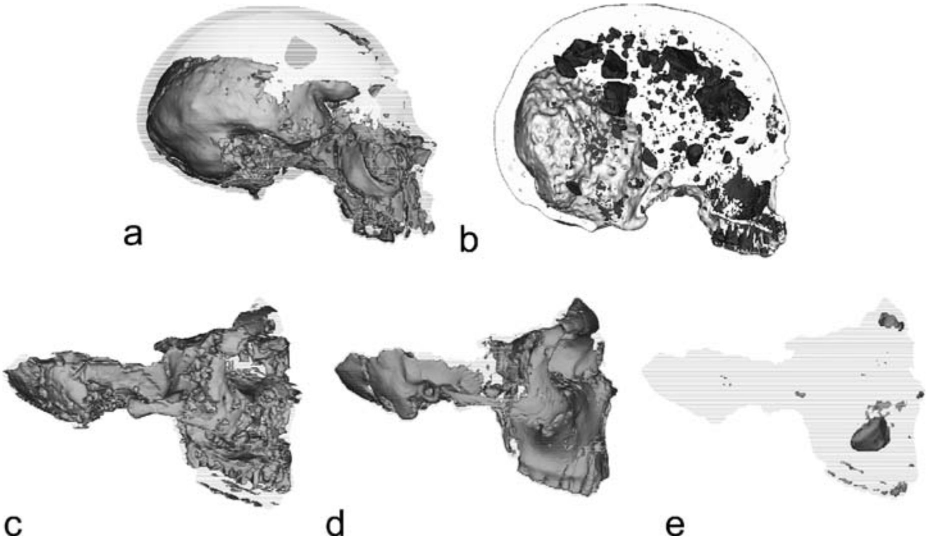

Figure 3 Above: the high-density components of the specimens shown in Fig. 2 are segmented, showing the geological matrices pervading Saccopastore 1 (a) and Fonterossi (b), respectively, in three dimensions. Below: low (c), medium (d), and high (e) density components found within Saccopastore 2 are shown.

findings. Hence, this information can be rather useful to gain inferences on the diagenetic processes, including the geological composition of the deposit and the position and movements of the fossil remain(s) within the sediments. Of course, the same information is useful to quantify and describe the qualities of a fossil specimen, such as resistance, weight distribution, physical loading and moments, and other variables that should be considered in order to optimize recovery, restoration, and handling.

Another application of tomography in dealing with fossil remains is the possibility to obtain digital surveys aimed at localizing fractures and areas of high fragility (Fig. 4). Superficial fractures can be traced within the inner volumes, and deeper fractures can be recognized and localized easily. Areas of high fragility can be defined according to the physical condition of the internal aspect of the specimen (multiple fractures, fragmented surfaces, etc.) or according to the presence of heterogeneous but well-separated densitometric components (e.g., presence of stones and other inhomogeneous inclusions).

