

# Paleoradiology: Advanced CT in the Evaluation of Nine Egyptian Mummies<sup>1</sup>

*Heidi Hoffman, MD • William E. Torres, MD • Randy D. Ernst, MD*

Axial thin-collimation state-of-the-art spiral computed tomography (CT) was combined with sagittal and coronal reformatting, three-dimensional (3D) reconstruction, and virtual “fly-through” techniques to nondestructively study nine Egyptian mummies. These techniques provided important paleopathologic and historical information about mummification techniques, depicted anatomy in the most informative imaging plane, illustrated the soft-tissue preservation and physical appearance of mummies in superb detail, and generated an intriguing virtual tour through hollow mummified remains without harming the specimens themselves. Images generated with these methods can help archaeologists and Egyptologists understand these fascinating members of mankind and can serve as adjunct visual aids for laypersons who are interested in mummies. CT has emerged as the imaging modality of choice for the examination of Egyptian mummies due to its noninvasive cross-sectional nature and inherently superior contrast and spatial resolution. As multi-detector row CT and postprocessing tools evolve, the capabilities and applications of CT will continue to proliferate, attesting to the expanded versatility and utility of CT as a noninvasive research tool in the multidisciplinary study of Egyptian mummies.

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**Abbreviation:** 3D = three-dimensional

**Index terms:** Computed tomography (CT), thin-section, \*\*.12118<sup>2</sup> • Computed tomography (CT), three-dimensional, \*\*.12117 • Computed tomography (CT), utilization • Computed tomography (CT), volume rendering • Mummies

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<sup>1</sup>From the Department of Radiology, Emory University Hospital, 1364 Clifton Rd, Atlanta, GA 30322 (H.H., W.E.T.); and the Department of Radiology, University of Texas Medical Branch, Galveston (R.D.E.). Received May 23, 2001; revision requested July 5 and received August 7; accepted August 22. **Address correspondence to** H.H. (e-mail: [hhoff1313@aol.com](mailto:hhoff1313@aol.com)).

<sup>2</sup>\*\* indicates multiple body systems.

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## Introduction

Egyptian mummies have been a source of fascination for thousands of years. Before the advent of radiologic imaging, unwrapping and anatomic dissection were the only means available for studying these ancient Egyptians (1–3). These irreversible autopsies were destructive and defeated the Egyptians' wish for eternal preservation. With Roentgen's discovery of x rays in 1895 came a new opportunity to study mummies noninvasively and thereby safeguard their physical form. The first published radiograph of mummified remains appeared in 1898 (4) and was followed by many more such radiographs in a variety of publications (5–9). Although radiography provided a wealth of information, particularly about bony structures, it was not until the emergence of computed tomography (CT) that noninvasive study could be performed to obtain information about the soft tissues and internal body cavities. The benefits of CT include superior contrast and spatial resolution and the capacity to remove superimposed embalming materials from images of internal structures (10–12).

With the advent of more sophisticated CT technology and postprocessing software, it is now possible to view mummies in coronal and sagittal planes as well as manipulate the raw data to create three-dimensional (3D) models of mummies and reconstruct their physical appearance (13–17). Current software allows data manipulation that can produce superb surface detail as well as the use of virtual "fly-through" techniques in an attempt to explore and evaluate the internal body cavities of mummies; these techniques are currently used for virtual colonography and virtual bronchoscopy but, to our knowledge, have never been reported in the literature as a means of studying mummies.

