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Morphometrical Assessment of Brain of Human Remains and Historical Objects by Medical Imaging Technologies: Promising Intelligent Systems

Evaluación Morfométrica del Cerebro de Restos Humanos y Objetos Históricos Mediante Tecnologías de Imagen Médica: Sistemas Inteligentes Prometedores

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SUMMARY: As an interdisciplinary research field, paleopathology focuses on the occurrence and progression of ancient diseases and their development in societies. Mummified bodies, historical human objects, and hominin fossils are valuable materials for answering questions about the passage of history, human origins, and timeline phylogeny. Since mummies and antiquities are very rare, in addition to examining and evaluating them, they must be preserved with the utmost care and delicacy. Conventional methods only performed on the data acquired from the study of the external properties of materials, and these approaches limited the study of human phylogeny. Computed tomography (CT) has an important role in criteria development and morphological characteristics of a human, which led to the establishment of a new field of research called paleoradiology. Rapid progress in CT reconstruction tools such as maximum intensity projection (MIP), multiplanar reconstruction (MPR), shaded surface display (SSD), and volumetric rendering technique (VRT) provided better visualization of the anatomical and pathological disorders and malformations in mummies. Also, a CT scan is one of the most frequently utilized methods to look for mummified pathology without any physical destruction or damage to its surface. Some analytic methods including microbiology and biochemistry require direct contact with the objects and mummies. At the same time, most museums and researchers of cultural heritage have emphasized the use of non-invasive techniques e.g. CT. In archaeological surveys, it is suggested that more consideration should be given to applying these reconstruction tools since it provides the interpreter with a comprehensive understanding of the diagnosis.

KEY WORDS: Paleopathology; Image reconstruction; Anthropometry; CT scan.

INTRODUCTION

Archeology is a major science in the identification of human history. Mummies represent a unique source of information about ancient diseases and their evolution (Tryon *et al*., 2010). Mummies and historical objects are valuable remains of information about the origin and time of the onset of diseases and the evolution of creatures, especially humans, which can be used as a gateway into the history of our species (Cesarani *et al*., 2003; Jackowski *et al*., 2008). One of the most challenging issues is maintaining the integrity of archaeological specimens and historical objects (Huffman & Antoine, 2010). The other issue is about the processes used in embalming and preserving the mummies which cannot be explained by traditional techniques (Tchapla *et al*., 2004; Ajao *et al*., 2010). Recently, volumetric cross-sectional examination of the mummified, especially for evaluation of valuable specimens of antiquities in the museum, has almost completely replaced classical autopsy (Moissidou *et al*., 2015). Currently, for paleomorphology and assessment of paleopathology with no object dissection, certain types of noninvasive imaging techniques are being used: X-ray radiography, computed tomography (CT) and magnetic resonance imaging (MRI) (Rühli *et al*., 2004;

