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CT-scanning and virtual reproduction of the Saccopastore Neandertal crania

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Summary – *The two early Neanderthal crania from Saccopastore (Rome, Italy) have been CT-scanned and virtually reproduced using computer-assisted techniques. The matrix, still pervading many internal volumes, was partially removed in order to identify and isolate endocranial structures and internal features. Saccopastore 1 shows high degree of mineralisation. In addition, calcareous inclusions permeates the deeper layers of the bone, involving some degree of overflow and difficulties to clearly identify part of the anatomical structures of the basicranium. Anyhow, the endocast (never described so far) is almost entirely reproduced, as well as features of dental roots, maxillary sinuses, and inner ear elements. Saccopastore 2 shows also a high level of fossilisation, but with less problems for the scan process (given also the smaller volume of the anatomical districts preserved); even in this case, dental roots, maxillary and frontal sinuses, and inner ear elements can be identified. These two important specimens, dated to a crucial (Eemian) stage along the Neanderthal evolutionary lineage, are now available for CT-based analyses and comparisons.*

Keywords – *Computed tomography, Computer graphics, Neandertal, Cranium, Italy.*

Introduction

In 1973, G.N. Hounsfield introduced computed tomography (CT) among medical diagnostic techniques. In a CT analysis, the X-ray beam turns around the object, producing a bidimensional section that records attenuation coefficients as a function of density and composition of each single unit of volume (voxel) crossed by the radiation (see e.g. Spoor et al., 2000a,b). This representation is unbound from both superimposition of signals and parallax distortion, that are conversely typical of classic radiographic reproductions. Slides can be printed on hardcopies, or treated as single files and visualised by using a grey values scale to represent the unitary attenuation coefficient (CT-numbers). Sequential slides can be eventually assembled for: a) reproducing the entire scanned volumes, to be analysed on different perspective (multiplanar reformatting); or (b) to reconstruct the original structures by 3D imaging techniques.

During the following decade, improving and spreading of computer facilities made these techniques available for different (even non-medical) applications, such as human paleontology (Tate & Cann, 1982; Conroy & Vannier, 1984; Wind, 1984, 1989; Vannier & Conroy, 1989a,b; Zonneveld et al., 1989). Finally, in the last decade, a new level of resolution and technical skill allowed a full and competitive application of CT tools to evolutionary biology (e.g., Zollikofer et al., 1995, 1998; Recheis et al., 1999a; Spoor et al., 2000b), with case-studies including analyses of bone thickness and dental enamel (Spoor et al., 1993; Weber & Kim, 1999), bony labyrinth (Spoor & Zonneveld, 1995), endocranial capacity (Conroy et al., 1998, 2000; Recheis et al., 1999b), cranial anatomy (Seidler et al., 1997; Thompson & Illeraus, 1998; Bookstein et al., 1999; Maureille & Bar, 1999), and maxillary sinuses (Rae & Koppe, 2000).

With current medical scanners it is possible to achieve a spatial resolution of 0.3-0.5 mm in the scan plane, and a slice thickness of 1.0-1.5 mm (Spoor et. al, 2000a). After a specimen or a part of it has been scanned, virtually reproduced, and elaborated with computed graphics techniques, it can be physically "duplicated" with all its structural features (internal and external ones), using a technique based upon laser-induced polymerisation of artificial resin, known as stereolithography (Zur Nedden et al., 1994; Hjalgrim et al., 1995). Application to human paleontology requires obviously some additional tricks, due to the nature of the target to be scanned, which is basically represented by mineralised structures. High level of fossilisation often leads to saturation of the reference scale (overflow), total attenuation of the signal (lack of detection), or differential selection of the beam frequencies (beam hardening) (Spoor et al., 2000a,b). Due to these problems, artefacts and other scanning outputs can limit the resolution and the perspective of this approach. Anyhow, it is clear that CT-based paleoanthropology represents a new level of analysis for the study of the fossil record, allowing the access to anatomical structures and entire specimens not available using conventional techniques. This allows also to test our previous knowledge by means of a more complex and powerful tool.

Material and methods

The Saccopastore crania

Two fossil crania of Neandertal morphology were recovered between 1929 and 1935 within the gravels and sands of a quarry near Rome; these were referred to a Late Pleistocene deposit of the last interglacial, possibly to the OIS 5e, i.e. to about 120 ka (Sergi, 1929; Breuil & Blanc, 1936; Sergi, 1944; Sergi, 1948; Manzi & Passarello, 1991; Condemi, 1992; Caloi et al., 1998). They are respectively known – from the old toponym of the area (now included within the rapidly expanded outskirts of the city) – as Saccopastore 1 (Scp-1) and Saccopastore 2 (Scp-2).

