

SEEING IS BELIEVING – THE APPLICATION OF THREE-DIMENSIONAL MODELLING TECHNOLOGIES TO RECONSTRUCT THE FINAL HOURS IN THE LIFE OF AN ANCIENT EGYPTIAN CROCODILE

ABSTRACT

The application of non-invasive radiography (X-ray and CT) to an ancient Egyptian crocodile mummy demonstrated a high level of corporeal preservation achieved through artificial embalming. Analysis revealed numerous anomalies within the abdomen of the crocodile which merited further investigation using digital three-dimensional modelling technologies. Improving the clarity of the CT scan data enabled the authors to identify the anomalies which included a metal fish hook and a small fish. Segmentation of the CT scan data enabled the virtual extraction of the hook from within the confines of the mummy and its replication, firstly in plastic and then in its original material, bronze.

Through the scientific analysis of the mummy, the authors reconstruct the biological biography and life history attributes of the animal, and consider the human-animal relationships and religious beliefs behind its post-mortem preservation. The study explores the application of the 3D technologies applied to archaeological materials and the novel implementation of experimental techniques to reproduce the anomaly. The investigation provided the ability to enhance the study, interpretation and display of the mummy; a matter of particular relevance in the case of mummified remains where anomalies are not directly visible. The authors consider the improved accessibility to cultural artefacts made possible through the application of enhanced visualization techniques in the heritage sector.

Keywords – radiography, CT, 3D Printing, animal mummy, experimental archaeology, Egypt

1. INTRODUCTION

1.1 Crocodiles in Ancient Egypt

The ancient Egyptians venerated crocodiles as avatars of Sobek, Lord of the Nile and of the primeval swamp from which they believed the earth was created (Pinch 2004). Ammut, a composite creature responsible for devouring the hearts of those denied entry to the Afterlife and symbolizing Egypt's three most feared predators, is depicted with the body of a lion and hippopotamus, and the head of a crocodile. Crocodiles were associated with dichotomous character traits, a combination of which defined their position within the Egyptian pantheon of deities. Resting overnight in the dark, murky waters of the River Nile, emerging every morning to bask open-mouthed on the sun-soaked banks, crocodiles appeared to move seamlessly between opposing worlds. Their behavioural characteristics reinforced this; displaying immense power and strength, crocodiles were ferocious predators atop the Nile's ecosystem and considered omens of danger to both human and animal life. Despite this sense of foreboding, healthy crocodile population levels were celebrated; believed to signify the prospect of a successful annual inundation upon which life-sustaining agricultural activities in the Nile Valley would thrive. The connection with fertility was reinforced as the Egyptians watched how diligently crocodiles

cared for their young, carrying them delicately in their powerful jaws, earning them respect as protective parents.

Images of crocodiles as apotropaic symbols used to ward off dangerous encounters and protect spaces from negative influences are widespread throughout pharaonic Egypt, often positioned above entrances to habitations (Ikram 2010). By means of sympathetic magic, it was believed that a person could summon the strength of a crocodile and protect themselves from danger by wearing clothing made from the skin of the animal or from fabric designed to represent its scaly texture. One example of such a garment is curated in the British Museum (EA5473) which is believed to date to the Roman period when it would have been worn by a soldier during ceremonial parades (Ikram 2010).

1.2 ARCHAEOLOGICAL CONTEXT

Centres of sacred activity dedicated to the crocodile have been discovered in Upper Egypt and in the Fayum, an oasis located 100 kilometres south-west of Cairo. These sites provide archaeological evidence for the significance of the crocodile in the form of artistic representations, artefacts representing the animals' form, and the burial of large numbers of mummified crocodiles, some measuring up to six metres in length. Despite this wealth of archaeological evidence, comparatively little is known concerning the practicalities and logistics of the wild- versus captive-management, exploitation and worship of crocodiles during ancient times.

Archaeological evidence for the rearing of crocodiles has been discovered in the form of hatcheries (such as at the site of Medinet Madi) and at temple sites where enclosures with large water basins are believed to represent artificial habitats for holding live animals. The archaeology, supplemented by mentions in textual sources of titles relating to the cult of Sobek, stands testament to the captive management of crocodiles for cult purposes within the sacred spaces at Crocodilopolis, Karanis, Qasr el Qarun, Elkab, Esna and Kom Ombo (Bresciani 2005; 199-202, De Cupere et al. 2023).

Recent excavations at the site of Qubbat al-Hawā uncovered the remains of ten preserved crocodiles in small rock tombs (De Cupere et al. 2023). Alongside five isolated skulls and the largely skeletonised remains of four animals, excavators found one individual complete and articulated with preserved soft tissues. Visual examination of the mummified individual confirmed natural preservation and areas of damage revealed the presence of gastroliths. No evidence was found for the use of resin or mummification substances applied to the individuals, and the only evidence of human interaction was the presence of linen, palm leaves and rope associated with a number of the remains.