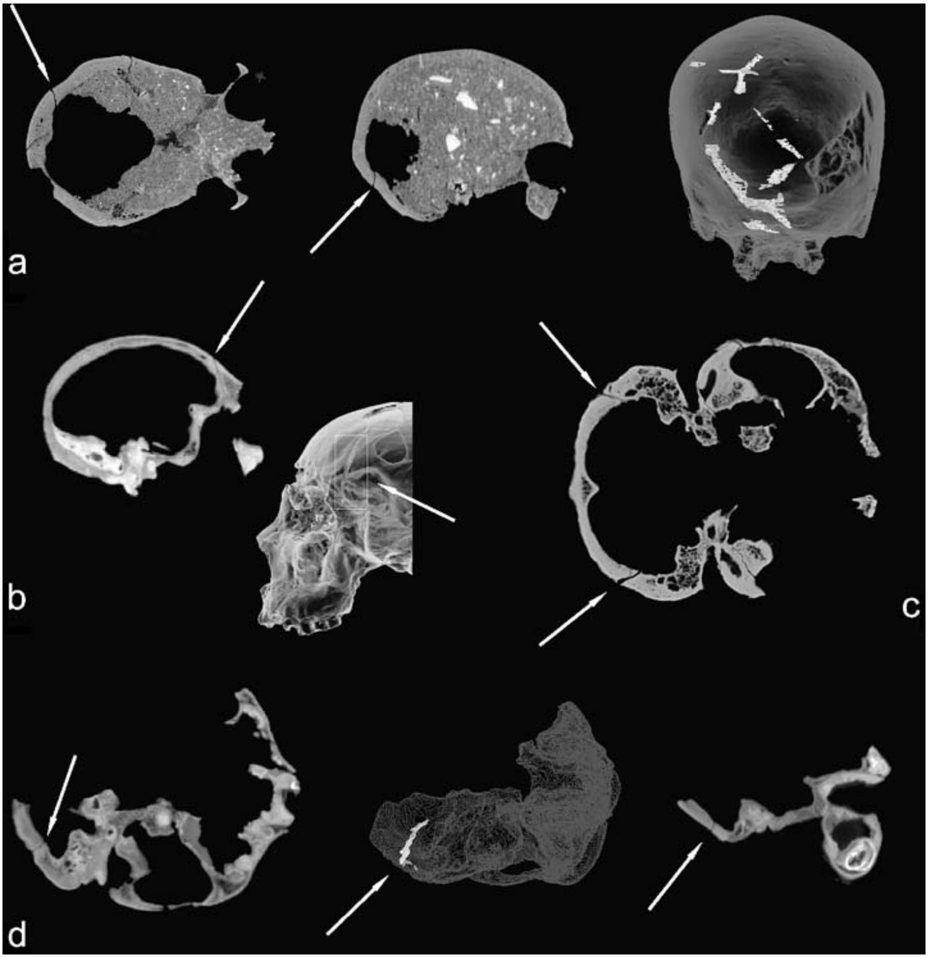

Figure 4 Lines of fractures evidenced by the digital replicas of Fonterossi (a), Saccopastore 1 (b), Nazlet Khater (c), and Saccopastore 2 (d).

Digital Moulding, Virtual Reconstructions, and Chimeras

Computed tomographic facilities can gauge a large amount of the morphological and physical information concerning a fossil remain. The specimen is sectioned and replicated in detail, allowing a full exploration and investigation of its anatomy (Fig. 5). The final product of the tomographic analysis and digital imaging is a model, useful to describe and synthesize a set of properties of the original object. Actually, biomedical imaging can be intended properly as a "digital histology" (see [3]), involving sections (slides), staining (segmentation), and visualization lens (software). The digital replica is thus available for any computed analysis and transformation, free from the physical constraints of the fossil remain.

Fossils are usually reconstructed by assembling the available fragments in a tentative way. A three-dimensional reconstruction of the original morphology is a necessary step in order to approach the morphology of the specimen with descriptive and analytical procedures. Physical reconstructions are always stepwise processes, and the fossil specimens have to undergo various stages of physical interpretation according to the changing information and paradigms. In fact, fossil reconstructions are based on a certain percentage of assumptions made *a priori*, applied to the available anatomical evidence. Fragments are assembled using plaster, glues, and other artificial compounds, which are more or less invasive and aggressive. In permeating the fossilized tissues and as a consequence of the more or less permanent cohesion with the fossilized surfaces, these materials can alter a certain amount of information. By contrast, the digitizing of the fossil fragments by CT and biomedical imaging makes it possible to operate a virtual assembling of the specimen without producing structural damages on the fossil remains (e.g., [29, 40]). It is also possible to rescue the original morphology distorted over time by the diagenetic forces (e.g., [6, 33]). This approach preserves the fossil remains and can be repeated

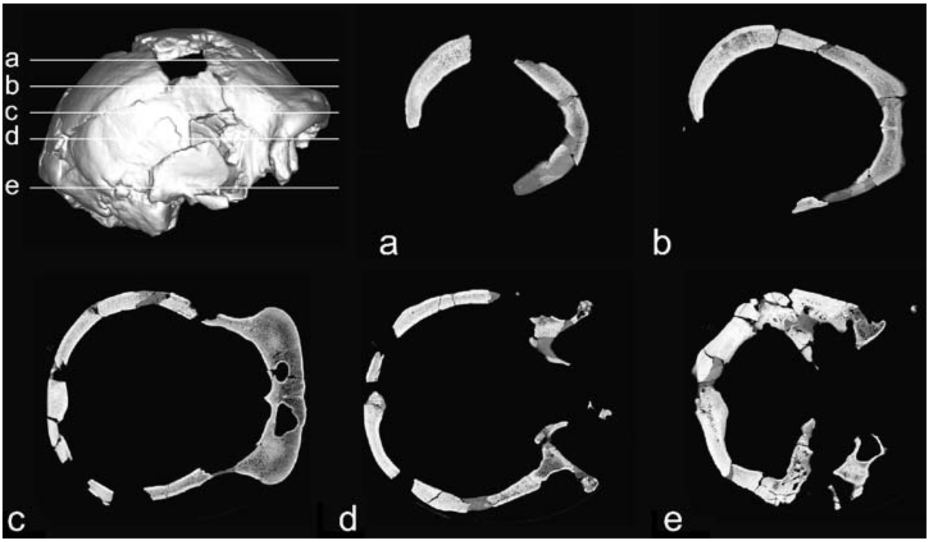

Figure 5 Transverse tomographic slices of the Ceprano calvarium, showing the inner and outer surfaces; plaster and other artificial matrices are partially visible in dark grey.

