Identification of avian remains contained within wrapped ancient Egyptian mummies: Part 1, A critical assessment of identification techniques

PLEASE CITE THE PUBLISHED VERSION

https://doi.org/10.1016/j.jasrep.2022.103585

PUBLISHER

Elsevier

VERSION

AM (Accepted Manuscript)

PUBLISHER STATEMENT

This paper was accepted for publication in the journal Journal of Archaeological Science: Reports and the definitive published version is available at https://doi.org/10.1016/j.jasrep.2022.103585

Identification of avian remains contained within wrapped ancient Egyptian mummies: Part 1, A critical assessment of identification techniques.

Authors – Lidija McKnight[1], Judith White[2], Amy Rosier[2], Joanne Cooper[2], Richard Bibb[3]

[1]School of Earth and Environmental Sciences, University of Manchester, 3.503 Stopford Building, Oxford Road, Manchester, UK. lidija.mcknight@manchester.ac.uk Telephone: 0161 306 4184

[2] Bird Group, Department of Life Sciences, The Natural History Museum, Akeman Street, Tring, Hertfordshire, HP23 6AP, UK.

[3] School of Design & Creative Arts, Loughborough University, Epinal Way, Loughborough, Leicestershire, LE11 3TU, United Kingdom

Keywords – avian, experimental, identification, morphology, 3D printing

Highlights -

- A targeted study of bird remains mummified as offerings to the gods in ancient Egypt.
- An experimental study to investigate the difficulties encountered when attempting to identify incomplete and comingled bird remains within wrapped mummy bundles.
- A comparative study evaluating experts' opinions of bird identification using radiographic modalities (X-ray and CT scanning) compared to bone-in-hand identification of physical bird bones.

Abstract –

Ancient Egyptian bird mummies manufactured in huge numbers present a unique and intriguing body of material with great archaeological and zooarchaeological significance. Research into this ancient practice is gaining momentum; however, one area that lacks clarity, but that is vital for the accurate interpretation of mummies as objects of ritual significance, is our ability to proffer accurate identifications of remains contained within wrapped mummy bundles. This is particularly relevant in the case of bird mummies where morphological variation between species can be minimal.

This paper presents the results of a multi-faceted research project combining non-invasive radiographic modalities, experimental techniques and 3D replication, designed to assess the accuracy of avian skeletal identification when physical access to the bones themselves is not possible.

1. Introduction

1.1 The Importance of Birds in the Religious Landscape of Ancient Egypt

The Egyptians lived in close harmony with their natural environment, witnessing the forces of nature and the appearance and behavioural characteristics of animals as they went about their daily lives. Animals were believed to occupy a liminal space between the living and the gods (Scalf 2012), and were themselves considered semi-divine. Each deity in the pantheon was associated with one or more animal species, appearing in art as hybridized creatures, often with the body of a human and the head of an animal.

Fig. 1 - This photograph depicts a plaster-cast reproduction of a wall scene from the temple of Esna. The original dates to c.50 AD. The scene shows the pharaoh, the Roman Emperor Claudius, being ritually washed by two gods in hybridized form; Thoth is depicted with the head of an ibis (left) and Horus with the head of a falcon (right).

The Egyptians believed that objects created in the image of the god – in either animal or hybrid form - from man-made or organic materials could act as a communication device, effectively enabling a dialogue between the devotee and the deity. Mummified animal remains concealed within linen wrappings, or housed within containers made from wood or metal, were popular votive offerings (Fig. 2). Votives often outwardly resemble the god with their votive efficacy enhanced by the inclusion of animal remains from one of the god's earthly representatives (Price 2015).

Fig. 2. Photograph of a) an Ibis mummy (Acc. No. 11501, Manchester Museum) with appliqué detail depicting the god, Thoth (Reproduced by permission of Manchester Museum, University of Manchester); b) votive bronze statuette in the form of the seated lion-headed deity, Sekhmet, goddess of warfare (Plymouth City Museum and Art Gallery, Acc. No. Learn0844 / AEABB596); c-d) an area of damage reveals the presence of a fabric package concealed within the seat. Radiography confirmed the presence of disarticulated skeletal remains, believed to belong to a cat (Photographs by L. McKnight).

Although the majority of faunal taxa were considered sacred, evidence suggests that aviformes occupied a position of elevated significance (McKnight 2020). The power of flight allowed them to travel physically closer to the heavenly gods, leading to birds being closely associated with the sun god, Re and with the human 'soul' (ba) depicted as the so-called ba-bird, represented as a human-headed hawk (Fig. 3). This hybridized creature was able to leave the tomb each night through the false door (a symbolic architectural construct representing a sealed door) before returning to the sanctuary of the tomb at dawn (Assman 2005).

