Utilizing X-Ray Computed Tomography for Heritage Conservation: The case of Megalosaurus bucklandii

Conference Paper · May 2017

DOI: 10.1109/I2MTC.2017.7969983

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Utilizing X-Ray Computed Tomography for Heritage Conservation: *The case of* Megalosaurus bucklandii

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***Abstract*—Of key importance to any cultural institution is the practice of conservation, the method by which specimens at risk of severe degradation or destruction are treated to ensure that they survive into the future. However, surface inspection is often insufficient to properly inform conservators of the best treatment approach, and where there is little to no record of the conservational history of an object it can be difficult to identify exactly what form of conservation has been undertaken. X-Ray Computed Tomography (XCT) grants a way to overcome these issues by allowing conservators to non-destructively investigate the subsurface details of an artefact to provide essential information on condition of a specimen. Here, the potential of this approach is demonstrated using the first XCT scans of the iconic dentary of *Megalosaurus bucklandii* Mantell, 1827 (1); the first dinosaur ever named and described scientifically. XCT analysis reveals that the degree of repair is less extensive than previously thought and also elucidates two different material types, M1 and M2, thought to be representative of at least two phases of repair. Finally the potential of this approach is further explored, highlighting its importance for conservation practice, identifying forgeries and hoaxes in addition to potential applications in public engagement.**

***Keywords*— conservation; X-Ray CT; 3D printing; inspection; heritage, Megalosaurus**

I. INTRODUCTION

Chief among needs for all heritage organizations is a need to protect and conserve the objects and structures that characterize both culture and history. The process of conservation, the practice in which fragile or damaged specimens are restored to functional or stable condition, is an essential convention within modern cultural institutions. This key task remains an extremely high priority in ensuring that the precious objects housed within museum collections remain untarnished by poor storage conditions, chemical degradation and wear over time (2,3). Through a variety of different conservation approaches, including preventative, remedial and, in extreme cases, restorative the museum safeguards its collections from damage and preserves precious artefacts so that they retain an indispensable record of cultural heritage. Equally important is a need to keep track of conservation treatments and repairs carried out upon vulnerable specimens, ensuring that the conservational issues responsible for the initial problem do not re-emerge at a later date. However, records of conservation treatment are not always present or complete. Records can be destroyed through loss or fire damage, such as the 2016 fire at the Natural History Museum in Delhi (4), or may simply fail to be noted at the time. The far-reaching implication of this is an inability to assess the true condition of restored specimens via non-destructive means, which can threaten to undermine the curatorial practice of an institution and hinder future conservational approaches. Far more threatening is the risk of elaborate forgeries and artificial grafts on incomplete genuine specimens that can, on occasion, even fool the most elite of subject experts (5). A robust method of exploring conservation, repair and alteration is thus required.

Fortunately, the increasing accessibility of lab-based XCT, in particular the sub-discipline of Micro-CT (μCT), now presents an opportunity for many institutions to start exploring the subsurface details of the objects that compose their collections. XCT and μCT are beginning to grow in popularity as techniques for inspecting the composition and internal structure of restored or degraded objects. Many approaches have been undertaken in this field, including the restoration of stonework (6,7), evaluating the subsurface construction of artwork (8,9) and even in identifying high-profile, elaborate forgeries (10). The major draws of utilizing this technique for inspecting the condition of an object is the ability to retain the integrity of the original specimen through non-invasive imaging while revealing the morphology and construction of the internal structure (11,12,13). As a result, XCT appears to be an extremely promising and well-suited technique for exploring the conservational history of key museum specimens.

In this paper, we highlight such an application of XCT for the inspection of the conservation history of *Megalosaurus bucklandii*, the iconic first discovered and described dinosaur housed at the Oxford University Museum of Natural History (OUMNH) (14,15). The specimen, collected over 200 years ago, has undergone extensive repair work throughout its history through natural and presumably accidental degradation, many parts of the specimen being replaced with what is assumed is plaster. However, no records to date have been found in the museum archives for any repair-work having been undertaken, and thus the materials used, their

