CHAPTER 3

Direct Digital Radiographic Imaging of Archaeological Skeletal Assemblages: An Advantageous Technique and the Use of the Images as a Research Resource

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3.1 INTRODUCTION

The Museum of London, London, United Kingdom (MoL) is faced with the complicated task of maintaining archives of large and diverse skeletal collections. The collections have been recorded over the years in a variety of ways and the resultant data stored in a range of formats, from traditional paper records to early incarnations of electronic recording systems. The Centre for Human Bioarchaeology (CHB) at the MoL curates extensive collections of archaeologically-derived human skeletal remains from the Prehistoric, Roman, Anglo-Saxon, Medieval, and Post-Medieval time periods. The skeletal collections curated at the CHB are captured in a broad range of integrated digital methods, including databases, photographs, radiographs, and computed tomography (CT) scans. These methods have extremely advantageous applications, but there are also concerns with the implications of long-term sustainability in a world of rapidly changing technologies. The importance of using multiple modalities to record these collections is that they are each designed to capture a different type of data, which then presents the option of examining a single, large collection using multiple lines of evidence. Studies that might have previously focused only on a single methodology can now incorporate data that speak to multiple aspects of the same question, creating more efficient and holistic explorations of these unique skeletal collections.

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3.2 OSTEOLOGICAL DATABASE

The initial digitization of the MoL skeletal collections was the result of the large-scale excavations (1998–2001) at Spitalfields Market (Thomas, 2004). Excavations of the market uncovered the monastic site of St Mary Spital and revealed over 14,000 medieval skeletal remains, of which 10,500 are curated at the MoL (Connell et al., 2012; Thomas, 2004). The prospect of analysis of such an unparalleled number of skeletal remains precipitated the development of a new electronic database system (Fig. 3.1); the skeletal remains were also to be retained as part of the archaeological archive. Osteologist Brian Connell and IT specialist Dr. Peter Rauxloh devised and created a bespoke osteological database for recording and retaining the large osteological dataset, leading to the creation of a rapid recording system (Connell and Rauxloh, 2003), an osteological method statement (Powers, 2012), and the Wellcome Osteological Research Database (WORD) supported on an Oracle platform. The Oracle platform allows for the maintenance of large datasets, enabling the creation of a dynamic search engine and a powerful tool for recording, research, and conservation.

Funding in 2003 awarded by the Wellcome Trust established the CHB and funded a team of osteologists to analyze skeletal remains from earlier excavated sites in the City of London and Greater London Area. Between 2003 and 2007 there were two osteological teams, the developer-funded Spital team and the Wellcome-funded team, working in tandem to record the osteological data into the WORD using the same methods and standards for osteological recording (Brickley and McKinley, 2004; Buikstra and Ubelaker, 1994). The launch of the CHB website in 2007 marked the sharing of osteological data at a scale no other institution curating skeletal remains had previously achieved. It also allowed for the production of a groundbreaking publication in bioarchaeology (Connell et al., 2012), based upon the data of over 5000 individuals recorded and analyzed from St Mary Spital.

The CHB curates the skeletal remains of c.20,000 individuals and the WORD holds records for over 16,000 individuals. The digitized osteological data are freely shared, allowing researchers worldwide to create direct comparative studies. In addition to those accessing the datasets remotely, annually over 50 researchers visit the CHB to collect data. There has been a profound impact on the field of osteology; in fact, this ready access has caused a noticeable London bias in the osteological output of studies (Roberts and Mays, 2011).

