

**RESEARCH ARTICLE**

# 3D Imaging as a Public Engagement Tool: Investigating an Ox Cranium Used in Target Practice at Vindolanda

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Museums have an ethical code of research and education, and 3D imaging has great potential in helping to achieve some of these objectives by providing accurate replications without barriers to access. Digital and printed models may remove object authenticity, but they do provide direct encounters with heritage and archaeological science whilst preserving the archaeological record. To demonstrate the potential for 3D imaging in archaeology and public engagement, this paper investigated an Ox cranium used for target practice at Vindolanda, Northumberland, UK. Vindolanda is a World Heritage Site on the Frontiers of the Roman Empire, known for its exceptional preservation of artefacts.

The trauma type, shaping, impact direction and mortem period were identified, followed by comparisons and physical fits with weaponry used by the military at Vindolanda. The digital and printed models provide effective tools for displaying this evidence within the context of Roman archery to the public. The cranium had evidence of repeated target practice from arrows and potentially lances. The fragmentation of the trauma was angled internally, showing that the arrows were aimed from the front and toward the facial area of the Ox. The high-precision of the archers had separated the lower right portion of the facial area from the rest of the cranium. Several arrowhead sites and two lance head sites overlapped with little additional destruction, showing that some weapons were removed and retargeted. These features provide supporting evidence of individuals in the Roman military at Vindolanda actively participating in high-level archery target practice. The success of this pilot study will be developed to produce 3D models of the crania recovered from Vindolanda for the public to directly interact with this complex, contextual information for deep and effective learning.

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**Keywords:** 3D imaging; 3D printing; projectile trauma; public engagement; Roman archaeology; target practice

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## Introduction

Historic museum and public engagement models such as the Interactive Experience Model are focused on visitor experience and engagement with heritage resources (Dierking and Falk 1992). American principles of archaeological ethics placed the archaeologist as responsible for educating the public and supporting the need for preservation of archaeological materials (Kintigh 1996). These principles elaborated on the need to produce clear and easily accessible results from archaeological investigations whilst still safeguarding originals (Kintigh 1996). Public outreach and inclusion in archaeological projects have since been essential components of archaeological research (King 2016). This is a trend which is likely to increase due to the changing nature of funding for archaeological projects and the public's fascination with research on the past.

To assist in educating the public, developments in the public engagement models progressed from the dictation of selected knowledge to using useful tools, science and open interaction (Richardson and Almansa-Sánchez 2015; Grima 2016). Actively engaging with museum exhibitions can help to promote skill development and deep learning (Lumb and Sutherland 2009). The deficit model of engagement takes a

theory-oriented approach to archaeological education, explaining the need for scientific techniques, expertise and good science communication (Merriman 2004; Richardson and Almansa-Sánchez 2015). Alternatively, the multiple perspective model of engagement takes a practice-oriented and hands-on approach, focusing on the need for creativity and emotion to stimulate ideas on archaeological issues for all audiences (Merriman 2004; Richardson and Almansa-Sánchez 2015). These models have since been combined into educational, public relation, critical and multi-vocal approaches to engagement, with development on understanding socio-political interactions and social diversity (Holtorf 2007; Matsuda and Okamura 2011). The Manchester Museum has developed codes of learning to achieve aspects of all the above approaches to museum engagement with excellent success. The codes state that exhibits should be dialogic, personalised, philosophical and imaginative, explorative and choice-making, collaborative and multi-sensory (Lumb and Sutherland 2009: 170).

### **3D Imaging and Public Engagement**

Public engagement is required to maintain archaeological excavations and interest (Rua and Alvito 2011) and there is great potential for the integration of 3D imaging into the ambitious and inspirational public engagement of museums (Greenhill et al. 2004; Historic England 2018). Engagement within museums is a deep, sensory interaction that results in a personal interpretation of response (Bitgood 2010; Bonacchi 2017). Digital approaches such as social media, television, and 3D modelling have been effective modernisations on engaging the public irrespective of distance (Bonacchi 2017). 3D imaging, in particular, joins the spatial and thematic aspects of archaeology excellently; digital and printed models provide a direct encounter with heritage resources, interacting with scientific techniques in a social dimension (Tzortzi 2015). 3D imaging has been used in several public archaeology projects. For example, the Virtual Curation Laboratory scanned artefacts to improve the conservation and recognition of cultural resources on military lands (Means 2013; 2015), whereas displays at George Washington's Ferry Farm held a display for the public to view the scanning process and handle printed models (Means 2013; 2015). These models are valuable to the education and research missions of public engagement.

