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COMPUTED TOMOGRAPHY AND CAD/CAE METHODS FOR THE STUDY OF THE OSSEUS INNER EAR BONE OF GREEK QUATERNARY ENDEMIC MAMMALS

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ABSTRACT

It is undisputed that the use of computed tomography gives the researcher an inside view of the internal morphology of precious findings. The main goal, in this study, is to take advantage of the huge possibilities that derive from the use of CT Scans in the field of Vertebrate Palaeontology. Rare fossils skull parts (Ospetrosum of *Elephas tiliensis* from Tilos, *Phanourios minor* from Cyprus and *Candiacervus* sp. from Crete) brought to light by excavations, required further analysis of their inside structure by non destructive methods. Selected specimens were scanned and exported into Dicom files. These were then imported into MIMICS Software in order to develop the required 3D digital CAD models. By using distinctive reference points on the bone geometry based on palaeontological criteria, section views were created thus revealing the extremely complex inside structure and making it available for farther palaeontological analysis.

KEYWORDS: computed tomography, CAD, Elephas tiliensis, Phanourios minor, Candiacervus, Mediterranean Islands

1. INTRODUCTION

Nowadays, the extensive use of computed tomography has become common practice in the field of bioengineering and orthopedics in general. Spine, Knee or Hip Orthopedics and Kinetics are modeled and investigated mainly with the use of CT scans, which constitute the main raw data for these computer aided studies. Taking this into consideration, a combined effort was suggested in order to thoroughly study and visualize a very specific area of vertebrate Palaeontology, the Inner Ear Bone of mammals, which is an endochondral ossification of the bassicranium (Ladevèze and Muizon 2007). Inner Ear Bones (Ospetrosum) are extremely rare findings in paleontological excavations, although the reason for this scarcity is yet to be determined. Equally rare are the papers dealing with them. (Sanchez-Villagra and Wible, 2000). The skeletal parts examined in the current paper belong to tree taxa of dwarf island endemics:

- Elephantidae: *Elephas tiliensis*, Fig. 1, Theodorou *et al*, 2007.
- Cervidae (deer family): *Candiacervus* sp., Fig. 2 a&b, Van Geer *et al.* 2006, excavated in the seventies from caves near Rethymno, Crete.
- Hippopotamidae*: Phanourios minor,* Fig. 2c, Theodorou *et al.* 2004, excavated at Aghia Napa, Cyprus.

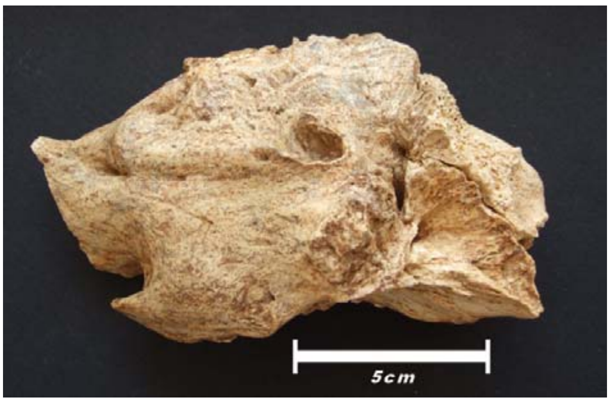


Figure 1. ***Elephas tiliensis*** **Inner Ear Bone**

Elephas tiliensis was excavated at Charkadio-Cave, Tilos Island, Dodecanese, Greece, and lived during Late Quaternary. Its first occurrence on the Island dates back to about 45.000 years. They disappeared during Holocene about 3.500 years ago. This date makes them the last European endemic dwarf elephants. Their maximum height did not exceed 180 - 190 centimeters. The excavations started at 1971 (Symeonidis, 1972) and they still go on under the auspices of the University of Athens.

