Forensic Sciences Research

ISSN: 2096-1790 (Print) 2471-1411 (Online) Journal homepage: http://www.tandfonline.com/loi/tfsr20

Virtual anthropology – a brief review of the literature and history of computed tomography

Tanya Uldin

FORENSIC SCIENCES RESEARCH, 2017
VOL. 2, NO. 4, 165–173
https://doi.org/10.1080/20961790.2017.1369621

REVIEW

OPEN ACCESS Check for updates

Virtual anthropology – a brief review of the literature and history of computed tomography

Tanya Uldin

Department of Medicine and Community Health, University Center of Legal Medicine Lausanne-Geneva, University Hospital of Lausanne, Lausanne, Switzerland

ABSTRACT

Computed tomography (CT) has influenced numerous fields since its inception in the 1970s. The field of palaeoanthropology significantly benefited from this efficient and non-invasive medium in terms of the conservation, reconstruction and analysis of fossil human remains. Over the past decade, there has been a steady increase in the number of forensic anthropological studies incorporating virtual osteological analyses. Because of the increasing importance of these modern cross-sectional imaging techniques and the requirement for standardized parameters in forensic science, we deemed it important to outline the history and development of CT applications in these related academic areas. The present paper outlines the history of "virtual anthropology" and osteological multi-detector CT in the context of palaeoanthropology and forensic anthropology.

ARTICLE HISTORY
Received 1 March 2017
Accepted 16 August 2017

KEYWORDS
Forensic science; forensic anthropology; virtual anthropology; palaeoanthropology; computed tomography; MDCT; bone imaging

Introduction

The use of digital imaging techniques, such as computed tomography (CT) or optical surface scanning, has contributed to numerous medical-related domains, including biology, palaeontology, biological anthropology, archaeology, forensic science and materials science. As a non-invasive diagnostic tool, these techniques have many advantages. The digitized object can be examined externally and internally, while being simultaneously manipulated without causing damage to the object. Investigations are repeatable and verifiable at any time, and digital data or 3D-printed hard copies of the object can be easily replicated and shared within the scientific community.

Over the past two decades, there has been a steady increase in the use of multi-detector computed tomography (MDCT), and the demand for specific data-acquisition and post-processing parameters in medical research has led to various recommendations and protocols [1–6]. However, different research areas require specific solutions. Indeed, the implementation of CT in palaeoanthropology and forensic anthropology arose to specifically address the needs of these fields. This review aims to outline the history of "virtual anthropology" and CT in the fields of palaeoanthropology and forensic anthropology.

The use of CT in palaeoanthropology

The introduction of clinical CT by Hounsfield [7–9] led to immediate benefits for palaeoanthropology; the non-invasive aspect of the technique allowed researchers to conserve precious and often fragile fossils, prehistoric human skeletal remains and mummified remains [10,11]. Around the same time, specific scanning protocols and guidelines were developed for the technique [12–16]. Subsequent discussions by Tate and Cann [12] to modify the Hounsfield unit scale for the high density of fossil bones led to the development of an extended scale for the better visualization of internal structures. Sumner et al. [14] focused on improving the accuracy and precision of the measurements, providing a solution for the treatment of beam-hardening artefacts. In particular, the studies by Ruff and Leo [15] and Spoor et al. [16] highlighted the potential sources of error in this technique, such as inaccuracies in measurement due to partial volume effect and incorrect threshold values, or the problematic correlation of CT-number values and tissue densities depending on the X-ray beam energy (tube voltage); these issues still occur in modern medical research [17–19]. The authors also provided specific guidelines for bone scanning, image processing and interpretation of the data.

The development of spiral CT in 1989 [20] provided enhanced cross-sectional data acquisition and better image processing software for 3D surface reconstruction. This proved to be an advantage for the investigation of the Tyrolean Iceman, also known as "Ötzi", a mummified corpse from the Chalcolithic period discovered at the Austrian–Italian border in the Alps in 1991 [21–24]. Full-body, 3-mm, spiral CT scanning

CONTACT Tanya Uldin taul@protonmail.ch

was performed to examine the internal bony structures of the corpse. The high-resolution images obtained made it possible to detect particularly small fractures that would have remained invisible using conventional radiography. zur Nedden and colleagues [23,24] reconstructed the skull of the Tyrolean Iceman in 3D using post-processing software of the CT workstation and though 3D printing. They applied stereolithography, a computer-guided 3D printing technique that uses UV lasers and photohardening resin, to create a 3D model, layer by layer. The group then compared measurements from the real skull, the virtual skull and the model, and demonstrated the accuracy of the measurements. The study also shed light on various problematic artefacts, such as pseudo-lesions, which may occur due to volume averaging effects [23]; this problem has yet to be solved in medical research [25–27].