### ***Education mission***

3D digital and printed models create a discussion point for learners to develop confidence and enquiry skills. Although digital and printed models remove the authenticity of viewing the original artefact, the replica allows individuals to physically handle and manipulate it for self-directed and personalised learning (Merriman 2004; Kuzminsky and Gardiner 2012). Regarding the codes of learning, demonstrations involving 3D models provide the essential sense of discovery when exploring artefacts and engaging the imagination (Serota 2000; Lumb and Sutherland 2009; Sylaiou et al. 2010). For example, the Fairfield Model Project produced a 3D-printed model of their excavation site that could be "excavated" layer by layer to uncover the archaeology inside, allowing the public to explore from undisturbed land through to the final artefact (Fairfield Foundation 2018). This use of 3D imaging is a successful implementation of educative co-creation, where the different parties (archaeologist, researchers, volunteers, and the community) all contribute toward the development and completion of a project (Bollwerk et al. 2015). For example, Heritage Together and ACCORD had the public select sites and features for 3D modelling, resulting in resources valuable to researchers and the local community (Bonacchi 2017). This interactive relationship provides a rich and personalised experience for all individuals involved (Bollwerk et al. 2015).

Lumb and Sutherland (2009) emphasised the importance of discussing controversial issues, whether about the display of sensitive remains, or social issues such as race and identity. 3D models can reduce some of these controversies; for example, displaying digital and printed models rather than the original human remains to overcome dark tourism (Stone and Sharpley 2008). Courtroom presentations have already incorporated 3D imaging to provide effective and objective explanations of material to the layperson whilst removing the sensitive nature of some skeletal remains (Errickson et al. 2014). However, 3D modelling can pose controversial or legal concerns, such as the discussion of 3D printing functional firearms and body parts (Lewis 2014).

The portability of digital and 3D-printed models removes access issues to support museum learning values. Digital 3D models are accessible online and can assist with classroom teaching throughout the curriculum without needing to access the museum (Greenhill et al. 2004; Lumb and Sutherland 2009). Models can be brought to hospitals or schools, effectively bringing the archaeology to the public without risking conservation (Greenhill et al. 2004). Furthermore, Rütter et al. (2009) used 3D scanning to model safe access routes through Wonderwork Cave, safely bringing the public closer to the archaeology and engaging them with the direct source of heritage.

### ***Research mission***

Museums have an ethical code to conduct research and collaboration (Museums Association 2015). Additional research of artefacts is essential to museums by discovering knowledge and interpretations that were previously hidden (Museums Association 2015). Without improving research, the cultural value of objects may be underestimated. Digital models can be shared with other researchers to greatly expand their sample sizes, confirm measurement precision, and capture a wider range of human variation (Kuzminsky and Gardiner 2012; Kuzminsky et al. 2016). Once a database of 3D models is established, the logistic and monetary needs for maintenance are minimal, so they can fit with most research strategies on an international scale of collaboration (Museums Association 2015). Research using 3D models can increase visibility to a range of audiences, including stakeholders, researchers and the public (for example, the online collection of models provided by The British Museum; <https://sketchfab.com/britishmuseum>). Therefore, 3D imaging can be invaluable to the research community by providing potential for international collaboration.

3D imaging can be an appropriate and effective support to conservation, documentation and planning procedures in archaeological research (Errickson et al. 2017). Modern 3D scanners have the capacity to achieve the needs for techniques in cultural heritage; they are accurate, rapid, portable, relatively low cost, and have a user-friendly assembly and interface (Bruno et al. 2010; Remondino and Rizzi 2010). Destructive sampling is undesirable and problematic when applying scientific techniques to archaeological material. The non-destructive and non-contact nature of 3D imaging makes it suitable for archaeological research (Errickson et al. 2017). In most applications, 3D imaging is arguably more appropriate than 2D imaging. 2D images can suffer distortion from camera angles and lighting, scales are not recorded on the same level as the object, and the 3D object is effectively flattened into the 2D plane, resulting in an inaccurate capture of geometric and morphological details (Boehler and Marbs 2004; Evans et al. 2014; Shamata and Thompson 2018).

Upon correct setup, the accuracy of 3D scanners results in no significant differences in morphology or size between the original object and digitised model (Errickson et al. 2014, 2015; Shamata and Thompson 2018). Measuring 3D digital models is also more accurate than measuring the topography of the original object due to the pinpoint accuracy of imaging software (Ampanozi et al. 2010; Errickson et al. 2014; Shamata and Thompson 2018). Digital representations of artefacts, caves and excavation sites can be explored with excellent accuracy and without restrictions (Lerma et al. 2010). This accuracy is critical to research but is likely unnecessary for the typical public display (3D printing can also disguise the precise features). Overall, the archaeological research community can benefit well from the robustness, standardisation and transparency provided by 3D imaging and the accurately representative models (Kuzminsky et al. 2016).