indefinitely and by different operators, promoting a continuous debate on the status of the reconstruction, as well as several alternative solutions. Furthermore, digital reconstructions can be computed also with the aid of surface and volume alignment functions that provide a more standardized and pragmatic tool for such purposes. Computed reconstructions also allow the use of the information relating to inner surfaces and volumes to perform the fragment alignment, which is generally scarcely considered (usually, it is not available at all) in the traditional physical assemblage.

Diagenetic biases and incomplete structures may be partially controlled with digital applications. Deformations can be quantified and tentatively balanced by using biomechanical analyses, geometrical approaches, and interpolant functions. In Fig. 6, a tomographic coronal section approaching the maximum cranial width of the Ceprano calvarium is outlined using the available inner and outer surface, and the diagenetic deformation analysed with deformation grids (Fig. 6). As reported elsewhere [6], each half of the endocranial outline was divided into 50 equally spaced landmarks. The two halves were superimposed using generalized Procrustes analysis by translation to a common centroid, scaling to unitary centroid size, and performing a rotation following a least-square procedure. Hypothesizing similar but opposite vectors of deformation for the two halves because of the diagenetic pressure, the average outline was computed and each half configuration was compared by using the thin-plate spline interpolant function and visualized through the deformation grids. The left side shows an almost vertical compression of the vault with lateral stretching at the temporal bone, while the right side mainly shows the bulging of the parietal area. Within this simple model, the first change (left vertical pressure) can be interpreted as the cause of the other changes (temporal stretching, right parietal bulging). This approach necessarily requires *a priori* assumptions and must be verified through models and experimental procedures; nevertheless, it may be a useful tool in exploratory surveys. The Ceprano case study, for instance, resulted in an inferred coronal profile of tent-like morphology, which appears more consistent than the original deformed outlines – one compressed and the other unnaturally angled – with other plesiomorphic features displayed by the calvarium.

It must be stressed that digital operations, which add information not formerly included in the geometrical and densitometric properties of the fossil itself, must always be interpreted merely as a description of hypotheses and inferences. Missing morphological

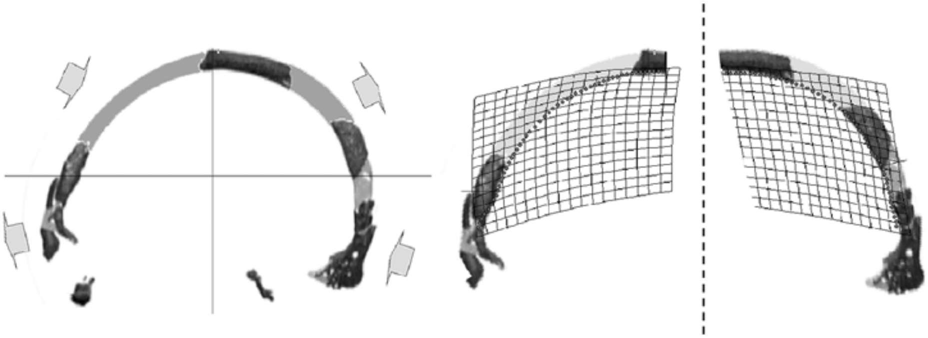

Figure 6 A coronal CT section of the Ceprano calvarium approaching the maximum cranial width (left) was used to obtain – by means of Procrustes superimposition and thin-plate spline interpolant function – a reproduction of the most probable original shape (right). Arrows and grids show the direction of the diagenetic forces and the resulting deformations, respectively.

regions can be reconstructed by using mirror imaging of the counterside elements (Fig. 7a). This process does not add information; it simply visualizes the complete structure using the available anatomy. Similarly, "chimeras" may be obtained by mixing parts from different specimens, with the explorative aim to reflect phylogenetic interpretations (Fig. 7b). Clearly, even this procedure improves neither the quality nor the quantity of the data already available. Analyses involving mirrored parts or chimerised individuals are but tautologies, in which the final results display the researcher's own scheme. Mirror-imaged reconstructions and heterologous chimeras should be used with a lot of caution in analytical contexts because they can add circularity to the scientific arguments and cause redundancy within the statistical and comparative framework. On the contrary, such digital interpretations (as well as their physical replicas, or "stereolithographies"; see [13]) have a proper application in museology, didactics, and popularization of science, as they are a very useful tool for the improvement of communication (even among scholars) and the dissemination of the palaeontological disciplines.