Both specimens represent a morphotype along the diachronic variability of the Neandertal lineage where the clear occurrence of features that are common among the Wurmian (or typical) Neandertals are blended with structures shared with more archaic and less derived European Middle Pleistocene samples (e.g., Arsuaga et al., 1997). Scp-1 was assigned to an adult female (Fig. 1b). The skull is almost complete, lacking the mandible and the zygomatic arches. Some local damages are localised to the supraorbital region and some dental crowns; in addition, two holes in the vault were produced at the time of the discovery by the cave workers. The endocranial cavity is partially filled with stone matrix, and the cranial capacity is believed close to 1200 ml – 1174 ml was the best estimate obtained by S. Sergi (1944). The vault shows a marked platicephaly, associated to a rounded occiput. In posterior view, the typically Neandertal elliptical (or *en bombe*) profile is observed. Facial size of Scp-1 is rather large, without presence of a canine fossa, with pronounced alveolar height, marked orthognathism, and midfacial prognathism. Pyriform aperture is wide, the orbits are large and circular, and the high, broad, and rectangular nasal bones show a gradual but deep curvature in transverse section. The palate is narrow and high, with a palato-dental area and teeth rather small viewed in the range of the Neandertal variability.

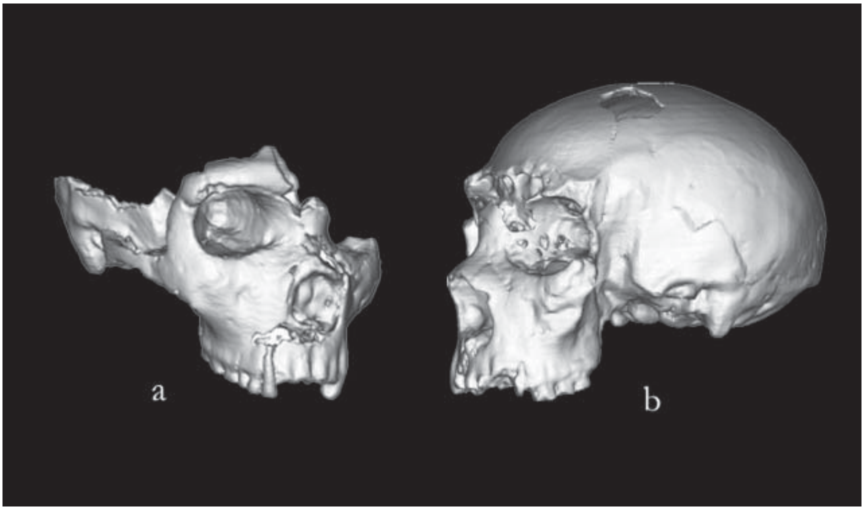

Fig. 1 - Complete virtual reproduction of Saccopastore 2 (a) and Saccopastore 1 (b) skulls.

Scp-2 is more damaged, lacking the whole vault and the left fronto-orbital areas (Fig. 1a). Morphological differences from Scp-1 are supposed to be the result of sexual dimorphism, this fossil representing probably a young adult male. Cranial capacity estimates approximate 1280-1300 ml. The facial size is smaller than the Wurmian Neandertals, but larger than Scp-1, showing a marked mid-facial prognathism due to the lateral inclination of zygomatic bones and orbits. The supraorbital torus is well developed. The nasal bones, the alveolar area and the palato-dental structures resemble those of Scp-1, except for the palatal height that is slightly shorter. The dental arcade show a marked bi-canine distance, compared to the bi-molar one.

Scp-1 and Scp-2 show both a greater basicranial flexion compared to that of the Wurmian Neandertals, due to the extreme inclination of the *planum sphenoidalis*. The two skulls show also an extremely high level of fossilisation.