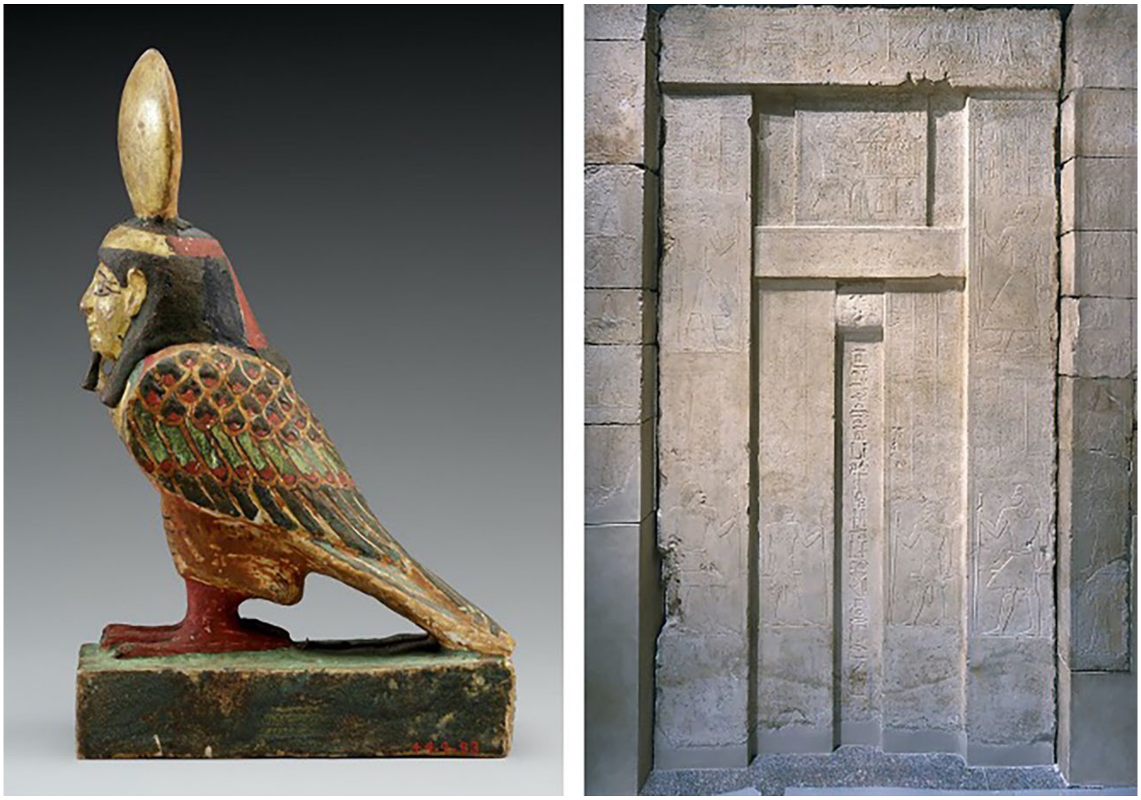

Fig. 3 – Photograph of a painted wooden ba bird (Ptolemaic Period c.332–30 BC) (Metropolitan Museum of Art, New York, acc. No. 44.4.83) and the false door located on the west wall of the Tomb Chapel of Raemkai at Saqqara, (5th Dynasty c. 2446–2389 B.C.) (Metropolitan Museum of Art, New York, acc. No. 08.201.1e).

In total, 243 avian native and migratory species have been identified from ancient Egyptian hieroglyphic inscriptions, artistic representations, skeletal and mummified remains. Of this total, 77 species have been identified from mummified remains (John Wyatt, pers. Comm; see also von den Driesch et al 2005). The most commonly mummified birds include the Sacred Ibis (*Threskiornis aethiopicus*), worshipped as the avatar of Thoth, god of wisdom and writing; and raptors such as the Common Kestrel (*Falco tinnunculus*) and the European Sparrowhawk (*Accipiter nisus*), sacred to Horus, god of the sky and of the living pharaoh.

Despite the enormous numbers of mummified birds interred in subterranean catacomb complexes in Egypt, relatively few have been studied in any detail (Atherton-Woolham et al. 2019). With the difficulties associated with the generally poor condition of the majority of these specimens and problems accessing material on archaeological sites in Egypt, specimens in museum collections are a particularly valuable resource. Research at the University of Manchester conducted over the past two decades has comprehensively studied in excess of 1200 votive animal mummies from 69 museum collections worldwide, around one third of which represent aviformes (McKnight 2012; McKnight and Atherton-Woolham 2016). Non-invasive radiography of ancient mummies, coupled with the experimental mummification of modern bird cadavers, have been applied to expand our understanding of votive animal mummification.

1.2 Research Considerations

Animal mummies present unique challenges for researchers because, unlike human mummies, the range of potential taxa contained within varies extensively. The identification of skeletal remains to species level is vital to our understanding of the role of these offerings within the ancient religious landscape. The high likelihood (>60%) that a bundle will contain incomplete or disarticulated remains of one or more individual or species (McKnight et al. 2015a) makes the identification of diagnostic elements difficult. Visualization and interpretation are often hampered by the compression of the bundle, the application of mummification substances, the use of packing materials, and the multiple layers of linen bandages, all of which constitute distracting radiographic ‘noise’.

Research has shown that only approximately one third of animal mummy bundles contain a complete and articulated skeleton. The remaining percentage contain either incomplete or co-mingled remains (from one or more individual or species) or are fabricated entirely from non-animal material (McKnight et al. 2015a). Providing positive identifications for avian remains from within wrapped mummies using radiography is problematic even when the specimens are complete and articulated. The presence of incomplete, co-mingled and fragmented elements compounds these issues and reduces the likelihood of reaching a positive identification using radiography alone (McKnight et al. 2015a). In collaboration with colleagues at the Natural History Museum’s Bird Group in Tring, Hertfordshire (NHM, Tring), the authors present evidence for the radiographic accuracy of avian species identification within wrapped bundles, and the implications for zooarchaeology and Egyptology.

