risk, and to determine the modes of LAV and AIDS transmission in Africa, which may be more diverse than those observed in Europe and the United States.

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14 May 1984; accepted 27 July 1984

Noninvasive Three-Dimensional Computer Imaging of Matrix-Filled Fossil Skulls by High-Resolution Computed Tomography

Abstract. *A noninvasive computer imaging technique allows three-dimensional images of fossil skulls to be generated from two-dimensional serial computerized tomographic scan data. The computer programs can "dissect" the skull in different planes by making portions of it and any obstructing matrix transparent in order to reveal intracranial morphology. The computer image is geometrically precise so that linear distances, angles, areas, volumes, and evaluations of symmetry can be determined.*

There has not been a satisfactory method for noninvasively visualizing intracranial morphology in fossil skulls in more than two dimensions. Skulls subjected to such paleontological study are normally "dissected" by sectioning the skull in the desired plane or by piecemeal removal of calvarial fragments. Conventional skull x-ray radiographs and computerized tomography (CT) scans are abstract, two-dimensional representations that fail to reveal important three-dimensional relations among intracranial structures. These limitations to morphologic analysis are particularly severe in paleoanthropology because most fossil skulls are too precious to be physically "invaded" by scientists wishing to examine intracranial structure (*1–3*).

For fossil crania filled with hardened matrix (*4–6*), noninvasive examination of intracranial three-dimensional morphology or direct measurement of intracranial dimensions and volume has not been possible without matrix removal. If attempted, such direct measurements would necessarily damage the original fossil. Thus, some potentially important fossil specimens lie unprepared on museum shelves with hardened matrix obscuring anatomical information.

New computer imaging techniques now enable the viewing and analysis of fossil specimens filled with matrix. The techniques involve computer imaging capabilities that produce three-dimensional images from two-dimensional CT data. The three-dimensional images are formed from a series of high-resolution, transaxial CT scans of the skull taken at 2-mm intervals. The method has already been used to examine over 500 patients with craniofacial deformities, facial trauma, neoplastic disease of the head and neck, intracranial soft-tissue abnormalities, and musculoskeletal diseases (*7–9*).

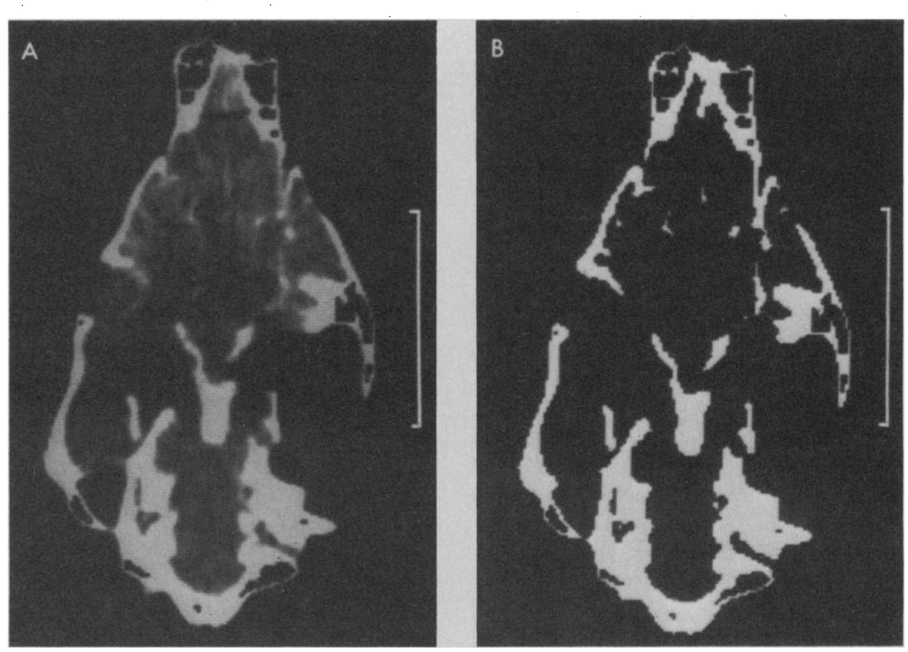


Fig. 1. (A) A 2-mm slice through the cranial and nasal cavities showing the CT scanner's ability (in extended bone range) to clearly distinguish mineralized fossil bone from the hardened sandstone matrix within these cavities. (B) The osseous contours are separated from the sandstone matrix in each CT slice by setting the window width to 0 and the window level to the threshold value representing the CT attenuation that distinguishes mineralized bone from the particular matrix. The computer program repeats this procedure for each CT slice to produce the three-dimensional images. Scale bars, 5 cm.