The popularity of the crocodile cult is most clearly attested by the large deposits of mummified crocodiles; however, the sheer volume involved in the practice raises questions as to how the animals were sourced in sufficient quantity to meet the high demand for offerings. Archaeology supports the theory that live animals were kept in captivity at least to some extent although how these were originally captured is unclear. It is plausible to suggest that live animals would have been encouraged to live as close to their natural habitat as was practical, possibly through the creation of managed areas located along the banks of the Nile or its associated canal system (Molcho 2014, 190-91). The identification of the hatchery at Medinet Madi suggests that unhatched eggs and live young were

harvested from the wild and raised by temple staff until they were required as cult offerings (Molcho 2014, 183). Rearing juvenile crocodiles presents a reduced danger to humans than when tending adults whose formidable strength would have been terrifying for those tasked with their care. The large number of mummified mature crocodiles suggests that these creatures were likely collected from the wild as and when they were required, rather than being kept for lengthy periods in captivity. Artistic representations depict the capture of live animals through netting and spearing from boats, and ethnographic observations support the construction of barriers along the riverbank designed to protect livestock, but in which crocodiles often became trapped (De Cupere et al. 2023).

As with many elements of ancient life, the accounts of classical authors provide valuable (and in some cases the only) insight into the relationship between the Egyptian people and the natural world. Writing in the fifth century BC, Herodotus mentions hooks baited with pork being placed in the Nile, whilst a live pig was beaten on the riverbank in order to attract the predators and facilitate capture (Herodotus, 69, II). Diodorus Siculus writing four centuries later records that the Egyptians hunted crocodiles using nets and spears, suggesting that the use of fish hooks was no longer practiced (I, 84). The hunting of wild crocodiles is reported in Roman times (30BC-AD395), some centuries later than the peak in the veneration of the animal witnessed during the Ptolemaic Period (332-30BC).

The earliest mention of a high-status cult crocodile comes from the late 1st Century BC in the writings of Strabo who describes the captive upkeep of a tame crocodile, named Suchus, at the cult centre of Crocodilopolis. Believed to be the living incarnation of Sobek, Suchus was provided with a dedicated pond within the temple complex where he received a lavish diet of bread, meat and wine delivered by the priests, and adornments of precious metals and jewels (Strabo XVII, 1, 38). Archaeological evidence found within the temple complex suggests some truth in Strabo's words. As a cult animal, Suchus received the levels of care befitting a god on earth and upon his natural death a successor was selected to replace him as the cult animal.

The overwhelming majority of preserved crocodile remains were produced as votive offerings rather than preserved cult animals. Yet whilst votives provide the largest body of evidence relating to the practice of crocodile mummification, only a small percentage of the remains have been analysed in sufficient detail to enable a critical evaluation of the practice. Many questions surround the monumental infrastructure required to sustain the prolonged industrial-scale procurement of crocodiles and the resulting production of mummified offerings. It seems sensible to assume that small juvenile crocodiles would be easily obtained and dispatched, yet the procurement of larger animals which exist in the mummy record becomes more problematic with the increase in the size of the animals and the relative level of danger they pose to humans.

Studies on a small number of larger crocodile mummies have yielded insights into potential ancient procurement strategies; however, their relevance to the votive cult remains subjective, particularly in cases where definitive geographic and chronological provenance is not available. Recent scientific investigation of a crocodile mummy from the Musée des Confluences, Lyon, suggests that the animal, estimated to be between three and four years of age, was hunted in the wild and killed by a sudden blow to the head before being immediately mummified, as indicated by the identification and intact

nature of the stomach contents (Porcier et al. 2019). A similar fatal skull injury was identified during the radiographic analysis of a crocodile from the Manchester Museum collection (Accession no. 1772), again suggestive of the use of blunt force trauma to immobilise and kill the creature for the purposes of mummification (McKnight 2015, 74-5). Investigation of a crocodile mummy from the British Museum (Accession no. EA38562) collection measuring over 3.8m revealed a diet of bovine origin, indicating that the animal was fed and therefore potentially cared for in captivity at least for the latter period of its life (Anderson and Antoine 2019).

This research seeks to establish evidence for the human/animal relationship through the reconstruction of the biological biography of one animal made possible by the scientific analyses of its mummified remains. It provides a case study to emphasize the application of 3D technologies and experimental techniques to improve engagement with cultural heritage.