2. Materials and Methods

2.1 Experimental Mummification Protocol – Partial Cadavers and Multiple Individuals

Zooarchaeological identification traditionally relies on the ‘bone in hand’ method in which archaeological remains are compared directly to skeletal collections. Sight and touch allow the often-miniscule differences in the size, morphology and texture of the skeletal elements to be compared, thereby narrowing the potential list of species to which the archaeological bones belong. When the bones themselves are hidden from view as is the case with mummies, the ‘bone in hand’ method is impossible and researchers must rely on radiographic images in order to attempt identification.

In 2015, six packages of partial and co-mingled avian remains assembled by an NHM curator (White) were delivered to the University of Manchester. The individual contents of the packages were recorded at source, and the identity of the remains kept secret from other members of the team so as not to influence the experiment. Each package was numbered (EM11-16), and mummified following a published experimental protocol designed to mimic ancient animal mummies (Atherton and McKnight 2014) (Fig. 4).

Fig. 4 – Photographs showing the mummification process; a) the six packages of co-mingled bird remains as they arrived at The University of Manchester, b) EM12 following the application of a molten beeswax and pine resin emulsion, and the initial layer of linen, and c) EM12 once completely mummified [Note the area of intense discolouration to the exterior of the linen wrappings caused by the leakage of fluids from the remains] (Photographs by L. McKnight).

The mummies were transported to the Royal Manchester Children’s Hospital for radiographic study using dual modalities - digital X-ray and CT scanning. The radiographic data was shared with a second member of NHM staff (Rosier) who, without prior knowledge of their identity, was tasked with attempting identification using only the radiographs and the museum’s extensive skeletal reference collection. Avoiding inaccurate results caused by ‘suspected identifications’, Rosier was unable to identify the remains beyond tentative species groupings in all cases. Considering the high quality of the radiographic data obtained through the dual imaging techniques and the availability of post-processing software to enable data manipulation, this confirmed that so-called ‘definitive identifications’ offered for incomplete avian remains are likely to be inaccurate when based upon radiographic evidence alone.

After six months, the mummies were dissected to reveal completely desiccated bird remains. The linen wrappings were cut away and discarded, and the feathers and soft tissue removed by hand as far as was possible. The skeletal ‘portions’ were macerated in cold water in glass laboratory beakers and stored in a fume cupboard with the water changed weekly. The waste-water was sieved to ensure that no small bones were lost. Once clean, the bones were placed on paper towels on labelled trays to dry before being bagged, labelled and taken to the NHM (Fig. 5).

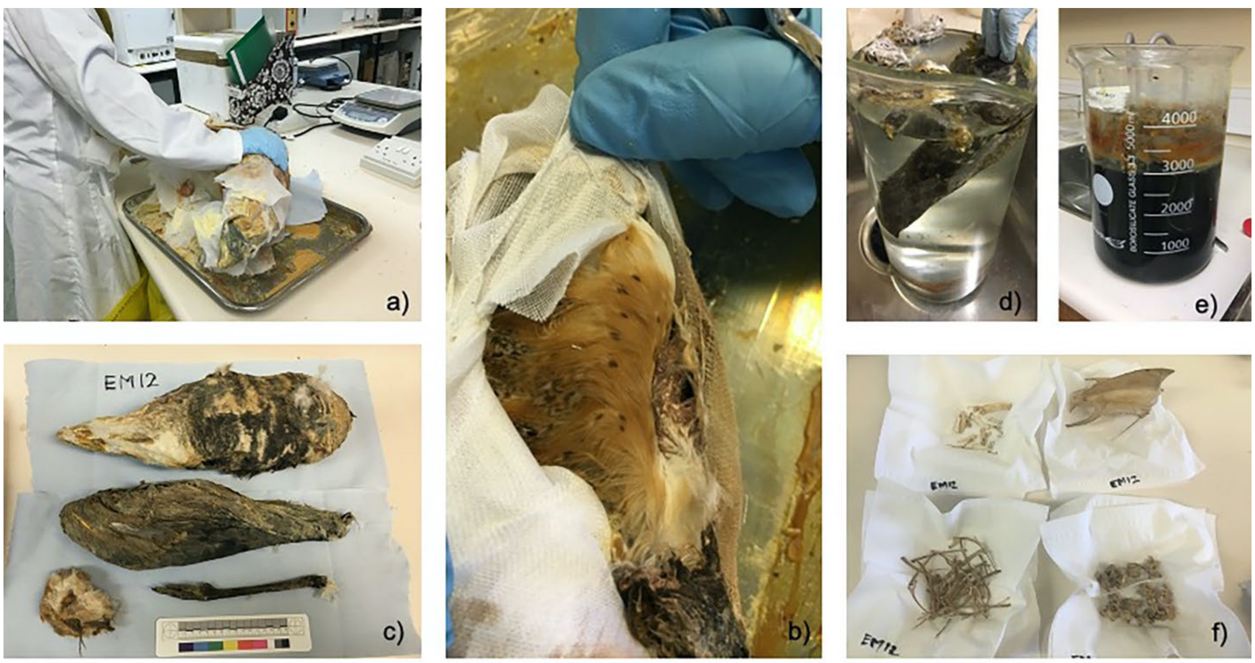

Fig. 5 – This image shows the stages of dissection and maceration used to obtain the skeletal elements from EM12. Image a) the removal of the outer layers of linen wrappings, b) the desiccated remains are revealed, c) the isolated body parts removed from the mummy, d) maceration in cold water, e) the maceration liquid after one week, and f) the skeletal remains from the various body parts once fully clean (Photographs by L. McKnight).