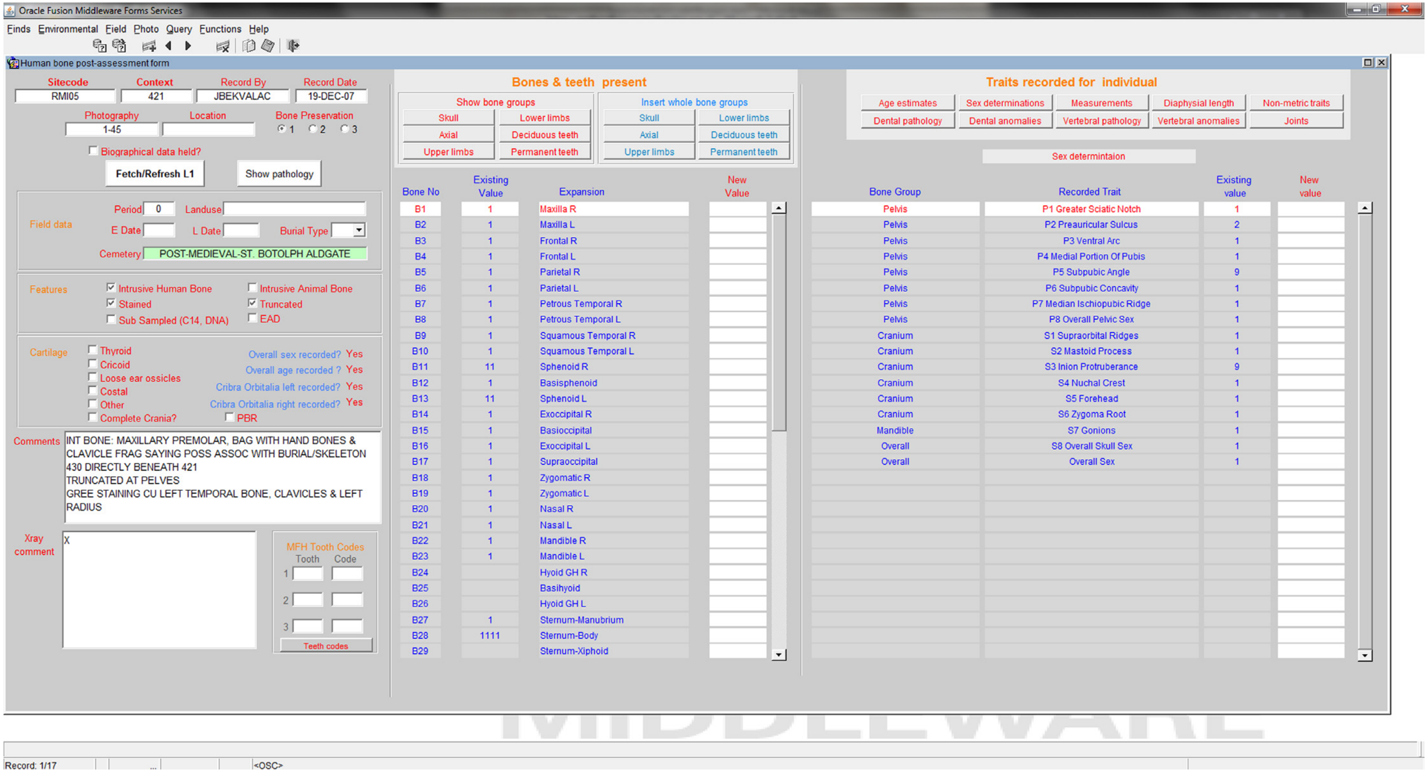

Figure 3.1 Image of database record on Wellcome Osteological Research Database (WORD), RMI05 421.

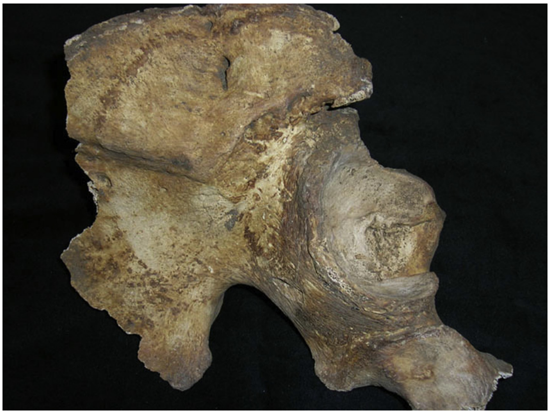

Figure 3.2 Digital photographic image (OCU00 668) healed fracture of right ilium (posterior view).

