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Modern techniques for ancient bones: Vertebrate Palaeontology and medical CT analysis

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ABSTRACT - In recent years, the application of three dimensional tomographic images in vertebrate palaeontology has contributed to improve and greatly expand the range of information derived from the study of fossilized bones. By using computed tomography (CT) scan and medical software it is possible to procure precise measurements, analyses of the internal structures and the material density gradient, carry out virtual restoration, with bones and teeth separated from lithological matrix, produce virtual casts of cavities (frontal sinuses, brains, inner ear) and hence provide greater definition in the search for diagnostic elements. It is therefore possible to obtain important information from the virtual models, that otherwise could not be acquired using conventional investigation techniques. Due to the versatility of these technologies, application of this kind of analysis is becoming crucial in many sectors of vertebrate palaeontology, especially in palaeoneurology, palaeopathology and in 3D reconstructions.

RIASSUNTO - [Tecniche moderne per ossa antiche: Paleontologia dei Vertebrati e analisi tomografiche mediche] - *La produzione di immagini tomografiche tridimensionali, applicata alla Paleontologia dei Vertebrati, negli ultimi anni ha contribuito a migliorare e ampliare enormemente la gamma di informazioni ricavabili dallo studio delle ossa fossilizzate. Molte osservazioni su reperti ossei sono complesse o impossibili da effettuare a causa del tipo di fossilizzazione o perché i fossili si trovano inglobati in matrici di sedimento difficili da rimuovere. Queste condizioni, pertanto, limitano notevolmente la capacità di analisi di un reperto. Attraverso l'utilizzo delle TAC e software dedicati è possibile superare queste difficoltà tecniche. Le immagini tomografiche virtuali, bi- e tridimensionali, consentono di indagare i reperti sia nelle loro componenti esterne che interne, eliminando il rischio di danneggiamento dei reperti originali e ricavando informazioni altrimenti non ottenibili con metodi di studio convenzionali. Con questo approccio è pertanto possibile operare su un osso fossile effettuando misure di precisione, analizzando le strutture interne, il gradiente di densità del materiale, le volumetrie, estraendo virtualmente le ossa e i denti dalla matrice di sedimento, realizzando calchi virtuali di cavità (seni frontali, encefali, orecchio interno), alla ricerca di elementi diagnostici.*

Data la versatilità di queste tecnologie, questi interventi sono diventati indispensabili in alcuni settori della Paleontologia dei Vertebrati, in particolar modo nella Paleoneurologia, nella Paleopatologia e nel campo delle ricostruzioni 3D.

INTRODUCTION

Computers and quantitative methods are currently fundamental tools in all branches of modern science, and palaeontology is not an exception. Nowadays, those technologies are used in many steps of the palaeontological research, from field work to data collection and visualization, and finally to morphometric analysis and data management. The term "computational palaeontology" was introduced in 1996 by Oyvind Hammer (Ashraf, 2011), a Norwegian palaeontologist and mathematician, to indicate the use of mathematical models, simulation, computer graphics and computers in palaeontology. A "classic" method for obtaining 3D data from a fossil, for making virtual simulations, visualizations and analysis, is through tomography (Sutton, 2008) (Fig. 1). Palaeontological science and radiological techniques have a long-standing collaboration dating since the discovery of X-ray (Branco, 1906; Zollikofer & Ponce de León, 2005). Almost 100 years after 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 (slices or tomographs), as well as to reproduce their inner volumes and surfaces (Spoor & Zonneveld, 1998; Zollikofer & Ponce de León, 2005; Coleman et al., 2010). One of the first fossils to be studied through X-ray CT scanning was the Eichstätt specimen of the famous *Archaeopteryx lithographica* von Meyer (1861) (Haubitz et al., 1988). This study used each slice singly, and was limited to fairly rough images. Afterwards, the first *Archaeopteryx* body fossil ever found, the London specimen, was scanned to gain information on the brain and inner ear (Alonso et al., 2004), which due to technical progress could be gleaned from high resolution 3D visualizations of the skull, both entire and in parts.

The inclusion of these biomedical diagnostic tools into anatomical and palaeontological frameworks is currently in rapid expansion.

From the virtual model it is possible to obtain important information that otherwise would not be obtained through conventional analysis techniques, such as internal architecture of the bones, extraction of skeletal parts embedded in matrix of sediment, molds of soft tissues (brains and frontal sinuses) (Figs 1-4).

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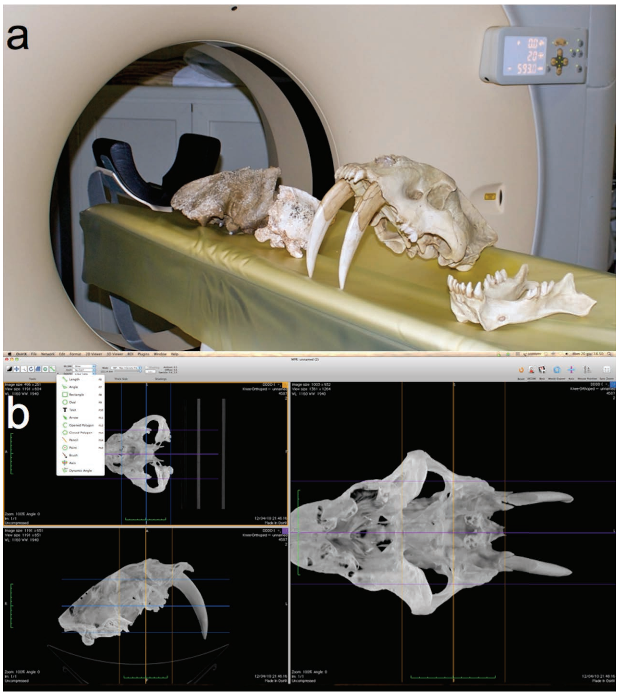

Fig. 1 - a) Fossil skull scanning in the Dipartimento di Radiologia of the Hospital M.G. Vannini, Rome. b) Screen display of Osirix 3.9.4 software, during the processing of 3D tomographic images.