3. Results

Table 1 provides details of the original contents of the six bundles (as compiled at the NHM by White), alongside the radiographic (X-ray and CT) and the ‘bone in hand’ identifications conducted by Rosier.

Table 1 - Comparisons between identification methods

No.	Actual Contents	X-ray Observations	CT Observations	Bone in Hand Identification
EM11	***Anthropoides virgo*** Head Tibiotarsus	A skull and tibiotarsus are visible. The lateral view of the skull suggests the *Gruidae* family. The tibiotarsus suggests *Gruidae, Ciconiidae* or *Anatidae* family.	Slightly improved visualisation, except for the skull which required data processing to view from an alternate angle.	***Anthropoides virgo*** Skull and mandible Right tibiotarsus With the actual specimen in hand it was possible to confidently identify the skull and tibiotarsus to species, by physically comparing the specimen with those in the reference collection.
	Tyto alba Left wing	Two articulated wings belonging to different individuals of a smaller species.	Presence confirmed, but lacking sufficient detail for further identification.	***Tyto alba*** Left wing Left humerus Left carpometacarpus
	Falco tinnunculus Right wing			***Falco tinnunculus*** Left wing Left radius Left ulna Left humerus Left carpometacarpus
	Charadrius hiaticula Trunk Right leg	Trunk and legs belonging to a smaller bird.	Presence confirmed, but lacking sufficient detail for further identification.	***Calidris/Charadrius*** Trunk and leg Sternum Left and right scapula Left and right coracoid Furcula Pelvic girdle Synsacrum Right femur Right tibiotarsus Right tarsometatarsus
EM12	***Anthropoides virgo*** Right wing Leg	An articulated wing, possibly from the left side is visible, but the details are not clear. A separate tarsometatarsus and foot are present and do not appear to articulate with the trunk.	The carpometacarpus of the separate wing is clearly visible in the dorsal view, and provides the only diagnostic element indicative of the *Gruidae* family.	***Anthropoides virgo*** Left wing Left ulna Left radius Left humerus Left carpometacarpus Right tarsometatarsus
	Anser albifrons Trunk Leg Humerus	The trunk (including coracoid and furcula) and a femur and tibiotarsus from the right side are visible, however the outlines are faint and further identification was not possible. The left humerus may be present, but could be broken.	The thinner bones (sternum and pelvis) are not as visible. The rounded shape of the furcula is similar to that found in *Anatidae,* reinforced by the shape of the scapula and coracoid. The details of the distal end of the tibiotarsus are clear and this detail combined with lopsided shape is indicative of *Anatidae*.	***Anser albifrons*** Trunk Leg Humerus Sternum Pelvic girdle Left and right coracoid Left and right scapula Right femur Right tibiotarsus ***Anser/Branta***

				Furcula Left humerus – broken [However, these elements articulate to the others and therefore the identification can be confirmed as *Anser albifron*s]
	Tyto alba Head	Two rounded masses are visible, one to the side of the trunk and one inside the trunk. Possibly both skulls.	The skull to the side of the trunk is present, but only identified as such from the denser mandible. The round mass inside the trunk is visible as an internal organ.	***Tyto alba*** Head Skull and mandible Easily identifiable once the actual specimen was seen.
EM13	***Anthropoides virgo*** Humerus	Close by there is another humerus of similar size but does not appear to articulate with any other elements.	The proximal end of the isolated humerus has a jagged form and may have pathology.	***Anthroides virgo*** Right humerus (with pathology, identified as bony growth on the proximal end)
	Anser albifrons Head Wing	The x-ray shows a skull with cervical vertebra attached, and from the lateral view it appears to be in the Anatidae family. There is a humerus that appears to articulate with an ulna and radius.	The skull is not clearly visible in the CT although the mandible and tongue are very clear. A fractured ulna and radius articulate with the humerus. From the x-ray and CT, the skull and wing were identified from the reference collection as *Aix galericulata*, Mandarin Duck.	***Anser albifrons*** Skull and mandible Right humerus Right ulna Right radius Identification amended from *Aix galericulata* upon physical identification.
	Tyto alba Leg	It is also possible to see from the x-ray that there is a tibiotarsus articulated with tarsometatarsus and toe bones of a smaller bird.	The CT provides a good frontal and lateral view of the distal tibiotarsus. The lack of supratendinal bridge and shape of the outline suggests it could be Barn Owl. The size and shape of the tarsometatarsus and claws supports this identification.	***Tyto alba*** Left tibiotarsus Left tarsometatarsus
	Falco tinnunculus Trunk		A small trunk is vaguely visible in the CT that was not apparent in the x-ray, the furcula being the most noticeable part as it is the densest.	***Falco tinnunclus*** Left and right scapula Sternum Furcula Synsacrum Left coracoid Right coracoid
EM14	***Anser albifrons*** Wing Foot	The x-ray shows a large tarsometatarsus in articulation with toe bones and a large articulated wing consisting of radius, ulna, carpometacarpus and wing digits. Carpometacarpus looks	CT provided greater clarity of the larger limbs. The proximal end of the ulna of the large articulated wing could be seen in finer detail which supported the identification of Anatidae of the articulating carpometacarpus.	***Anser albifrons /Branta canadensis*** Left ulna Left radius Left carpometacarpus Left wing phalanx Right tarsometatarsus and foot bones