2 MATERIALS AND METHODS

This paper discusses the investigation of a large, mummified crocodile held in the collection of Birmingham Museum and Art Gallery, UK. Unfortunately, but not wholly unusually, little is recorded about the provenance, date or acquisition history of the mummy, which is known only by its accession number, 2005.335. The mummy is a sizeable and visually impressive artefact measuring 2230 x 214 x 135mm with a dorsal cranial length of 346mm and a maximum cranium width of 167mm. The physical remains of the crocodile are clearly visible as the linen wrappings have been previously removed. A resinous substance which now appears black in colour has been applied directly to the upper surface of the body in liquid form during the embalming process. Small fragments of the original linen wrappings and weave patterns are visible as imprints in the resin indicating that the body was wrapped before the molten substance had been allowed to fully solidify (Fig. 2). The end of the tail is missing, lost either at the time of the unwrapping, or at some point afterwards, indicated by the resulting 'clean' edge of the fracture line.



Fig. 1 – Photograph showing the drip lines caused as the molten resin and beeswax emulsion settled prior to solidification.

The mummy, along with other animal mummies from the Birmingham collection, was transported to the Royal Manchester Children's Hospital by specialist heritage couriers in May 2016 to undergo a suite of radiographic analyses including digital radiography (DR) and computed tomography (CT scanning) (Fig. 2).



Fig. 2 – Photograph of crocodile mummy 2005.335 on the CT scanner gantry.

Due to the large size of the mummy, digital X-rays¹ were obtained in eight overlapping images. A radio-opaque ruler was included as a point of reference to enable the separate images to be composited (in a process known as ‘stitching’) during the post-processing phase. As is common practice with all mummy investigations conducted using the Manchester Protocol (McKnight et al. 2015), CT scanning was conducted during the same imaging session². The scanning process yielded 3105 axial images gathered at increments of 0.625mm along the total length of the body (this encompassed $(0.625 \times 3105 = 1940$ mm) and excluded the distal part of the tail, which was not scanned) with a field of view of 512 by 512 pixels. No imaging data was captured for the distal portion of the tail due to the physical confines of the

¹ Radiographic images acquired using a Philips Eleve Digital Diagnostic system 57kV 1mAs.

² Computed tomography data was acquired using a 128-row MDCT Siemens Somatom Definition AS+ Scanner at a pitch of 0.9691 with a slice thickness of 0.625mm. The data was reformatted using the B30 (medium smooth) and B60 (sharp) reconstruction kernels for soft tissue and bone respectively.

scanning facility and the likelihood of causing damage to the mummy as it moved through the ring of detectors towards the wall.

In this application, CT data were viewed and processed using OsiriX software (Version XX, Pixmeo SARL, Bernex, Switzerland), an open-source DICOM viewer. Windowing the images via CT numbers, by adjusting image brightness (window level, WL) and contrast (window width, WW), facilitated the differentiation of various tissue densities. The authors found that using pre-set windowing parameters commonly employed in clinical pulmonary imaging (WL: -500, WW: 1400) was effective for visualizing mummified animal remains, where desiccated soft tissues exhibit a bone-like radiodense appearance (McKnight et al. 2015, Panzer et al. 2019).

3 RESULTS

3.1 RADIOGRAPHIC ANALYSIS

The radiographic investigation confirmed that the crocodile is complete (except for the loss of the distal tail) and articulated with the limbs positioned close to the body. The level of preservation of anatomical structures is high, with skin, musculature, internal organs and soft tissue features such as the trachea visible (Fig. 3).

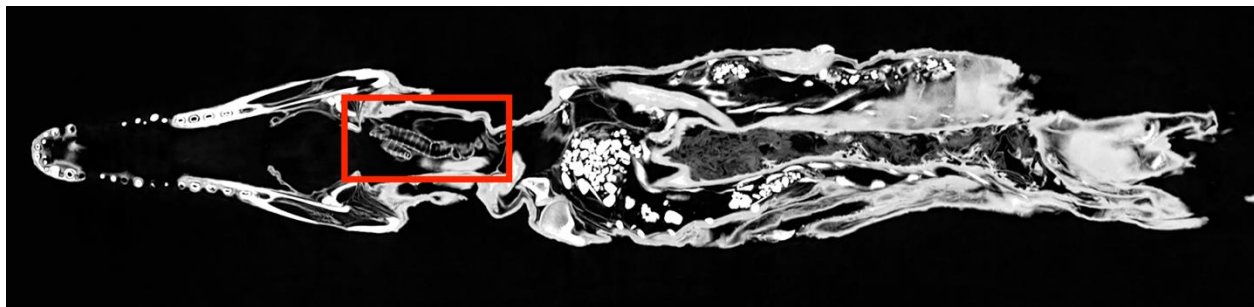


Fig. 3 – CT reformat and magnified region of interest (ROI) showing the desiccated trachea. Gastroliths are visible in the abdominal cavity.