### ***Games and Virtual Reality***

Novel archaeological applications of 3D imaging include the development of digital catalogues into replications of museums and artefacts, whether as a video game or virtual reality exhibition. The movement of virtual and augmented reality technology into the mass market is reshaping the perspectives of the person and the place (Grima 2017). For example, Dawson and Levy (2016) replicated the polar heritage site Fort Conger into an explorable, virtual environment for effective communication toward the public. This included additional reconstructions of the site for different time-periods and expeditions, resulting in an excellent boost in experience and awareness of the need for site preservation. Rua and Alvito (2011) reconstructed 3D models of the Roman villa Freiria into Bethesda Softworks' Oblivion game engine, providing an interactive scientific visualisation of the site with cross-referenced information and event scripting. Scripts can be written to automatically assign farmer characters to work, guards to patrol duty, or invaders to attack, providing an excellent platform for interacting the public with interpretations of the site (Rua and Alvito 2011). These applications simulated the experience of being in an accurate, historical reconstruction of the archaeological site without needing extensive resources, or even having to travel (Grima 2017). Complete environmental reconstructions are not necessary; Bruno et al. (2010) received good public reception when displaying their 3D models in virtual reality, accompanied with soundbites that explained features of interest when selected on the model. There is excellent potential for 3D modelling in augmenting the museum experience by digitally overlaying displayed artefacts, bringing the public out of the confines of the museum space and into the resource itself (Tzortzi 2015; Grima 2017).

### ***3D Imaging in Archaeology***

There are several types of 3D scanners available to the archaeologist. 3D imaging with laser or light-structured scanning involves the collation of many surface images and scans to construct a composite model. Laser scanners capture the object morphology using laser lines targeted to individual points, whilst structured

light scanners capture the entire area using a collection of projected white and blue light patterns. Structured light is cheaper and more accurate than laser scanning, whereas laser scanning is faster and more effective on reflective or moving objects (Jecić and Drvar 2003).

Using laser surface and light-scattered scanning, the geometric details of objects ranging from whole statues down to coins can be quickly and precisely captured (Lapp and Nicoli 2014). Terrestrial laser scanning (TLS) applies 3D imaging principles to landscapes and other large-scale targets. This allows caves, buildings and excavation sites to be quickly scanned and explored in modelling software off-site, providing a digitised representation of the site of interest (Lerma et al. 2010). Although the benefits of Digital heritage are being actively debated across museum working groups and conferences, the archaeologist may opt for photogrammetry instead; the requirements for 3D imaging may be inaccessible (Errickson et al. 2017).

Photogrammetry involves building a 3D composite model from a collection of 2D photographs (Addison 2000). Photogrammetry is more readily accessible due to not requiring 3D scanning equipment and achieves excellent texture detail (particularly on smooth surfaces). Photogrammetry can bring the public to the core of the archaeological project; Project Mosul crowdsourced photographs from the public and combined them into a 3D recreation of destroyed sites (Grima 2017). However, photogrammetry models are not true 3D models due to the relatively inaccurate capture of geometric and morphological details in the 2D plane as discussed earlier (Boehler and Marbs 2004; Evans et al. 2014). This is problematic when the research requires finer and more accurate details, though typical public engagement applications may not have these requirements. An example is the capturing morphological details, which are essential when demonstrating bone trauma to the public. When deciding whether photogrammetry is sufficient enough to capture the detail required or to outsource for 3D imaging, the operator must consider the target material; **Table 1** provides suggestions of when photogrammetry may be suitable. Overall, 3D scanning offers a much simpler, more automated stitching process, with higher accuracy in the captured topography.

3D imaging and reproduction have already been used in a wide range of applications within archaeology (see **Table 2** for a summary). Most applications are for recording and conserving material. Artefacts can be viewed and handled without risking damage or causing irreversible changes in the original object (Kuzminsky and Gardiner 2012). Models can also be visualised to help determine which restoration methods to use on the original object (Brutto and Meli 2012). For example, early applications include the replication of the skull of Ötzi the 5,300-year-old Iceman for other scientists to analyse without needing to handle, thaw or invasively sample (zur Nedden et al. 1994). Most other applications of 3D imaging in archaeology consist of terrestrial scanning of a site, with artefact modelling limited to objects of particular interest such as fingerprints in clay lamps (Lapp and Nicoli 2014) or analysing and reconstructing skeletal remains (Kuzminsky and Gardiner 2012). 3D imaging is more precise than traditional hand-drawn plans of sites and more effective at demonstrating to the public how the excavation site appeared, with artefacts overlaid into position (Rüther et al. 2009; López et al. 2016). However, the expensive equipment, time-consuming methods and complicated methodologies created barriers of entry that prevented 3D imaging from being the widely applicable method it is today (Rusinkiewicz et al. 2002). Modern equipment can provide automated

**Table 1:** Suggested archaeological applications for photogrammetry and 3D scanning. Please note that these are recommendations; both techniques have and still can be used for each application with varying success.

Artefact	Photogrammetry	3D Scanning
Amphora	✓ (if painted)	✓ (if engraved)
Bones		✓
Environments		✓ (terrestrial laser scanning)
Irregular Shapes		✓
Paintings	✓	
Pliable, moving objects	✗	✗ (potential for laser scans)
Statues	✓ (if simple)	✓ (if complex)
Tools and weaponry		✓

**Table 2:** Summary of previous applications of 3D imaging to archaeological analysis and public engagement. This list is comprehensive but not exhaustive.