Moreover, the virtual model can provide data about the bone density, the dental enamel structures and enable to test the virtual assemblage and remodelling of skeletal fragments without manipulating the original elements with the risk of damaging them (Rossi et al., 2004; Mallison, 2011; Iurino et al., 2013). In addition to the visualization of all these components it is possible to take measurements of areas, distances, angles and volumes of shares both superficial and internal ones. Digital data in the form of complete vertebrate skeletons, either as complete scans of mounted specimens or as digital skeletal mounts, can be used for estimates of the volume, total mass, mass distribution and centre of mass position of extinct animals (Gunga et al., 2007, 2008). In addition, digital files can be used for all kinds of shape analyses, including full surface representations or just selected data points for morphological landmark studies (Lohmann, 1983; Bonnan, 2004; Brombin et al., 2009). In the last few years and even more in the next, these investigation methods have been applied not only in research but also in the restoration of some problematic fossils. Currently, many natural history museums have large palaeontological collections of the early years of the last century. In those years, the techniques of restoration for the exhibits were particularly invasive, with the skeletal structures and architecture compromised by the introduction of metal bars within bones (Fig. 2). At the present time, before the restoration of these old collections, it is recommended to perform X-rays or CT scans for defining the types of interventions that have been made in the past (Iurino, 2010).

The production of tomographic images also lends itself to the realization of osteological database, easily accessible and viewable by a great audience directly from the internet platform, thus contributing to the rapid diffusion of materials essential for comparative studies. This could allow combining data from world-wide collections by email, without requiring one person to undertake expensive travels (Mallison, 2011).

Therefore, 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. Recently these technologies have been widely employed in some particular branches of palaeontological sciences, especially in palaeoneurology, with the production of virtual endocasts (encephalic casts), in palaeopathology, for the identification and interpretation of trauma and diseases found on both human and animal fossils, and in the field of reconstructions of 3D models.

3D DATA ACQUISITION AND IMAGE PROCESSING

The main limitation of radiography is that all the structures of the object are superimposed onto a single image plane, where extraneous structures may obscure important findings (Saab et al., 2008). Unlike conventional radiography, CT (computed tomography) is a medical imaging procedure that utilizes computed-processed X-ray to produce distinct images from multiple planes (or "cuts") through the object (Bushong, 2004). Accordingly, the word "tomography" originates from the Greek word "tomos", which means "to cut."

In its basic form, a CT scanner consists of an X-ray source and several detectors, half of them rotating around the sample; medical scanners rotate the source/detector pair, while scanners for inanimate specimens rotate the sample on a stage. Volume CT is the scanning mode normally used in a palaeontological context; here the detector is a two-dimensional charge-coupled device (CCD) array used to capture digital radiographs of the sample from many rotational positions, typically every degree of a 1808 rotation (Murray et al., 2008; Sutton, 2008). Tomograms perpendicular to the axis of rotation are derived from this data computationally, using a filtered back projection algorithm to implement an inverse Radon transform (e.g., Kak & Slaney, 2001). This scanning methodology, formally 'X-ray computed axial tomography', produces isotropic data (voxels are cubic), which is ideal for visualization. Many other CT variants exist; see Ketcham & Carlson (2001) and Kalender (2006) for an exhaustive treatment.

The resolution (voxel count) of a tomographic dataset from an axial scan is directly proportional to detector resolution, but the range of absolute voxel sizes a scanner can achieve depends on the physical configuration and precision of the device, and varies from millimetres to less than one mm (Sutton, 2008). Within these limits, absolute voxel size is proportional to the maximum sample dimension perpendicular to the rotational axis, as tomogram computation requires each radiographic image to contain all the sample which lies in the tomographic plane. This requirement restricts resolution from fossils inside flat slabs of rock; axial scanning is best suited to near equidimensional samples, or elongate samples that can be rotated around their long axis and scanned in sections down their length. Dierick et al. (2007), however, have demonstrated a 'region of interest' scanning technique which avoids this stricture, at least for fossils in the relatively homogenous material of amber (Sutton, 2008).

The derived image is composed of information containing zones, called pixels (typically in a matrix with a lateral dimension of 256 or 512 pixels). Each pixel corresponds to a specific, three-dimensional location inside the specimen and has an "attenuation value," expressed as Hounsfield units. This definition of the amount of X-ray photons "perceived" at a particular "point" in the specimen is expressed as a comparison to the effect of water (standardized as equal to zero) on X-ray penetrance. The formula is expressed as the difference between the attenuation of the area of interest and that of water. Thus, the difference is divided by the attenuation of water and multiplied by 1000. In this system, air has a value of -1000 Hounsfield units, while +1000 Hounsfield units is found with dense bone. The density of some fossil materials may, however, complicate this issue, reaching up to +3000. One approach to fossils is utilizing 120 kV, 200 mA, four second exposures with a 4000 unit window width. The best visualization appears to be between 1.566 and 2.188 Hounsfield units. The wider the window setting, the greater the information loss (Rothschild & Martin, 2006). Because contemporary CT scanners offer isotropic or near isotropic resolution, display of images does not need to be restricted to the conventional axial images. Instead, it is possible for a software program to build a volume by "stacking" the individual slices one on top of the other. The program can then display the volume in an alternative manner.