		similar to those in the Anatidae family.		
	Tyto alba Sternum	Separate trunk present		***Tyto alba*** Sternum Left and right coracoid
	Falco tinnunculus Wing Leg	A smaller articulated wing is visible and also a smaller articulated leg consisting of femur, tibiotarsus, tarsometatarsus and toe bones.	Smaller articulated leg could not be made out clearly.	***Falco tinnunculus*** Right ulna Right radius Right humerus Right carpometacarpus Right tibiotarsus Right tarsometatarsus Right femur
	Charadrius hiaticula Head	Skull visible	Skull not visible	***Charadrius hiaticula/Vanellus vanellus*** Skull and mandible
EM15	***Anthropoides virgo*** Leg Foot Wing	The X-ray shows an articulated leg consisting of tibiotarsus, tarsometatarsus and toes. A large wing is visible consisting of ulna and radius and what appears to be a clipped carpometacarpus.	Where the bones are articulated it can be difficult to see the distinctive features, for example, the bent leg.	***Anthropoides virgo*** Left tarsometatarsus Left tibiotarsus Foot bones Left ulna Left radius Left carpometacarpus (clipped)
	Anser albifrons Leg Foot	An articulated leg is visible consisting of the femur, tibiotarsus, tarsometatarsus and toes. This belongs to a different species than the other leg represented.	The extended leg allows the distinguishing features of the tibiotarsus – supratendinal bridge – and both the anterior and posterior views accessible allowing it to be tentatively identified as a goose.	***Anser albifrons*** Left femur Left tibiotarsus Left tarsometatarsus
	Tyto alba Wing	The smaller wing includes the humerus, ulna, radius, carpometacarpus and wing digits.		***Tyto alba*** Right ulna Radius Humerus Carpometacarpus Distinctive spiny projections on the bony bridge of the intermuscular line suggested corvids or owls. Through direct comparison of the ulna, this was narrowed down to Barn owl.
	Falco tinnunculus Head	A small skull is also visible that looks similar to that of a raptor.	The skull is not so visible in the CT scan, only a vague outline of the mandible is noticeable.	***Falco tinnunculus*** Skull and mandible
EM16	***Anser albifrons*** Wing	A wing consisting of carpometacarpus, and wing digits. The carpometacarpus that	Presence confirmed, but lacking sufficient detail for further identification.	***Anser albifrons*** Right carpometacarpus Right phalanx

		looks like it's from the Anatidae family		Direct comparison of the wing was needed to identify it as goose.
	Tyto alba Leg	The x-ray shows a leg consisting of femur, tibiotarsus, tarsometatarsus and toe bones.	The larger leg is visible in the scan and from this you can see that there is no supratendinal bridge, which is indicative of parrots and owls. This is supported by a nice profile of the lateral side of the tibiotarsus, suggestive of Barn Owl.	***Tyto alba*** Right femur Right tibiotarsus Right tarsometatarsus
	Falco tinnunculus Leg	A smaller leg consisting of femur, tibiotarsus, tarsometatarsus and toe bones.	Presence confirmed, but lacking sufficient detail for further identification.	***Falco tinnunculus*** Left femur Left tibiotarsus Left tarsometatarsus Easily identified from 3 holes very distinctive of falcons, and using the reference collection narrowed down to Kestrel.

Table 1 – The results of the avian identification assessment as compiled from the different study techniques described in relation to the original bundle contents.

4. Discussion

4.1 Radiographic Identification – X-Ray

Conventional radiography is an excellent triage method used in the study of mummified remains enabling an initial insight into the contents of wrapped bundles. However, there are a number of widely reported complications which hamper the effectiveness of the technique on desiccated material. By producing a two-dimensional image of a three-dimensional object, structures located within the artefact appear overlapped and superimposed (Fig. 6a-b). Elements appear magnified depending on their position in relation to the X-ray source. This causes structures to appear overlapped, leading to difficulties in gauging depth and perspective of the contents, all of which hinder the identification process (Adams 2015).