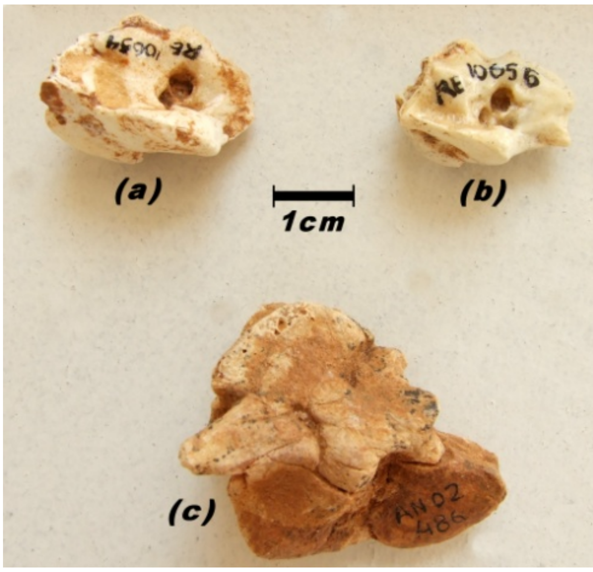


Figure 2. (a&b) ***Candiacervus sp.*** **(c)** ***Phanourios minor***

Phanourios minor has been collected at Aghia Napa, Cyprus during the excavations that have been conducted at the site since 2001 by the Geological survey of Cyprus in collaboration with Athens University. *Phanourios minor* lived at the area of Aghia Napa up to Late Pleistocene (13.500-11.000 years BP). Its height did not exceed 75-80 cm, making him the smallest endemic hippo that ever lived in one of the Mediterranean Islands (Theodorou *et al*., 2004).

Candiacervus bones have been collected by many different researchers at numerous localities of Crete (Van Geer *et al.* 2006*)* in the seventies. These deer belong to at least six morphotypes or size groups. The material included in this paper belongs to sizes I to III (Van Geer *et al.* 2006*),* which is the smallest extinct Cretan deer, with height no more than 50-70 cm.

The morphology of the Inner Ear Bone in detail is established only in few cases (Fox and Meng, 1997) for all fossil mammals. It is well known that sometimes it is very difficult to poke even a hair from side to side in a way to show a connection (Sanchez-Villagra and Wible, 2000), in petrosal bones of marsupial mammals. The existence of hyaline cartilages, that cannot be fossilized, makes their study for the paleontologist even more difficult. Extensive bibliographic research has yet to reveal any findings regarding the use of CT scans or 3D modeling methods for the visualization of petrosal bones from elephants, hippopotamuses or deer. Due to the scarcity of ospetrosum for these three dwarf endemic mammals there is no morphological study, no biometrical information or any other reference on *Elephas tiliensis, Phanourios minor* and *Candiacervus* sp. up to now.

The aim of this study is to provide a new powerful visual tool for paleontologists with the use of high quality 3D models, making it possible to efficiently analyze – with non destructive methods – the complicated internal morphology of the Inner Ear Bone known also as osseous labyrinth, a name clearly implying the high Inner complexity of the bone.

2. MATERIALS AND METHODS

2.1 Osseous Inner Ear

Totally 7 Inner Ear Bones of *Elephas tiliensis* have been scanned, 8 of *Phanourios minor* and 9 of *Candiacervous* sp. From these we chose to proceed mainly with those of *Elephas tiliensis,* due to their larger size. The elephant Inner Ear Bone was first described by Blair (1776) in his classical work. For all these three species there is no available publication incorporating CT scans and CAD methods or any other method. To study the osseous part of Inner Ear Bone (petrosal bone) of a fossil mammal all the sediment that has entered the different open foramen had to be totally removed. This was better achieved for *Elephas tiliensis* specimens whose dimensions (length) did not exceed 12 cm. The unconsolidated sediment was removed during preparation at the laboratories of the Department of Geology and Geoenvironment (University of Athens) long before acquiring the CT scans. The large dimensions of the sections of the main canals in the elephant Inner Ear Bone allowed us to have specimens almost free from residual internal sediments.