3.3 DIGITAL PHOTOGRAPHIC IMAGES

The CHB curates an archive of digital photographic images of recorded pathologies and skeletal anomalies shared in jpeg format and linked to the individual contexts on the WORD database (Fig. 3.2). This database serves as a conservation tool mitigating the over handling of skeletal remains from repetitive analysis. The images capture pathological alterations and aid in observing any changes or damage to the integrity of the skeletal elements. Currently, the digital photographic images can be viewed on the CHB website, annotated with site code and context numbers. Work is ongoing to directly upload them into the database record on the Oracle platform.

3.4 DIRECT DIGITAL RADIOGRAPHY

Previously, radiography has not been a routine aspect of analysis for archaeological skeletal collections. Radiography had more commonly been employed in relation to the study of mummies with studies such as the Manchester Mummy Project (Isherwood and Hart, 1992). Wet film radiography requires a dedicated area for processing and the variable quality of clarity, cost, problems with long-term storage, and the limited ability to share and view the wet film images are major issues (Fig. 3.3). The development of digital X-raying was considerable; as Burgener (2008) notes, "the transition from film to digital radiography has had a great impact on conventional radiology" (p. v).

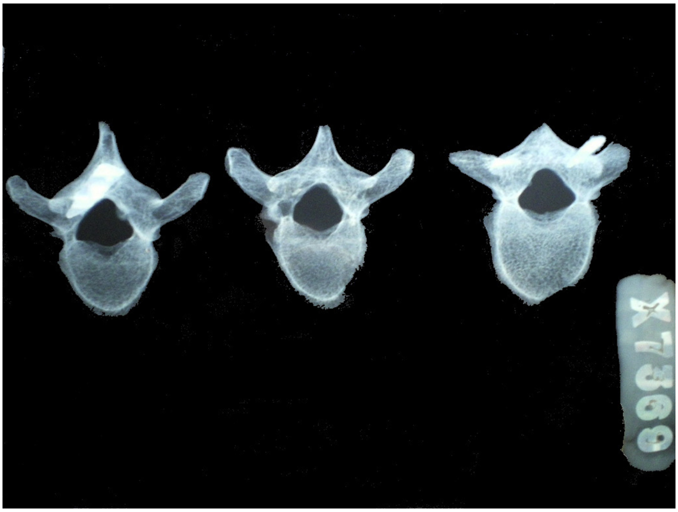

Figure 3.3 Wet film radiograph of vertebrae showing projectile injury (MIN86 5343).

Direct digital radiography (DDR) provides a rapid and relatively inexpensive means for visualizing and analyzing the internal structure of skeletal remains, revealing information otherwise impossible to access with only macroscopic analysis. The application of DDR provides important information and pathological data, allowing for an additional level of interpretation for the varying types of skeletal assemblages (Western and Bekvalac, 2015). It is nondestructive, mobile, and can produce large datasets of digital images in multiple formats that are compatible with many online platforms. The application of DDR with a radiographer enables the use of clinical protocols to be followed, aiding in the interpretation and comparison of the archaeological remains. Clinical standards and strategies in place for DICOM (Digital Imaging and Communications in Medicine) and PACS (Picture Archiving and Communication System) are well established, with protocols and standards that can be applied to the digital radiography of archaeological materials (eg, Kim et al., 2015; Müller et al., 2004; Tello et al., 2014).