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Karlik *et al*., 2007; Licata *et al*., 2016; Eppenberger *et al*., 2018). Paleopathology is an interdisciplinary field that integrates disciplines such as anatomy, anthropology, primatology, neuroscience, statistics, computer science, and medical forensics (Weber, 2015). Because this new scientific branch examines the condition of tissues in a mummy and historical objects, it is called Paleoimaging or Paleoradiology (Rühli *et al*., 2004; Panzer *et al*., 2013; Licata *et al*., 2016). Paleoimaging is a multidisciplinary science in which studies can be conducted by scientists from diverse backgrounds, including archaeology, anatomical sciences, biochemistry, anthropology, microbiology, radiological sciences (Moissidou *et al*., 2015). CT is not only used to examine mummified bodies, but also to date and identify the components of handmade objects (artefacts) such as clay tablets, scrolls, pottery, and swords (Lynnerup, 2010; Moissidou *et al*., 2015). One of the most important medical events of the twentieth century was the discovery of X-rays by Wilhelm Roentgen in 1895. The medical use of X-rays includes diagnosis of bone diseases, especially trauma, infection, tumor, congenital diseases, and rheumatoid arthritis. Three years later, radiography entered the field of non-medical applications, namely mummification archeology. Osteoarthritis was the first mummy disease to be diagnosed in Egyptian mummies by a British radiologist, Gray, in 1968 (Gray, 1973; Öhrström *et al*., 2013; Beckett & Conlogue, 2021; Panzer *et al*., 2021). Among the most important early studies conducted in the field of examining ancient objects and mummified bodies with conventional radiography, are the studies of Dedekind in 1896 who worked on the ancient Egyptian mummies, Leonard in 1898 who worked on the Peruvian mummies, Gardiner in 1904 who worked on the ancient Egyptian mummies, and Elliot Smith in 1912 who worked on the ancient Egyptian mummies (Chhem, 2006). Numerous mummy studies have been performed with advanced CT scan techniques, the most important of which include Harwood-Nash in 1979 (whole-body), Marx and D'Auria in 1987 (three-dimension (3D) skull), and Hoffman in 2002 (Virtual endoscopy) (Cox, 2015). Another important application is that by using CT we can determine the type and quality of the mummification materials which is known as "mummification engineering" (Cox, 2015). CT is a widely used diagnostic method in cultural heritage and paleopathology and visualizes the internal structure of objects, thereby yielding valuable information about the history of artistic, and archaeological objects, and human remains (Villa *et al*., 2019). Since the CT provides data over the entire volume of the object and has fundamental importance for solving archaeological and anthropological issues such as the evolution of diseases, dating, and conservation methods, the main aim of the study is the review of the investigations in this field.

Method search strategy

The search strategy for conducting this review article was as follows: The search query of the PubMed and Scopus medical databases and used terms ("archaeology" OR "radiology" OR "morphology" OR "image reconstruction") AND (mummify OR paleoradiology OR paleoimaging) AND (paleopathology) AND (computed tomography scan OR CT scan). The inclusion criteria were high-impact articles, peer review journals, and relevant subjects regarding our work. In addition, all human remains which were studied by tomographic techniques were included (completely preserved, unwrapped mummies, parts of mummies, skeletal remains with partially or no preserved soft tissue). Studies with non-English language, other imaging techniques and review articles were excluded from the study data collection.

Paleoradiology and applied role of CT

This new science could have been used to enhance the diagnosis and assessment of the human diseases of ancient times. CT served as the key imaging modality for diagnosis of pathologies in forensic medicine and the mummified because tissue is not manipulated by CT, and it provides thin slices in millimeter, optimize image contrast, enables post-processing algorithms such as multiplanar reconstruction (MPR), volume rendering technique (VRT), and quantitative and volumetric tools (Panzer *et al*., 2015). Currently, CT is an applied modality in the structural differentiation between soft tissues and bone and also diagnosis of mummy diseases called paleopathology as well as estimation of sex and age at death by using morphological evaluation of the pubis symphysis, dental and bone density (Davey *et al*., 2013; Hawass & Saleem, 2020). Although the soft tissue is better visualized by MRI in a living person (Heidari *et al*., 2017a,b, 2020, 2023), in mummified tissue due to dehydration, spatial strength is decreased and MRI is inefficient; because soft tissue density increases due to the desiccate phenomenon, CT scan is a better modality about density, size as well as developmental location within the body (Romell *et al*., 2018). In conclusion, establishing methodological and procedural standards known as Radiological Scoring Checklist (RSC) for assessment in mummies is a key strategy for information management from the ancient to the future (Panzer *et al*., 2015). Although in the 1970s decade both scan and image reconstruction by a conventional algorithm known as filtered back projection (FBS) took about 5 min and image resolution was approximately 80×80 pixels (Hounsfield, 1973). In contrast, in the last decade image resolution increased to 512×512 pixels with reduced-dose CT acquisitions using beam-shaping filters and iterative reconstruction (IR) technology especially in Siemens Healthineers entitled advanced modeled iterative reconstruction (ADMIRE) and in Canon Healthcare entitled forward projected model-based iterative reconstruction solution (FIRST) (Qiu & Seeram, 2016; Kataria *et al*., 2021). Therefore, the reduction of radiation dose in CT is necessary to prevent damage to important historical artifacts or rare mummies and maintain the integrity of ancient remains for research based on future advances in imaging modalities that are likely to occur. Imaging technologies based on computed tomography can greatly reveal the field of detection of many paleopathological disorders and diseases of different periods of the origin of the human race. More information is presented in Table I.