The lack of recent material from the species at hand did not allow for a complete morphological comparison and study based on CT scans from living or other extinct representatives of their families.

The situation was quite more difficult for the petrosal bone of *Phanourios minor* and *Candiacervus* due to the consolidated sediment that was deposited in parts of their canals in addition to their very small dimensions (Fig. 3). Although CT scans were taken from all the species, it proved –specifically for the *Candiacervus* bones– that the CT scans were not suitable for further image processing and the generation of Computer 3D models, where only the outer geometry could be established.

Figure 3. Consolidated Sediment partly filling the Inner Ear bone (*Candiacervus* sp.)

2.2 CT Scans And Post Processing

Computed Tomography Scans (CT's) from the Inner Ear Bones (ospetrosum) were taken at a private medical examining center "Ag. Anargyroi" in Athens. The Inner Ear Bones were all placed directly on the table of the scanner under the same orientation. The slice thickness was set to 0.8 mm for three (Sample Number 1, 2, T10355) of them and to 1 mm for the rest (4, 5, 6, 7). The scans were then stored under the Digital Imaging and Communications in Medicine (DICOM, *.dcm files) format which is a standard for handling, storing, printing, and transmitting information in medical imaging. The Scanner used was a *Proven Excellence SOMATOM Sensation 4 by Siemens.*

The digital scans of *Elephas tiliensis* –they were of excellent visual quality & clarity due to the lack of living tissues– were then imported into *Materialise MIMICS v8.1* Software (Fig. 4) at the Laboratory of Dynamics and Structures, N.T.U.A. for the next step of the procedure. Due to the non typical bone structure and bone age the CT scans had to undergo significant improvements. At this point we must mention the main principal function of MIMICS software:

- The CT Scans are sequentially read (Fig. 4a).
- Two more views are automatically generated (Fig 4b & c).
- According to the brightness (grey values) of the scanned objects processing masks are calculated, that can be further processed.
- From the resulting masks several export option are possible.

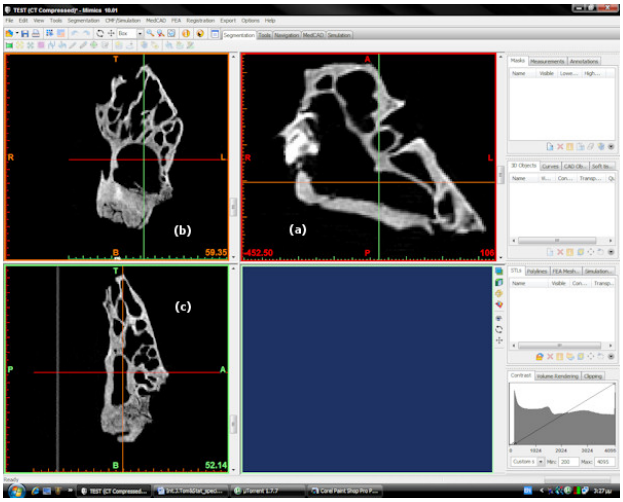


Figure 4. MIMICS Software Interface. (a) Actual CT scan, (b & c) Generated Views.

Upon insertion of the CT scans the upper and lower threshold values of the processing masks were calculated (Fig. 5).