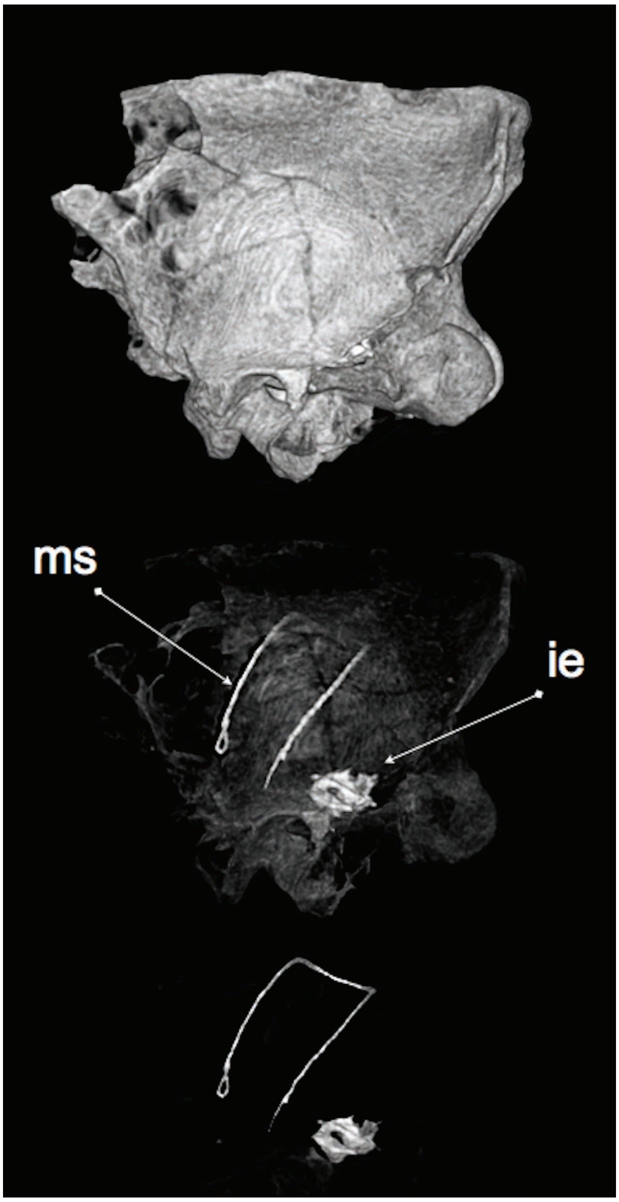

Fig. 2 - The software elaboration shows the presence of the metal support (ms) and the inner ear structure (ie) in *Homotherium latidens* (Owen, 1846) skull from Pirro Nord (South Italy, Early Pleistocene).

Below the main stages of CT images processing are listed:

Surface rendering: a threshold value of radiodensity is set by the operator (e.g., a level that corresponds to bone). From this, a three-dimensional model can be constructed using edge detection image processing algorithms and displayed on screen. Multiple models can be constructed from various thresholds, allowing different colours to represent each anatomical component such as bone, muscle, and cartilage. However, the interior structure of each element is not visible in this mode of operation (Udupa & Herman, 2000).

Volume rendering: surface rendering is limited in that it will display only surfaces that meet a threshold density, and will show only the surface that is closest to the imaginary viewer. In volume rendering, transparency and colours are used to allow a better representation of the volume to be shown in a single image. For example, the bones of the pelvis could be displayed as semi-transparent, so that, even at an oblique angle, one part of the image does not conceal another (Udupa & Herman, 2000).

Image segmentation: where different structures have similar radiodensity, it may become impossible to separate them by simply adjusting volume rendering parameters. The solution is called segmentation, a manual or automatic procedure that can remove the unwanted structures from the image (Shapiro & Stockman, 2001).

HISTORICAL BACKGROUND

> "*... by far the greatest technical advance was made when radiology began to be used in the examination of anthropological and paleontological materials.*" ... "*The Roentgenological examination, moreover, has the great advantage in that it permits the investigator to examine bones without destroying them and to inspect mummies without unwrapping them.*"
>
> (Sigerist, 1951)

Palaeoradiology is the study of bioarcheological and palaeontological materials using modern imaging methods, such as X-ray radiography, computed tomography (CT), magnetic resonance imaging (MRI), micro-CT and synchrotron X-ray tomographic microscopy (SRXTM) (Chhem & Ruhli, 2004). The first reported X-ray study

