Journal of Archaeological Science: Reports 8 (2016) 173–177

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

Imaging ancient and mummified specimens: Dual-energy CT with effective atomic number imaging of two ancient Egyptian cat mummies

James M. Bewes [a,*], Antony Morphett [b], F. Donald Pate [c], Maciej Henneberg [d], Andrew J. Low [a], Lars Kruse [b], Barry Craig [e], Aphrodite Hindson [e], Eleanor Adams [e]

[a] Department of Radiology, Royal Adelaide Hospital, North Terrace, Adelaide 5000, Australia
[b] Dr Jones and Partners, Medical Imaging, 270 Wakefield St, Adelaide 5000, Australia
[c] Department of Archaeology, Flinders University, Adelaide, SA 5001, Australia
[d] Biological Anthropology and Comparative Anatomy Research Unit, School of Medical Sciences, University of Adelaide, Adelaide 5005, Australia
[e] South Australian Museum, Adelaide, SA 5000, Australia

ARTICLE INFO

Article history:
Received 8 April 2016
Received in revised form 3 June 2016
Accepted 3 June 2016
Available online 11 June 2016

Keywords:
Paleoradiology
Computed tomography
Ancient Egypt
Mummies
Paleopathology
Effective atomic number
Dual-energy CT
Animal mummies

ABSTRACT

In mummified animals and humans, soft tissues like skin and muscle become more dense over time due to dehydration. At the same time, bone becomes less dense as marrow is replaced by air. This is a problem for the radiological examination of ancient specimens, as currently used methods such as single-energy CT and MRI rely on density and water content to produce tissue contrast in an image. Dual energy CT with effective atomic number imaging overcomes this problem, as the elemental constituents and consequently effective atomic number of a specimen remain relatively constant over time. This case study of two ancient Egyptian cat mummies demonstrates that effective atomic number imaging can differentiate desiccated soft tissues from low-density bone in ancient remains. Effective atomic number imaging has the potential for superior tissue contrast resolution when compared to single energy CT and can be used to provide new paleoradiological perspectives.

1. Introduction

1.1. Limitations of imaging ancient specimens using traditional single energy CT

A challenge in the field of paleoradiology, which is the radiological examination of ancient tissues, is differentiating between tissue types in mummified specimens. The combination of mummification processes and post-mortem changes cause the density of body constituents to become very similar. Bone becomes less dense as marrow is replaced by air, while soft tissues desiccate, becoming relatively more dense (Wanek et al., 2011). This presents a problem for the paleoradiologist, as conventional CT imaging depends heavily on a specimen's density to differentiate between tissue types (Bushberg and Boone, 2011; Gostner et al., 2013; Wade et al., 2012). This problem is magnified in small specimens, such as animal mummies, where spatial as well as contrast resolution is an issue.

Dual-energy CT offers a potential solution to the problem of converging material density in ancient specimens. By using two different x-ray energies to interrogate a material it is possible to derive a number of the material's properties that are unavailable on traditional, single energy CT scanners (Johnson et al., 2007; Wanek et al., 2011). Specifically, the electron density, effective atomic number and dual-energy index of a specimen can be calculated. These variables are potential discriminators between tissue types and inorganic materials for the paleoradiologist.

Effective atomic number imaging has theoretical advantages that make it a particularly promising candidate for use in paleoradiology. The effective atomic number of a specimen is independent of the density of a specimen (Brooks, 1977). While the density of ancient tissues changes over time, due to processes such as dehydration, the elemental constituents of mummified tissue stay relatively constant. Chemical variation due to tissue diagenesis is assumed to be comparatively small, particularly in specimens that are wrapped and not in direct contact with soil. Consequently, imaging with reference to atomic number should provide good discrimination between soft tissues and bone, as the latter has greater amounts of high atomic number elements such as calcium and phosphorus.

There are no published studies using atomic number imaging in the analysis of ancient remains. This preliminary study aims to demonstrate that dual-energy derived effective atomic number imaging is able to differentiate desiccated soft tissues from low density bone in ancient

* Corresponding author.
E-mail address: bewesj@gmail.com (J.M. Bewes).

http://dx.doi.org/10.1016/j.jasrep.2016.06.009

remains and is a superior discriminator when compared to single energy CT.

If validated, atomic number imaging has the potential to improve paleoradiological diagnosis, enabling a better understanding of ancient pathologies and the cultures associated with them.