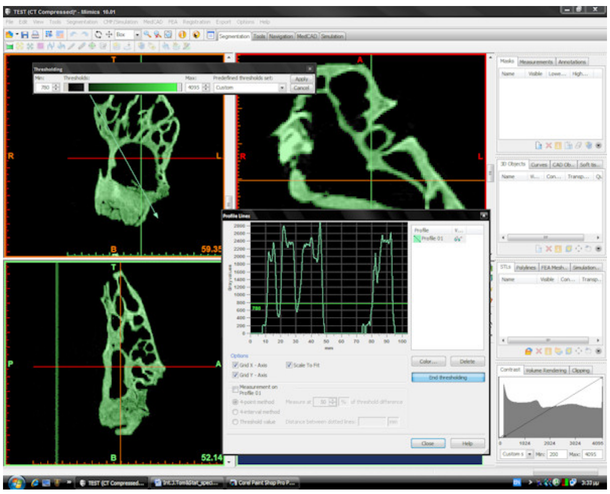
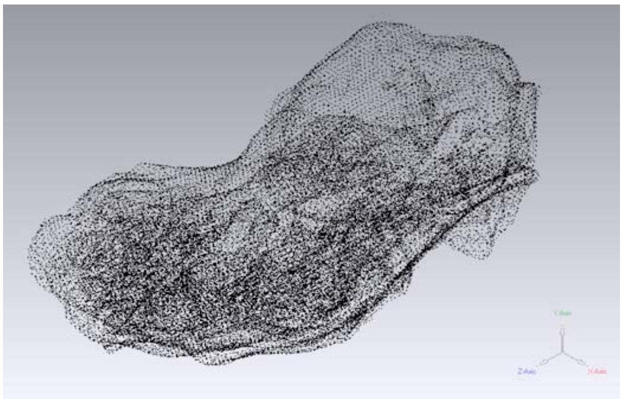


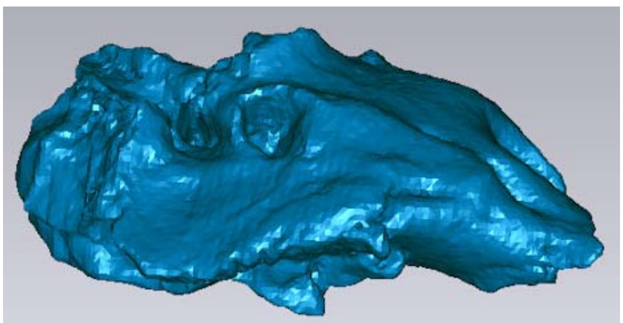
Figure 5. MIMICS Thresholding Phase

These two values correspond to the segmentation process, where the bone will be isolated from its surrounding elements based on the grey values of each pixel of the image. The automated values for Bone CTs suggested by the software had to be specifically adjusted to compensate for low bone mineral density and the sediment residues located inside the bone structure. The resulting masks for each bone were isolated and exported both as a point cloud file (point number & coordinates) and as an STL file. STL is the file format native to the stereolithography CAD software and describes a triangulated surface using a three-dimensional Cartesian coordinate system.

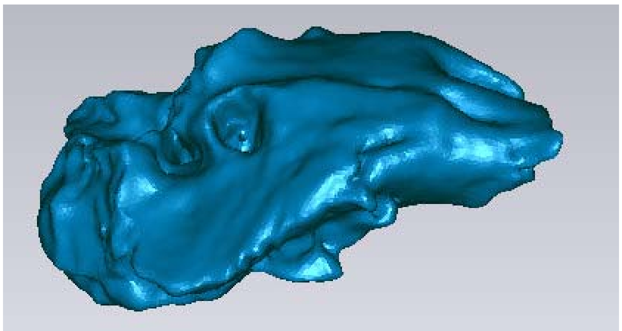
In order to develop the 3D Computer models, which will reveal the interior structure, the exported files were imported in to Geomagic Studio V.9, software specialized in Digital Shape Sampling and Processing (DSSP). Within the Geomagic GUI the original information provided by the point cloud (Fig. 6a), already reveals elements of the bone geometry. The surface is created by using oriented triangles, thus creating the primary 3D view of the unique fossil bone (Fig. 6b). Based on automated algorithms the model is smoothed, for better visual results (Fig. 6c).