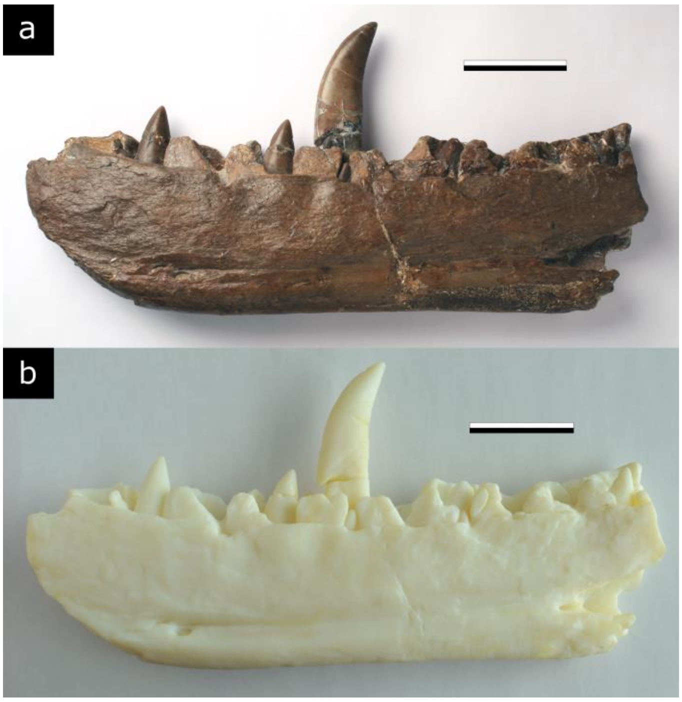

Fig. 1: The M. bucklandii *dentary with 3D Printed Replica. a) Photograph of the lectotype right dentary of* M. bucklandii*. b) 3D print of the lectotype dentary in a photopolymeric resin. Scale bars represent 50mm.*

stability over time and even the amount of repair the specimen has undergone remains unclear. As a result, this iconic specimen represents an excellent opportunity to assess the use of XCT as a conservational tool.

II. MATERIALS AND METHODS

A. Materials

The material used within this paper is the lectotype partial right dentary (lower right jaw) of *Megalosaurus bucklandii*, accession number OUMNH J.13505 from the collections of the Oxford University Museum of Natural History (OUMNH) (*Fig. 1a*). This specimen was recovered from the Stonesfield Slate of the Taynton Limestone Formation from a quarry near the village of Stonesfield in Oxfordshire (15,16). The specimen is associated with two other slabs of matrix, counterparts OUMNH J.13505b and J.13505c, which bear a small amount of superficial bone material from the lateral and medial surfaces of the dentary respectively. The dentary itself is preserved in fossilized bone material, thought to be calcium phosphate that has replaced the original bone of the jaw and the enamel and dentine of the teeth.

B. Methods

The specimen was transported to the µCT facilities at the Institute of Imaging, Metrology and Additive Technology (IIMAT) at the University of Warwick where it was scanned using a Nikon (Xtek) XT H 320LC µCT scanner with a 320kV reflection target head. Due the size of the specimen, it was scanned in three sections to be digitally stitched together later. A beam energy of 243kV and a beam current of 127µA were used to image the specimen, with an exposure of 1.42s and a 4mm copper filter. For the reconstruction process, the Filtered Back Projection (FBP) method (17) was used, generating three final volumes with a voxel resolution of 94µm each. These volumes were then imported into VGStudio Max (Volume Graphics) were they were automatically aligned through a grey-level dependent best fit method , and exported as a single volume for segmentation in Avizo (FEI). The segmentation process separated each of the different materials recognized; the matrix infill, the dentary and the two plaster materials from each other in order to recognize and differentiate between them clearly. Following this, the segmented volumes were converted into surface files and exported into .stl file format for 3D printing. These mesh files were imported into Geomagic Studio 2014 (Geomagic) for automated mesh repair and cleaning, before being re-exported and printed on an Objet260 Connex3 3D printer in a photopolymeric resin (*Fig. 1b*).

III. RESULTS

A. Prior Knowledge of Repair

It well known that the *M. bucklandii* dentary has undergone a degree of plaster replacement, although the exact position of these has only ever been derived from surface observation. No official museum records on the conservation of this specimen have been discovered to date and only (16) have highlighted suspected zones of repaired material. These authors highlight that the majority of treatment has been carried out on the lateral surface of the jaw, mostly posterior of the large break towards on the ventral surface. This breakage zone has been filled in extensively with plaster, particularly on the lateral surface, the dorsal edge along the posterior portion of the lateral surface and a large along the posterior part of the ventral surface on both medial and lateral sides. Another, smaller, plaster infill is found on the dorsolateral surface towards the anterior of the dentary. The fifth tooth, the largest and most prominent one, has also been broken halfway along its length and subsequently repaired using a conservation-grade acrylic resin (Paraloid B72). None of the missing

B. CT Diagnosis

Overall, the results of the XCT scanning of the *M. bucklandii* dentary support what is known about the conservation of the specimen, although differs in a few key regards (Fig. 2). First and foremost, the areas known to be replaced by plaster are for the most part identical to those described by (16) (text-fig. 1), although the extremity of repair appears to be less than expected (*Fig. 2ab*). As noted by these authors, the majority of plaster repair is concentrated on the posterior part of the lateral surface, particularly on the dorsolateral and ventrolateral surfaces. However, the CT scans show additional parts of dentary material which were previously thought to be plaster replacements (*Fig. 2ab*), typically being set within the plaster, presumably to retain these fragments within their original position (R1,2,3). This is particularly notable on the large