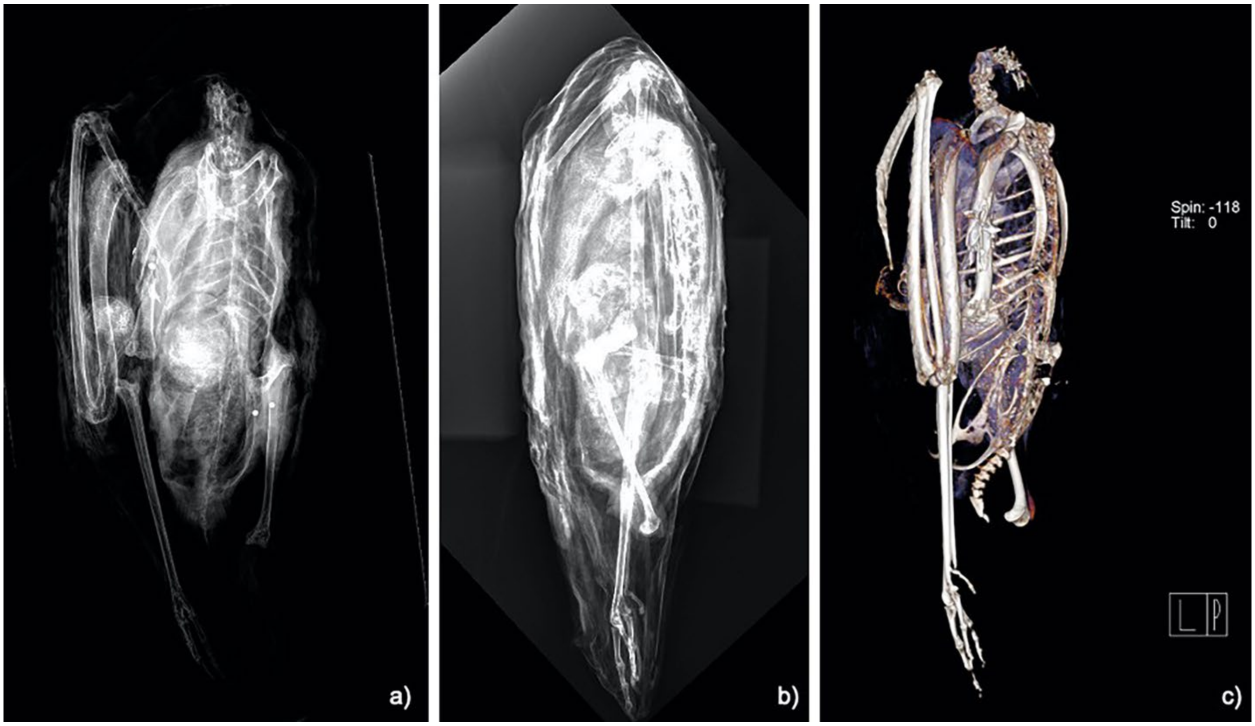

Fig. 6 – a) Anterior-posterior digital radiograph and b) sagittal digital radiograph of EM12 demonstrating the vast difference in the visibility of skeletal elements between the two projections, and c) an example of a volume render created from the CT data showing the capability of the technique to offer increased visibility of individual skeletal elements (Images courtesy of the Ancient Egyptian Animal Bio Bank, The University of Manchester and the Manchester University NHS Foundation Trust).

With wrapped animal mummies, there are no 'standard' contents, unlike the living human or animal body where the position of skeletal elements is known. Difficulties in the visualization of spatial relationships between elements, compounded by the often fragmentary and incomplete nature of the remains, and the inability to manipulate the image to view the elements from another angle, all proved critical (McKnight et al. 2015a). Identification was only possible using X-ray where the outline and form of elements could be clearly visualised and was immediately recognizable.

4.2 Radiographic Identification – CT

CT proved beneficial in demonstrating the shape of long bones and therefore increased potential for identification. Image rotation enabled a clearer understanding of the placement of individual elements and the spatial relationship between them (Fig. 6c). The slight reduction in contrast resolution in CT meant that lower density elements visible on X-ray were either not visible at all or more difficult to visualise using this method.

Thresholding of the CT data based upon the radiographic density of tissues was conducted to enable the creation of volume renders; however, the results were not totally successful as low-density elements such as the sternum, cranium and smaller skeletal elements became 'lost' during processing (Fig. 7). Attempts to counteract this were attempted by manually altering the threshold values. Decreasing the threshold caused more of the non-skeletal content and wrappings to be visible, thereby further concealing diagnostic traits. Raising the threshold to remove the wrappings caused more of the skeletal information to be lost.

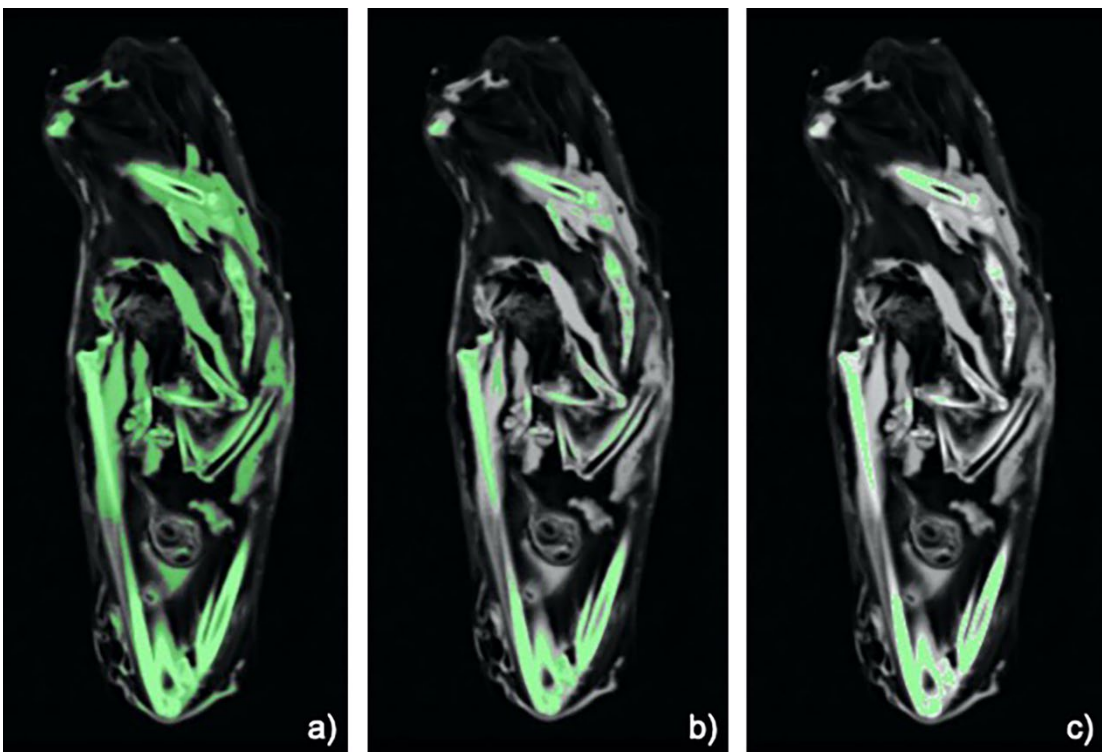

Fig. 7 – Reformatted CT data of a bird mummy demonstrating the problems encountered when thresholding skeletal remains within wrapped mummy bundles - a) threshold too low resulting in interference from adjacent desiccated soft tissues, b) optimal threshold for bone, and c) threshold too high resulting in the loss of clarity of the skeletal remains (Image courtesy of R. Bibb).