Table I. The role of using CT scan in detecting paleopathological disorders.

Diagnosed Disorder	**Technique**	**Anatomical integrity (segments present)**	**Source**	**Reference**
- Sclerosis and thinning of the cranial plate - Osteoarthritis of the temporomandibular joint - Epidermoid cyst	CT scan	Human skull	The University of Padua (Italy) preserved the skull of Santorio Santorio	Beck De Lotto *et al.* (2023)
- Dentoalveolar complex	micro-CT scan	Human skull	Archaeological specimens	Gurr *et al.* (2023)
Osseous cranial tumor	CT scan X-ray	Human skull	Hellenistic-era individual excavated by the Mugla Archaeological Museum in Gülagzı, Turkey	Bews *et al.* (2023)
Heart Defect	micro-CT scan Metaproteomics	Human heart	The heart of Blessed Pauline Jaricot	Bourdin *et al.* (2023)
Fetal cranial defect	CT scan	Tarchia Skull	Skulls of the Mongolian ankylosaurids Shamosaurus, Tarchia, and Saichania	Tumanova *et al.* (2025)
Pituitary tumor	CT scan 3D reconstructions	Valgipes bucklandi skull	The pituitary gland of the specimen MCT 3993-M	do Amaral *et al.* (2022)
- Spondylolysis - Spina bifida occulta	CT scan	Vertebral column	A sample from the general contemporary French population from the Nord hospital in Marseille Digne-les-Bains, Alpes-de-Haute-Provence a corpus	Murail *et al.* (2005)
Hyperostosis frontalis interna	CT scan	Human skull	skulls from the collections of the Anuchin Research Institute and Museum of Anthropology, Moscow State University	Cvetkovic *et al.* (2020)
Mycobacteria of the M. tuberculosis complex	Macro-histomorphology CT scan Organ radiography	Human body	The well-preserved natural mummy of the Royal Bavarian General, Count Heinrich LII Reuss-Köstritz (1763-1851 CE)	Nerlich *et al.* (2021)
Trauma Infection Neoplasia	X-ray CT scan 3D reconstructions	1. Skull 2. Thoracic spine 3. Coxal/sacrum 4. Skull 5. Femur 6. Femur	Six palaeopathological cases: 1. Qafzeh, Israel adolescent individual 11, Middle Palaeolithic 2. Saint-Martial of Angouleme, France, adult female, Middle Age 3. Iboussières, France, adult male, Upper Palaeolithic 4. Saint-Come Priory, Middle Age (12th cent.), elderly male, France 5. Saint-Laurent de Grenoble, Modern period (18th cent.), adult, France 6. Kaliningrad, Contemporary period (1812), young male, Russian Federation	Coqueugniot *et al.* (2020)
Heart structural abnormality	3D CT scan reconstruction	Human heart	Mummified heart from a person embalmed in Egypt around 2,700 years ago	Olszewski *et al.* (2019)
Mastoid osteoma	CT scan	Human skull	The skull derives from the Chunchuri (today Dupont-1 site) Pre-Hispanic site in Northern Chile (1390 A.D)	Castro *et al.* (2019)
Gallstone Choleliths	SEM XRD CT scan	Human gallbladder	Two pre-Hispanic Colombian mummies	Cárdenas-Arroyo *et al.* (2019)
Metastatic prostate carcinoma	CT scan X-ray	Human skeletal	The skeleton of an adult male recovered in the necropolis of Casal Bertone in Rome (Italy)	Minozzi *et al.* (2018)
Occipital osteoma Tuberculous Spondylodiscitis	Multidetector computed tomography (MDCT)	Human mummies	Chachapoyan mummies of Peru	Friedrich *et al.* (2010)
Atherosclerosis	CT scan	Human cardiovascular	52 ancient Egyptian mummies from the Middle Kingdom to the Greco-Roman period	Allam *et al.* (2011)