Digital radiography is more versatile and has increased the opportunities for radiography to be more widely available to use on archaeological skeletal collections. DDR equipment can also be portable, which is a major advantage for skeletal remains that may be stored in difficult-to-access locations, reducing the amount of

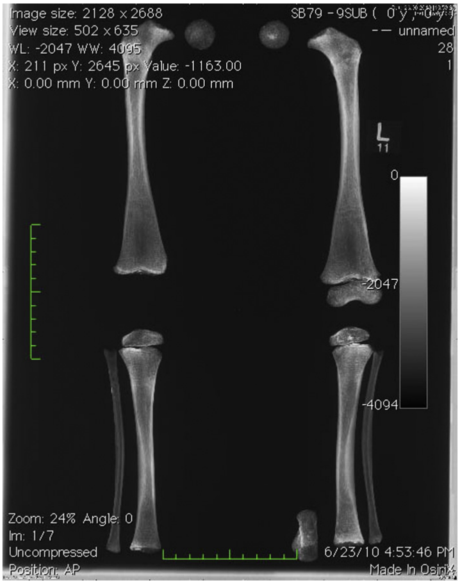

Figure 3.4 Digital radiograph of nonadult long bones of the right and left leg (SB79 9).

potential damage that may affect the remains whilst in transit. DDR has proven to be a useful tool at the CHB, with its first application to the crypt assemblage at St Bride's Church, Fleet Street, London, then to MoL collections, and excavated material from Worcester Royal Infirmary. Prof. Jerry Conlogue of Quinnipiac University, United States used a portable radiographic kit (Reveal Imaging Ltd) in the crypt at St Bride's Church, Fleet Street, establishing the basis of a burgeoning and extremely beneficial and valuable data source. The clarity of the images produced was excellent and provide another method for researching this unique biographical collection (Fig. 3.4).

The initial application of DDR to the skeletal remains retained in St Bride's crypt has already opened avenues of collaborative research (Bekvalac, 2012; Conlogue et al., in press) and more will be possible in the future when mechanisms are in place to more readily share the digital radiographic images online. DDR has also been applied as part of a number of postgraduate research projects on the curated collections at the museum, such as studies investigating growth and development in nonadults (Newman, 2015) and aiding in the identification of trauma in nonadults (Verlinden and Lewis, 2015).

Ongoing collaborative research with Gaynor Western (Ossafreelance) and Mark Farmer (Teesside University), using radiographs of female crania from St Bride's, enabled investigation into Hyperostosis Frontalis Interna (HFI) that previously would not have been possible. The results this radiographic research produced led to further research into HFI with funding in 2014 from the British Association for Biological Anthropology and Osteoarchaeology, enabling the digital radiography of 50 female crania from the Christ Church Spitalfields collection at the Natural History Museum, London, United Kingdom, with a selection of these to be scanned in a micro CT scanner (Bekvalac et al., 2014).

The newest exciting project borne of this radiographic research is "The Impact of Industrialisation on London Health." With generous funding from the City of London Archaeological Trust Rosemary Green Grant, this project is now in place for 2015−18. This project will radiograph c.2500 adults from archaeological skeletal collections in London and regional areas outside of London to expand knowledge of diseases, and address questions about the impact of urbanization on health by studying pathologies revealed from the radiographic images and macroscopic analysis. The scale of the archive will dramatically increase and the critical challenge with this developing and growing digital archive is making it accessible and maintaining it for the future. Fortunately, it is possible to store the images in a number of formats, and the clinical protocols in place with DDR used by hospitals are a good vanguard for the long-term sustainability of the digital radiographs (Western and Bekvalac, 2015).

3.5 COMPUTED TOMOGRAPHY

Medical imaging such as CT and micro CT scans are becoming increasingly available to use on osteoarchaeological material as costs decrease and access to specialist equipment becomes easier. A small number of the skeletal remains from the CHB have had CT scans, which, as with digital radiography, is a desirable nondestructive method of investigation. The CT and micro CT scans enable the skeletal remains to be viewed internally in the form of virtual slices, allowing for even greater detail than a radiograph. CT scans are made up of many radiographic images from multiple angles creating 2D images (virtual slices) that are combined in stacks to form volume data (thickness) that can be viewed in 3D. The cross-sectional images enable the skeletal elements to be viewed in sliced sections of varying thickness and provide finite details of the structure of the elements and any variations, with micro CT scanning providing a very high resolution, in the range of microns (Weber, 2015). Weber (2015) discusses the variety of imaging applications applied for creating virtual anthropology and some of the problems using them, but highlights how, with the access to such applications, the data have important implications for comparative morphology and functional analysis. CT as a method of investigation has been readily embraced in the study of mummified remains, which has led to a number of innovative research projects and exhibitions (eg, Friedman et al., 2012; Gardner et al., 2004; Nelson and Wade, 2015; Wade and Nelson, 2013; Wade et al., 2011a, 2012).