CT scanning and computed assisted analyses

Both crania have been CT scanned using a Tomoscan AUEP (Phylips), with sequential and contiguous 1 mm scans (slice thickness 1mm; slice index 1mm). Spiral scanning was not used in order to avoid interpolation of data. The skulls were scanned on transverse planes, using the machine light pointer to place the cranium with the Frankfurt horizontal aligned to the radiation beam. Scp-2, lacking the left porion, has been oriented using the two orbitals and the right porion. The specimens were held onto the head resting base commonly used during CT analysis, and fixed with adhesive tape and stuffs. No gantry tild was used. Data were exported as DICOM files, with a matrix of 512X512 pixels. Scp-1 was scanned at 75 mA and 140 kV (scantime = 4 sec), with a FOV of 250 mm and a consequent pixel size of 0.49 mm. The high level of fossilisation, the stone matrix inclusions and the large depth of the layers caused marked streak artefacts and diffuse noise. Therefore, besides increasing the beam power (mA), a filter n°1 was necessarily used to clean the signal. It must be stressed that generally a neutral filter is recommended, to avoid artificial interpolation of the boundaries (Spoor et al., 2000a). Scp-2 was scanned at 25 mA and 140 kV (scantime = 4 sec), with a FOV of 300 mm and a pixel size of 0.59 mm.

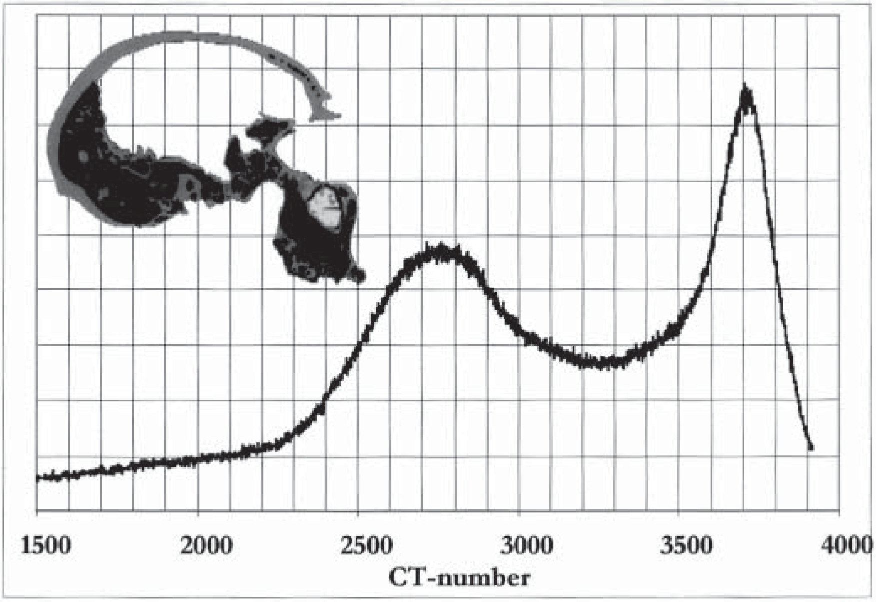

Fig. 2 - Attenuation spectrum (pixels per CT-numbers) of Saccopastore 1 showing a bimodal distribution of density; the parasagittal slice shows the distribution of the light infiltrations (light grey), the fossil matrix (phase 1; grey) and the included stone matrix (phase 2; black).

Data have been analysed using MIMICS 7.0 package (Materialise). Volumes have been segmented by thresholding the different CT number (CTn) following mainly the Half Maximum Height technique (Spoor et al., 1993).

Results and discussion

Saccopastore 1

In Figure 2, attenuation coefficient values (or CT-numbers; CTn) recorded on the CT scan of Scp-1 are plotted against their frequency, giving the attenuation spectrum for this fossil specimen. The spectrum can be divided in three components, while the bimodal distribution indicates the presence of two partially distinguishable phases. A first component, set between 1500 and 2200 CTn (1894 ± 186 CTn) mainly includes weak infiltration and a large inclusion in the right maxillary sinus; it also accounts for most of the partial volume effect (see Spoor et al., 2000a). The second component – represented by the lower density phase – can be set between 2200 and 3250 CTn (2768 ± 252 CTn); it includes most of the fossil matrix, with the exclusion of teeth (enamel and cementum). Outer and inner layers are respectively represented by the lower and higher halves of the distribution. The third component, from 3250 to 4095 CTn (3623 ± 178 CTn), represents the higher density phase and is mainly composed by the stone matrix, including extrabone (endocranial cavity, petrous pyramids, and sinuses) and intrabone (frontal and occipital diploe) inclusions. Teeth attenuation coefficients fall inside the distribution of this second phase, due to the extreme density of the enamel; dental roots are also clearly distinguishable. Considering the fossil volume, the vault is totally defined by the first phase, while in