From as early as the 1990s, it became popular to digitize fossils in palaeoanthropological studies, no longer restricting data collection to CT alone. Optical surface scanning and micro-CT are two additional techniques commonly used according to the purpose of the research [28]. Weber and co-workers, who took part in the study of the Tyrolean Iceman, first coined the term "virtual anthropology" [29–31] as a multidisciplinary approach combining knowledge from related academic areas such as anthropology, palaeontology, primatology, medicine, mathematics, statistics, computer science and engineering [31]. According to the authors, the potential of digitized objects lies in the permanency of the data, and the accessibility to internal anatomical structures that would otherwise remain hidden during routine external examinations. Digitization also allows for reproducibility and the use of advanced analyses (i.e. geometric morphometrics), not to mention, the ease of data sharing [31]. CT-based research in palaeoanthropology using 3D reconstructions has focused primarily on morphometric and shape analyses to investigate human evolution [30,32–39]. To meet the complexity of this new field of research, two textbooks on virtual anthropology were published, providing profound technological insight and specific guidelines [28,40].

One of the most recent discoveries in palaeoanthropology – *Homo naledi*, an extinct hominin species from South Africa [41] – shows the positive effects of this "digital revolution", and is a good example of the consistent application of Weber's [29] demand for "Glasnost in Palaeoanthropology"; i.e. free accessibility of digitized fossil data to enhance scientific progress and transparency. Weber and his co-workers published the first data-set of a hominid skull [29]. Fifteen years on, many scientists now publish their 3D data, i.e. surface scans of several skeletal parts of *Homo naledi* were made available (open-access) on the MorphoSource website, a data archive for 3D fossil data [42]. Making the data accessible allowed for the immediate exchange of information among the research community.

Palaeontology and zooarchaeology are two related academic areas of palaeoanthropology that have benefited from imaging techniques. MDCT and other digital visualization tools have been extensively used to reconstruct extinct species, apply advanced statistical methods and facilitate the sharing of data [43]. Additionally, comparative osteological collections have been established to highlight the anatomical variations in the skeleton among species. This is particularly advantageous when access to reference collections of real bones is restricted or unavailable [44,45]. du Plessis and co-workers [46] have demonstrated the potential of automated laser preparation, which is used to separate fossil bones and surrounding sediments. The technology is based on density differences in materials using data obtained from a micro-CT scanner. The authors found that preliminary planning and preparation in a virtual environment before the laser ablation of the rock prevents damage to the object and is also time-saving.

Current studies on craniometrics and virtual reconstruction [47,48] are showing a rising interaction among palaeoanthropology, medical research and forensic sciences. Benazzi and Senck [47] have explored different methods of virtual 3D reconstruction for preoperative planning incorporating knowledge and methods garnered from palaeoanthropology. Guyomarc'h et al. [48], in their comparison of different post-processing software, have discussed the uncertainties in measurements due to surface reconstruction, showing that every phase of digitization involves a certain risk of shape alteration. This problem affects not only palaeoanthropology or preoperative planning, but also facial reconstruction. These examples illustrate the importance of knowledge transfer from one discipline to another. Indeed, forensic medicine has benefited from advances in palaeoanthropology and medical research, but has also contributed to numerous methodological advances; this concept is further developed in the following section.

Post-mortem MDCT and forensic anthropology

Radiographic techniques are well established in forensic medicine and forensic anthropology [49–51], and are used for trauma diagnosis and to identify unknown deceased remains by comparing individual features using ante- and post-mortem radiographs [52–54]. Quatrehomme et al. [55], for example, emphasized that trabecular bone morphology can lead to positive identification. Stephan and co-workers [56,57] developed a geometric–morphometric method of clavicle-shape comparison using optical surface scan and radiographs. Furthermore, Derrick et al. [58] have modified software used in spine injury diagnosis to identify vertebrae in ante- and post-mortem comparisons of radiographs. Plain radiography is inexpensive and easy to use, and methods specific to forensic radiography are still being developed. In contrast, the routine application of MDCT in forensic medicine and forensic anthropology is a relatively recent development, presumably because its high cost and limited accessibility previously hindered its regular use.