The lateral X-ray confirms that the mouth of the crocodile is closed, with no evidence of intra-oral or cranial packing. The anterior-posterior projection reveals that the cranium is complete and undamaged, with no evidence of trauma (in contrast to the work of McKnight 2015 and Porcier et al. 2019). A number of teeth have been lost, evidenced by empty tooth sockets in both the mandible and maxilla. Osteoderms, naturally occurring bony scale-like features are clearly visible covering the upper surface of the crocodile, and a considerable volume of radio-dense gastroliths can be seen extending from the throat down through the thorax. A slight curvature to the thoracic spine is visible. A pad of linen is visible underneath the animal between the folds of skin.

Digital X-ray (DR) allowed for the initial 'triage' assessment of the mummy contents; however, the technique lacks the ability to differentiate spatially between skeletal elements and features located within the bundle (Licata et al. 2019, McKnight et al. 2015). CT demonstrated the extent and dispersal of gastroliths within the body cavity. Data manipulation highlighted the presence of a radio-dense artefact

located in the abdominal cavity amongst the mass of gastroliths. The artefact, measuring 34 x 24 x 5mm, resembles the recognisable form of a fish hook with a distinctive barb. There is no visible aperture through which a fishing line would have been introduced; however, this is not unusual for ancient hooks. Further interrogation of the CT data revealed a second region of interest within the abdomen, appearing as an articulated row of vertebrae bearing the characteristic cross-sectional star shape distinguishing them as Piscean in origin. Measuring 230mm in length, the fish appears to lie within the stomach of the crocodile, located adjacent to the hook. The skull of the fish is not visible on the CT data and it is not possible to conclusively establish whether the fish is directly associated with the hook; however, their relative location suggests that they are likely to be connected.

3.2 SEGMENTATION AND REPRODUCTION OF THE FISH HOOK

The original CT images were provided to the School of Design and Creative Arts, Loughborough University in DICOM format. The images were imported into specialist CT data manipulation software for segmentation and the generation of three-dimensional data (Mimics v21, Materialise NV). The processing steps taken are typically used in medical applications of design and 3D printing and is well described in the previous work (Bibb, Eggbeer and Paterson 2015). Data was first segmented by density by applying upper and lower Hounsfield Unit thresholds (effectively the grey scale of the pixels). Isolating the gut contents involved setting maximum upper density thresholds and a high lower threshold. This isolated the densest bones and the gastroliths. Raising the lower threshold still higher isolated the hook from its immediate surroundings.



Fig. 4 - Visualisation showing the complex context of the gut contents and the difficulty in locating the fish hook. The fish vertebrae are clearly visible.

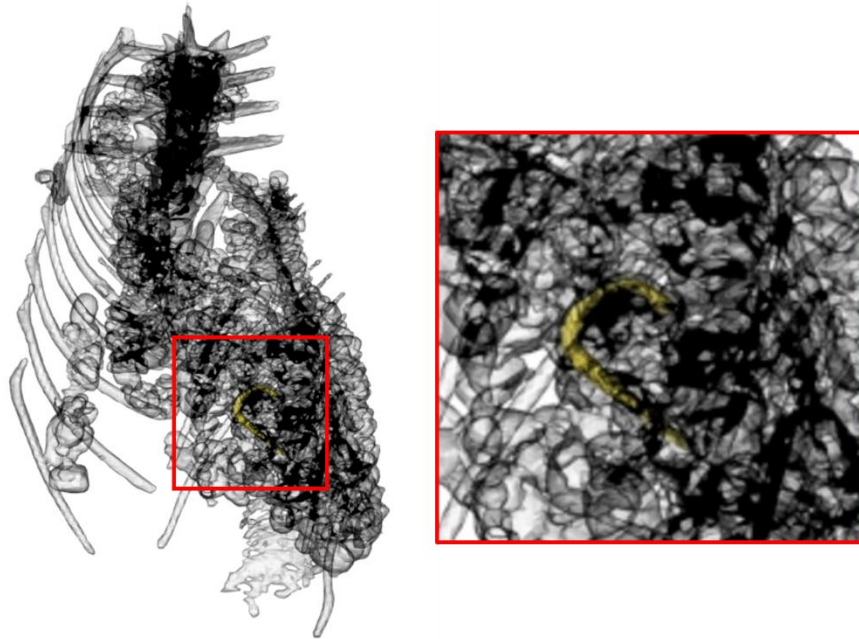


Fig. 5 - Visualisation showing the hook highlighted in yellow by making the surrounding objects transparent.

The high density indicated the hook was metal although it is not possible to determine from the CT data exactly which metal or alloy it is. The shape of the hook with its clear barb suggests that it was wrought or cast.