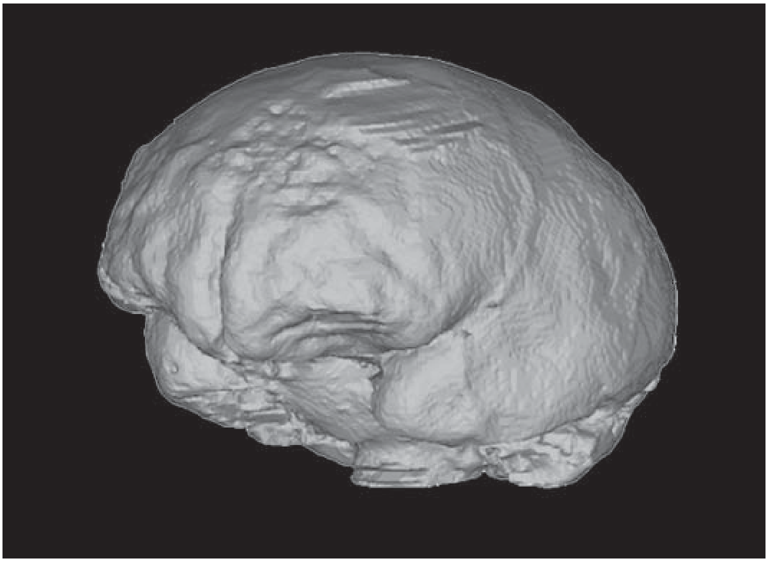

Fig. 3 - Virtual endocast of Saccopastore 1.

the face the two matrices are blended, the second phase distribution increasing from orbits to teeth. Both phases result well distinguishable, but a certain level of superimposition (where fossil and stone matrix are indistinguishable) occurs.

A light amount of overflow (white overflow – see Spoor et al., 2000a) is widespread and recorded mostly in the teeth, turbinates and petrous pyramids. The endocranial cavity is partially filled with an homogeneous inclusion which can be easily removed from the skull, and which reproduces a very precise "natural" cast of the underlying structures, namely both the cerebellar and occipital poles, the right temporal lobe and the proximal areas of the right 3rd frontal circumvolution. The empty space of the endocranium can be used to obtain a complete endocast of this specimen (Fig. 3). In this reconstruction, only the basal structures can not be entirely resolved, due to the marked admixture between fossil and stone matrix in these areas. The prefrontal circonvolutions are well expressed, the sinuses pattern and the meningeal systems are clearly defined as well as all the cerebral and cerebellar lobes. Even if some cautions must be taken in account using this kind of endocast reconstructions (Zollikofer & Ponce de Leon, 2000), the endocranial general morphology results well accessible.

The right maxillary sinus is filled both with high density and very low density matter, probably representing different sequences on inclusion. This admixture of components and some damages of the sinus itself make difficult to interpretate the exact shape and boundaries of the cavity, even if the structure is clearly localizable. The left maxillary sinus is, on the contrary, well preserved and filled with an homogeneous matrix, and the whole volume is easily recognised (Fig. 4).

Both the vestibular structures of the inner ears are localisable (Fig. 5). Being both the petrous pyramids markedly blended and permeated with hard inclusions, the exact boundaries of the whole anatomy can not be entirely isolated by thresholding, but the contrast is enough pronounced to allow the identification of a large part of it.

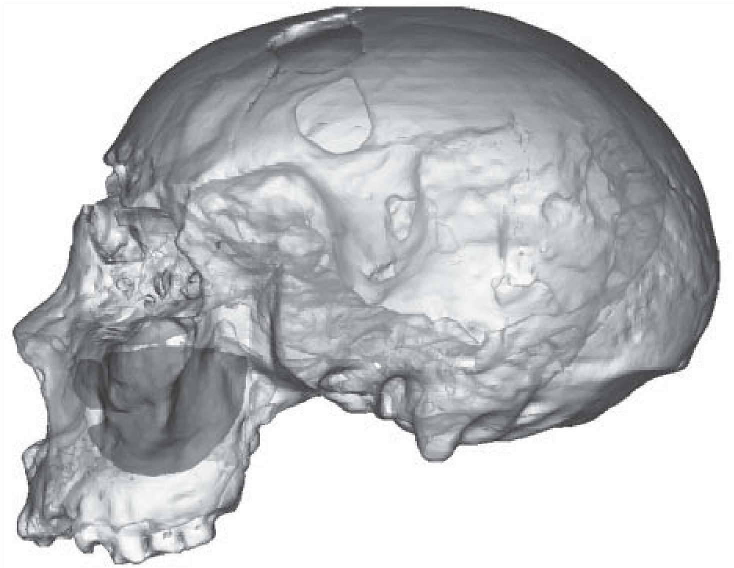

Fig. 4 - Virtual reproduction of Saccopastore 1 showing the left maxillary sinus volume.