The radiologic study and evaluation of mummies necessitates a basic understanding of how the Egyptians prepared their dead for burial (1–3,18). The practice of mummification began in its most primitive form in the late fourth millennium BC (ie, before 3100 BC) but did not reach its zenith until around 1000 BC. The underlying goal of mummification was to preserve the physical form of the deceased so that the *ba*, or soul, and various other spirits could recognize and be reunited with it in the afterlife. Although techniques of mummification changed over the years, tradition-



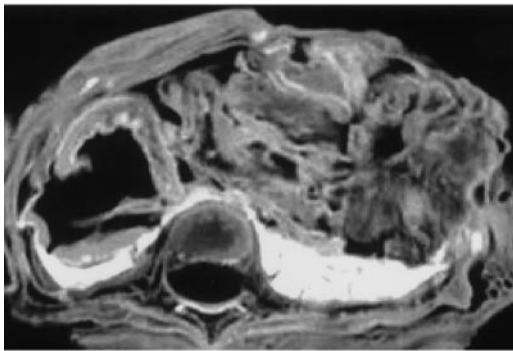
**Figure 1.** Photograph shows an Egyptian mummy, removed from its coffin but still wrapped in linen, positioned in the CT scanner in the Radiology Department at Emory University Hospital. This individual was thought to have lived during the 21st dynasty (1070–946 BC). The inscription on the coffin referred to the inhabitant as a "scribe," a generic title for an Egyptian man that probably referred to a person who was literate and perhaps involved in bureaucracy.

ally all internal organs except the heart, which was considered the seat of the emotions and intellect, were removed to prevent decomposition and putrefaction. According to the Greek historian, Herodotus, who provided early eyewitness accounts of mummification, this removal of organs was typically performed through an incision in the left side of the abdomen below the rib cage. Depending on the era, the removed organs were either discarded, placed in canopic jars to be buried with the body, or placed back in the body cavity later during the mummification process. The brain, which was assigned no particular value by the Egyptians, was also removed. This was traditionally done with a transthemoidal approach in which a curved metal hook was inserted into a nostril and the cribriform plate was punctured to gain access to the cranium. After evisceration and excerebration, the body was usually packed with a variety of inorganic materials (eg, sawdust, stones, linens) before being "cured" for up to 70 days with a dehydrating salt known as natron. Once the dehydration process was complete, the body was wrapped in linens and prepared for burial.

Our goal was to evaluate current CT and postprocessing techniques in the examination of nine ancient Egyptian mummies. Specifically, with use



a.



b.

**Figure 2.** (a) Radiograph of a pediatric mummy demonstrates numerous areas of increased opacity of uncertain character and location projecting over the chest, abdominal, and pelvic cavities. (b) Axial thin-collimation CT scan of the pelvis demonstrates packing materials, predominantly folded linens, which produced the radiographic findings.

of conventional axial imaging, multiplanar reformatting, 3D reconstruction, and virtual fly-through tours, we hoped to provide important paleopathologic and historical information as well as demonstrate the efficacy of combining these imaging techniques to evaluate both the superficial soft tissues and the internal body cavities of these ancient Egyptians.

## Materials and Methods

Nine Egyptian mummies from the collection at the Michael C. Carlos Museum at Emory University in Atlanta, Georgia, including those of seven adults and two children, were brought to the university's Department of Radiology by the museum staff. The deceased were thought to have lived during various eras between 1300 BC and 395 AD. All of the specimens were removed from their coffins for study. The amount of linen wrappings on the mummies varied significantly. The mummies were studied with a helical CT scanner (GE Medical Systems, Milwaukee, Wis) (Fig 1). Initial axial 1-mm helical CT scans were obtained from the vertex of the skull through the midcervical spine, followed by contiguous 3-mm scans from the vertex of the skull through the feet. Overlapping reconstruction (50% overlap) was performed on the resulting data sets. Scanning parameters were as follows: 70–100 mA, 120–140 kV, and 2:1 pitch. There was no gantry tilt. The total number of images generated per mummy ranged from 398 for the smallest pediatric specimen to 1,017 for a large adult male. Multiplanar reformatted images and advanced 3D reconstructed images of soft tissues, bones, and internal organs were obtained on-site on an Advantage Windows Version 3.1 workstation (GE Medical Systems). Virtual fly-through endoscopy of the skull, chest, and abdomen was performed in selected mummies, and conventional radiographs were also obtained.