Material	Reference	Application
Cave scanning	Lerma et al. (2010) López et al. (2016) Rüther et al. (2009)	Enhance visualisation, recording, access plans and conservation.
Excavation site	Ahmon (2004) Dawson and Levy (2016) Forte et al. (2012) Guidi et al. (2009) McPherron et al. (2009) Neubauer et al. (2005) Remondino (2011) Rua and Alvito (2011) Valzano et al. (2005)	Imaging of site and structures to reconstruct for excavation records, public display, and raising awareness.
Museum exhibit	Bruno et al. (2010) Boehler and Marbs (2004) Pujol (2004)	3D imaging of artefacts for virtual exhibition and effective interaction.
Pottery	Karasik and Smilansky (2008) Lapp and Nicoli (2014)	Recording artefacts, and visualising small features of interest.
Skeletal remains	Duches et al. (2016) Kuzminsky et al. (2016) Kuzminsky and Gardiner (2012) zur Nedden et al. (1994)	Accurate records of degraded material and trauma marks, and sharing materials with other researchers.
Statues	Boehler and Marbs (2004) Valzano et al. (2005) Zheng et al. (2000)	Recording artefacts, and displays in virtual exhibitions.
Weaponry	Grosman et al. (2008) Woźniak et al. (2012)	Accurate measurements and fitting suspected weaponry into trauma sites.

procedures that register, fuse and fill scans after the operator selects areas that approximately match, making the technique significantly more accessible to museums and archaeologists. Considering the potential value of 3D imaging, it should be exploited more frequently in archaeology.

### Application of 3D Imaging to a Cranium Used in Target Practice

Vindolanda is a World Heritage Site on the Frontiers of the Roman Empire, and has excellent preservation of delicate material due to the limited bacterial activity, anaerobic conditions, areas of waterlogging, and preserving soil composition. Vindolanda was under Roman occupation between AD 85 and 370, during which the site was demolished and rebuilt by at least nine different communities, each one leaving distinct features at the site. Artefacts from these occupations are displayed in the Roman Vindolanda Museum and Roman Army Museum. The museum has embraced a 3D film feature which transports you back into Roman army life. The artefacts on display in both museums provide context and additional information about the daily lives of the domestic and military communities stationed at Vindolanda, and interactions with the Vindolanda community and wider Roman Empire. Many artefacts are kept behind glass cases for their own protection, as chemicals such as oxygen, humidity and bacteria from handling items can lead to excessive degradation. However, many artefacts cannot be viewed and engaged with to fully integrate the museum visitor; one example is the Ox crania. The Vindolanda Museum has several Ox crania described as having evidence of target practice. One cranium is used in teaching sessions, whilst the cranium in this paper is kept behind a glass display due to its fragility (see **Figure 1**), and the other crania are kept in storage. The distinction between the weaponry used in these crania had not been made in depth, nor had the direction of shooting, positioning or the post-mortem use of the crania prior to targeting. Therefore, some trauma analysis was needed, followed by 3D modelling and Roman contextualisation of the evidence to support effective and accessible learning.



**Figure 1:** Current museum display of the Ox cranium examined by this paper, alongside other animal remains. The room is set up styled like an examination room, with shelves full of crania on display, though there is no writing to describe and contextualise what features are on display in the remains (Photo: The Vindolanda Trust. Reproduced with permission).

The Ox crania are special archaeological resources; they hold undiscovered information about the archers stationed at Roman Vindolanda. There are also few surviving cases of arrow trauma in archaeological remains, and even fewer showing evidence of repeated target practice. Most arrow trauma resulted from battle, including 80 Late Iron Age Dorset remains with projectile wounds (Redfern 2009), crossbow trauma from Battle of Wisby (Thordeman 1939), the one case of arrow trauma out of 641 skeletons in the Zadar Roman necropolis (Novak 2010), and the Towton mass graves with up to six occurrences of arrow trauma (Novak 2000).