The CHB has been fortunate to have access to CT and micro CT scanners in collaboration with institutions including the Moorfields Eye Hospital, the National Hospital for Neurology and Neurosurgery, St Bartholomew's Hospital, and the Natural History Museum, London. The initial collaboration was spurred by biomedical and medical student researchers from St George's Hospital carrying out research on selected elements from the museum's skeletal collections. The students' research used the CT scanned images to aid them in investigations concerning bone density, cranial variation, and cribra orbitalia. One of these students examined two post-medieval collections at the CHB to define a protocol to be used clinically for the detection of cribra orbitalia using CT (Naveed et al., 2012). The CHB shared a CT scan of a complete skeletal individual through the exhibition *Doctors, Dissection and Resurrection Men* at the MoL in 2012–13. This was possible with access to a more sophisticated CT scanner based at The National Hospital for Neurology and Neurosurgery and the support of experienced radiologist Indran Davagnanam from Moorfields Hospital.

The size of the CT slice images can be large, which can be problematical for organizations that must ensure that they have computer systems capable of rendering the images for diagnostic interpretation and sharing. Currently the MoL does not have the computer systems, programmes, or specialist knowledge necessary to render the images for diagnostic interpretation and sharing of CT images.

3.6 3D MODELING

3D modeling is an area of developing innovation that has become increasingly popular as a beneficial interactive teaching tool. The uses of 3D modeling are found in a wide spectrum of industries, including the forensic and medical fields, with the application to archaeological and skeletal collections being more recent (eg, Gualdi-Russo et al., 2015; Szikossy et al., 2015; Woo et al., 2015). The process of 3D modeling uses specialized software, which captures the surface features of objects using a series of geometric points enabling the resultant data to be remodeled to create a virtual representation that can then be manipulated and viewed in numerous ways. As with the other digital modalities outlined, 3D modeling does have challenges and issues in its usage and application, particularly the size of the resultant dataset and the requirement for powerful computers with the necessary capacity and functionality to be able to interpret, store, and share the resultant virtual output.

The creation of a virtual 3D model has the potential for a greater tangible interaction with the skeletal collections for teaching and research while safeguarding delicate pathological lesions from over handling. The Digitised Disease Project (https://digitiseddiseases.wordpress.com/) is a groundbreaking approach to increasing access to 3D digital models of human skeletal remains with pathological lesions. A number of the individuals from the collections at the MoL were included in this project. As an integrated method of research at the CHB, 3D scans and modeling have been used in postgraduate research projects such as O'Mahoney's (2009) work concerning upper limb biomechanics using a Next Engine scanner. This model of scanner was also used by Dr. Louise Humphrey (Natural History Museum) as part of an ongoing interdisciplinary study on growth and development of nonadult skeletal remains, scanning targeted elements from the nonadult individuals from St Bride's crypt. In 2015, PhD student Rebecca Gibson (American University, Washington, DC) used a Next Engine scanner to scan ribs and vertebrae of selected adult females from St Bride's Lower Churchyard to investigate plastic thoracic deformation. Further, the virtual skeletal analysis 3D scanning project, initiated in 2012 by Roland Wessling, Dr. Sophie Beckett, and Jessica Bolton (Cranfield Forensic Institute, Cranfield University), uses 3D scanning to quantitatively investigate features of the bone surface that can otherwise only be observed qualitatively.