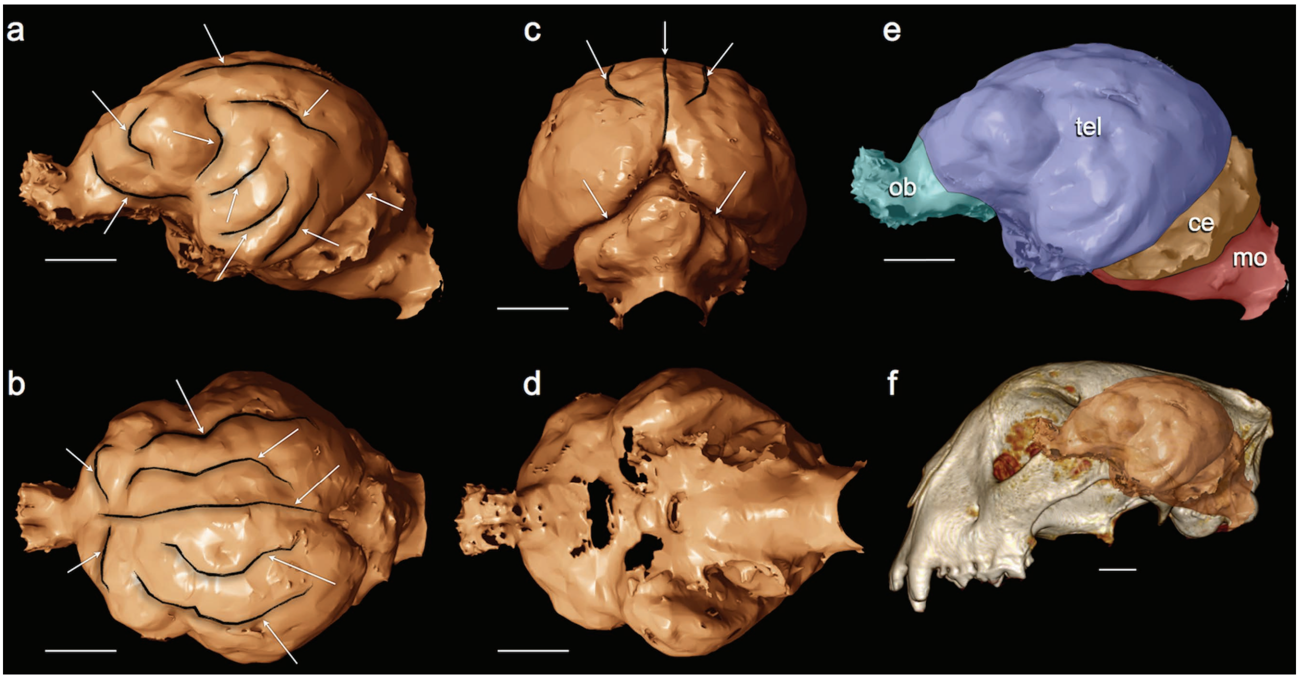

Fig. 3 - a-d) *Acinonyx jubatus* (Schreber, 1775) endocast with in evidence the main sulci (furrows: see the arrows). a) lateral view, b) dorsal view, c) nuchal view, and d) ventral view; e) chromatic division of the main areas of the brain: ob) olfactory bulb, tel) telencephalon, ce) cerebellum, and mo) medulla oblongata; f) transparent skull of *A. jubatus* (from the osteologic collection of the Museo Civico di Zoologia of Roma) with endocast highlighted. Scale bars = 2 cm.

of human and animal mummies was performed by Koenig (1896). Early publications on X-ray studies of mummies and skeletal remains include descriptive techniques, anatomy, and some of the palaeopathology results. In those early stages of X-ray technical development, radiological studies were performed on mummies for several reasons. X-ray images of the contents and the wrapping often were taken to distinguish authentic mummies from fake ones, to evaluate the bone age, to detect skeletal diseases, and to search for burial goods (Moodie, 1930; Chhem, 2007). The most common geographic origins of mummies were Egypt and Peru, which served as materials for the first monography of palaeoradiology published in 1930 (Moodie, 1930). X-ray studies were occasionally performed to evaluate bones and teeth in Palaeolithic human fossils (Gorjanovic-Kramberger, 1901, 1902).

The availability of CT scanners in the early 1970s and the ongoing development of CT methods in the subsequent decades provided better visualization of the anatomy and of palaeopathological lesions in mummies and in ancient skeletal remains. In August 1974, two cerebral hemispheres were retrieved from an autopsy performed at the Medical Science Building at the University of Toronto by an international multidisciplinary team sponsored by the Academy of Medicine, University of Toronto, the Royal Ontario Museum in Toronto, and the Paleopathology Association in Detroit, Michigan (Hart et al., 1977). The first CT scan of Egyptian mummy material was performed on September 27th, 1976 at the Hospital of Sick Children in Toronto on the preserved and desiccated brain of Nakht, a 14 year old weaver who died 3200 years ago in Egypt (Lewin & Harwood-Nash, 1977a, b).

Nowadays, the newer generations of CT scanners with their three-dimensional and surface rendering capabilities can create 3D face reconstructions, or whole-body reconstructions of mummies, fossils and other palaeobiological remains (Chhem, 2008).

CT ANALYSIS IN PALAEONEUROLOGY

Skull bones, especially those involved in neurocranial anatomy, do not grow by self-expansion, but in response to cerebral growth pressures (Moss & Young, 1960; Enlow, 1990). The growth of cerebral mass separates the bones at the sutures, inducing osteoblasts to “fill the gap” and promoting ectocranial bone deposition, while on the endocranial surface the osteoclastic processes allow a shift in the bony elements. This correspondence between the inner table and the brain makes the endocranial cavity a very useful cast of the cerebral surface and volume, as well as of the supporting structures like vessels and meninges (Figs 3-4). Small structures can leave large traces, and conversely large structures can leave no imprints at all, depending upon species-specific, as well as individual and local, anatomical conditions. Thus inferences about cerebral anatomy can be made directly from palaeontological remains. This approach is the basis of palaeoneurology, namely the examination and analysis of natural or artificial endocasts reproducing details of the external morphology of the brain (Falk, 1987; Bruner, 2008) (Fig. 3).

The basic information available from an endocranial cast is the shape of the brain itself, that is the geometry of the entire structure, its general morphology, and the spatial relationships between each single cerebral district (Fig. 4). Because of the tight structural relationship between the brain and the inner table of the vault, the endocranial

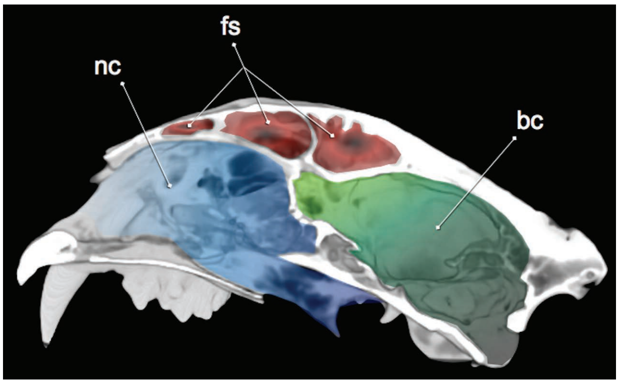

Fig. 4 - Virtual section of *Panthera pardus* (Linnaeus, 1758) skull (from the osteologic collection of the Museo Civico di Zoologia of Roma); in evidence the most important internal cavities: nc) nasal cavity, fs) frontal sinuses, and bc) brain cavity.

surface is a useful record of the pre-existent soft tissue, such as the arterial networks and the venous drainage. Of course, a trace is not the object itself, but a partial information. What can be detected on the bone is the trace of something that was there. In contrast, the presence of what cannot be detected cannot be excluded. The vascular vessels leave their traces proportionally to variables such as the endocranial local pressures, or the thickness of the interposing tissues. Their network is related to the main cerebral functions and requirements, namely energy supply and thermoregulation. Energy means metabolism, thus biochemical power and activation of neural processes (Holloway et al., 2004; Bruner, 2008).