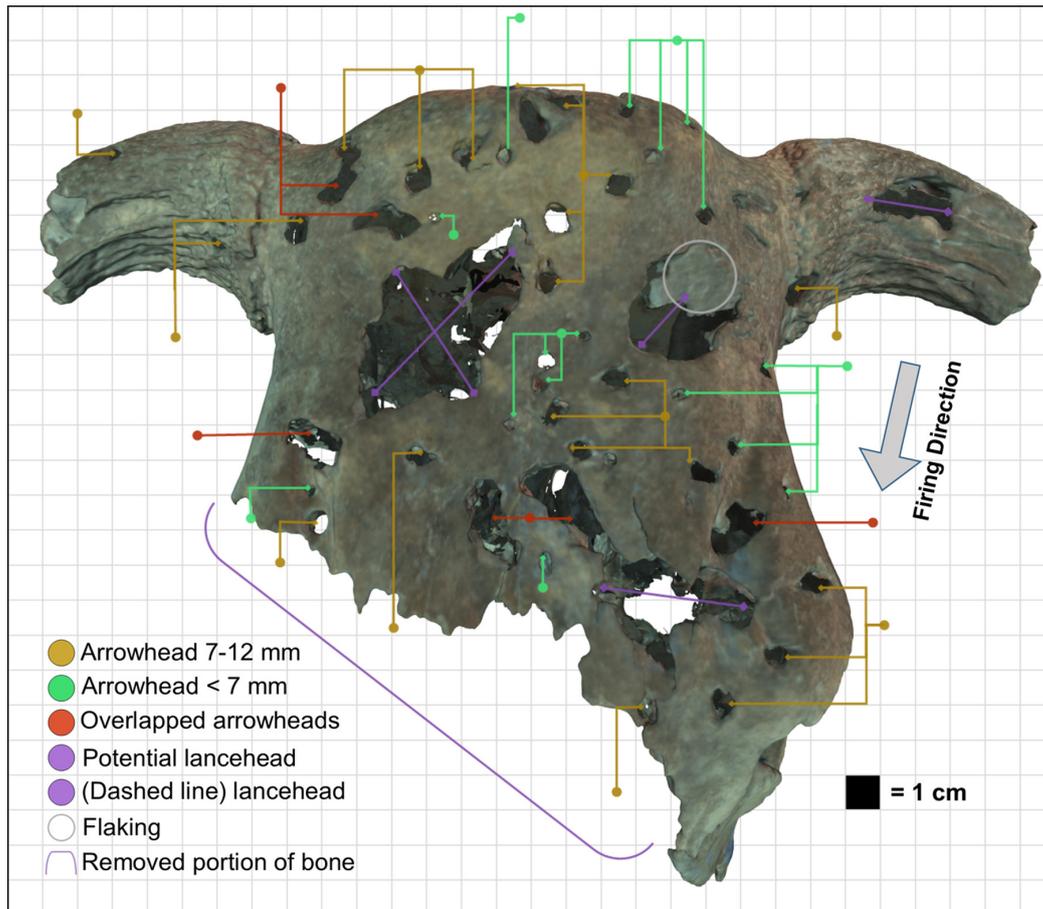
### Method – Ox Cranium Analysis and Modelling

Bioarchaeological assessments identified the trauma type category, trauma shaping, fracture sequencing, impact direction, mortem periods, surface staining, and comparisons with recovered weaponry to aid the overall interpretation (Berryman and Haun 1996; Lovell 1997; Berryman and Gunther 2000). Digital models enhanced the bioarchaeological analysis by magnifying and splicing the characteristic features without obstruction. Despite the potential of 3D imaging in archaeology and public engagement, only generic 3D scanning procedures have been provided (Kuzminsky and Gardiner 2012; Historic England 2018). A flow-chart for the 3D scanning, modelling and printing processes based on this research and suggestions by Erickson et al. (2015) is provided in **Figure 2**.

An HP 3D Structured Light Scanner Pro S3 with a single camera was used to scan the cranium, followed by a range of suspected weaponry including iron arrowheads, lance heads and ballista bolts. Objects were scanned in a room with dim, diffused lighting, using 1/4 shutter speed to prevent colour banding in the surface texture. The projector and camera were calibrated to 240 mm when scanning the cranium, and to 120 mm when scanning weaponry. Objects were rotated until all visible surfaces were scanned.

Scans were registered together using HP 3D Scan Pro 5. Separate scans were aligned sequentially with pairwise fine registration using surface features. After all scans were aligned, global fine registration was run. The Ox cranium was fused into one model (resolution = 1500, sharpness = 0, close holes = 0%). The weaponry were fused into separate models (resolution = 1500, sharpness = 0, close holes = 100%).