The term post-mortem computed tomography (PMCT) was introduced in the early 1980s by Krantz and Holtås [59], who used CT scanning to enhance autopsy findings in diving fatalities. However, CT was not used frequently until the mid-1990s. Reichs [60,61] was the first to compare radiographic and CT images of the frontal sinuses, and provided technical and methodological recommendations for standardization. Donchin et al. [62] conducted one of the first studies comparing whole-body CT scanning with the findings of conventional autopsy. The authors showed that while neither method was superior, combining the methods could potentially improve the results of medico-legal investigations. On the other hand, in studies evaluating the potential of CT data to enhance methods for forensic facial reconstructions, Phillips and Smuts [63] found that soft tissue thickness measurements obtained by CT were more accurate than those obtained by conventional methods. Using a semi-automated method, Quatrehomme et al. [64] presented various advantages and pitfalls of using CT data for 3D facial reconstruction.

About 10 years ago, Dirnhofer and co-workers [65,66] developed the "image-guided virtual autopsy" as a supporting tool for conventional autopsy techniques. As emphasized by Weber [29], there are several advantages of virtual autopsy, including the permanency of the digitized images, the reproducibility of the methods and the potential to share the data for more objective investigations.

At present, forensic imaging is routinely used in several medico-legal institutes and this has provided more opportunities for forensic anthropologists to use post-mortem MDCT. Hence, there has been a rapid surge in the use of post-mortem MDCT in forensic anthropology, with two main types of publications: (1) studies describing the generalized use of MDCT in disaster victim identification in the medico-legal context, and case reports, highlighting the utility of MDCT-imaging for specific cases [67–80]; (2) other studies have used MDCT to evaluate skeletal traits to build a database for the biological profiling of unidentified human remains. Most of these types of studies have used MDCT for age [81–100], sex [86,101–130], stature [116,119,128,131–137] and body mass [138–140] estimations; or to validate a range of general measurements [48,141–148]. Several other studies have compared conventional radiographic methods to MDCT: for example, MDCT has been used to compare ante- and post-mortem radiographic images of frontal sinus patterns [60,61,149] – which are reliable in positive identification [150,151] – and paranasal sinuses [152]. Other studies have tested the utility of MDCT to measure trabecular bone for estimations of age at death [81,84–86,96]. Wade et al. [90] and de Froidmont et al. [144] sought to compare conventional radiography and MDCT, both showing the superiority of MDCT over conventional radiography in the analysis of fine anatomical structures.

Improved access to MDCT devices in the past five years has led to an increase in the list of publications using this technique. By routinely using post-mortem MDCT, it is now possible to continuously collect digital data, which provides a foundation for sound research. Indeed, the work by Torimitsu et al. [122–126,133–136] and Zhang et al. [128-129,137] has resulted in scanning protocols that allow for better comparability and reproducibility.

Radiography and MDCT are also used to estimate age of the living. Specialists of different disciplines, including forensic pathologists, odontologists, radiologists and anthropologists take into consideration mainly physical, dental and osseous (hand wrist, medial clavicle) developmental changes to assess the age of minor or young adult individuals [153–155]. The methods used are mainly derived from paediatric radiology and odontology, and the acquisition protocols follow clinical guidelines to keep radiation doses as low as possible. MDCT acquisition parameters, such as tube potential, tube current, beam collimation, among others, must be adequately balanced to obtain appropriate image quality [2,156–159]. Schmeling and co-workers, who mainly explore the ossification of the medial epiphyses of the clavicle [158–161], have tested different reconstruction slice thicknesses to determine the optimal parameters for measurements. They recommend working with the thinnest slice thickness possible, as this parameter considerably influences the results of the ossification stages [162].