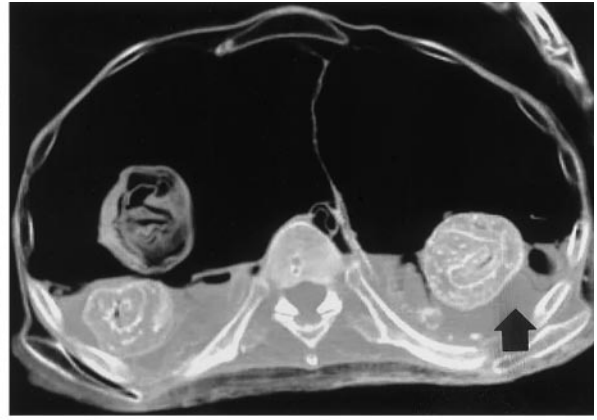
## Results

### Axial Imaging and Multiplanar Reformatting

Axial thin-collimation (1–3 mm) spiral CT produced high-resolution images that were useful in evaluating the internal composition of the cranial, chest, abdominal, and pelvic cavities. The superior contrast and spatial resolution inherent in cross-sectional imaging were particularly helpful in differentiating organs from packing materials used during the embalming process. For example, conventional radiography of one pediatric specimen demonstrated a diffuse area of increased opacity within the abdomen and pelvis (Fig 2a).



3.



4.

**Figures 3, 4.** (3) Axial CT scan of the abdomen of a female mummy demonstrates an atrophic liver (curved arrow) and left kidney (straight arrow) as well as residual peritoneum lining the body cavity. (4) Axial CT scan of the chest of a male mummy, possibly that of Ramesses I, reveals at least three linen bundles in the thorax atop a mass of solidified resin (arrow). No organs were positively identified within these bundles. The relatively small size of the linen rolls relative to the chest and abdominal cavities may reflect shrinkage of the bundles over time.

Thin-collimation CT characterized and resolved these opaque areas, demonstrating multiple stacks of packed linens that accounted for the radiographic findings (Fig 2b). Three of the mummies showed evidence of intact, albeit atrophic, abdominal organs, including the kidneys and liver (Fig 3), refuting historical accounts of traditional mummification procedures and perhaps indicating that techniques varied according to the socioeconomic status of the deceased. The body cavity of one mummy, thought to possibly represent the “lost pharaoh,” Ramesses I, a ruler during the 19th dynasty (1320–1200 BC), had been eviscerated and repacked with neatly rolled linen bundles (Fig 4). Axial imaging of these bundles failed to demonstrate convincing evidence of internal organs, giving credence to the theory that this person may have lived during the New Kingdom (1567–1085 BC), a time when organs were not typically replaced in the body cavity. The presence of solidified resin within the thoracic, abdominopelvic, and cranial cavities also corroborated accounts of materials and methods of mummification used during this period.

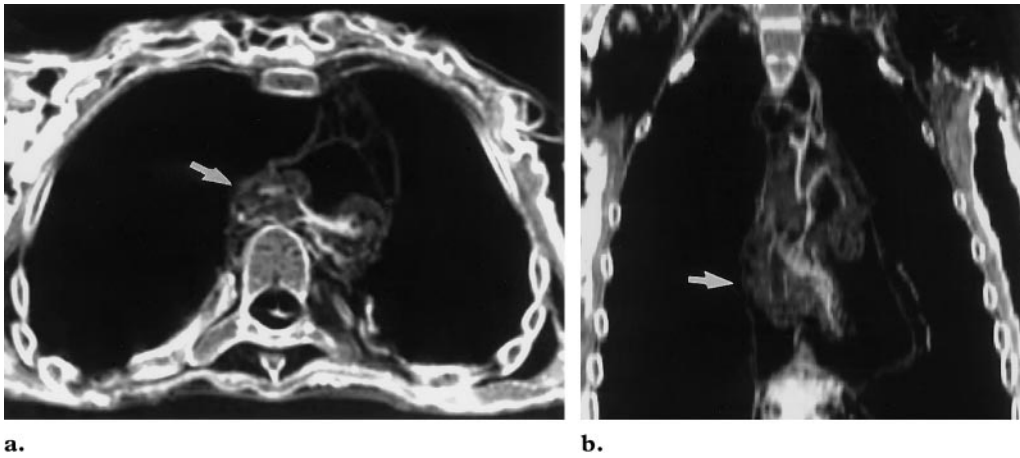
Thin-collimation CT produced raw data that could also be reformatted in the coronal and sagittal planes, offering varying perspectives on both