(a) Point Cloud



(b) Bone Geometry – Raw Triangles



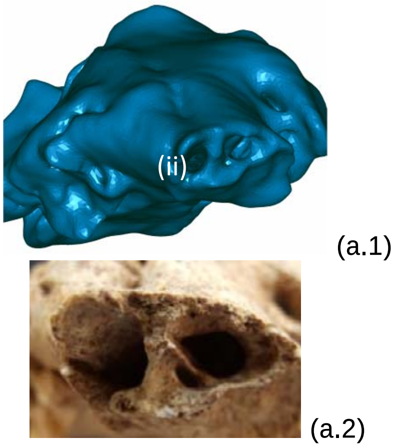
(c) Bone Geometry – Smoothed Triangles

Figure 6. Processing Steps for the generation of the 3D models.

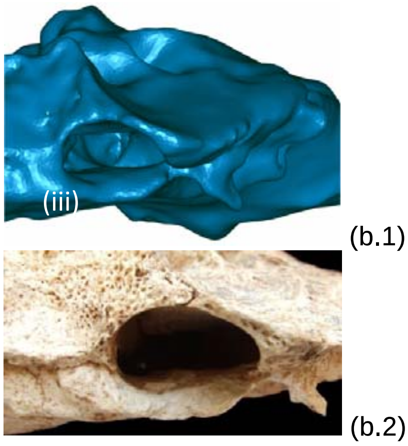
3. RESULTS

As already mentioned, the use of CAD/CAE methods in modern Palaeontology is a non – destructive method and the goal of the current study is to have an inner view of the complex geometry of the Inner Ear Bone and more specifically of the auditory canal. The aforementioned isolation and modeling of these was achieved within the environment of Geomagic Studio by selecting three points on the bone geometry: Two points in the area of two windows –(Fig. 7a) round (i) and oval(ii)– of the canal complex and one at the end of the canal that widens out- (Fig. 7b), thus creating a cutting plane. As shown in the images (Fig. 7c & 7d) below the main internal auditory canal is clearly visible.

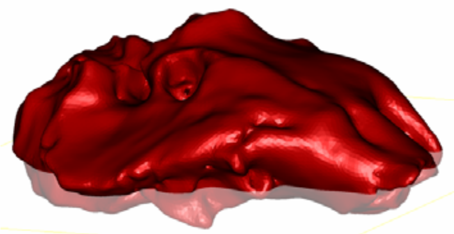
Sections of the 3D models from different specimens by this non destructive method allow for the scientist to "see" the general shape and the connections of the channels among different windows of the Inner Ear Bone. Canals of small dimension (starting from oval and round window) combine and form one bigger canal. Chambers not open to external surface of the Inner Ear Bone but connected to the main channels, come to light. Internal, post sedimentary fractures of the Inner Ear Bone appear only as isolated findings. By changing the direction of the sections, while working with the PC the palaeontologist can observe the general shape of all internal canals and chambers, changing at will the orientation of the observations. Since the specimens at hand belong to animals of different ages, the method allows for studies of the ontogenetical changes of the auditory canals. In the future the isolation of a digital 3D cast of the auditory canal and the internal chambers will make possible phylogenetical studies on a new basis.



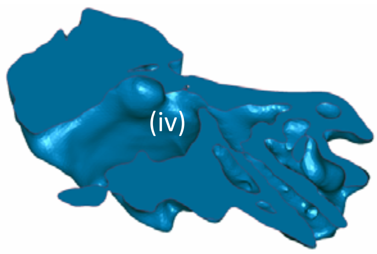
(a) Round (i) and Oval (ii) Windows – Comparison with the fossilized bone (a.2)



(b) Wide Auditory Canal End (iii) – Comparison with the fossilized bone (b.2)



(c) Section Plane



(d) Section View of the canal (iv)

Figure 7. 3D Modeling And Section View Selection of the Inner Ear Bone

By applying the same process for all of our samples (*Elephastiliensis*) we have the following models with the section plane and the section view as previously:

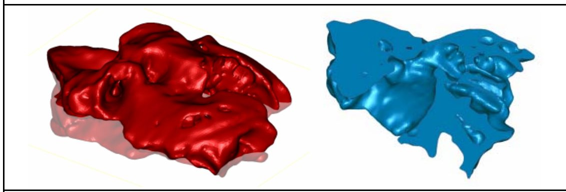
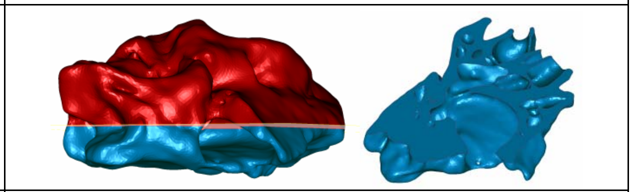
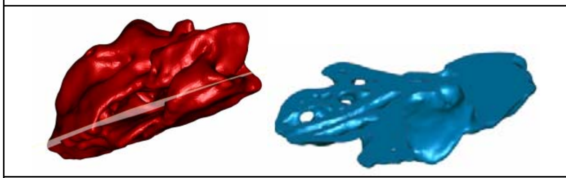
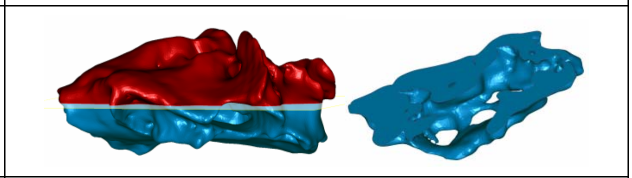
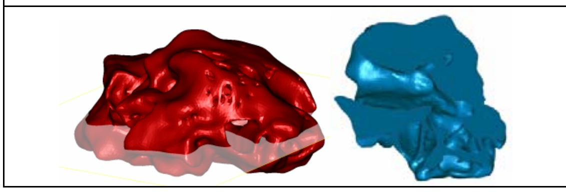
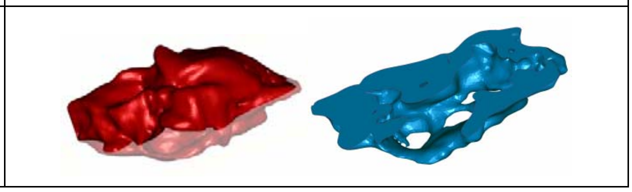
Sample Number 1	Sample Number 2
	
Sample Number T10355	**Sample Number 4**
	
Sample Number 5	**Sample Number 6**
	

Figure 8. Sections of the 3D models from different specimens

4. DISCUSSION & CONCLUSION

The method applied gave us good results for the specimens of *Elephas tiliensis*. During the image processing of the CT scans from the two other species, it became clear that the common CT is not the best way to investigate the Inner Ear Bone structure of fossil mammals, of small size, especially if residuals of consolidated sediments are present. Only an outer boundary was taken and modeled giving us information only about the basic exterior characteristics of ospetrosum. Clearly there is a need for more specialized CT scans with smaller slice thickness and the total removal of the consolidated internal sediment, which is probably not possible for the specimens at hand. From the paleontological point of view the method is non-destructive, giving an opportunity to acquire numerous sections at every possible orientation. Generated views increase the possibilities for observations and specific statistical analysis. This is not possible with destructive methods used so far in palaeontology or even by taking inner casts, regardless of the collection of bones at hand. The method and the technologies applied here, open new fields for vertebrate palaeontology. The use of 3D Computer models allows for a more detailed study of the Inner Ear Bone structure leading us to wider range of research fields, regarding the agility of these mammals, since the Inner Ear (soft and osseous parts) morphology is responsible for the sense of hearing and balance. Although no engineering problems (CAE – Computed Aided Engineering) were at hand in the current study, the use of this methodology is clearly suitable for further structural and functional (for example in the field of acoustics) analysis after further research on the subject.

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The CT Scans were conducted at the private clinic "Aghioi Anargiroi", under the direction of Dr. A. Souvatzouglou and with the help of Mr. Ch. Anastasiou.

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