Despite the increase in studies on MDCT, few have published appropriate technical parameters, which minimizes reproducibility and limits cross comparisons with other studies. In their review of the literature on CT examinations of human mummies, O'Brien et al. [163] criticized the lack of reproducibility due to insufficiently published technical parameters, indicating that clearly defined scanning protocols were missing in about one-third of papers (n = 31) published between 1979 and 2005. This is in line with our observations [164] during a review of forensic anthropological studies on MDCT bone imaging published between 2005 and 2015 (n = 40). While most studies mentioned the device manufacturer, post-processing software (or at least the workstation) and slice thickness, few (n = 8) published all parameters shown in Figure 1. Two current papers in mummy research have revisited this topic: Conlogue [165] described basic scanning parameters and discussed the advantages and limitations of MDCT applied to mummified human remains. Cox [166] criticized the lack of technical knowledge and standard parameters for MDCT. However, in

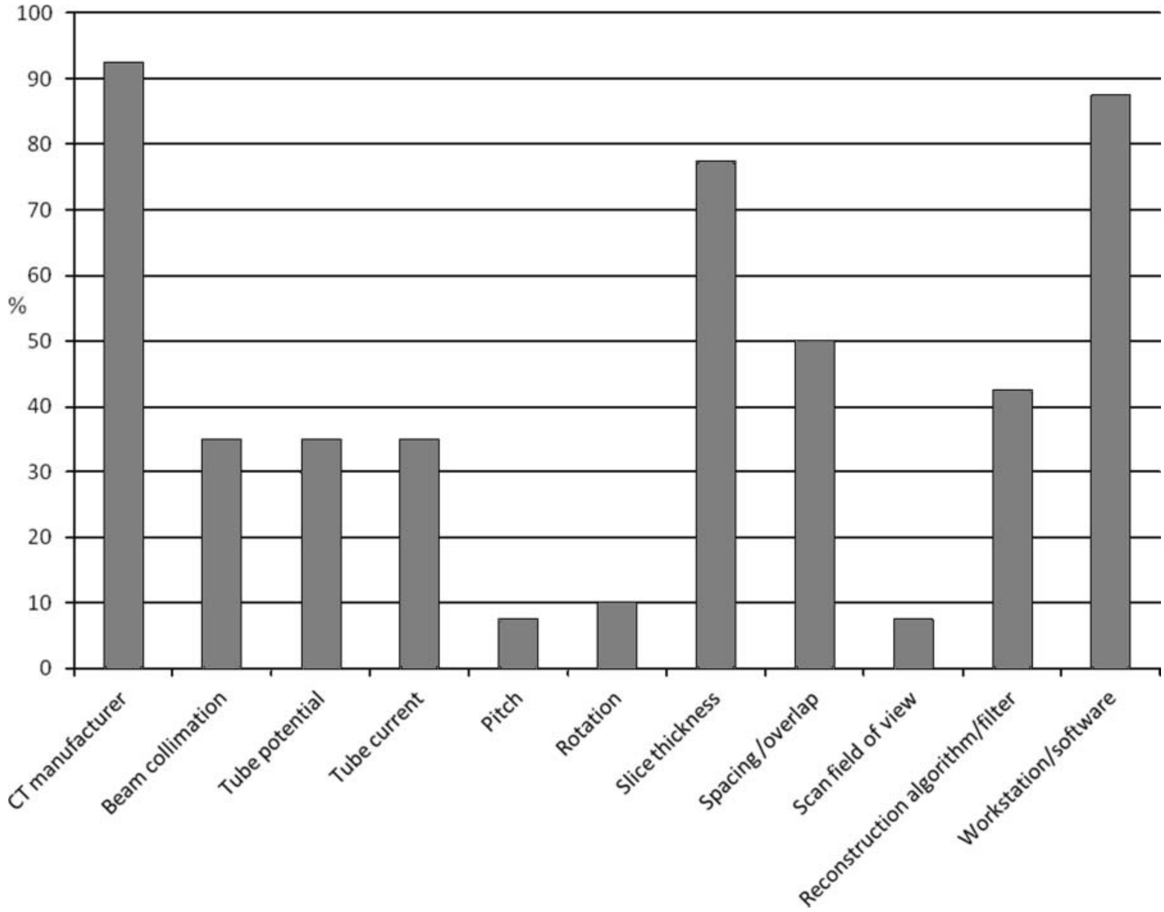

Figure 1. Quantity of acquisition parameters published in forensic anthropological studies from 2005 to 2015 ($n = 40$) [164, p. 22, Fig. 2].

forensic anthropology, there are an increasing number of papers that critically discuss the technical parameters of MDCT. Grabherr et al. [86] explain the influence of slice thickness and reconstruction filters and, as mentioned above, Guyomarc'h et al. [48] detail how surface reconstruction is affected by the choice of the segmentation algorithm. Likewise, Villa et al. [96] highlight the issues concerning the visualization of surface reconstruction of virtual bones, and emphasize that CT scanning parameters have an impact on surface reconstruction, as small osseous structures are improperly displayed.