**Figure 5.** Sagittal CT scan of the skull of a pediatric mummy demonstrates a defect in the roof of the ethmoid sinuses (arrow) that was created for excerebration.

normal anatomy and the defects created by mummification. Sagittal and coronal reformatting provided a better perspective on the length and location of the cribriform plate fracture created for removal of the brain than did axial





**Figure 6.** (a) Axial thin-collimation CT scan of the chest of a female mummy helps confirm the expected presence of the heart (arrow), an organ that was accorded special attributes by the Egyptians and therefore typically left in the body prior to burial. (b) Coronal reformatted image provides additional information as to the character, location, and overall appearance of the residual heart tissue (arrow).



**Figure 7.** Color 3D reconstructed image of the head of the possible royal pharaoh demonstrates deformity and partial absence of the pinna of the right ear, a detail that was difficult to appreciate at axial imaging but became quite evident with this postprocessing algorithm.

imaging alone (Fig 5). Similarly, although axial scans clearly demonstrated the presence of the heart in several mummies, coronal reformatted

images offered a complementary view of its appearance and location (Fig 6). Interestingly, the heart was not identifiable in four mummies, suggesting either that there was no attempt to preserve it or that it may have inadvertently been removed during evisceration and embalming.

### Three-dimensional Reconstruction

Postprocessing algorithms enabled us to generate color 3D reformatted images of the head and body of each mummy, allowing depiction of the preserved soft tissues with excellent resolution. The images could be manipulated electronically on the workstation, displaying areas of interest in multiple dimensions. Facial features could be studied by rotating the head around multiple axes; in one case, a dysmorphic right ear was identified that was not appreciated on the axial scans (Fig 7). Although nonspecific, this finding suggests pre- or postmortem trauma to the pinna in a mummy that was otherwise pristinely preserved. The braided hair of one female mummy, which was also poorly appreciated on axial scans, became clearly evident with volume-rendering

**Figure 8.** Color 3D reconstructed image of a female mummy, aptly nicknamed “The Braided Lady,” demonstrates the deceased woman’s hairstyle in considerable detail.