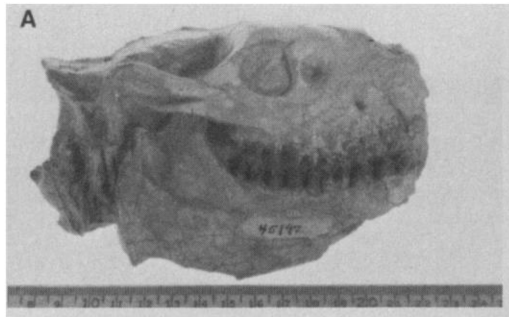
Lifesize, geometrically accurate models have also been produced from the CT scan data with advanced computer-aided design and computer-aided manufacturing technology (*10–12*).

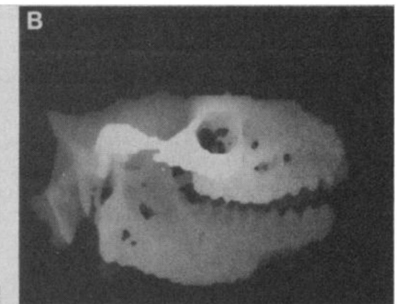
The computer routinely generates more than 50 different three-dimensional images of the skull from the serial CT scans for each specimen. Depth information is encoded in the gray scale. Specific regions of anatomical interest can be defined and expanded on the computer screen while maintaining geometrical accuracy. Precise data on area, volume, symmetry, and linear and angular dimensions can be generated instantaneously. Linear measurements in the plane of section have an accuracy in the submillimeter range, which are more accurate, objective, and reproducible than the same measurements taken by hand on the original specimen. Precise angular and linear measurements of structures even within a matrix-filled cranial cavity can also be instantaneously generated; such measurements have been impossible to obtain previously.

Of major paleontological significance is the fact that any portion of the skull may be made transparent by the computer program to show three-dimensional "dissection" of the skull in various planes. For example, the top of the calvaria may be "removed" to show the intracranial base of the skull (Fig. 3C), or the side of the skull can be "removed" to view the cranial cavity in a sagittal view (Fig. 2C). In addition, if the computer program could be adapted to make transparent the hardened matrix from extra and intracranial surfaces of fossil skulls, then the underlying bony anatomy would be revealed.

To investigate this possibility, we examined a complete fossil skull of the Miocene ungulate *Stenopsochoerus* (*13*). The specimen is from the Middle Oligocene (Orellan, approximately 30 million years old), Brule Formation, Hat Creek Basin, Wyoming. The brain case is completely filled with a hard buff-colored, fine- to medium-grained sandstone. In addition, the lower jaw is embedded in matrix and fused to the underside of the cranium such that the palatal and basicranial morphology of the fossil are completely hidden from view (Fig. 4A). The temporal fossae are also completely filled by the sandstone matrix, obscuring the anatomy of the orbit and postorbital region (Fig. 3A).

Sequential high-resolution, narrowly collimated (2 mm) CT scans of *Stenopsochoerus* were obtained from third-generation CT scanners (Siemens Somatom 2 and Somatom DR 3). The resolution of the images is excellent with pixel size in the plane of section being less than 1 mm^2. A 256 by 256 reconstruction matrix is used. The fossil was placed in a water bath during scanning to reduce scanning artifacts. Water emulates the soft tissue coverings of the skull in life for which CT





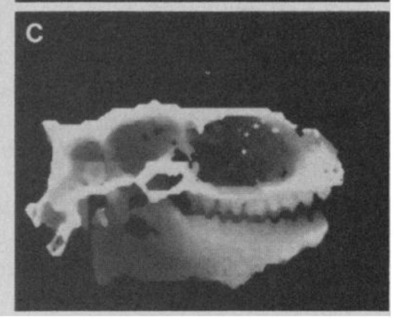


Fig. 2. (A) Lateral view of the original fossil skull. (B) Three-dimensional image of fossil in lateral view produced from 2-mm serial CT scans of the skull. Note matrix "removal" from orbit and interdental region. (C) The skull can be "sectioned" in any plane to look inside the cranial cavity; in this case a sagittal three-dimensional image has been generated from the same 2-mm serial CT data. The matrix filling the cranial and nasal cavities in the original fossil has been "removed" in the reconstructed image to reveal the supra and infra tentorial portions of the cranial cavity and the overall size of the nasal cavity.

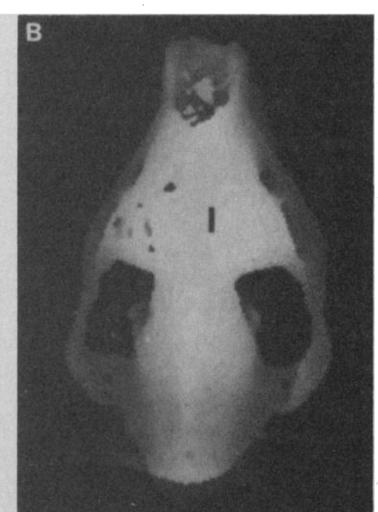


Fig. 3. (A) Top view of original fossil. (B) Three-dimensional top view of fossil generated by 2-mm serial CT scans. Note the matrix "removal" in the temporal fossae. (C) A bird's eye view into the cranial and nasal cavities after the computer has "removed" the top of the calvaria and the intracranial matrix.