DISCUSSION

The tremendous advances in CT reconstruction techniques over the last years such as maximum intensity projection (MIP), MPR, shaded surface display (SSD), and VRT provided better visualization of the anatomical and pathological malformations in mummies and ancient/ historical human objects (Dalrymple *et al*., 2005; Hawass & Saleem, 2020). MIP is a standard diagnostic algorithm because it can distinguish structures that are hyperdense concerning surrounding tissues, and as a result of the higher density enables the interpreter who can be a radiologist or anatomist to better understand the morphology of complex superimposed structures in mummifying such as nodules, calcifications, surgical clips, foreign bodies (Dalrymple *et al*., 2005; Perandini *et al*., 2010). MPR is a very fast and interactive tool that instead of representing in one specific direction, displays all voxels contained in a curved surface as a single two-dimensional image (Dalrymple *et al*., 2005). One of the most important uses of this technique is that it allows the operator to follow body foramina and canals, particularly in the maxillofacial region, vessels filled with special fixing materials, fracture lines in the skeletal system, and also in the dental area (Davey *et al*., 2014; Perandini *et al*., 2010). Using MPR due to artifact elimination can examine the layering of materials used for the mummification process as well as the climate and geological changes that affect mummified bodies over time. With the help of this algorithm, structures that cannot be seen in the axial plane are accurately assessed (Davey *et al*., 2014; Panzer *et al*., 2013; Perandini *et al*., 2010). SSD or the same as surface rendering is a powerful post processing algorithm for the display of whole anatomic regions and planning of dissection procedures of object/mummify internal structures. Providing a 3D view like MPR, this algorithm is one of the important tools for designing an intervention map to the internal structures of the body similar to autopsy approach (Dalrymple *et al*., 2005; Perandini *et al*., 2010; Davey *et al*., 2014) (Fig. 1). SSD plays a crucial role in the visualization of vessels abnormalities and diagnosis and differentiation of normal tissues and pathological conditions, such as calcified tissue from premortem periods (Dalrymple *et al*., 2005; Coqueugniot *et al*., 2020). Radiological algorithms are mathematical operations based on biological findings that represent tissue information. For example it can be seen as density in the conventional radiography or signal intensity in the MRI modality (Dalrymple *et al*., 2005; Perandini *et al*., 2010). Recently 3D reconstruction techniques have provided more anatomical details due to the design and development of oblique or curved reconstruction algorithms. These new algorithms are important in paleoradiology because many of the organs were oblique when embalmed or even curved over many years due to ground pressure or frame coffin (Rühli *et al*., 2004; Chhem, 2006; Oras *et al*., 2020). In addition, these techniques reinforce the sensitivity to differentiate healthy tissue from lesions, fixing materials as well as any external bodies around it. However, a radiologist must have sufficient knowledge of the process of mummification and its effects on his body in order to understand morphologic changes found between samples of

