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Application of clinical imaging and 3D printing to the identification of anomalies in an ancient Egyptian animal mummy

Lidija M. McKnight [a,*], Judith E. Adams [b], Andrew Chamberlain [a], Stephanie D. Atherton-Woolham [a], Richard Bibb [c]

[a] KNH Centre for Biomedical Egyptology, Faculty of Life Sciences, University of Manchester, UK
[b] Radiology, Royal Infirmary, Central Manchester University Hospitals NHS Foundation Trust and Manchester Academic Health Science Centre, Manchester, UK
[c] Loughborough Design School, Loughborough University, UK

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ABSTRACT

Non-destructive assessment of wrapped mummified animal remains from ancient Egypt using imaging techniques is the most ethically viable manner by which to investigate bundle contents. Bundles studied to date revealed complete and incomplete animal skeletons, multiple individuals (or parts thereof) wrapped together in one bundle, non-skeletal material, organic matter and anomalies of unknown origin. The identification of animal species using imaging alone can be fraught with difficulty, especially in cases in which the skeleton is incomplete and diagnostic elements are lost or significantly damaged.

This paper describes the radiographic investigation of a mummy bundle wrapped in the form of a canid, a species closely associated with ancient Egyptian embalming deities. Computed tomography (CT) was performed, and the bundle contents were computer modelled, leading to the production of a laser sintered 3D replica.

Imaging identified three skeletal fragments carefully positioned to act as structural support for the bundle; however, radiographic data proved inadequate to enable definitive identification of these elements. 3D printing enabled direct comparison with skeletal reference collections and confirmed that the bones were of human origin.

This paper demonstrates that imaging of wrapped animal mummy bundles and 3D printing of unidentified elements or non-skeletal anomalies will assist in their accurate identification in a non-destructive manner.

1. Introduction

1.1. Applications of 3D printing

Virtual reconstruction and three-dimensional printing are emerging tools in clinical practice (Chia and Wu, 2015; Lv et al., 2015; Murphy and Atala, 2014; Schievano et al., 2007) and their implementation is gaining momentum in other disciplines. The study of cultural artefacts, where destructive analysis is generally not permitted, can benefit greatly from the use of non-invasive imaging and increased visualisation made possible by such techniques (Niven et al., 2009; Schilling et al., 2014; Spring and Peters, 2014). The results of such analysis have important implications for the display of wrapped mummified material, the contents of which cannot be directly observed (Du Plessis et al., 2015).

1.2. History of mummy studies

Destructive autopsies of Egyptian mummies were popular spectacles during the eighteenth and nineteenth centuries and provided the only available method by which to determine the contents of wrapped mummy bundles at the time (Blumenbach, 1794; Moshenska, 2013). Animal mummies were amongst the first artefacts upon which radiographic techniques were tested in the 1890s (Glasser, 1933), although imaging by radiography and computed tomography (CT) is now widely applied in the study of mummified human and animal remains (D'Auria and Marx, 1988; Hoffman et al., 2002; Ikram and Iskander, 2002; Jackowski et al., 2008; McKnight, 2010; McKnight and Atherton-Woolham, 2015; McKnight et al., in press; Moodie, 1931; Raven and Taconis, 2005; Vanlathem, 1983; Wade et al., 2012). The ability of imaging to assess the contents of wrapped mummy bundles whilst maintaining their integrity has ensured its place as the preferred investigative tool.

1.3. Animal mummies as votive offerings

Mummified animals were deposited as votive offerings in enormous numbers in ancient Egypt, acting as a physical form of 'prayer' either

* Corresponding author.
E-mail addresses: lidija.mcknight@manchester.ac.uk (L.M. McKnight), judith.adams@manchester.ac.uk (J.E. Adams), andrew.chamberlain@manchester.ac.uk (A. Chamberlain), stephanie.woolham@manchester.ac.uk (S.D. Atherton-Woolham), R.J.Bibb@lboro.ac.uks (R. Bibb).

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seeking divine assistance or in thanks to the gods to which they were dedicated (Ikram, 2005; Atherton-Woolham and McKnight, 2015; Taylor, 2001). Catacombs containing an estimated 8 million mummies are located at the Sacred Animal Necropolis at Saqqara (Nicholson et al., 2013; Nicholson et al., 2015). The mummies recorded from the site include domestic dogs (*Canis lupus familiaris*), jackals (*Canis aureus*), foxes (*Vulpes* sp.), cats (*Felis catus*), jungle cats (*Felis chaus nilotica*), ichneumon (*Herpestes ichneumon*) and the occasional kestrel (*Falco tinnunculus*); indicating that other species were intentionally buried in the dog catacombs, possibly for mythological reasons (Nicholson et al., 2015).

From 2000 to 2012, 152 wrapped votive animal mummies were studied using clinical imaging to identify the contents non-destructively and to enable their classification as either true or pseudo mummies (McKnight, 2010; McKnight and Atherton, 2014; McKnight and Atherton-Woolham, 2015; McKnight et al., in press).