**a.**



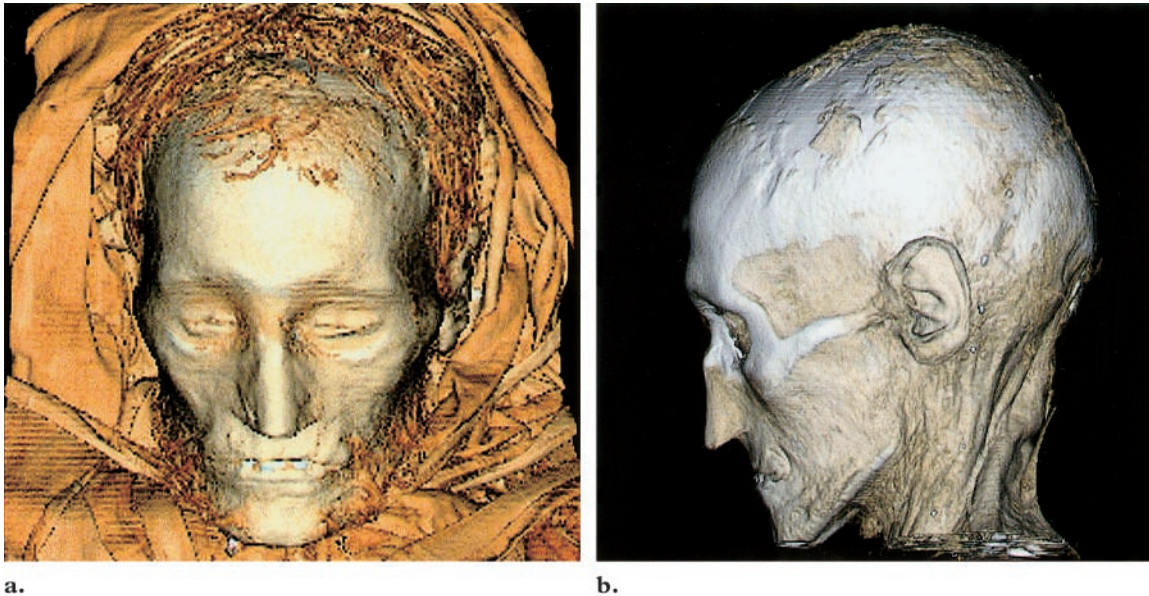
**b.**

**Figure 9.** (a) Three-dimensional reconstructed image of a male mummy from the Roman era shows linen wrappings overlying the pelvis in a geometric pattern that was not evident at axial imaging. (b) Image created by digitally removing the linen wrappings with volume rendering reveals the well-preserved underlying musculature and genitalia. The small white areas of increased opacity (arrowhead) represent scattered calcifications in the soft tissues. This digital process essentially allows virtual “unwrapping” of a mummy.

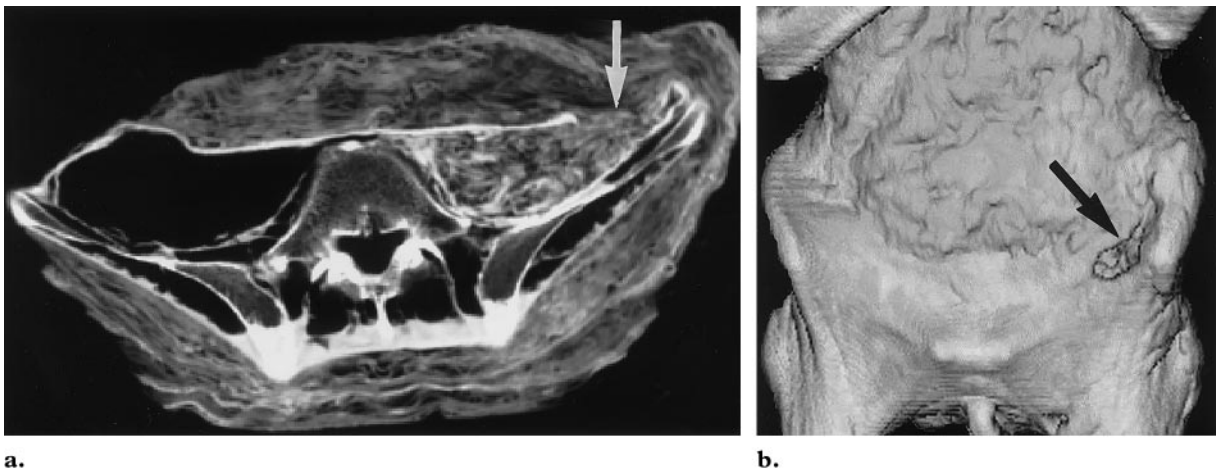
techniques (Fig 8). The linens overlying the pelvis in one male mummy were digitally reconstructed and then removed, displaying the hand position along the outer thighs and the excellent state of

preservation of the underlying phallus and leg muscles (Fig 9). The red hair and beard of the deceased were assigned a similar color by the computer and could be digitally subtracted and the face turned in profile, giving the observer a sense of the underlying bone and facial structure





**Figure 10.** (a) Frontal color 3D reconstructed image of the head of a male mummy demonstrates the preserved facial and scalp hair as well as the linen wrappings surrounding the head. (b) Image created by digitally removing the overlying facial hair and linen wrappings with volume rendering shows the mummy's head in profile. This allows the viewer to study the profile and specific facial features from a different perspective without having to touch or physically manipulate the specimen itself.