Region growing was used to select only the pixels connected to the hook. The software tools are then used to generate three-dimensional models of the selected data. Interpolation algorithms are used to produce a relatively smooth model. The highest possible quality settings were used as the object is small in comparison to the field of view – i.e. the small object is described by a relatively small number of pixels. Software functions in the Mimics software enable surfaces to be smoothed further by applying mathematical algorithms that recalculate the triangulated surface. In this case a single process of smoothing was applied using default settings in Mimics.

Once the three-dimensional model was created it was exported in the industry standard STL file format (see Fig. 6). This format describes the surface of a three-dimensional object and is used to produce physical replicas via 3D Printing (also known as Additive Manufacturing and previously Rapid Prototyping). Given the small size of the fish hook, stereolithography was used enabling very thin layers and very precise dimensional accuracy using a FormLabs Form 2 machine and FormLabs Clear resin. The layer thickness for the printing process selected was 0.05 mm ensuring the smoothest possible surface.

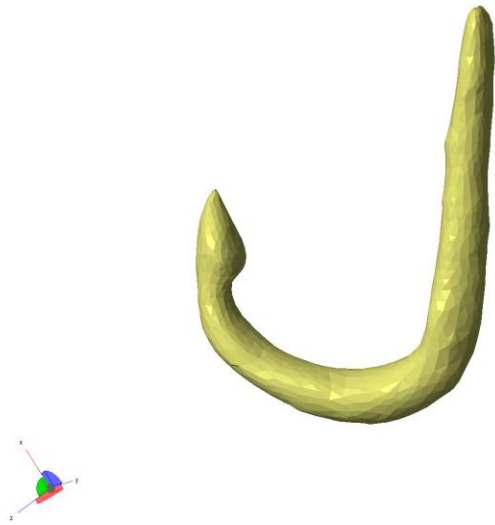


Fig. 6 – Final STL file of the fish hook

The resin replicas were evaluated by the team and the decision was taken to progress to investment casting metal replicas. The STL file was sent to the School of Jewellery at Birmingham City University to enable the replicas to be investment cast into bronze; a copper-tin alloy with a melting point around 1000°C. This was achieved by 3D printing wax replicas using a 3D printer and material specifically tailored for casting (ProJet 3500 CMX Max, 3D Systems Inc.). Multiple sacrificial patterns were 3D printed to be used in the typical lost wax investment casting process. The patterns shown in Fig. 7 show the wax patterns (blue) on a supporting material (white) necessary for the 3D printing process. The white supporting material was removed in a solvent bath to leave just the blue wax patterns.