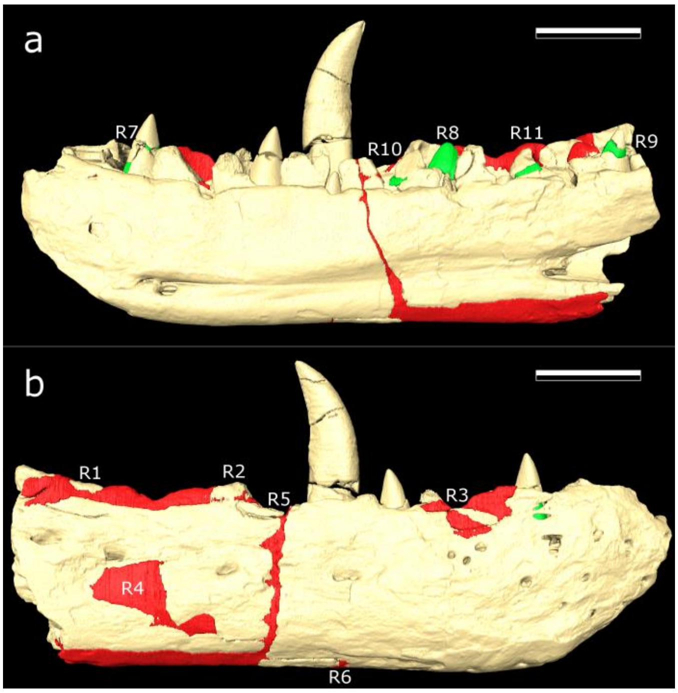

Fig. 2. XCT diagnosis of zones of repair and materials. *a) Medial surface of the dentary. b) Lateral surface of the dentary. Red zones represent those of Material 1 (M1) and Green zones those of Material 2 (M2).*

replacement on the posterior part of the medial surface, which in the observations of (16), continues anteriorly towards the large central break, rather than terminating abruptly as observed in the CT data (R4). Other areas of previously unreported plaster include the anterior portion of the seventh dental alveolus, a continuation of the plaster used to repair and infill the large central crack (R5) in addition to a small infill on the ventral surface approximately halfway along the antero-posterior axis (R6). Additionally, more plaster was found to have been used to repair some of the teeth (R7, R8, R9) in addition to being used to infill gaps in dentary material on the dorsal surface along the tooth row (R10, R11). One of these tooth repairs (R8) comprises the entire crown of the eighth tooth and appears to be slightly misaligned relative to the base of the tooth (*Fig. 3a*). The remaining tooth repairs infill damaged areas and are fairly extensive, serving to stabilize the teeth. Notably, these latter repairs (R7,8,9,10,11) are composed of a different plaster material to the remaining repair work.

In total, two different repair materials can be readily identified. The most common material, Material 1 (M1) (Red), comprises the largest areas of repair, mostly those in posterior section and ventral surface (*Fig. 2ab*). This material can be readily recognized from the CT scans via darker greyscale values signifying a lower density than the surrounding matrix and dentary, with frequent, evenly disseminated particles with extremely bright greyscale values, the extreme density of which generating minor artefacts within the scan data (*Fig. 3b*). These high-density particles appear to be fairly evenly distributed throughout this material, suggesting that they are likely mixed into the plaster material, rather than being secondary mineral growths. These properties allow this plaster to be readily differentiated from the surrounding dentary, matrix and other repair material. The second material, Material 2 (M2) (Green) mainly appears to be used in replacing missing tooth material, although is also used to replace some dentary material as mentioned above. This material can be readily differentiated from M1, the dentary material and the matrix via a lack of the high density particles found in M1 and consistently lower greyscale values, and thus lower density, typically being ~1000-2000 values lower than those found in M1. The presence of both of these materials, M1 and M2, suggests multiple phases of repair, although to the best of our knowledge no archival records of repair exist to corroborate this hypothesis.

IV. Discussion

In summary, XCT scanning has revealed the true extent of repair that the *M. bucklandii* specimen has undergone in addition to the composition of the plaster used to replace missing or damaged parts of the specimen. Analysis shows that the degree of repair is less extensive than was previously understood and has identified additional regions of repair that have not been previously noted, especially the plaster supporting and replacing missing material of the teeth. From XCT data, two different plaster-types have also been recognized, M1 and M2 although their compositions are as of yet unknown. This suggests multiple phases of repair throughout the specimens lifetime, M1 mainly being concentrated on the damaged posterior portion of the specimen while M2 being focused on repair along the tooth row, particularly in the teeth. This information could only be gleaned using these non-destructive XCT scanning methods. With the intervention of non-destructive XCT scanning, the major conservation efforts upon the *M. bucklandii* lectotype dentary have been readily recognized and have shown this suite of techniques to be a powerful tool for inspecting the condition and conservation of key artefacts.