The approaches to digitize bones differ between forensic anthropology and palaeoanthropology. The close connection between forensic anthropology and forensic medicine has meant that imaging techniques primarily used as diagnostic tools employ standard parameters taken from routine clinical assays. In addition, research has focused on the development and evaluation of methods that are used for identification.

Conclusion and perspectives

Ideal research conditions for anthropologists would include a comprehensive collection of documented skeletons, with a balanced distribution of age and sex, and information pertaining to stature, weight and/or medical history. Routine post-mortem MDCT generates an invaluable data pool that could serve future research and method evaluation. The ease of accessibility, the permanency of the data and the non-invasiveness of the investigation has fuelled research using CT approaches in forensic anthropology over the past decade. However, until it becomes routine practice to publish the scan parameters, technical information and types of post-processing performed, the potential for MDCT will remain underused. Indeed, the choice of appropriate image processing software affects the data [48]. Comparative studies on post-processing parameters, such as segmentation algorithms, are thus also required so that adjustments can be made to standardize the data for its generalizability. Finally, there is a need to intensify the transfer of knowledge among palaeoanthropology, palaeontology, archaeology and other related academic fields. With almost 30 years of experience with bone imaging, research into forensic anthropology could profit from already-existing methods for better future solutions.

Acknowledgments

The author thanks the anonymous reviewers for their insightful comments and suggestions that helped to improve the manuscript.

Disclosure statement

The author declares that she has no conflict of interest.