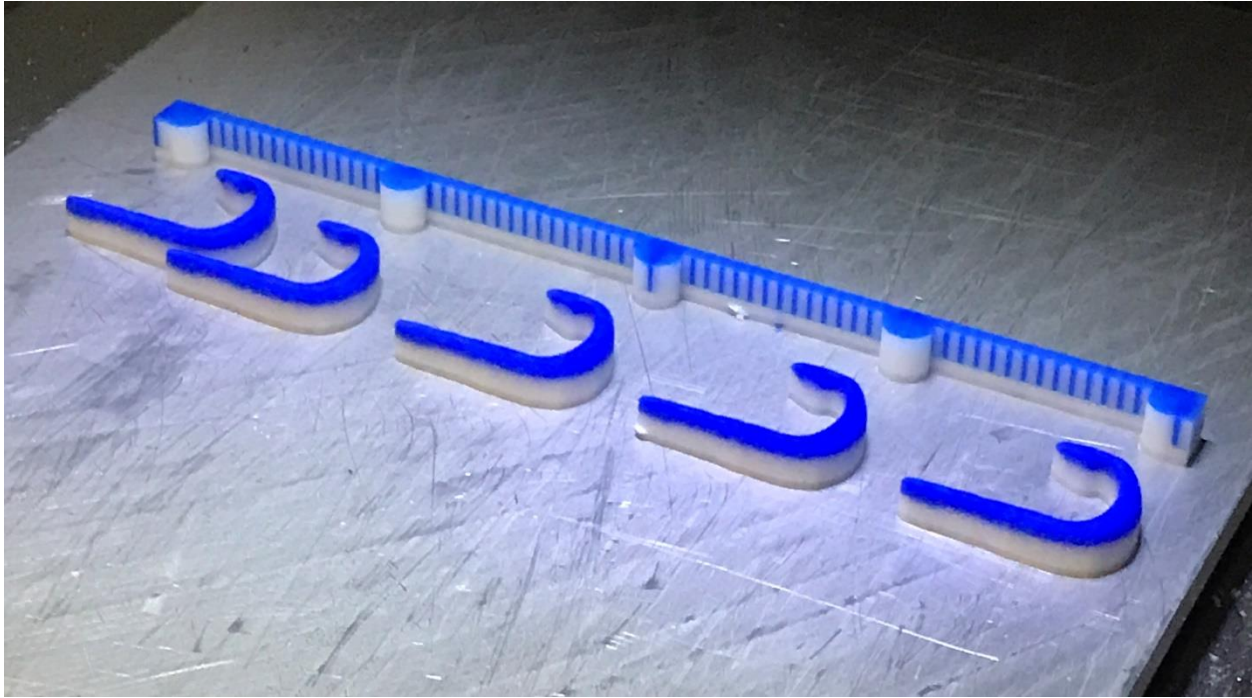


Fig. 7 – 3D Printed wax patterns

A number of replicas were mounted into a wax tree that includes a central core (trunk) and runners (branches) ensuring that none of the patterns touch each other to ensure proper filling of the cavity. In the modern technique, a ceramic slurry is poured around the pattern within a constraining metal flask. The flask is then fired in an electric kiln, a process similar to that used to fire pottery and ceramics which hardens the ceramic and burns away the resin pattern. The casting machine utilises induction electric heating, and vacuum over gravity assistance is then used to pour molten metal into the resulting negatively profiled cavity. Once cooled the ceramic flask is broken away revealing the metal castings. After cooling the fish hooks were sawn off from the tree (see Fig. 8a) and the witness marks of the runners removed by filing to achieve the final result (Fig.8b).



Fig. 8 – a) the casting seen from tree and b) the final casting.

4 DISCUSSION

4.1 THE MUMMIFICATION PROCESS

Despite presenting considerable challenges, the use of non-invasive clinical radiography (X-ray and CT) remains the primary tool available to researchers in the study of wrapped ancient mummified bodies (McKnight et al. 2015, Panzer et al. 2019). Whereas earlier studies favoured invasive techniques (unwrapping, autopsy and ultimately the destruction of mummies), radiography provides the ability to see inside wrapped mummies whilst maintaining the integrity of the artefact. Applying the technique to mummified remains can be problematic as the altered density of the desiccated body tissues; mummification substances (e.g. resins and linen bandages); unnatural presentation of the body/body parts within a wrapped bundle (including skeletal orientation, presence of partial skeletons, remains of multiple individuals (of the same or different species) and the prevalence of fragmented and incomplete remains, can make interpretation of radiographic images and 3D data of mummies difficult (McKnight et al. 2015).

The application of multiple imaging modalities and post-processing visualisation as outlined in the Manchester Methodology enabled details relating to the biological biography and life history attributes of a crocodile caught and mummified by the ancient Egyptians as an offering to the god Sobek to be hypothesised.

The body cavity contains a considerable volume of small stones known as gastroliths, ingested by the animal during life to assist the breakdown of chunks of meat and regulate buoyancy (Wallace and Leslie 2008). The location of the gastroliths which extend from the throat down through the thorax indicates that the process of evisceration, the removal of the internal organs via a surgical incision or natural orifice, was not conducted in this case. Although invasive procedures were considered integral to human mummification during pharaonic history, they may have been considered unnecessary for small animals which would have desiccated quickly and effectively in the arid conditions without such time-consuming treatment. Evidence suggests that evisceration, certainly on the small animals, was not routinely practiced (McKnight et al. 2015) and even where evidence exists it can be difficult to visualize radiographically in relatively small creatures (McKnight 2015, 77-8; McKnight et al. 2015). Undoubtedly, the larger the animal, the more significant the risk of putrefaction of the abdominal organs prior to desiccation; however, imaging confirmed that this was not conducted in the case of mummy 2005.335. A relatively simple embalming treatment consisting of the application of resinous substances directly to the body prior to wrapping in linen bands, would have expedited the mummification process at times when the demand for completed mummies was great (Atherton and McKnight 2014).

The curvature in the spine most likely represents a post-mortem artefact caused by the embalmers during the positioning of the body, rather than as evidence of pathology. This phenomenon was also noted in the case of Manchester Museum crocodile Accession no. 1772 where the animal had solidified in a bow-shaped profile. The linen pad visible beneath the crocodile would have provided stability prior to the application of the linen wrappings; a feature noted in many other mummified animals (McKnight et al. 2015) where pads or rolls of linen were used for support.