Some Deontological Comments

When the use of the X-rays to study fossil specimens found its early applications in anthropology, it was called *palaeoradiology* [1, 7]. The term *virtual anthropology* was introduced to describe the further development of the computed facilities [20]. Because of the current heterogeneous use of the word "virtual," the term *digital morphology* probably better describes and synthesizes the actual properties of these computed models and their possibilities.

Computed analyses and digital imaging provide a clear example of multidisciplinarity. Laboratories using these techniques need a set of competences that is hardly accessible to a single researcher. Anatomy and morphology, histology, computer sciences, statistics, physics, and engineering represent disciplines that are tied together in such approaches. A functional integration between these expertises can only be achieved through an adequate management of the research resources.

In general, ethical and deontological problems have followed each technological and cultural progress throughout the history of humanity. Laws and ethics generally come only after (i.e., never before) the violation of rights and the abuse of the newly discovered tools

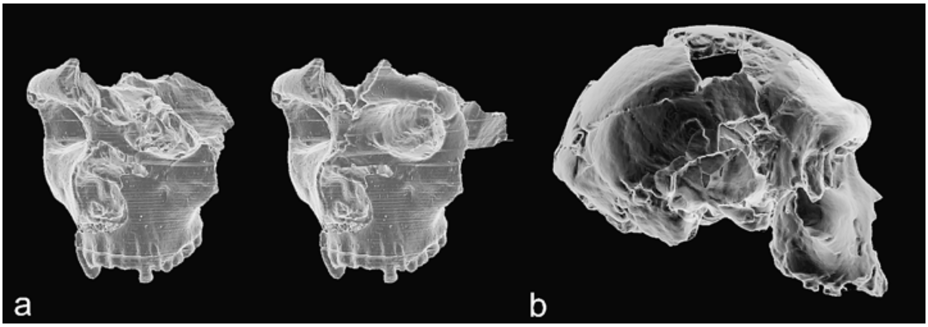

Figure 7 Fossil specimens can be digitally remodelled for explorative and/or museographic purposes by mirror imaging: Saccopastore 2 before and after its facial reconstruction (a); or using heterologous parts: chimeric specimen obtained appropriately combining the Ceprano calvarium and the face of the African cranium from Bodo (b).

and concepts. Anthropology knows what the historical products of the hegemonic approach of our socio-economical system are (even better than other sciences). Thus, to prevent errors that will cause useless regrets in the future, we should try to hypothesize what kind of problems might arise from the application of these new techniques.

One of the major problems of the digital era is the concept of "property." A digital object is presently more difficult to control in terms of rules and administration because of a lack of laws and experience. Objects representing local or even national heritages are easily exported out of the original countries in the form of digital information, thereby forming a new kind of abuse. A well-known example of this is industrial spying, but the same procedure can be applied also to other contexts ranging from archaeology to art. The transformation of the palaeontological information from mineralized tissues to digitalized pixels obviously requires new considerations regarding the relationship between high-tech and fossil-rich countries. The former are generally industrial countries (Europe, North America), while the latter are often developing countries (Africa, Asia). Computed analyses are usually expensive both in terms of direct costs (hardware, software, scans) and in terms of expertise and know-how. Consequently, an uncontrolled market of digital properties or even raw sharing of databases can lead to a deep exploitation of resources and information by high-tech institutions and the exclusion and isolation from the scientific international networks of the fossil-rich (but economically poor) counterparts. Digital morphology offers a very interesting tool to enable the sharing of data and projects (e.g., [34]), but cautions must be provided when the professional environment is not fully accustomed to the new deontological requirements. On the other hand, when controlled for such geopolitical problems, digital approaches represent one of the best examples of the new emerging international network in the current scientific scenario. The case study of Neanderthals [22, 23] is worth noting, as for biogeographical reasons, it provides a good example of cooperation between development of technology and safeguard of the fossil heritage.

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