Although CT was able to contribute additional detail over that offered by digital radiography, the process requires extensive data processing which is both time- and labour-intensive. Access to scanning equipment is costly and logistically difficult unless collaborations with clinical facilities can be formed. In addition, it should be noted that this study had access to state-of-the-art imaging and 3D replication technology, and a world-renowned reference collection; realistically, studies adopting less sophisticated resources and methods will be less effective.

4.3 Bone in hand Identification

The ability to hold physical remains and compare these to reference collections enables positive identifications to be made in all cases. Miniscule variations in size, form and texture of the bones enables a specialist to narrow down species identifications with relative ease, particularly when skilled in the navigation of reference collections.

In cases where skeletal elements appeared articulated in the radiographic data, it was possible to link identifications for now-isolated bones. For example, in EM12, a number of elements were positively identified to *Anser albifrons***.** The furcula and left humerus suggested an identification of *Anser/Branta*; however, as they clearly articulate to the elements belonging to *Anser albifrons*, their identification could be updated.

5. Conclusions and Future Research

The project enabled a critical appraisal of the radiographic modalities and post-processing techniques in use in mummy studies, and their relative potential value when attempting to identify avian remains to species. Although disheartening in terms of the difficulties with confident identifications of avian remains using radiography alone, this research establishes an important baseline upon which researchers working on this type of material can build. Identifications should be provided based upon the level of certainly with which the researcher is confident of their identification, with suspected identifications being discounted as such. The study of archaeological artefacts and their interpretation as ancient material culture is more worthwhile when tentative identifications are discounted, to limit the chances of inaccuracies leading to misinterpretations. With bird mummies, an incorrect identification could skew the interpretation of an archaeological site or falsely challenge existing knowledge of ancient religious practices. As researchers, it is advantageous to be certain that we do not know the answer, rather than be uncertain that we do.

Research projects such as this are important in gauging our current level of expertise and in adding to our existing knowledge base. As an archaeological resource, ancient Egyptian animal mummies demonstrate extensive variation in their contents, construction and external appearance. They are complex artefacts, the production of which was motivated by intangible religious practices, further enhanced by social, economic and political nuances. As archaeologists, our best hope of understanding this ancient practice is through the analysis of the artefacts themselves. The levels of confidence we can attribute to our methods assists in the validation of current research, and helps to measure the reliability of the results. This paper, along with further research (i.e. Bibb and McKnight, in review), highlights the issues faced by researchers working on this material in the hope that future work can be aware of its limitations and objective of its capabilities.

Bibliography -

Adams, J. 2015. 'Imaging animal mummies: history and techniques' in L. McKnight and S. Atherton-Woolham (eds) *Gifts for the Gods: Ancient Egyptian Animal Mummies and the British*. Liverpool University Press, Liverpool, pp. 68-71.

Assman, J. 2005. *Death and Salvation in Ancient Egypt*. Cornell University Press, New York.

Atherton, S. D. and McKnight, L. M. 2014. 2014. 'The Mummification of Birds: Past and Present' in *Experimental Archaeology* 2014/1. Available online at http://journal.exarc.net/issue-2014-1/ea/mummification-votive-birds-past-and-present.

Atherton-Woolham, S. D., McKnight, L. M., Price, C. and Adams, J. 2019. 'Imaging the gods: animal mummies from Tomb 3508, North Saqqara, Egypt' in *Antiquity* 93, 367: 128-143. DOI: https://doi.org/10.15184/aqy.2018.189

Bibb, R. and McKnight, L.M. In Review. 'Identification of bird taxa species in ancient Egyptian mummies: Part 2, An evaluation of the utility of CT scanning and 3D Printing' submitted to the *Journal of Archaeological Science: Reports*.

Brettell, R., Martin, W., Atherton-Woolham, S., Stern, B. and McKnight, L. 2017. 'Organic residue analysis of Egyptian votive mummies and their research potential' in *Studies in Conservation*, 62:2, 68-82, DOI: 10.1179/2047058415Y.0000000027.

Buckley, S.A., Clark, K.A. & Evershed, R.P. 2004. 'Complex Organic Chemical Balms of Pharaonic Animal Mummies' in *Nature*, 431: 294–99.

Buckley, S.A. & Evershed, R.P. 2001. 'Organic Chemistry of Embalming Agents in Pharaonic and Graeco-Roman Mummies' in *Nature*, 413: 837–41.

von den Driesch, A., Kessler, D., Steinmann, F., Berteaux, V., & Peters, J. 2005. Mummified, Deified and Buried at Hermopolis Magna—the Sacred Birds from Tuna el-Gebel, Middle Egypt. *Ägypten Und Levante / Egypt and the Levant*, 15: 203–244.

McKnight, L. M. 2020. 'On a Wing and a Prayer: Ibis Mummies in Material Culture at Abydos' in *Arts*, 9 (4), 128; DOI: https://doi.org/10.3390/arts9040128.