A. A Conservational Tool

As earlier highlighted XCT is slowly becoming adopted as a tool for investigating the conservation of museum artefacts, both in terms of recognizing internal defects, the construction of the artefact, the efficacy of previous conservation treatments and for assessing what course of conservation is best undertaken. The power of this approach is noted by a number of authors (12,13,18,19,20,21,22) and has frequently been demonstrated to be an excellent diagnostic tool for imaging fragile, priceless specimens and artefacts.

One particularly key application has been the ‘digital unrolling’ of the Herculaneum scrolls of the Naples National Library, allowing authors to assess the condition of the scrolls (18) while also successfully being able to recognize and interpret some of the text upon them for the first time (22). (23) also highlight the use of XCT for investigating the subsurface detail of paintings for the purpose of best identifying the conservation process that will be most to preserving the integrity of the piece, similarly highlighting

Fig. 3. Identification of Plaster Masterials from XCT Data. *a) Identification of Material 1 (M1). b) Identification of Material 2 (M2) alongside M1. Both materials can be easily differentiated from eachother. Insets representative of slice location.*

the non-destructive advantage that this approach has over more traditional, destructive methods of painting investigation. XCT is also commonly applied to investigating the porosity and weathering of building materials for the purpose of their conservation. These approaches seek to determine the best approaches for preventing the weathering of protected structures and buildings for the purpose of cultural heritage, as demonstrated by (7). XCT proves to be the most effective method to carry out this procedure, due again in part to the non-invasive approach that yields the internal structure of the scanned material with minimal disruption. These are but a few examples of the conservation approaches that utilize an XCT approach to inspect rare specimens to best inform the conservation approach that should be idealistically undertaken.

B. An Investigative Approach

However, conservation is not the only approach for which XCT may be utilized. It also provides an excellent tool for exploring the authenticity of valuable specimens, both for valuation of potentially expensive artefacts that on occasion find their way onto the market and, far more nefariously, for identifying potential forgeries and repair jobs that may stand up to visual examination (19). (24) demonstrate such an application, carrying out XCT on 17 different classical bowed stringed instruments, identifying internal damage and considerable repair to every single one that failed to be recognized from visual inspection. They then place emphasis upon the importance of this technique for assessing condition to ensure the quality of the instrument in additional to detecting fraudulent instruments. In the vein of hoax prevention, another high-profile example is that of the infamous "*Archaeoraptor liaoningensis*" (5). Controversial from the outset, the 'specimen' first appeared in the National Geographic Magazine, flying in the face of species description convention by not being described in a peer-reviewed journal (25). The apparently transitional nature of the specimen between bird and dinosaur made the issue even more significant and it was claimed that the specimen had been verified by experts beforehand (5). However, the specimen was subsequently proved to be a hybrid of two other dinosaur specimens cleverly combined and filled with additional matrix material to create a coherent specimen, insights revealed only by the investigation of the specimen using XCT (5,10).

C. A Method of Public Engagment

The data generated from XCT scans can also be of further use. Growing in popularity are a myriad of online repositories for storing CT data for exploration by academics and the public and could provide an important avenue for further presenting iconic specimens to those who may never be able to achieve direct access (26,27,28). This information can be further utilized by using the CT data to digitally restore a specimen and use the medium of 3D printing to produce a surrogate that can be used in outreach, helping to preserve the original specimen from sustaining further damage through excessive handling (Fig. 1b).

D. A Scientific Instrument

This approach can also be key for scientific approaches. Digital restoration utilizing scan data of such iconic artefacts also permits experts to digitally repair virtual surrogates without risking the original, retaining the integrity of the real specimen. This process of digitally repairing and piecing together damaged artefacts gives them new scientific purpose and has been demonstrated to be a powerful research approach by a number of authors (29,30). The *M. bucklandii* specimen in particular is associated with two slabs with large sections of the dentary material still attached, highlighting the potential to digitally reconstruct the specimen the true morphology of this iconic specimen for the first time.

In conclusion, XCT promises to be an extremely powerful tool for analyzing the conservational history of key specimens and new acquisitions of either unknown or dubious lineage, as is shown here by the analysis of *M. bucklandii*. The adoption of this practice as a standard within heritage conservation could help to inform key conservational decisions, mitigate the risk of purchasing fraudulent specimens and even contribute to outreach schemes utilizing digital and physical surrogates.

ACKNOWLEDGMENT

Thanks go to Dave Waters for valuable insights into the conservation of the specimen. Also to Greg Gibbons of the University of Warwick for generating creating the 3D print.

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