ORCID

Tanya Uldin http://orcid.org/0000-0001-7958-232X

References

[1] Geijer M, El-Khoury GY. MDCT in the evaluation of skeletal trauma: principles, protocols, and clinical applications. Emerg Radiol. 2006;13:7–18.
[2] Kalra MK, Saini S, Rubin GD (eds.). MDCT: from protocols to practice. Milan, Berlin, Heidelberg, New York: Springer Italia; 2008.
[3] Davies AM, Pettersson H (eds.). Orthopedic imaging: techniques and applications. Berlin, Heidelberg: Springer; 2012.
[4] Halliburton S, Arbab-Zadeh A, Dey D, et al. State-of-the-art in CT hardware and scan modes for cardiovascular CT. J Cardiovasc Comput Tomogr. 2012;6:154–163.
[5] Parmar HA, Ibrahim M, Mukherji SK. Optimizing craniofacial CT technique. Craniofacial Trauma Neuroimaging Clin N Am. 2014;24:395–405.
[6] Zhang Y, Smitherman C, Samei E. Size specific optimization of CT protocols based on minimum detectability. Med Phys. 2017;44:1301–1311.
[7] Hounsfield GN. Computerized transverse axial scanning (tomography). 1. Description of system. Br J Radiol. 1973;46:1016–1022.
[8] Hounsfield GN. Picture quality of computed tomography. AJR Am J Roentgenol. 1976;127:3–9.
[9] Hounsfield GN. Potential uses of more accurate CT absorption values by filtering. AJR Am J Roentgenol. 1978;131:103–106.
[10] Jungers WL, Minns RJ. Computed tomography and biomechanical analysis of fossil long bones. Am J Phys Anthropol. 1979;50:285–290.
[11] Harwood-Nash DCF. Computed tomography of ancient Egyptian Mummies. J Comput Assist Tomogr. 1979;3:768–773.
[12] Tate JR, Cann CE. High-resolution computed tomography for the comparative study of fossil and extant bone. Am J Phys Anthropol. 1982;58:67–73.
[13] Conroy GC, Vannier MW. Noninvasive three-dimensional computer imaging of matrix-filled fossil skulls by high-resolution computed tomography. Science. 1984;226:456–458.
[14] Sumner DR, Mockbee B, Morse K, et al. Computed tomography and automated image analysis of prehistoric femora. Am J Phys Anthropol. 1985;68:225–232.
[15] Ruff CB, Leo FP. Use of computed tomography in skeletal structure research. Am J Phys Anthropol. 1986;29:181–196.
[16] Spoor CF, Zonneveld FW, Macho GA. Linear measurements of cortical bone and dental enamel by computed tomography: applications and problems. Am J Phys Anthropol. 1993;91:469–484.
[17] Whyms BJ, Vorperian HK, Gentry LR, et al. The effect of computed tomographic scanner parameters and 3-dimensional volume rendering techniques on the accuracy of linear, angular, and volumetric measurements of the mandible. Oral Surg Oral Med Oral Pathol Oral Radiol. 2013;115:682–691.
[18] Molteni R. Prospects and challenges of rendering tissue density in Hounsfield units for cone beam computed tomography. Oral Surg Oral Med Oral Pathol Oral Radiol. 2013;116:105–119.
[19] Cotter MM, Whyms BJ, Kelly MP, et al. Hyoid bone development: an assessment of optimal CT scanner parameters and three-dimensional volume rendering techniques. Anat Rec. 2015;298:1408–1415.
[20] Kalender WA, Seissler W, Klotz E, et al. Spiral volumetric CT with single-breath-hold technique, continuous transport, and continuous scanner rotation. Radiology. 1990;176:181–183.
[21] Höpfel F, Platzer W, Spindler K (eds.). Der Mann im Eis: Bericht über das Internationale Symposium 1992 in Innsbruck. Innsbruck: Eigenverlag der Universität Innsbruck; 1992.
[22] Seidler H, Bernhard W, Teschler-Nicola M, et al. Some anthropological aspects of the prehistoric Tyrolean ice man. Science. 1992;258:455–457.
[23] Zur Nedden D, Knapp R, Wicke K, et al. Skull of a 5,300-year-old mummy: reproduction and investigation with CT-guided stereolithography. Radiology. 1994;193:269–272.
[24] Zur Nedden D, Wicke K, Knapp R, et al. New findings on the Tyrolean "Ice Man": archaeological and CT-body analysis suggest personal disaster before death. J Archaeol Sci. 1994;21:809–818.
[25] Fasel JH, Beinemann J, Schaller K, et al. A critical inventory of preoperative skull replicas. Ann R Coll Surg Eng. 2013;95:401–404.
[26] Fasel JHD, Beinemann J, Schaller K, et al. Computer science tools for manual editing of computed tomographic images: impact on the quality of 3D printed models. Surg Sci. 2014;05:439–443.
[27] Huotilainen E, Jaanimets R, Valášek J, et al. Inaccuracies in additive manufactured medical skull models caused by the DICOM to STL conversion process. J Craniomaxillofac Surg. 2014;42:e259–e265.
[28] Weber GW, Bookstein FL. Virtual anthropology: a guide to a new interdisciplinary field. Wien, London: Springer; 2011.
[29] Weber GW. Virtual anthropology (VA): a call for glasnost in paleoanthropology. Anat Rec B New Anat. 2001;265:193–201.
[30] Weber GW, Schäfer K, Prossinger H, et al. Virtual anthropology: the digital evolution in anthropological sciences. J Physiol Anthropol Appl Human Sci. 2001;20:69–80.
[31] Weber GW. Virtual anthropology. Am J Phys Anthropol. 2015;156(Suppl 59):22–42.
[32] Zollikofer CPE, Ponce de León MS, Martin RD. Computer-assisted paleoanthropology. Evol Anthropol. 1998;6:41–54.
[33] Zollikofer, CPE, Ponce de León, MS. Visualizing patterns of craniofacial shape variation in homosapiens. Proc R Soc Lond B Biol Sci. 2002;269:801–807.
[34] Gunz P, Mitteroecker P, Neubauer S, et al. Principles for the virtual reconstruction of hominin crania. J Hum Evol. 2009;57:48–62.
[35] Neeser R, Ackermann RR, Gain J. Comparing the accuracy and precision of three techniques used for estimating missing landmarks when reconstructing fossil hominin crania. Am J Phys Anthropol. 2009;140:1–18.
[36] Wu X, Schepartz LA. Application of computed tomography in paleoanthropological research. Prog Nat Sci. 2009;19:913–921.