A palaeoneurological approach has a real analytical background in the experimental advances and database of the neurosciences. Neontological studies provide the best complementary information to compare palaeontological data with in vivo systems, allowing inferences about functional processes based on the morphological domain. As in palaeontology, imaging and biomedical engineering currently represents an incredible source of information. Using techniques like Magnetic Resonance Imaging (MRI) or Positron Emission Tomography (PET) it is possible to quantify and describe morphology and physiology with extreme resolution and details, allowing direct analyses not biased by post-mortem and dissection consequences (Bruner, 2003, 2008; Bruner & Manzi, 2006).

The smoothed and heterogeneous morphology of the brain makes it very difficult to localise and characterise many structures and features. Traces are often hardly recognisable, and the anatomical references are not represented by landmarks but rather through areas with no clear boundaries. The detection of some traits is also dependent upon the different orientation of the casts, the shading factor, or the possibility to touch the specimen. The only reference plane is the midsagittal one, that is rather biased by cerebral asymmetries. What should be constantly considered is that the endocranial reconstructions are models, either physical or virtual, with specific resolution limits related to techniques or problems concerning the state of preservation of the specimens. Therefore we must be cautious when inferring brain morphology from endocranial analyses, which mainly describe the partial variability of endocranial features and not the original cerebral structures themselves. Anyway, the palaeoneurological analysis of the endocranial morphology still represents the major source of direct knowledge on the evolution of the cerebral structures. The large amount of information available from fossil endocasts will be fully exploited only by considering their functional meaning and the structural processes involved (Bruner, 2003, 2008; Holloway et al., 2004; Zollikofer & Ponce de León, 2005).

Thus, endocasts must inevitably be a significant part of any study of brain evolution in fossil vertebrates such as jawless fish (Gai et al., 2011), flying reptiles (Witmer et al., 2003), dinosaurs (Brochu, 2000) and in particular on fossil hominids and humans, as amply demonstrated in literature (e.g., Manzi et al., 2001; Holloway et al., 2004; Bruner, 2007; Berger et al., 2010). The applications of shape analysis (Richtsmeier et al., 1992; Rohlf & Marcus, 1993; Slice, 2004; Zelditch et al., 2004) and computed tomography (Zollikofer et al., 1998; Zollikofer & Ponce de León, 2005) to the study of endocasts deeply improved and enlarged the available palaeoneurological and consequently palaeontological data.

CT ANALYSIS IN PALAEOPATHOLOGY

Palaeopathology is the study of ancient disease processes in skeletal remains using a spectrum of methods consisting of gross observation and radiological, palaeohistopathological, biochemical, isotope, and DNA studies. Each of these tests carries both advantages and limitations, and almost all require the irreversible destruction of the specimen. In contrast, X-ray study is an appealing option because it can be performed without any significant damage to the specimen (Rothschild & Martin, 2006; Saab et al., 2008).

Dental abnormalities, fractures, trauma, supernumerary teeth, tumours, tuberculosis, and bacterial infections are some of the diseases that leave traces on fossilized skeletons, but their identification is not always possible by external observation on the specimen (Tinalli & Rook, 2007; Iurino et al., 2013). The analysis of their structures is influenced by the degree and type of fossilization, the state of preservation and the fossil size. To overcome these difficulties, the digital viewing can be an extremely useful tool. X-ray study may bring a wealth of information on bone and teeth diseases, by allowing the "visualization" of the internal structure of the bones, without the inevitable alteration and/or destruction of the specimen. Despite their non-destructive properties, radiological studies are unfortunately still underutilized in the analysis of ancient bones (Saab et al., 2008).

All bone lesions can be categorized as destructive, formative, or more commonly a combination of both (Resnick & Kransdorf, 2005). Their shape, size, number, and location within the bone and their distribution within the skeleton are important considerations in the differential diagnosis. Several dental and bone anomalies are able to provide important information on metabolism, physiology, ontogeny of fossil animals, and on the origin and spread of particular pathologies in the past.

For a better X-ray interpretation, many diagnostic imaging software provide a wide range of digital tools