A secondary question that we aim to answer in analyzing the two cat mummies with imaging is regarding cause of death. It has been hypothesized that a common method of dispatching the cats prior to mummification was by cervical spine dislocation (breaking their necks) (Armitage and Clutton-Brock, 1981; Ikram, 2005). Consequently, a specific focus of the CT analysis is cervical spine integrity.

2. Materials and methods

2.1. Subject description and sample preparation

Two mummified ancient Egyptian cat specimens were made available by the South Australian Museum - specimen numbers A40436 and A40437 (Fig. 1). The specimens were acquired by the museum in the early 20th century however unfortunately little more is known regarding their provenance. Votive offerings in the form of animal mummies were associated with Egyptian cults celebrating living animal deities and became particularly popular from c. 600 BCE until the Roman era, ceasing at c. CE 250 (Ikram et al., 2015; McKnight et al., 2015). The cat mummies have not been previously imaged. Protective casings were removed for the study. One specimen was fixed to a wooden backing board, which was unable to be removed.

2.2. Dual energy imaging

Dual energy CT is well established in clinical radiological practice (McCollough et al., 2015) and a clinical scanner (SOMATOM Definition Dual Source; Siemens, Munich, Germany) was used. The samples were positioned perpendicular to the bore of the CT to reduce artifact. Samples were simultaneously imaged at 80 keV and 140 keV, as these energies are compatible with the post-processing software used to calculate effective atomic number maps. These energies also reflect the extremes of single-energy imaging on most CT scanners. Theoretically any two energy levels can be used to derive effective atomic number. Multiplanar reconstructions were performed at 0.75 mm intervals (matrix size 512 × 512). Imaging was performed at Dr. Jones and Partners, Calvary Wakefield Hospital, Adelaide on 17/12/2015.

Fig. 1. Mummified cats imaged in current study (A40436 and A40437).

2.3. Post-imaging data acquisition

Following image acquisition, post-hoc image analysis was performed using a commercially available software package (SyngoDE – Siemens) on a dedicated clinical radiology workstation. This software allows automated derivation of effective atomic number maps, as well as quantitative effective atomic number values within a user-designated region of interest (ROI).

2.4. Imaging and tissue analysis

Analysis and interpretation of the mummified cat bundles was performed by two radiologists using dedicated clinical radiology workstations with multiplanar reconstructions.

Different tissues types were identified in the scanned ancient remains and representative ROI markers placed on each tissue type. The ROI markers were necessarily very small in size, secondary to the small size of the mummified cats. Tissue types examined include cortical bone, trabecular bone, soft tissue and linen.

The tissue types were identified on conventional single-energy CT images by two radiologists using anatomical landmarks in regions of high intrinsic spatial and contrast resolution. For example, to obtain ROI's for cortical bone, long bones were identified and ROI's only placed on continuous cortical bone. ROI's were not placed where there was radiological ambiguity regarding the physical composition of a tissue on an anatomical basis, such as in conglomerate masses of tissue and bone within the central thorax or abdomen, or in areas of fragmented tissue and bone. Using unequivocal anatomical and morphological features to identify tissue types excluded regions of the specimens from analysis but was necessary to ensure the specificity of tissue ROI markers.

Within each ROI, the effective atomic number for the tissue type of interest was calculated. Hounsfield units (HU) at 80 keV and 140 keV were also recorded for comparison. At least 20 ROI's for each tissue type in each specimen were tabulated to obtain a representative sample. To improve the generalizability of the results, ROIs from both cat specimens were pooled for final analysis.

2.5. Statistical analysis

Derived imaging parameters were compared in a pairwise fashion to determine the imaging parameter that provides the best material contrast. Following a significant Kruskal-Wallis test, pairwise comparisons were made using non-parametric Mann–Whitney tests with Bonferroni adjustments made for multiple comparisons. (18 comparison groups used in total) An adjusted p-value of less than $0.05/18 = 0.003$ was used as significant. Statistical analysis was performed using a commercially available software package SPSS (IBM SPSS Statistics for Windows, Version 21.0).

Noting that effective atomic number imaging and traditional CT Hounsfield units use different scales, a derived non-parametric effect size estimate ‘r’ was obtained (Fritz et al., 2012) in order to measure contrast magnitude between the parameters under investigation. The higher the effect size, the greater the magnitude of contrast between two tissues. Using Cohen's effect size estimates, 0.1 is a small difference, 0.3 is a moderate difference and 0.5 is a large difference.