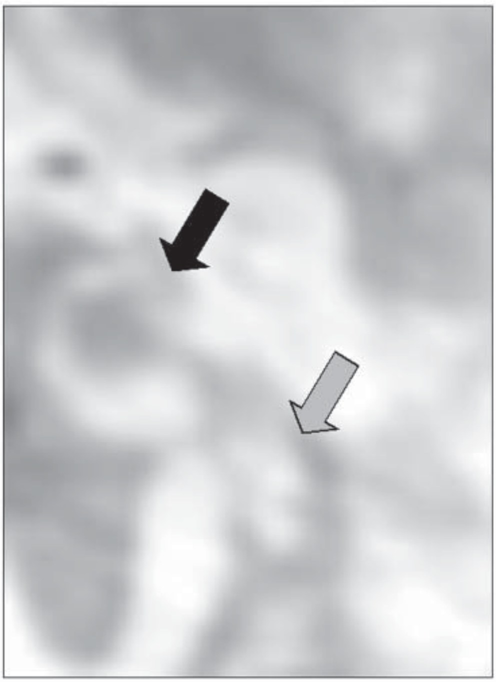

Fig. 5 - Transverse slice of Saccopastore 1 showing structures of the right inner ear (black arrow: lateral semicircular canal; grey arrow: cochlea).

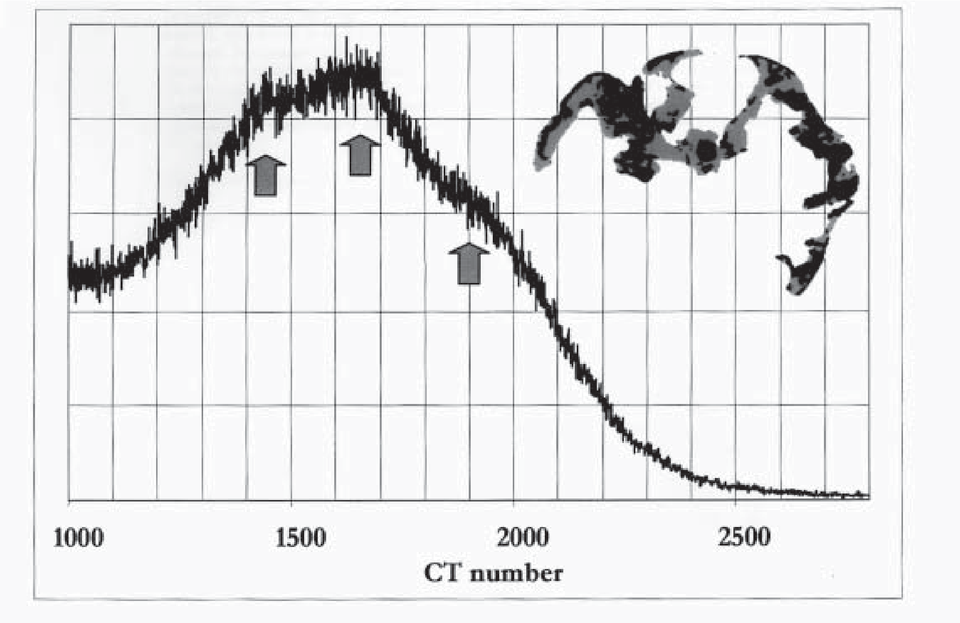

Fig. 6 - Attenuation spectrum (pixels per CT-numbers) of Saccopastore 2 showing a unimodal distribution of density (three sub-peaks are indicated by arrows); the transverse slice shows the distribution of lower and higher halves of the phase distribution.