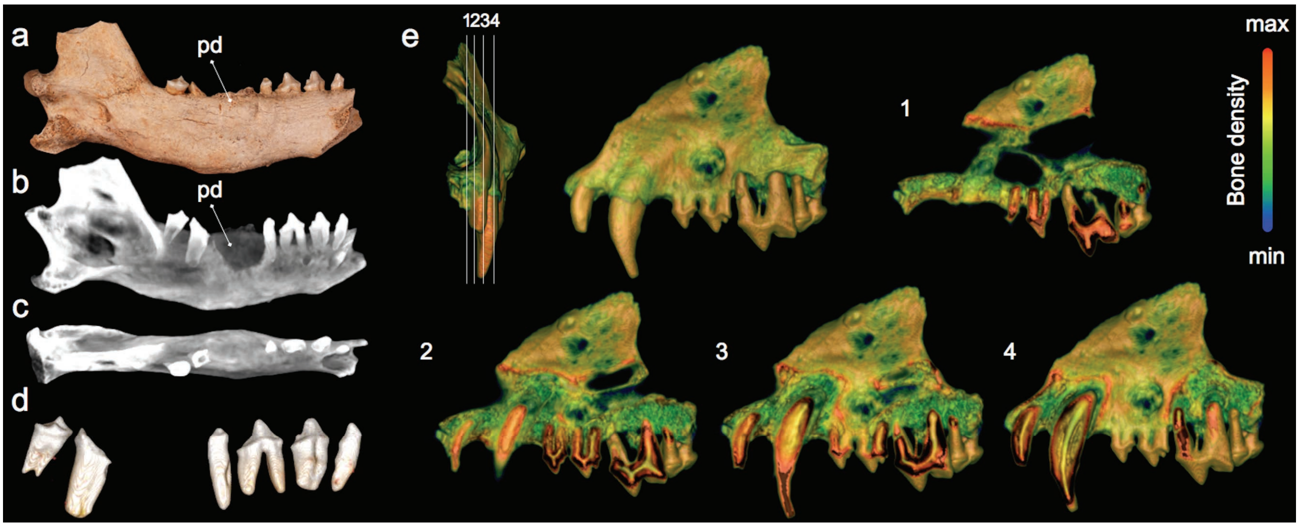

Fig. 5 - a-e) Pathological mandible of a Late Pleistocene *Cuon alpinus* (Pallas, 1811) from San Sidero (Apulia, South Italy): a) photography of the mandible in lingual view, with the periodontal disease in evidence (pd); b) tomographic section of the mandible with the periodontal disease in evidence (pd); c) tomographic image in occlusal view; d) teeth virtually extracted from the mandible; e) tomographic image of the maxilla in frontal (left) and lateral (right) view; 1-4) section planes of the fossil maxilla in lateral view.

that can accelerate and facilitate the recognition of bone pathology (Rothschild & Martin, 2006; Sutton, 2008). Among the different image filters, the skeletal density gradients applied to 2D and 3D models reveal any trace of fractures, swelling and abnormalities of the internal and external structures of the bones (Rossi et al., 2004; Iurino et al., 2013) (Fig. 5). Hard objects can be highlighted and isolated because of their different density. Teeth enamel is one of the hardest organic materials in nature, and due to this feature the software are able to separate them from the less dense bone structure. Therefore, it is possible to evidence the teeth getting the bones transparent, and to produce high-quality 3D images of dental roots, erupting or still unerupted teeth (Bastl et al., 2011) (Fig. 5a-d). The classification of the fossil mammals in palaeontology is essentially based on dental morphology (Benton, 2005; Kemp, 2005), thus the three-dimensional tomographic analysis of teeth is a valuable diagnostic tool.

An interesting example of tomographic analysis comes from the scan performed in 2001 on the mummy's body of the iceman Ötzi. The investigation showed the presence of a hard object, highly radiopaque (arrowhead in flint), at the apex of the left lung (left shoulder). Through these analyses it has been possible to understand the cause of the death, the presence of a wound on the right hand and its age (approximately 50 years old) (Murphy et al., 2003; Nerlich et al., 2003; Kean et al., 2012). A second tomographic investigation has been realized in 2009, highlighting the stomach content, thus making possible to reconstruct the last meal of the individual. From 3D images of the skull it was also possible to reconstruct the man's face (Murphy et al., 2003).

Therefore, these analyses allow not only to reveal traces of pathology and the course of disease, but they also offer the opportunity to obtain significant information about diet, health, but also ethology and physiology in extinct animal and human populations (Dettwyler, 1991; Iurino et al., 2013). Many aspects of animal and human life are regulated by the health condition; therefore individuals with evident disability due to the pathology and injuries are not able to perform properly some basic activities, such as foraging, locomotion, defence and reproduction. In case of social animals, disabled individuals are non-productive members of the group, with negative influence on the "economy" of the whole group. Traces of healing from relatively serious disease have been found on fossil bones, allowing to develop hypotheses about the treatment of disabled individuals by other members of the group (Dettwyler, 1991; Iurino et al., 2013).

3D RECONSTRUCTIONS

In palaeontological research the retrodeformation of fossil shapes is one of the most difficult tasks to achieve. The term retrodeformation is related to the attempt to reconstruct how a fossil was shaped before taphonomic or sedimentological processes and, worst of all, the diagenetic compressions, resulting in the loss of biological information (Hughes & Jell, 1992). Taking the process of editing files a step further, instead of just removing deformation, missing parts can be replaced by scaled copies from other specimens, and small damaged areas digitally repaired. Extreme caution is required, because any repaired or composite digital file is speculative, and any science conducted using it is therefore at a risk of being less accurate than it would be if complete real specimens were used (Zollikofer & Ponce de León, 2005; Iurino, 2010; Mallison, 2011). However, digital repair can deliver best approximations that, cautiously used, may be much more useful than broken and incomplete specimens. Similarly, mirror images can be easily created, allowing easier comparison with other taxa, provided contralateral elements are known.

The inner ear is a structure located inside the petrous temporal bone. This structure houses the organs of hearing and balance (Spoor & Zonneveld, 1998). It consists of two parts, the osseous labyrinth and the membranous labyrinth. The osseous labyrinth, in turn, consists of three parts: vestibule, semicircular canals and cochlea. The membranous labyrinth is contained within the bony part (Gray, 1995). The bony labyrinth leaves an empty space in the temporal bone that can be filled to obtain a cast for subsequent studies. CT scans allow three basic points of study: 1) descriptive and comparative works, 2) biophysical relationship with the function of the vestibular organ, the dimensions and the planar orientations of the semicircular canals, 3) angular and distance measurements to describe morphological features of the labyrinth that are said to be related to the ontogenetic and phylogenetic development of the cranial base (Rook et al., 2004; Poza-Rey & Arsuaga, 2011). The use of the CT scans was demonstrated to be a sufficiently accurate method for morphometric analysis of this intraosseous region in many fossil vertebrates.