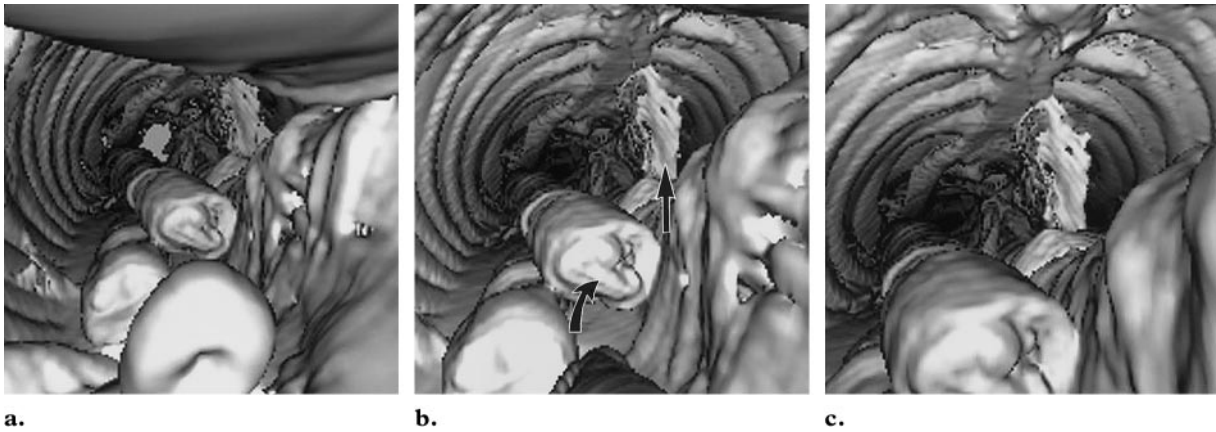


**Figure 11.** (a) Axial thin-collimation CT scan of the lower abdomen of the possible royal pharaoh demonstrates a defect in the skin surface (arrow) representing an incision made for removal of the abdominal and pelvic organs. Linens can be seen overlying the abdominal surface and packed deep to the incision. (b) Three-dimensional reconstructed image shows the incisional defect in the left lower quadrant (arrow). This method of image display provides a complementary perspective on the defect and gives the observer a better sense of its location, length, and shape.

(Fig 10). Similarly, although axial imaging clearly demonstrated the characteristic abdominal incision through which the organs were removed, 3D reconstructed images provided a better sense of the location, length, and curvature of the incision (Fig 11).

### Virtual Fly-through Techniques

By applying postprocessing algorithms typically used for virtual colonoscopy and bronchoscopy, we constructed a virtual fly-through tour through



**Figure 12.** Sequential 3D fly-through images through the hollow abdominal and chest cavities of the possible royal pharaoh demonstrate linen rolls along the dependent surfaces (curved arrow in **b**) as well as a finding that probably represents residual pleura lining the midline of the chest (straight arrow in **b**). When they were viewed sequentially as part of a motion clip on the computer workstation, these images simulated an endoscopic journey through the body without risking physical damage to the specimen.

the hollow body cavities of selected mummies. Five of the specimens in the collection were partially explored with this method; in the remaining four specimens, dense internal packing materials precluded evaluation with this technique. A virtual tour through the chest and abdomen of the possible royal pharaoh was generated, providing an intriguing perspective on the linen bundles and presumed residual pleura lining the chest cavity (Fig 12). Another tour takes the observer up the right nostril, through the punctured cribriform plate, and into the cranium, demonstrating the exact transnasal route of excerebration. In several mummies, hollow structures either not amenable to or too fragile for routine endoscopy (eg, the respiratory tree and spinal canal) were likewise visualized noninvasively and found to have intact tracheobronchial structures and atrophic dural lining.