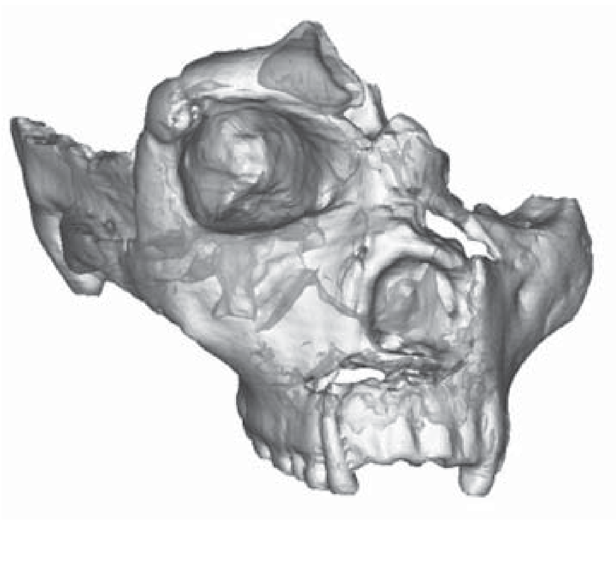

Fig. 7 - Virtual reproduction of Saccopastore 2 showing the right frontal sinus volume.

Saccopastore 2

Diversely from Scp-1 – more complete and more pervaded by stone matrix –the attenuation spectrum of Scp-2 does not allow to clearly separate different phases. A single component is then apparent (Fig. 6); however, the spectrum seems to be the result of three sub-entities (registered by small peaks along the distribution) almost completely overlapping. It is therefore practically impossible to distinguish different components in this fossil specimen. The main mode range, from around 1000 to 2400 CTn (1595 ± 321 CTn), includes almost the whole fossil volume. A small amount of infiltration exceeds this distribution (>2400 CTn), representing a large inclusion in the right maxillary sinus, plus fragmented volumes in the frontal sinus, in teeth, and other quantitatively minor areas.

The teeth roots are well distinguishable, and the structure of the right inner ear are localisable. The right maxillary sinus is partially filled with a high density inclusion, plus some debris. The left one is almost all empty, but rather damaged and incomplete. The right frontal sinus is easy reproducible, showing an extension from the medial region to about halfway the supraorbital arcade, without growing backward to the frontal squama (Fig. 7). The paranasal sinuses of both Saccopastore crania have been investigated in the 80's by mean of xeroradiographic scans (Passarello, 1981; Passarello, 1983; Passarello e Diotallevi, 1982), which had shown the marked development of these structures in the two specimens, particularly in Scp-2. This hyperpneumatization is therefore not expressed only in the Würmian Neandertals, but also in the previous stages of the lineage, making improbable hypotheses in which skull pneumatisation can be linked to a particular climate conditions. Extreme patterns of pneumatisation was subsequently found in more archaic and robust morphotype such as those represented by the skulls of Petralona and Kabwe (Seidler et al., 1997).

Perspectives

Dealing with fossil specimens, the infiltration of geological matrix is often a problem and sometimes no differences are detectable to localise the morphological boundaries between different structures. About the Saccopastore Neandertals, which show high levels of mineralisation and a widespread permeation of the stone matrix into the inner volumes and layers, we have shown here that the virtual reproduction was successful in localising and characterising most of the hidden and included structures. These two important specimens, dated to a crucial stage along the Neandertal evolutionary lineage, are now available for CT-based analyses and comparisons.

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ABSTRACT

Scansione tomografica e riproduzione virtuale dei crani neandertaliani di Saccopastore

Riassunto – I due crani neandertaliani arcaici (o 'pre-neandertaliani') di Saccopastore, rinvenuti a Roma tra il 1929 e il 1935, sono stati sottoposti a completa scansione tomografica e a riproduzione virtuale attraverso l'uso di appropriati hardware e software. In entrambi i fossili, è stata virtualmente rimossa la matrice geologica che tuttora pervade molti dei loro volumi interni, allo scopo di identificare e isolare strutture e caratteri interni. Saccopastore 1 presenta un alto livello di mineralizzazione. Inoltre, alcune inclusioni calcaree permeano gli strati profondi dell'osso, provocando overflow e rendendo difficile l'identificazione di alcune strutture anatomiche del basicranio. Comunque, il calco endocranico può essere riprodotto quasi integralmente, così come i caratteri delle radici dentarie, dei seni mascellari e di alcuni elementi dell'orecchio interno. Anche Saccopastore 2 presenta un alto grado di fossilizzazione, ma con meno problemi per il processo di scansione dato il volume minore dei distretti anatomici conservati. Anche in questo caso possono essere identificati le radici dentarie, i seni frontali e mascellari, e gli elementi dell'orecchio interno.

Parole chiave – Tomografia computerizzata, Computer graphics, Neandertal, Cranio, Italia.

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