3.7 DISCUSSION

The opportunity to apply digital techniques to archaeological collections, notably skeletal remains, has provided remarkable means of storing, generating, engaging, interacting with, and interpreting extensive datasets. The CHB digital archive is already extensive and will continue to develop and grow. The osteological database is a powerful digital asset and has already proved to be the most invaluable research tool for integrated research. Working alongside radiographers, radiologists, and specialists in the digital imaging fields has been particularly important with the application of digital radiography integrated as a research tool for projects in the CHB.

The application of the digital imaging techniques discussed in this paper allows for the study of the MoL collections from multiple angles. Integration of the datasets can provide a more extensive yet nuanced understanding of the skeletal collections. The data provided from each technique are unique, thus the application of multiple modalities encourages the examination of research questions from many angles and increases not only the amount of information gained, but the strength of the evidence. Where digital photographs and 3D modeling provide detailed information on exterior structures of bone, digital radiographs and CT scans provide increasingly detailed information on internal morphology and microarchitecture. Combining, for example, radiographs and CT can be used to explore pathological changes (Wade et al., 2011b). Similarly, 3D modeling and radiographs or CT can be used to correlate exterior surface changes with interior morphological differences. Having this information accessible for researchers at the MoL allows for the creation of more complex research questions and more detailed answers that push the field of osteology forward. Use of these technologies does, however, require acknowledging their limitations in order to integrate them appropriately.

The next step for the CHB is to actively promote the use of integrated modalities in the research conducted at the Centre. For example the large-scale City of London Archaeological Trust (CoLAT) funded project, "The Impact of Industrialisation on London Health" will be the first project for the Centre that will be able to fully utilize all of the imaging modalities to address a particular research question. This project is intended as a large-scale investigation of the changing health patterns of medieval and post-medieval London, with specific attention to the role that industrialization played. For this project, uniting the multiple modalities is key to establishing a cohesive overview of change in general health patterns as it allows for examination of a wider range of indicators than would be accessible with any one method, and that together speak to larger shifts in human health.

There are enormous positive attributes to digital applications, but they have their associated challenges. Digital systems can develop rapidly and heritage institutions are under increasing financial pressures; thus, maintaining and updating digital assets can be difficult. Maintaining the integrity of and long-term access to digital records will continue to be a challenge. The security of data, server capacity, and back up for data are vital for the integrity of the data and long-term storage. The sustainability of digital archives requires the maintenance of systems and functionality, the prevention and management of the degradation of digital data formats, and support for digital assets and training.

Questions about standards and best practices in light of digital resources and access have recently been raised (Atkin, 2015) and a working group has been proposed to discuss the ethical implications of sharing digital images of human remains. Standards and codes of ethics exist for many aspects relating to human remains (eg, Historic England, 2005; British Association for Biological Anthropology and Osteoarchaeology, 2010; Department for Culture, Media and Sport, 2005), but such codes are often virtually nonexistent with digital resources. These challenges will continue to be an issue as digital technologies develop and images relating to human remains reach wider audiences.

Digital applications enhance the knowledge we can glean from the people of the past, open up channels of information, and have the potential to forge global interdisciplinary relationships for learning, but the applications themselves cannot replace the actual skeletal remains. The CHB firmly believes that the retention and curation of the physical remains is paramount and that the digital applications are a means of fully amplifying the bioarchaeological information, the "voice of the past" from the skeletons (Larsen, 2002, p. 3). Expectations of the providers and users have been completely altered by advancing digital technologies and provide access to untold treasures of information about the past. Managing that access can be problematic, but the CHB is an example of an institution where digital applications have been able to open up access to a unique archive, are an invaluable asset, and continue to share data on a scale that would have once been thought impossible.

REFERENCES

Atkin, A., 2015. Digging the digital dead. In: 17th Annual Conference of the British Association for Biological Anthropology and Osteoarchaeology, University of Sheffield, paper presentation.

Bekvalac, J., 2012. Implementation of preliminary digital radiographic examination in the confines of the crypt of St Bride's Church, Fleet Street, London. In: Proceedings of the Twelfth Annual Conference of the British Association for Biological Anthropology and Osteoarchaeology. BAR International Series 2380, 111–118.