[37] Benazzi S, Gruppioni G, Strait DS, et al. Technical note: virtual reconstruction of KNM-ER 1813 Homo habilis cranium. Am J Phys Anthropol. 2014;153:154–160.
[38] Guipert G, Lumley MA de, Lumley H de. Restauration virtuelle d'Arago 21. C R Palevol. 2014;13:51–59.
[39] Huseynov A, Zollikofer, CPE, Coudyzer W, et al. Developmental evidence for obstetric adaptation of the human female pelvis. Proc Natl Acad Sci USA. 2016;113:5227–5232.
[40] Zollikofer, CPE., Ponce de León, MS. Virtual reconstruction: a primer in computer-assisted paleontology and biomedicine. Hoboken (NJ): Wiley; 2005.
[41] Berger LR, Hawks J, Ruiter DJ de, et al. Homo naledi, a new species of the genus Homo from the Dinaledi Chamber. South Africa Elife. 2015;4:e09560; [cited 2015 Sept 28]; [1-35] DOI: 10.7554/eLife.09560
[42] Project: rising star [Internet]. Durham: Duke University [cited 2015 Sept 28]; Available from: http://morphosource.org/index.php/Detail/ProjectDetail/Show/project_id/124.
[43] Cunningham JA, Rahman IA, Lautenschlager S, et al. A virtual world of paleontology. Trends in Ecol Evol. 2014;29:347–357.
[44] Niven L, Steele TE, Finke H, et al. Virtual skeletons: using a structured light scanner to create a 3D faunal comparative collection. J Archaeol Sci. 2009;36:2018–2023.
[45] Betts MW, Maschner HD, Schou CD, et al. Virtual zooarchaeology: building a web-based reference collection of northern vertebrates for archaeofaunal research and education. J Archaeol Sci. 2011;38:755.e1–755.e9.
[46] Du Plessis A, Steyn J, Roberts DE, et al. A proof of concept demonstration of the automated laser removal of rock from a fossil using 3D X-ray tomography data. J Archaeol Sci. 2013;40:4607–4611.
[47] Benazzi S, Senck S. Comparing 3-dimensional virtual methods for reconstruction in craniomaxillofacial surgery. J Oral Maxillofac Surg. 2011;69:1184–1194.
[48] Guyomarc'h P, Santos F, Dutailly B, et al. Three-dimensional computer-assisted craniometrics: a comparison of the uncertainty in measurement induced by surface reconstruction performed by two computer programs. Forensic Sci Int. 2012;219:221–227.
[49] Hines E, Rock C, Viner MD. Radiography. In: Thompson TJU, Black SM, editors. Forensic human identification: an introduction. Boca Raton (FL): CRC; 2007, p. 221–228.
[50] Brogdon BG, Lichtenstein JE. Forensic radiology in historical perspective. In: Thali MJ, Viner MD, Brogdon BG, editors. Brogdon's forensic radiology. 2nd ed. Boca Raton (FL): CRC Press; 2011. p. 9–23.
[51] Leo C, O'Connor JE, McNulty JP. Combined radiographic and anthropological approaches to victim identification of partially decomposed or skeletal remains. Radiography. 2013;19:353–362.
[52] Riddick L. Identification of the dead. In: Thali MJ, Viner MD, Brogdon BG, editors. Brogdon's forensic radiology. 2nd ed. Boca Raton (FL): CRC Press; 2011. p. 79–83.
[53] Brogdon BG. Radiological identification: anthropological Parameters. In: Thali MJ, Viner MD, Brogdon BG, editors. Brogdon's forensic radiology. 2nd ed. Boca Raton (FL): CRC Press; 2011. p. 85–106.
[54] Brogdon BG. Radiological identification of individual remains. In: Thali MJ, Viner MD, Brogdon BG, editors. Brogdon's forensic radiology. 2nd ed. Boca Raton (FL): CRC Press; 2011. p. 153–176.
[55] Quatrehomme G, Biglia E, Padovani B, et al. Positive identification by X-rays bone trabeculae comparison. Forensic Sci Int. 2014;245:e11–e14.
[56] Stephan CN, Amidan B, Trease H, et al. Morphometric comparison of clavicle outlines from 3D bone scans and 2D chest radiographs: a shortlisting tool to assist radiographic identification of human skeletons. J Forensic Sci. 2014;59:306–313.