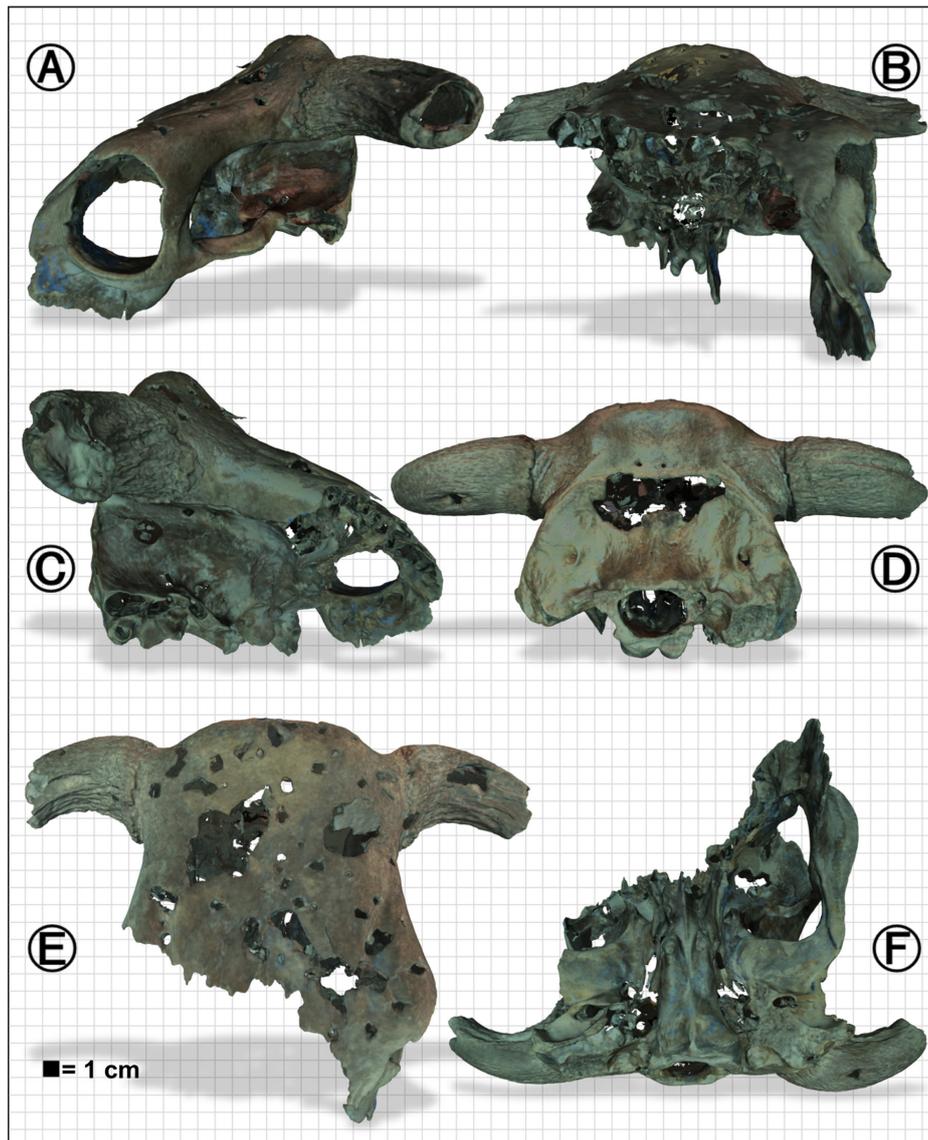




**Figure 3:** Annotated image of frontal portion of bone, capturing most the trauma sites. Trauma sites are categorised by weapon used and perforation size. The direction of most impact sites is marked. Textures are from the 3D scanner, not a 2D camera.

markers in **Figure 3**). The lower-right facial portion (orbit and maxilla area) of the cranium was removed and absent (blue bracket in **Figure 3**). The amount of projectile impacts around this area, and limited evidence of post-mortem damage, showed that this portion had been separated by the amount of impacts and not by burial or excavation processes (Sauer 1998). The fragmentation and bevelling at perforation sites were angled internally, showing that the arrows were aimed from the front and toward the facial area of the Ox (Berryman and Haun 1996). Despite the amount of impact sites, none could be sequenced due to insufficient radial fracturing in all sites (Hart 2005). Some perforations overlapped (red markers in **Figure 3**) but as with impact sequence, there was insufficient evidence to show whether arrows were removed or left in the cranium before the overlapping arrow was fired (Hart 2005). Imitating these activities on the 3D-printed models was a visually engaging approach for enhancing the public's understanding, irrespective of age.