Bekvalac, J., Western, G., Farmer, M., 2014. The impact of industrialisation on female health: understanding the aetiology of hyperostosis frontalis interna. In: 16th Annual Conference of the British Association for Biological Anthropology and Osteoarchaeology, University of Durham, poster presentation.

Brickley, M., McKinley, J., 2004. Guidelines to the standards for recording human remains. British Association for Biological Anthropology and Osteoarchaeology and Institute of Field Archaeologists. Available online: <http://www.babao.org.uk/HumanremainsFINAL.pdf>.

British Association for Biological Anthropology and Osteoarchaeology, 2010. Code of Ethics. Available online: <http://www.babao.org.uk/index/cms-filesystem-action/code%20of%20ethics.pdf>.

Buikstra, J.E., Ubelaker, D.H. (Eds.), 1994. Standards for Data Collection from Human Skeletal Remains. Arkansas Archaeological Survey, Research Series No. 44. Fayetteville, Arkansas.

Burgener, A.F., 2008. Preface. In: Burgener, A.F., Kormano, M., Pudas, T. (Eds.), Bone and Joint Disorders. Differential Diagnosis in Conventional Radiology, 3rd ed. George Thieme Verlag, Stuttgart, p. v.

Conlogue, G., Viner, V., Beckett, R., Bekvalac, J., Gonzalez, R., Sharkey, M., et al., 2016. A post-mortem evaluation of the degree of mobility in an individual with severe kyphoscoliosis using direct digital radiography (DDR) and multi-detector computed tomography (MDCT). In: Tilley, L., Schrenk, A. (Eds.), New Developments in the Bioarchaeology of Care: Further Case Studies and Extended Theory. Springer, New York (Chapter 7).

Connell, B., Rauxloh, P., 2003. A Rapid Method for Recording Human Skeletal Data. Museum of London Report, London.

Connell, B., Gray Jones, A., Redfern, R., Walker, D., 2012. A Bioarchaeological Study of Medieval Burials on the Site of St Mary Spital: Excavations at Spitalfields Market, London E1, 1991–2007. MoLA Monograph Series 60.

Department for Culture, Media and Sport, 2005. Guidance on the Care of Human Remains in Museums. London. Available online: <http://www.babao.org.uk/index/cms-filesystem-action?file=dcmsguide%20oct%202005.pdf>.

Friedman, S.N., Nguyen, N., Nelson, A.J., Granton, P.V., MacDonald, D.B., Hibbert, R., et al., 2012. Computed tomography (CT) bone segmentation of an ancient Egyptian mummy: a comparison of automated and semiautomated threshold and dual-energy techniques. J. Comput. Assist. Tomogr. 36, 616–622.

Gardner, J.C., Garvin, G., Nelson, A.J., Vascotto, G., Conlogue, G., 2004. Paleoradiology in mummy studies: the Sulman mummy project. Can. Assoc. Radiol. J. 55, 228–234.

Gualdi-Russo, E., Zaccagni, L., Russo, V., 2015. Giovanni Battista Morgagni: facial reconstruction by virtual anthropology. Forensic Sci. Med. Pathol. 11, 222–227.

Historic England, 2005. Guidance for best practice for treatment of human remains excavated from Christian burial grounds in England. Available online: <https://content.historicengland.org.uk/images-books/publications/human-remains-excavated-from-christian-burial-grounds-in-england/16602humanremains1.pdf/>.

Isherwood, I., Hart, C.W., 1992. The radiological investigation. In: David, A.R., Tapp, E. (Eds.), The Mummy's Tale. Michael O'Mara Books, London, pp. 100–111.

Kim, T., Heo, E., Lee, M., Kim, J., Yoo, S., Kim, S., et al., 2015. Medical image exchange and sharing between heterogeneous picture archiving and communication systems based upon international standard: pilot implantation. 15th International HL7 Interoperability Conference Proceedings, 37–42 <http://ihic2015.hl7cr.eu/Proceedings-web.pdf>.