### Discussion

Axial thin-collimation CT, along with coronal and sagittal reformatting, provided a pictorial essay of some of the methods and materials used in mummification. Because it is cross-sectional in nature, CT intrinsically offers better contrast and spatial resolution than conventional radiography. These advantages are particularly useful in evaluating mummies, many of which are densely packed with embalming materials. In our study, routine axial CT scans allowed characterization of the density, location, and appearance of packing materials that were obscured at conventional radiography. Coronal and sagittal reformatted images were helpful in depicting normal anatomy and

mummification-related defects in the most informative plane. Some of our findings were surprising; for example, abdominal organs were present in situ in four mummies, whereas the heart could not be positively identified in four mummies. These findings refute traditional accounts of the methods of mummification and led us to surmise that mummification techniques probably varied depending on the era and the socioeconomic status of the deceased. The most pristinely preserved mummy in the collection was found to have a characteristic incision in the middle left portion of the abdomen as well as linen rolls and resin within the chest, abdominal, and pelvic cavities. These were mummification techniques used during the New Kingdom, the era in which the Ramesside kings ruled. Our CT findings support the notion that this especially well preserved mummy is that of a person who likely lived during the New Kingdom and may even be the missing mummy of Ramesses I. The fact that the mummy's arms were placed across the chest also suggests that the deceased may have been of the nobility. Additional work that makes use of DNA testing is being carried out by Emory University researchers in an attempt to determine if this mummy is in fact the lost pharaoh. The goal is to extract viable DNA from the teeth or bones of the mummy and compare it with similar samples from the mummies of Ramesses' son and grandson, which reside in a museum in Cairo, Egypt. Thus, axial and multiplanar images not only shed light on how the bodies were mummified, but provide potential clues about the time period in which the deceased may have lived, information which has obvious value to Egyptologists and archaeologists.



The use of sophisticated postprocessing algorithms allowed the generation of 3D reconstructed images of the heads and bodies of the mummies. Although several authors have already generated and published reconstructed images (13–17), current software allows the production of images with superior resolution and depiction of superficial anatomy. Soft-tissue details that were poorly appreciated on traditional axial images, particularly facial hair and structural features, could be clearly displayed by applying volume-rendering algorithms to the raw image data. With further manipulation, superficial areas of increased opacity, whether representing hair or overlying linens, could be digitally removed, in one case revealing the excellent state of preservation of the soft tissues beneath the linen wrappings (Fig 9). This technique potentially allows virtual unwrapping of a mummy without specimen destruction, offering obvious advantages over standard anatomic dissection. Whereas early investigators sent the raw CT image data off-site to a computer graphics center for generation of 3D images (13), these reconstructed images can now be created on-site at a conventional CT workstation.

In addition to standard multiplanar and 3D evaluation of mummies, virtual fly-through tours of internal body cavities provide a new and intriguing means of exploring hollow mummified remains without risking the potential damage inherent in conventional endoscopy. Although this technique may be limited in the study of some mummies due to the presence of dense internal packing materials, it is a potentially useful adjunct tool in the evaluation of others, providing a unique perspective on the internal body cavities of an ancient human being.

## Conclusions

For over a century, mummies have been evaluated with nondestructive radiologic imaging, first with conventional radiography and subsequently with early CT. With use of advanced CT techniques and sophisticated postprocessing software, the bar for the radiologic study of mummies has been raised. Mummies can now be studied, not only with standard axial imaging, but also in both coronal and sagittal planes, as 3D models, and internally as part of a virtual fly-through tour. With these algorithms, it is possible to evaluate materials and methods of mummification, depict anatomy in the most informative imaging plane, illustrate the soft-tissue preservation and physical appearance of mummies in superb detail, and generate an intriguing virtual tour through hollow mummified remains. Images generated with these

methods can not only help archaeologists and Egyptologists understand these fascinating members of mankind, but can also serve as adjunct visual aids for laypersons who are interested in mummies. As multi-detector row CT and postprocessing tools evolve, the capabilities and applications of CT will continue to proliferate, attesting to the expanded versatility and utility of CT as a noninvasive research tool in the multidisciplinary study of Egyptian mummies.

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