McKnight, L. M. and Atherton-Woolham, S. D. 2016. 'The Evolution of Imaging Ancient Egyptian Animal Mummies at the University of Manchester, 1972 – 2014', *Mummies, Magic and Medicine in Ancient Egypt: Multidisciplinary Essays for Rosalie David*. Manchester, Manchester University Press. Pp. 345-354.

McKnight, L. M., Atherton-Woolham, S. D. and Adams, J. E. 2015a. 'Clinical Imaging of Ancient Egyptian Animal Mummies' in *RadioGraphics*, 35, 3, pp. 2108-2120. DOI: 10.1148/rg.2015140309.

McKnight, L. M., Adams, J. E., Atherton-Woolham, S. D. and Bibb, R. 2015b. 'Application of clinical imaging and 3D printing to the identification of anomalies in an ancient Egyptian animal mummy' in *Journal of Archaeological Science: Reports*, 3, 328-332.

McKnight, L.M. 2012. 'Studying Avian Mummies at the KNH Centre for Biomedical Egyptology: Past, Present and Future' in R. Bailleul-LeSuer (ed) *Between Heaven and Earth - Birds in Ancient*

Egypt. Chicago, Oriental Institute, University of Chicago. pp.99-106.

Price, C. 2015. 'Votive Practice in Ancient Egypt' in L. McKnight and S. Atherton-Woolham (eds) *Gifts for the Gods: Ancient Egyptian Animal Mummies and the British*. Liverpool University Press, Liverpool, pp. 21-22.

Scalf, F. 2012. 'The Role of Birds within the Religious Landscape of Ancient Egypt' in R. Bailleul-LeSuer (ed) *Between Heaven and Earth: Birds in Ancient Egypt*. Oriental Institute Publications 35. The Oriental Institute of the University of Chicago, Chicago, pp. 33-40.

Acknowledgements

The authors would like to express sincere thanks to colleagues at the Manchester University NHS Foundation Trust for their assistance with the radiographic imaging of the ancient and modern mummies; Stephanie Atherton-Woolham for her assistance with the experimental process; Rhea Brettell at the Department of Archaeological Science, University of Bradford for her work on the analysis of the resins used in mummification; and the curatorial staff and volunteers at the Natural History Museum, Tring for their support of this project.

Funding

This research is supported by awards from the Leverhulme Trust (RPG-2013-143) and the Arts and Humanities Research Council (AH/P005047/1).

Figure Legends

Table 1 – The results of the avian identification assessment as compiled from the different study techniques described in relation to the original bundle contents.

Fig. 1 - This photograph depicts a plaster-cast reproduction of a wall scene from the temple of Esna. The original dates to c.50 AD. The scene shows the pharaoh, the Roman Emperor Claudius, being ritually washed by two gods in hybridized form; Thoth is depicted with the head of an ibis (left) and Horus with the head of a falcon (right).

Fig. 2. Photograph of a) an Ibis mummy (Acc. No. 11501, Manchester Museum) with appliqué detail depicting the god, Thoth (Reproduced by permission of Manchester Museum, University of Manchester); b) a votive bronze statuette in the form of the seated lion-headed deity, Sekhmet, goddess of warfare (Plymouth City Museum and Art Gallery, Acc. No. Learn0844 / AEABB596); c-d) an area of damage reveals the presence of a fabric package concealed within the seat. Radiography confirmed the presence of disarticulated skeletal remains, believed to belong to a cat (Photographs by L. McKnight).

Fig. 3 – Photograph of a painted wooden ba bird (Ptolemaic Period c.332–30 BC) (Metropolitan Museum of Art, New York, acc. No. 44.4.83) and the false door located on the west wall of the Tomb Chapel of Raemkai at Saqqara, (5th Dynasty c. 2446–2389 B.C.) (Metropolitan Museum of Art, New York, acc. No. 08.201.1e).

Fig. 4 – Photographs showing the mummification process; a) the six packages of co-mingled bird remains as they arrived at The University of Manchester, b) EM12 following the application of a molten beeswax and pine resin emulsion, and the initial layer of linen, and c) EM12 once completely mummified [Note the area of intense discolouration to the exterior of the linen wrappings caused by the leakage of fluids from the remains] (Photographs by L. McKnight).

Fig. 5 – This image shows the stages of dissection and maceration used to obtain the skeletal elements from EM12. Image a) the removal of the outer layers of linen wrappings, b) the desiccated remains are revealed, c) the isolated body parts removed from the mummy, d) maceration in cold water, e) the maceration liquid after one week, and f) the skeletal remains from the various body parts once fully clean (Photographs by L. McKnight).

Fig. 6 – a) Anterior-posterior digital radiograph and b) sagittal digital radiograph of EM12 demonstrating the vast difference in the visibility of skeletal elements between the two projections, and c) an example of a volume render created from the CT data showing the capability of the technique to offer increased visibility of individual skeletal elements (Images courtesy of the Ancient Egyptian Animal Bio Bank, The University of Manchester and the Manchester University NHS Foundation Trust).

Fig. 7 - Reformatted CT data of a bird mummy demonstrating the problems encountered when thresholding skeletal remains within wrapped mummy bundles - a) threshold too low resulting in interference from adjacent desiccated soft tissues, b) optimal threshold for bone, and c) threshold too high resulting in the loss of clarity of the skeletal remains (Image courtesy of R. Bibb).