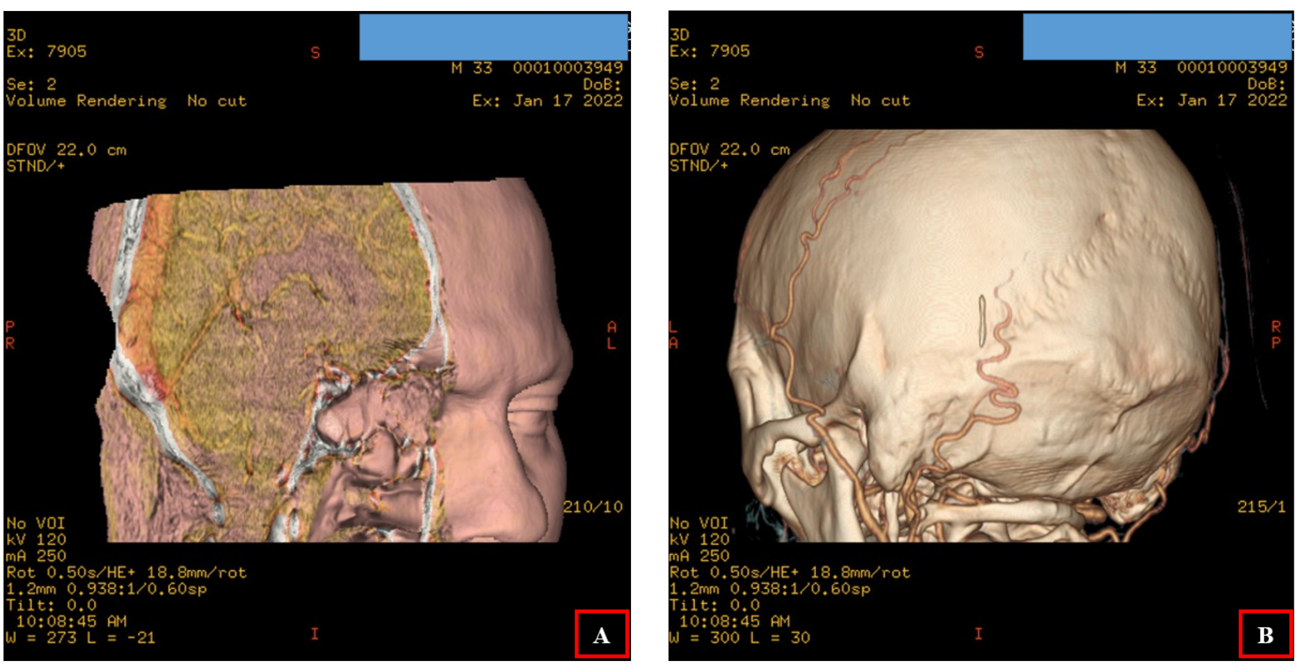

Fig. 1. An example of post-processing tools in CT scan to visualize the details of tissues in human. A) shaded surface display (SSD); B) volumetric rendering technique (VRT); visualizations of brain in a 33-year-old male.

mummified tissue (Beckett, 2014). The most practical diagnosis and data interpretation is possible when the radiologist has information about the mummification method, dietary habits of the culture, and knowledge of varied environmental impacts on human tissue over time, which requires consulting with an anatomist, physical anthropologist, dentist as well as archaeologist (O'Brien *et al*., 2009; Beckett, 2014; Beckett & Conlogue, 2021). So it is suggested that paleoradiology teamwork should be composed of different specializations, including paleopathology, epidemiology, forensics medicine, radiography, anatomy, endoscopy, radiology, biological anthropology, and physical anthropology. Member of a paleoradiology team should be trained and experienced in the process of human fixation techniques and cadaver/mummify morphological assessments (Beckett & Conlogue, 2021). Although there are very few outstanding paleoradiologist, through education and training in research workshops we can develop experts in the field of paleoradiology. Since the material used in mummified bodies is translucent radiation, the help of an advanced CT scan device can visualize very detailed information of the mummy body and allow simulating a 3D model and even reconstructing the face (Davey *et al*., 2013; Yatsishina *et al*., 2018; Hawass & Saleem, 2020). Although diagenetic changes in ancient tissues often lead to interpretive biases, CT slices with millimeter thicknesses can differentiate between surrounding tissue structures and mummy bodies (Moissidou *et al*., 2015). Furthermore, it may be able to display pre-mortem trauma from post-mortem human manipulations during the mummification process and reveal unknown mysteries about the methods of fixing corpses in which ancient people preserved their dead (Rühli *et al*., 2004). To identify a true history of life on Earth and reveal the phylogeny and ontogeny of human species in different cultures and societies, it is suggested that countries set up a national system for collecting their anthropological and archaeological information so that we can establish an integrated global system. Moreover, one of the important paleoradiological plans in the future can be the application of artificial intelligence to design and manage databases resulting from the imaging of ancient mummify/objects. Documenting valuable ancient mummies using historiographical criteria and characteristics provides evidence to help the bioarchaeologist answer questions regarding specific cultures or populations. Because CT data is presented in Digital Imaging and Communications in Medicine (DICOM) format which is sent through the picture archiving and communication system (PACS), it is possible to make accurate decisions about the living conditions and death of a mummy with different experts from around the world. In our opinion sharing of information between radiologists, anatomists, archaeologists, and anthropologists and also adding radiological findings to the bio-archaeological data can be one of the best criteria and guidelines for identifying the age at death, gender, stature, ethnic group, cultural style of mummifying (or historical human objects) in different societies of their time. As a strategic suggestion CT allows researchers to gain deeper historical and biological knowledge about the past in continuous evolution, so an international legal committee to define the framework of research boundaries and the principles of discovery and registration of objects and human remaining from archaeological excavations which is called Archaeological Imaging Bank (AIB), is needed.