The absence of pathological markers to indicate cause of death in the skeleton cannot be taken as conclusive evidence that trauma or disease was not responsible for the death of the animal, as fatal pathologies are difficult to identify in mummified remains unless they manifest within the skeleton (Adams and Alsop 2008). The skull is complete and shows no evidence of trauma in contrast to cases reported by McKnight (2015) and Porcier et al. (2019). The presence of a baited fish hook which rests in the crocodile's stomach, surrounded by gastroliths provides a possible cause of death. Further gastroliths present in the digestive tract suggest that the animal ingested further stones in an attempt to break down its most recent meal, but that it died before these gastroliths had reached the stomach. The skeletal integrity of the fish suggests that it was swallowed whole and that it had not yet been affected by the harsh digestive enzymes present in the first chamber of the stomach or the abrasive action of the gastroliths. Using data published by Wallace and Leslie (2008), the fish was consumed within 24 hours of the time of death; however, the relative completeness of the skeleton and the anatomically correct alignment of the vertebral column with no visible evidence of masticatory action would point to a much shorter window.

The apparent short time span between the ingestion of the fish and the death of the animal suggests that the crocodile was wild caught and the carcass processed for mummification shortly after. This is comparable to the uneviscerated crocodile studied by Porcier et al. (2019) which revealed the presence of extensive stomach contents including eggs, a rodent, insects, a fish vertebrae, feathers and plant material indicative of a natural diet in the wild. The extensive application of resin to the body, including

the filling of a depressed fracture in the cranium, and the subsequent wrapping of the body in linen suggests the ready availability of mummification products leading the authors to hypothesise that the animal was deliberately hunted to procure an animal for mummification (Porcier et al. 2019; 4-6). Considering the comparable findings demonstrated by mummy 2005.335, including the undigested stomach contents and treatment of the body with resins, the authors offer the same hypothesis – that mummy 2005.335 represents a wild animal hunted for the purposes of mummification.

4.2 FISH AND FISHING IN ANCIENT EGYPT

The exploitation of Piscean resources in ancient Egypt for food and sport is a common feature of Egyptian art, particularly in tomb scenes where depictions of relationships with and interactions between humans and the natural world are frequently represented. The consumption of fish was considered taboo in some locations, which according to Plutarch related to the Osiris Myth in which fish consumed Osiris' penis after his body was butchered by his brother, Seth (Brewer and Friedman 1989, 17). Nevertheless, fish were celebrated at sacred sites around Egypt, where large-scale mummification and interment of offerings to the gods was practiced.

Archaeological evidence for the use of hooks in fishing dates from as early as the Predynastic Period (before 3000BC) when they were commonly manufactured from natural materials such as bone, shell and ivory. Other implements include spears, bidents, harpoons, baskets and nets, often depicted in tomb scenes which show the tomb-owner engaging in fishing as a sporting pursuit. The earliest metal hooks found are made from copper and date to the late Predynastic; however, it was not until the Early Dynastic that their use becomes increasingly widespread, likely due to the wider adoption of metalworking technology. These early hooks were simple barbless structures, commonly with an eye through which a line could be introduced. Due to the lack of recorded provenance for the crocodile mummy and the relative similarity of the fish hook to other examples recorded from sites across Egypt, this research was not able to provide further evidence of provenance for the artefact.

4.3 METALWORKING IN ANCIENT EGYPT

Lost wax or investment casting was used by the Egyptians to produce artefacts of standardised form as demonstrated at the Late Period workshop at the site of Qubbet el-Hawa (Auenmüller 2017). Although earlier evidence for the working of gold and copper through the process known as hammering exists as early as the third millennium BC (Hunt 1980), the earliest bronze artefacts produced in Egypt date to between 1580 and 1350 BC. This date is further supported by artistic evidence from the tomb of the two sculptors, Thebes, where craftsmen are depicted smelting metallic copper and tin to produce bronze ingots (Davies 1925, 63; Wainwright 1943, 96-98). The ability to produce artefacts in easily recognisable forms was critical to the underlying precedents of Egyptian votive culture; donors selected or commissioned offerings which embodied the particular divine association they wished to channel, and which conformed to a recognised image which the intended deity would recognise and therefore accept. Although metal votives had high associated material costs, the adoption of replicable production technologies increased the standardisation of these offerings, in a similar way to how standardised

forms and decorative patterns can be identified in votive animal mummies. The crocodile mummy and associated bronze fish hook discussed in this paper combine popular votive culture, human-animal interactions and technological processes in one artefact.

The Egyptians likely used a hardened clay mould into which the molten metal (melted over a charcoal-based heat source) would have been poured. Despite the passing of several millennia between the production of the ancient fish hook and the modern replicas, the casting process remains remarkably similar.

4.4 ASSESSMENT OF 3D VISUALISATION APPLIED TO MUMMIFIED REMAINS

The accurate interpretation of radiographic data for mummified remains is problematic (Adams and Alsop 2008; McKnight et al. 2015) as modern clinical scanners use technology optimized for the study of living tissues. The nature of mummified tissues present complications as the process of desiccation alters the radiographic density, form and appearance of soft tissues, making it difficult to differentiate between tissue types using clinical radiography alone. Research published by Berruyer et al. (2020), Porcier et al. (2019) and Tanti et al. (2021) showcased the application of advanced imaging modalities including synchrotron and microtomography to mummified animal material. These techniques enable impressive levels of visualisation and the segmentation of minute features discovered within mummified bodies which are simply not achievable using standard clinical methods.