Even reconstructions of soft tissues can benefit from digital data, e.g., the musculature of extinct vertebrates (Fig. 6). It can be created a digital model that, being 3D, may be much more accurate and informative than the classic 2D drawings, where muscles are represented by lines (Mallison, 2011). Cases in point are the musculoskeletal models used by Hutchinson & Garcia (2002) and Hutchinson et al. (2005) of the hindlimb musculature of the theropod dinosaurs *Tyrannosaurus rex* (Osborne, 1905), and *Velociraptor mongoliensis* (Osborne, 1924) as well as an Asian elephant by Hutchinson et al. (2008). Surface marks such as attachment sites of the muscles and tendons on bones are sometimes visible as rugosities, but most have no special texture. Almost all, however, lead to a slight flattening of the bone surface, which can be easily missed due to the colours and textures on a real bone, but are immediately visible on a shallow-angle oblique view of a (texture-free) digital file (Mallison, 2011) (Fig. 6).

Many potential uses of digital reconstructions for exhibitions have barely been used in museology. Digital images can be used for explanatory videos or images on computer screens, for the production of high detailed stereolithograpy (three-dimensional layering) and for the planning process of exhibitions. Digital data have several advantages for presentation on the internet and on other media compared to classic photography or film of physical objects. For example they are able to make objects fully or partly translucent, and to dissect them virtually by hiding partial surfaces, so that internal architecture can be shown easily. This can be done while the view is rotated, so that the 3D structure becomes easily understandable even on the screen. Moreover, missing parts of a fossil can be reconstructed, and the process of reconstruction explained by switching the image between the scan of the real specimen and the reconstruction. These are a few examples of past and present uses of

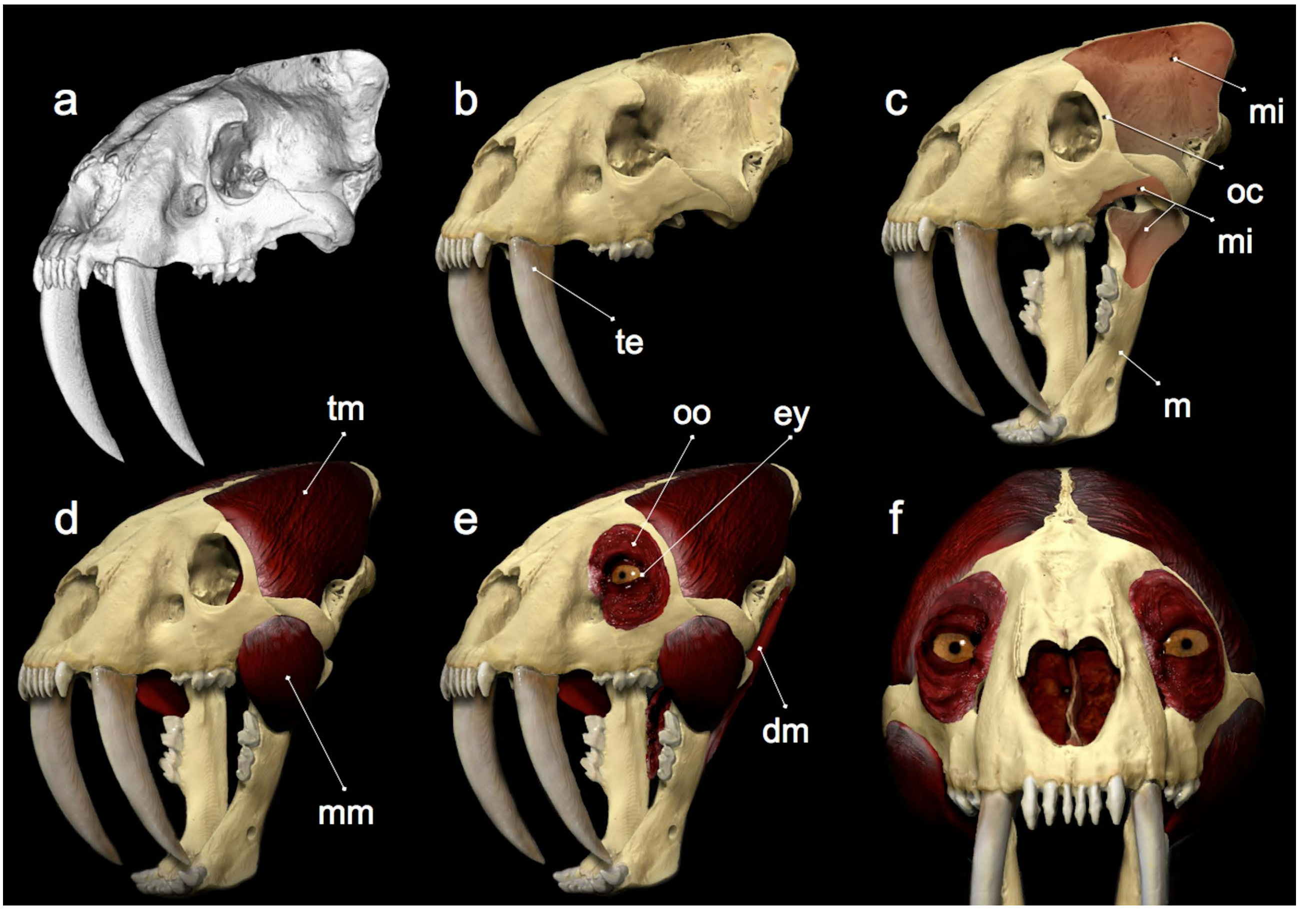

Fig. 6 - a-f) Deep muscles reconstruction sequence of *Smilodon fatalis* (Leidy, 1868), mold from Rancho La Brea (California, USA); a) 3D tomographic image; b) first 3D graphic processing, application of colour and tooth enamel (te); c) addition of the orbital cartilages (oc), mandible (m) and identification of the main areas of muscular insertion (mi); d) addition of the temporal (tm) and masseteric (mm) muscles; e) addition of the eyes (ey), the orbicularis oculi muscles (oo) and digastric muscles (dm); f) frontal view of the skull with rebuilt muscles.

digital reconstructions in palaeontology (Iurino, 2010; Mallison, 2011).