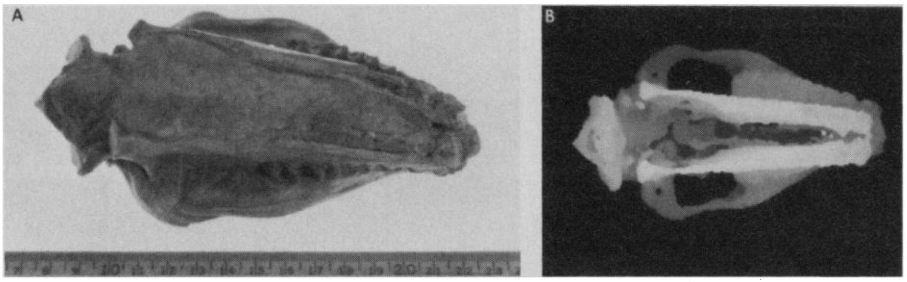


Fig. 4. (A) A bottom view of the original fossil. (B) Three-dimensional bottom image of the skull generated from the 2-mm serial CT scans. In the original fossil the palate and basicranial axis are completely hidden from view by the sandstone matrix. The computer image has "removed" the matrix to reveal the previously obstructed basicranial axis.

scanners are optimized. Extended range bone reconstruction was used since the CT density of fossil bone and matrix lies beyond 1000 Hounsfield units, the upper density limit for normal CT scanning. The scans were automatically stored on floppy disks (*14*).

Three-dimensional views included frontal, rear, 45° oblique (anterior and posterior), top, bottom, and both lateral projections. Selected portions of the skull were made "transparent" in order to look inside the fossil skull (for example sagittal and bird's eye views).

The computer program for surface reconstruction reads each of the original high-resolution axial CT scans in sequence from the cartridge disk and loads the image into the 256 by 256 display memory. In passing from the top to bottom of each image extracranial matrix, mineralized fossil bone, and intracranial matrix are sequentially encountered (Fig. 1A).

Each column of the image is read in sequence from left to right. The osseous contour is extracted (Fig. 1B) by comparing each value of CT density in the column from top to bottom of the image with a preset threshold (*8*). This threshold represents the CT attenuation that distinguishes the mineralized fossil bone from the sandstone matrix (approximately 1650 Hounsfield units in this fossil specimen). The index of the element in each column where the transition from matrix to bone occurs is the osseous contour for the CT scan slice being processed. This index value is scaled and output to the cartridge disk as a line in the reconstructed osseous three-dimensional surface image. In order to complete the surface reconstruction, each succeeding CT scan is loaded into display memory, the osseous contour is extracted, and the contour is written on the cartridge disk. At the completion of this process, over 50 geometrically accurate, three-dimensional views of the original fossil skull (with the hardened matrix "removed") are routinely generated (Figs. 2 to 4).

The gray-scale values in the three-dimensional reconstructions represent actual distances and, within the geometric resolution of the CT scanner, can be used for rectilinear measurements. Rotation of contour extraction from the original scan data by a selected angle (0 to 90°) permits reconstruction of surfaces from various oblique projections. Rotation is accomplished by elementary two-dimensional matrix operations and hidden surface removal frequently used in computer graphics (*15–20*).

In the examples of three-dimensional views of *Stenopsochoerus* derived from the serial CT scans (Figs. 2 to 4), the sandstone matrix has been made transparent by the computer program to reveal the actual bony contours of the fossil skull. Figure 2 shows a lateral view of the actual fossil as well as a three-dimensional reconstruction and a sagittal view reconstruction, both derived from the serial 2-mm CT scans. With the matrix filling "removed" from the cranial and nasal cavities in the sagittal view (Fig. 2C), the level of the tentorium cerebelli and the relative size of cerebral and cerebellar hemispheres can be determined. Linear and angular intracranial measurements can also be generated from this view. The top view of the actual fossil skull (Fig. 3A) compared with the same view generated by the computer (Fig. 3B) shows the complete "removal" of the matrix filling both temporal fossae. By having the computer "remove" the top of the calvaria and the intracranial matrix, one can look inside the cranial and nasal cavities (Fig. 3C). In Fig. 4, a bottom view of the actual fossil compared with the computer-generated image shows how the hard palate and basicranial axis, hidden in the original fossil, are revealed.

These computer techniques allow investigators to actually "dissect" a matrix-filled fossil noninvasively in any desired plane with a spatial resolution of less than 1 mm in the plane of section. Paleontologists will be able to generate highly accurate linear and angular measurements of a matrix-filled cranial cavity and will also be able to determine more accurate area and volume parameters in matrix-filled structures than has been previously possible.

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21. We thank M. Novacek of the American Museum of Natural History for the loan of the fossil specimens used in this study and R. Knapp, T. Compton, and R. Freund for technical and photographic assistance. Supported by NSF grant BNS-8406733.

2 March 1984; accepted 1 August 1984