The large size of crocodile mummy 2005.335 posed its own logistical and practical handling issues as it was considerably larger than the average human patient and, once acquired, the quantity of data continued to pose challenges. The absence of linen wrappings in this case meant that the only difficulties were caused by the desiccated body tissues and the resinous materials applied to the animal during mummification. Although initial visualisation of the fish hook was obvious on both the digital radiographs and the CT scan due to the very high density of the metal, the virtual extraction of the structure from the surrounding structures was complex and time-consuming. One issue encountered is the relatively small size of the fish hook compared to the animal. To capture images of the whole animal a wide field of view was needed. Field of view (FOV) is a user-defined variable but the number of pixels remains fixed, leading to a large pixel size. If the imaging could be repeated to specifically target the small object a greater resolution could be achieved. However, this would require a second scanning session which is highly unlikely due to the associated logistical and ethical considerations involved in this type of study.

4.5 EXPERIMENTAL TECHNIQUES AS A TOOL FOR ENGAGING THE PUBLIC

Mummies have long been a source of fascination for museum visitors of all ages; however, it can be a curatorial challenge to engage visitors with a mummy's 'story' in a clear and simple way. Learning pedagogy indicates that many people learn through visualisation – seeing *is* believing – and so it is the job of researchers and museum curators to develop strategies to explain complicated scientific results to an audience spanning a mixture of educational levels. Radiography of mummified remains provides a wealth of visual evidence for what is inside a mummy, but this can be difficult to interpret due to the

nature of the remains themselves. Three-dimensional modelling of structures identified radiographically provides a unique opportunity to engage visitors with artefacts on a deeper level. Although the use of 3D modelling in museum displays is becoming increasingly widespread, this is usually achieved through the use of coloured plastic or resin replicas which do not reflect the true nature of the item being replicated. In this project the expert application of software techniques including segmentation and smoothing and the selection of the most appropriate high-resolution 3D printing techniques ensured the best possible replication of the fish hook. In this project, the authors sought to take this process a step further by replicating the hook in its original material, bronze, using a manufacturing technique that is fundamentally the same as that used by the ancient Egyptians.

5 CONCLUSION

Crocodile mummy 2005.335 presented a unique opportunity to apply scientific analysis to a large animal mummy and provided evidence that unwrapped mummies where the physical remains are clearly visible by eye can reveal a great amount of information, both about the life of the animal and the post-mortem treatment of their remains. This case is the largest specimen to have been studied to date by the authors and the one which revealed the most surprising contents during radiographic investigation.

The life story of the crocodile and its unusual 'final meal' has enormous potential to engage the public with the ancient mummy by offering an easily recognisable insight into the contents of the abdominal cavity. Through the virtual removal of the artefact from within the physical confines of the body, the fish hook can be made visible after lying undisturbed for millennia.

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ACKNOWLEDGEMENTS

The authors would like to express sincere thanks to the Leverhulme Trust (RPG-2013-143) and the Arts and Humanities Research Council (AH/P005047/1) for funding aspects of this research. We are indebted to the curators and conservators at Birmingham Museum and Art Gallery for access and permission to study the animal mummy collection; the Manchester University Foundation Trust and the radiography department at the Royal Manchester Children's Hospital for their continued support and enthusiasm for animal mummy research; and, to Gina Baldwin, Casting Technician at Birmingham Jewellery School for her technical expertise and time spent in the physical recreation of the fish hook.

Funding: This work was funded by the Leverhulme Trust (RPG-2013-143) and the Arts and Humanities Research Council (AH/P005047/1).

483 ARTWORK AND TABLES WITH CAPTIONS

484 Fig. 1 – Photograph showing the drip lines caused as the molten resin and beeswax emulsion settled
485 prior to solidification.

486 Fig. 2 – Photograph of crocodile mummy 2005.335 on the scanner gantry.

487 Fig. 3 – CT reformat showing the desiccated trachea; an indication of the exceptional preservation
488 achieved by the embalmers.

489 Fig. 4 – Visualisation showing the complex context of the gut contents and the difficulty in locating the
490 fish hook.

491 Fig. 5 – Visualisation showing the hook highlighted in yellow by making the surrounding objects
492 transparent.

493 Fig. 6 – Final STL file of the fish hook

494 Fig. 7 – 3D Printed wax patterns

495 Fig. 8 – a) the casting sawn from tree and b) the final casting.

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