True mummies, those containing skeletal material, accounted for 81% (n = 123) of the bundles studied. Of these, 26% (n = 39) had lost their external wrappings. Of the wrapped bundles, 31% (n = 47) contained a complete skeleton and 11% (n = 17) contained a partial skeleton. In most cases, the species suggested by the external appearance of the bundle correlated with the contents; however, 1% (n = 2) contained the remains of different species. 6% (n = 9) contained the remains of more than one animal or species wrapped together in the same bundle (Atherton-Woolham and McKnight, 2014). The skeletal remains were unidentifiable in 6% (n = 9) of bundles. Pseudo mummies, those containing no skeletal remains, constituted the remaining 19% (n = 29) of the mummy bundles investigated (McKnight et al., in press; McKnight and Atherton-Woolham, 2015). The presence of pseudo mummies is previously reported (Ikram and Iskander, 2002; Ikram, 2005; McKnight, 2010; von den Driesch et al., 2006); however, this study presents the first published dataset incorporating quantitative analysis on animal mummies from multiple museum collections (McKnight et al., in press).

1.4. Species identification

The identification of mummified animal remains to taxa and species level using imaging was sometimes difficult, in particular, where diagnostic skeletal elements were absent or incomplete and in birds where morphological variation is slight. Two-dimensional radiographs, limited by magnification and superimposition of structures within a mummy bundle, made comparison of elements with reference material problematic. CT eliminated these issues and enabled accurate measurements for skeletal elements to be obtained. This was only feasible when diagnostic elements were present and clearly identifiable. The desiccated nature of mummified soft tissue further complicated visualisation as the X-ray density was similar to bone (McKnight et al., in press).

3D printing has potential in the field of mummy studies (Bibb et al., 2015; Hoppa et al., 2006), in particular in the visualisation of skeletal and anomalous inclusions within wrapped mummy bundles. Furthermore, the technique is applicable as an interpretive medium for display purposes (Du Plessis et al., 2015; Taylor and Antoine, 2014).

This manuscript presents the results of the radiographic investigation of a mummified bundle which demonstrated unexpected contents. Through the application of clinical imaging combined with 3D printing technology, these anomalies were investigated and replicated, both visually and materially, allowing an identification to be made.

2. Materials and methods

2.1. The case study

A wrapped mummy bundle (accession number TWCMS: 2001.406, Sunderland Museum, Tyne and Wear, UK) measuring 180 × 77 × 63 mm at the widest point, was recorded in museum archives as containing the remains of a jackal. There was an external stylised appearance of a jackal and an attempt at decoration crudely formed from four bands of coloured linen (Fig. 1). No provenance regarding the Egyptian origin of the bundle was recorded.

2.2. Imaging

The bundle was imaged at the Manchester Royal Infirmary in March 2011 to ascertain the contents and determine its authenticity. Digital radiography (DR) was performed on Siemens YSIO Fluorospot Compact equipment (Siemens Healthcare, Erlangen, Germany) with an exposure of 57 kV, 1 mA s and a focal spot size of 0.6 mm. CT was performed using a General Electric LightSpeed 64-row spiral multi-detector (MDCT) scanner (GE, Milwaukee, USA) using 120 kV p, 200 mA s with a pitch of 0.969:1.

Skeletal elements from a domestic canid (*C. lupus familiaris*) and a baboon (namely *Papio hamadryas*), both known to have been mummified by the ancient Egyptians (Ikram, 2013; Ikram et al., 2013; Von den Driesch et al., 2004), were imaged during 2013 for comparative purposes, together with human long bones from the University of Manchester anatomical teaching collections. DR was conducted using Philips Eleve Digital Diagnostic equipment (Philips Medical systems, Best, Netherlands) with an exposure of 57 kV, 1 mA s and a focal spot size of 0.6 mm. CT scans were obtained in the Radiology Department of the Royal Manchester Children's Hospital using a Siemens Somatom Definition AS + 128-row MDCT scanner (Siemens Healthcare, Erlangen, Germany) at a slice thickness of 0.625 mm and pitch of 0.969:1.

2.3. Data segmentation

CT images obtained in Digital Imaging and Communications in Medicine (DICOM) format were used to build a 3D print of the skeletal elements in the mummy bundle with the aim of improving visualisation and enabling an accurate identification. The CT images were segmented (Bibb et al., 2015) to isolate the bones by setting upper and lower CT number threshold values using specialist software (InVesalius, version 3, http://svn.softwarepublico.gov.br/trac/invesalius). The data relating to the largest single volume within that threshold range were generated as a three-dimensional computer model. These data were then translated and exported in the commonly used STL file format

Fig. 1. Photograph of mummy bundle TWCMS: 2001.406, stated in museum records to be the mummified remains of a jackal. The bundle had an unusually crude appearance, decorated with four horizontal linen bands. Photograph by Alex Croom.