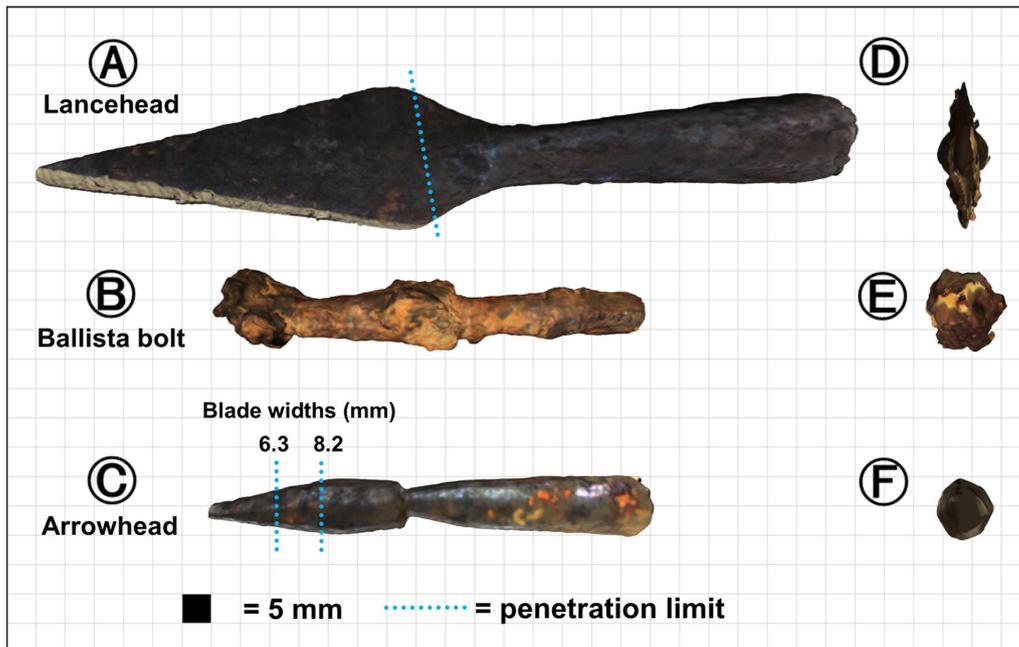
The large trauma sites in the frontal portion (purple markers in **Figure 3**) had flaking, bevelling on the internal table, and impressions on the outer table, indicating these as entrance wounds (Berryman and Haun 1996). No separate exit wounds were present. The large trauma sites matched the profile of the lancehead when angling it to simulate the shot direction, but with a wider hole due to the angle and weight of the lancehead causing more damage. Due to the extra damage and angle not allowing a smooth physical fit as with other weaponry, these were categorised as potential lancehead impacts. There was one exception; a perforation that physically fit a lancehead penetrating perpendicular to the bone (marked as a dashed lancehead line in **Figure 2**)—this site overlapped with a potential lancehead site. The size and solidity of the lancehead, combined with the absence of radiating fractures or destruction of the cranium, means that one lancehead was removed before being hit with the second, though the order cannot be determined. Similar to with bullet keyhole fracturing, the angle of the bevelling and flaking in these sites also indicated that the weapons were also fired from the top-left toward the bottom-right side (Berryman and Gunther 2000).



**Figure 4:** Ox cranium. **A)** shows the left side, **B)** shows the anterior view, **C)** shows the right side, **D)** shows the posterior view, **E)** shows the superior view, and **F)** shows the inferior view. These are textured digital models and not a 2D photographs. The perforation in the centre of **D)** was the entrance site for a lancehead, made to hold the cranium up.

The trauma site in the occipital area was similar to the lancehead sites on the frontal portion. The perforation was likely made to hold the cranium up for target practice (see the positioning in image **D)**, **Figure 4**). Considering the direction, and position of arrow sites on the border between the frontal and occipital bones, the cranium was held above the archers, though the distance from the archers cannot be determined without extensive experimental archaeology. Whilst text-based descriptions were difficult to follow, 3D models demonstrated this activity clearly to the public.

Categorising the mortem period was difficult due to the long burial period disguising some of the features and potentially causing additional damage. However, the trauma sites were categorised as perimortem trauma due to the clean breakage, smooth fracture edges with bevelling, absence of shattering, and uniformity with the surrounding bone (Sauer 1998; Moraitis et al. 2009). The presence of perimortem trauma means that the cranium cannot have been cooked as this would remove the organic material from the bone, thus exhibiting post-mortem features instead. The length of the perimortem period can last several months or even years depending on deposition variables such as temperature, moisture, sun exposure, and insect activity (Galloway et al. 1999). Therefore, the cranium will most likely have been fleshed whilst targeted, though the 'freshness' of the cranium cannot be determined.



**Figure 5:** Suspected weaponry. A, B and C show side-profiles of the weaponry whilst D, E and F show a view of these weapons from the blade tips. Textures are from the 3D scanner, not a 2D camera.

### Demonstrating Bone Response to Roman Archery

The use of 3D models can bridge the gap between theoretical and experimental archaeology by testing some theories such as weapon fits or positioning for effective and tactile demonstrations (Sylaiou et al. 2010; Di Franco et al. 2015; Schorch et al. 2015). However, experimental work may be impractical for many public engagement events due to equipment requirements (in this case, weapons and animal samples). In contrast, 3D models can be easily placed to assist and contextualise learning. For example, the Ox cranium models can educate on the prowess of Roman archers, and how archery practice may appear in bone.

Archers had just several minutes of clear aim toward an exposed enemy (Gabriel and Metz 1991; Ureche 2015). The Ox cranium evidences archers at Vindolanda practising their abilities to exploit this brief opportunity; experienced archers could fire a 30-arrow quiver into a target zone in just 3 minutes with 50–100% accuracy (Miller et al. 1986; Gabriel and Metz 1991). Composite bows provided an effective range of between 50 and 200 m, extending the exposure time while still maintaining enough accuracy to repeatedly hit the same target (Goldsworthy 1996; Ureche 2013). These archers would not have trained ‘internally’ by the Roman Empire as most archers were hired from auxiliaries to adapt to new territories (Ureche 2015). The public can be presented with this information as they proceed with handling the 3D models to truly engage them with the complex information presented and simplify learning for all ages (Sylaiou et al. 2010; Museums Association 2015; Schorch et al. 2015).