In a historical moment when people interface with the reality through an increasing number of multimedia devices, the ability of researchers and science communicators should be the adaptation of palaeontological disclosure to modern communication systems (Antón, 2007). In this context, the use of dynamic, attractive and of easy fruition images is an obligatory route for many museums and research centres. Therefore, the three-dimensional reconstructions of fossil animals, in the coming years, will be the most important tool in interfacing palaeontological research and scientific communication.

LIMITATIONS

Although these multidisciplinary studies are currently in rapid expansion, there are several issues related to their implementation. The structures capable of having expensive equipments such as CT scans are often few and not always easily accessible. Computational analysis are usually expensive both in terms of direct costs (hardware, software, scans) and in terms of expertise and know-how.

The fossils, in some cases, make digitizing difficult or impossible. Some specimens are simply too large for some methods. Complete articulated dinosaur or mammal skeletons may not fit into even the largest CT scanners, since such machines have been designed to perform scans of human bodies (Manning et al., 2009).

Also, there are a variety of technique-specific limitations. CT and similar techniques require differences in the density or other physical properties to exist in the specimen. If these are too small, surface extraction will fail. For example, Sutton (2008) reports that sparry calcite fossils in a largely micritic matrix could not be distinguished by high resolution computed tomography (HRCT) and synchrotron X-ray tomographic microscopy (SRXTM). However, some extraordinary results have been achieved, for example with calcitic fossils in limestone matrix (Dominguez et al., 2002).

Therefore, with the medical CT, heavily mineralized fossils are highly radiopaque to the passage of X-rays, preventing the display of internal structures. The latter problem is partly overcome with the SRXTM, where the equipment capability in discriminating materials of different densities is considerably higher than in common medical CT scans (Macchiarelli et al., 2006; Mazurier et al., 2006; Dumont et al., 2009; Pradel et al., 2009). This is true only for some categories of sediments and depends also on the thickness of the sedimentary matrix that covers the fossil remains.

CT computer reconstructions are prone to artefacts (errors and mistakes). Artefacts are usually manifested as a blurring of material boundaries or a grainy appearance. The errors are caused by several aspects of CT such as the matrix (voxel) structure of the volumes, the properties of X-ray beams, X-ray scatter and electronic errors in the digital detector panel (Abel et al., 2012). The "beam hardening artefact" is commonly associated with dense objects like fossils, and is caused by variation in the energy of the X-ray beam. Hardening is the process of selective absorption of low energy X-rays from the polychromatic beam. As low energy X-rays are absorbed or scattered by a fossil, the beam becomes progressively harder or more penetrating. Thus the material at the edge of a fossil appears to be more dense (i.e., greater X-ray absorption) than the centre (i.e., lower X-ray absorption) (Ronan et al., 2010, 2011; Abel et al., 2012). It is possible to reduce beam-hardening artefacts by scanning perpendicular to the long axis of the fossil or placing a copper filter in between the X-ray source and the fossil. The filter removes low energy X-rays and reduces the cupping artefact (Abel et al., 2012).

In the study of prehistoric remains the distinction between preservational damage and conditions that occurred in the living animal can be problematic issues. The major challenges to the study of palaeopathology is distinguishing pathology from diagenetic/taphonomic alteration (pseudopathology) and representative information from chance observations or conjecture (scientific misconceptions). For example, one of the most common taphonomic changes suffered by fossils is crushing, due to the compaction of the surrounding sediments. Like so many aspects of preservation, this has little to do with geologic age, although depth of burial is significant. It is important that taphonomic crushing has not to be confused with breakage due to trauma. The latter condition is generally localized to predictable points and, if not immediately fatal, shows repair. Taphonomic crushing creates a general pattern of fractures across the whole surface of the fossil, including a distinctive pattern of microfractures. The edge of all joined pieces should be sharp. Because the loading is from a single direction, all fractures should correspond to one loading pattern. Attribution of significance to skeletal lesions is predicated upon the assumption that taphonomic (post mortem) alterations do not produce similar changes as pathologic processes. The nature and distribution of damage, related to burial, defleshing, and the "retrieval process," must be understood, if pathology is to be confidently noted and identified (diagnosed). Therefore, biological, chemical, mechanical and meteorological factors may influence the tomographic analysis of fossil remains. The knowledge of taphonomical and pre-mortem factors is very important to make a correct diagnosis and interpretation of the fossils features. Also all the inferences starting from the CT analysis are closely related to a good interpretation of the tomographic images, therefore an analysis error may produce a series of incorrect physiological, anatomical, behavioural and ecological interpretations.

CONCLUSIVE COMMENTS

Computed analyses and digital imaging provide a clear example of multidisciplinarity. Anatomy and morphology, computer sciences, statistics, physics, and engineering represent the disciplines tied together in such approaches. A functional integration of these expertises can only be achieved through an adequate management of the research resources (Zollikofer & Ponce de León, 2005).

The success of these technologies shows that anatomically plausible 3D models are suitable techniques to reconstruct the body surface of extinct animals. Deformations of the entire model to accommodate new anatomical evidences are easy to perform rapidly. Compared to older techniques, 3D modelling allows the creation of less simplified and thus potentially more accurate results. As a side benefit, the new virtual reconstructions are also more aesthetically pleasing and less abstracted than previous attempts, looking more alive.

Apart from its important scientific implications, computed tomography must also be viewed as a tool to analyse the preservation conditions of fossil remains and to plan restoration processes.

In conclusion, the virtual palaeontology analysis represents a powerful investigative tool able to produce multimedia images informative for the palaeontological research and attractive for the public, allowing palaeontologists to extract the maximum amount of data from fossils.

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