Larsen, C.S., 2002. Skeletons in Our Closet: Revealing Our Past through Bioarchaeology. Princeton University Press, Princeton.

Müller, H., Michoux, N., Bandon, D., Geissbuhler, A., 2004. A review of content-based image retrieval systems in medical applications—clinical benefits and future directions. Int. J. Med. Inform. 73, 1–23.

Naveed, H., Abed, S.F., Davagnanam, I., Uddin, J.M., Adds, P.J., 2012. Lessons from the past: cribra orbitalia, an orbital roof pathology. Orbit 31, 394–399.

Nelson, A.J., Wade, A.D., 2015. Impact: development of a radiological mummy database. Anat. Rec. 298, 941–948.

Newman, S., 2015. The growth of a nation: child health and development in the industrial revolution in England, c. AD 1750–1850. Durham University, Department of Archaeology, Durham (unpublished PhD thesis).

O'Mahoney, T., 2009. Activity and allometry: a three dimensional study of humeri from contrasting populations using three dimensional laser scans. University College London, London (unpublished MSc dissertation).

Powers, N. (Ed.), 2012. Human Osteology Method Statement. Museum of London Report, London. Available: <http://archive.museumoflondon.org.uk/NR/rdonlyres/3A7B0C25-FD36-4D43-863E-B2FDC5A86FB7/0/OsteologyMethodStatementrevised2012.pdf>.

Roberts, C., Mays, S., 2011. Study and restudy of curated skeletal collections in bioarchaeology: a perspective on the UK and the implications for future curation of human remains. Int. J. Osteoarchaeol. 21, 626–630.

Szikossy, I., Pálfi, G., Molnár, E., Karlinger, K., Kovács, B.K., Korom, C., et al., 2015. Two positive tuberculosis cases in the late Nigrovits family, 18th century, Vác, Hungary. Tuberculosis 95 (S1), S69–S72.

Tello, A., La Cruz, A., Saquicela, V., Espinoza, M., Vidal, M.-E., 2014. RDF-ization of DICOM medical images towards linked health data cloud. IFMBE Proc. 49, 757–760.

Thomas, C., 2004. Life and Death in London's East End: 2000 Years at Spitalfields. MoLAS, London.

Verlinden, P., Lewis, M.E., 2015. Childhood trauma: methods for the identification of physeal fractures in nonadult skeletal remains. Am. J. Phys. Anthropol. 157, 411–420.

Wade, A.D., Nelson, A.J., 2013. Radiological evaluation of the evisceration tradition in ancient Egyptian mummies. Homo 64, 1–28.

Wade, A.D., Nelson, A.J., Garvin, G.J., 2011a. A synthetic radiological study of brain treatment in ancient Egyptian mummies. Homo 62, 248–269.

Wade, A.D., Holdsworth, D.W., Garvin, G.J., 2011b. CT and micro-CT analysis of a case of Paget's disease (osteitis deformans) in the Grant skeletal collection. Int. J. Osteoarch 21, 127–135.

Wade, A.D., Garvin, G.J., Hurnanen, J.H., Williams, L.L., Lawson, B., Nelson, A.J., et al., 2012. Scenes from the past: multidetector CT of Egyptian mummies of the Redpath Museum. Radiographics 32, 1235–1250.

Weber, G.W., 2015. Virtual anthropology. Yearb. Phys. Anthropol. 156, 22–42.

Western, A.G., Bekvalac, J., 2015. Digital radiography and historical contextualisation of the 19th century modified human skeletal remains from the Worcester Royal Infirmary, England. Int. J. Palaeopath. 10, 58–73.

Woo, E.J., Lee, W.-J., Hu, K.-S., Hwang, J.J., 2015. Paleopathological study of dwarfism-related skeletal dysplasia in a late Joseon dynasty (South Korean) population. PLoS One 10, e0140901. Available from: http://dx.doi.org/10.1371/journal.pone.0140901.