CONCLUSION

CT as a non-destructive method via post processing algorithm is highly effective, and also among these four reconstruction techniques, VRT and SSD have considerable importance in visualizing the internal structures of the objects/mummify. It is suggested that the use of these valuable reconstruction tools be given more consideration in archaeological surveys as it gives the interpreter a comprehensive understanding of the diagnosis and the characterization of preserved normal tissues and malformation conditions. As a forward-looking proposition, manufacturers of diagnostic/clinical CT scanners should note that the CT machine is in the hospital and the mummy has to be transported from the museum to the hospital, which is a difficult task both administratively and technically, therefore they have to develop a mobile CT scan with an especially large gantry diameter and at lower cost. A significant contribution to the ongoing discussions on temporal and geographical variability of neoplastic conditions in the past can be attributed to the identification of new cases at paleopathology. This technique can be useful to carry out a comparison study according to morphology and radiological criteria, which may help exclude suspicious cases in the analysis of pathological material from paleoanthropology. In addition, data that are useful for further paleopathology studies can be obtained in an exhaustive diagnostics study complemented by CT scans and 3D reconstitution. Moreover, further research is recommended to better understand the effects of benign neoplasms in ancient times, given a high incidence of benign tumors in clinical literature but very limited reports from paleopathological records.

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RESUMEN: Como campo de investigación interdisciplinario, la paleopatología se centra en la aparición y progresión de enfermedades antiguas y su desarrollo en las sociedades. Los cuerpos momificados, los objetos humanos históricos y los fósiles de homínidos son materiales valiosos para responder preguntas sobre el transcurso de la historia, los orígenes humanos y la filogenia cronológica. Dado que las momias y las antigüedades son muy escasas, además de examinarlas y evaluarlas, deben conservarse con el máximo cuidado y delicadeza. Los métodos convencionales solo se basaban en los datos obtenidos del estudio de las propiedades externas de los materiales, y estos enfoques limitaban el estudio de la filogenia humana. La tomografía computarizada (TC) desempeña un papel importante en el desarrollo de criterios y las características morfológicas del ser humano, lo que condujo al establecimiento de un nuevo campo de investigación denominado paleo radiología. El rápido progreso en las herramientas de reconstrucción por TC, como la proyección de máxima intensidad (MIP), la reconstrucción multiplanar (MPR), la visualización de superficies sombreadas (SSD) y la técnica de representación volumétrica (VRT), proporcionó una mejor visualización de los trastornos y malformaciones anatómicos y patológicos en las momias. Además, la TC es uno de los métodos más utilizados para detectar patologías momificadas sin causar destrucción física ni daños en su superficie. Algunos métodos analíticos, como la microbiología y la bioquímica, requieren contacto directo con los objetos y las momias. Al mismo tiempo, la mayoría de los museos e investigadores del patrimonio cultural han priorizado el uso de técnicas no invasivas, como la TC. En los estudios arqueológicos, se sugiere considerar con mayor atención la aplicación de estas herramientas de reconstrucción, ya que proporcionan al intérprete una comprensión integral del diagnóstico.

PALABRAS CLAVE: Paleopatología; Reconstrucción de imágenes; Antropometría; TC.

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