This study did not complete an exhaustive analysis of arrow trauma in bone. However, experimental studies of arrow trauma show a range of responses that were also present in the Ox cranium. Forsom and Smith (2017) observed internal bevelling in almost all the perforations in their experimental study on trauma caused by different styles of medieval arrowheads. Novak (2010) also observed bevelling on the internal table, physical fit between arrowhead and perforation, and an absence of fracture lines in the single arrow trauma site. When shooting replicate flint arrowheads into fresh bone, Smith et al. (2007) observed a lack of fracture lines, with bevelling similar to observations by Forsom and Smith (2017). Yeshurun and Yaroshevich (2014) and Duches et al. (2016) fired replicate bow and arrows into freshly killed animals, causing internal bevelling and arrow-shaped perforations in most cases (Yeshurun and Yaroshevich 2014), with fragmentation and notches or striations in bones with irregular shapes or thin structure (Duches et al. 2016). These observations show that arrows perforate bone without fracturing, fragmenting or splintering unless the structural integrity of bone cannot withstand the arrow or oblique shooting angle (typically in ribs, scapulae borders and diaphyses; Duches et al. 2016). Experimental work is required to discover the distance and speed of the archers at Vindolanda. The resulting trauma can be 3D imaged and shared with other research teams. A library of experimental bone trauma could be developed by combining 3D models from this proposed

experiment and those from a range of research teams. Such a library will remove the experimental practicality issues for many public engagement events and research teams, improving the research mission for all investigations into bone trauma.

### **Demonstrating Bone Response to Other Roman Weaponry**

The Ox cranium presented sites with features that did not reflect arrow trauma and would be enquired about in public demonstrations. The use of other weaponry is reflected in Roman military tactics; despite the importance of archers in providing manoeuvrability, speed and terror, more emphasis was placed on slings and close combat weaponry. This shows in wound reports: arrow wounds were lethal in just 42% of cases, whereas slings were lethal in 66%, spears in 80% and swords in 100% (Gabriel and Metz 1991; Goldsworthy 1996). Slings were considered more deadly and easier to resource than arrows (Redfern 2009). Thanks to their small size and strength requirements, slings could be considered a toy or small hunting weapon, allowing training from a young age alongside smaller bows (Redfern 2009). However, slings required extensive training for good accuracy and force and caused little damage when at range, so dedicated slingers were only recruited if specifically wanted (Gabriel and Metz 1991).

As with arrow trauma, experimental studies of suspected weaponry support the features presented in the Ox cranium and can be demonstrated on the 3D models. Spears have been experimentally tested in ballistic gel and synthetic bone plates with consistent velocities (Iovita et al. 2014). Low speeds caused penetrations and transverse fractures, whilst high speeds or oblique angles caused additional damage with longitudinal fractures. Stones result in depressions rather than perforations in most cases, though do cause some internal bevelling without outer table fractures if fired in close proximity (Redfern 2009). Rather than needing such elaborate and dangerous setups, the public can select from a range of printed arrowheads, lanceheads, ballista bolts and other suspected weaponry. The chosen weapons can then be fit into a printed cranium to discover which weapon was used in which location, providing a multi-sensory and imaginative approach to learning (Lumb and Sutherland 2009). As before, a 3D library of experimental investigations into the response of bone to other Roman weaponry will help address the questions raised by both the public and archaeologists.

### **Conclusion**

The Ox cranium from Vindolanda provides an exceptional example of how useful 3D imaging can be to archaeology and public engagement. The trauma in the cranium was not directly analysed via 3D imaging. However, the 3D imaging and printing process creates excellent potential for effective analysis and public presentation of the cranium. These methods, with comparisons against observations in experimental research, showed that most the trauma in the Ox cranium were caused by Roman archers practising their archery skills. Most of the perforations were from arrowheads and not *pila* as questioned by Bishop (2017), evidencing the militia at Vindolanda adapting and training as required by their location and tactical needs. The exceptional accuracy and range of these archers made them effective troops for either the battlefield or fort defences.

Following the successes of this trial study, the next steps are to image and analyse the remaining crania at Vindolanda for public display. These models will deliver the potential for the public to directly interact with this complex, contextual information for deep and effective learning. The crania models may be developed to include annotations and soundbites for features of interest, inspiring the public with expert information in an accessible and interactive manner. Digital models of the crania or related experimental samples can also be accessed by researchers worldwide to improve standardisation and robustness of archaeological research.

### **Note**

<sup>1</sup> <https://sketchfab.com/williamsrhy/collections/vindolanda-target-practice-crania>

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### **Competing Interests**

The authors have no competing interests to declare.

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