[57] Stephan CN, Guyomarc'h P. Quantification of perspective-induced shape change of clavicles at radiography and 3D scanning to assist human identification. J Forensic Sci. 2014;59:447–453.
[58] Derrick SM, Raxter MH, Hipp JA, et al. Development of a computer-assisted forensic radiographic identification method using the lateral cervical and lumbar spine. J Forensic Sci. 2015;60:5–12.
[59] Krantz P, Holtås S. Postmortem computed tomography in a diving fatality. J Comput Assist Tomogr. 1983;7:132–134.
[60] Reichs KJ, Dorion R. The use of computed tomography (CT) scans in the comparison of frontal sinus configurations. Can Soc Forensic Sci J. 1992;25:1–16.
[61] Reichs KJ. Quantified comparison of frontal sinus patterns by means of computed tomography. Forensic Sci Int. 1993;61:141–168.
[62] Donchin Y, Rivkind AI, Bar-Ziv J, et al. Utility of postmortem computed tomography in trauma victims. J Trauma. 1994;37:552–556.
[63] Phillips VM, Smuts NA. Facial reconstruction: utilization of computerized tomography to measure facial tissue thickness in a mixed racial population. Forensic Sci Int. 1996;83:51–59.
[64] Quatrehomme G, Cotin S, Subsol G, et al. A fully three-dimensional method for facial reconstruction based on deformable models. J Forensic Sci. 1997;42:649–652.
[65] Dirnhofer R, Jackowski C, Vock P, et al. VIRTOPSY: minimally invasive, imaging-guided virtual autopsy. Radiographics. 2006;26:1305–1333.
[66] Thali MJ, Dirnhofer R, Vock P (eds.). The virtopsy approach: 3D optical and radiological scanning and reconstruction in forensic medicine. Boca Raton (FL): CRC Press/Taylor & Francis; 2009.
[67] Haglund WD, Fligner CL. Confirmation of human identification using computerized tomography (CT). J Forensic Sci. 1993;38:708–712.
[68] Smith DR, Limbird KG, Hoffman JM. Identification of human skeletal remains by comparison of bony details of the cranium using computerized tomographic (CT) scans. J Forensic Sci. 2002;47:937–939.
[69] Rutty GN, Robinson CE, BouHaidar R, et al. The role of mobile computed tomography in mass fatality incidents. J Forensic Sci. 2007;52:1343–1349.
[70] Rutty GN, Robinson C, Morgan B, et al. Fimag: the United Kingdom disaster victim/forensic identification imaging system. J Forensic Sci. 2009;54:1438–1442.
[71] Sidler M, Jackowski C, Dirnhofer R, et al. Use of multislice computed tomography in disaster victim identification – advantages and limitations. Forensic Sci Int. 2007;169:118–128.
[72] Dedouit F, Telmon N, Costagliola R, et al. New identification possibilities with postmortem multislice computed tomography. Int J Legal Med. 2007;121:507–510.
[73] Dedouit F, Telmon N, Costagliola R, et al. Virtual anthropology and forensic identification: report of one case. Forensic Sci Int. 2007;173:182–187.

[74] Dedouit F, Gainza D, Franchitto N, et al. Radiological, forensic, and anthropological studies of a concrete block containing bones. J Forensic Sci. 2011;56:1328–1333.
[75] Dedouit F, Guglielmi G, Perilli G, et al. Virtual anthropological study of the skeletal remains of San Fortunato (Italy, third century AD) with multislice computed tomography. J Forensic Radiol Imaging. 2014;2:9–16.
[76] Blau S, Robertson S, Johnstone M. Disaster victim identification: new applications for postmortem computed tomography. J Forensic Sci. 2008;53:956–961.
[77] Bassed RB, Hill AJ. The use of computed tomography (CT) to estimate age in the 2009 Victorian Bushfire victims: a case report. Forensic Sci Int. 2011;205:48–51.
[78] O'Donnell C, Iino M, Mansharan K, et al. Contribution of postmortem multidetector CT scanning to identification of the deceased in a mass disaster: experience gained from the 2009 Victorian bushfires. Forensic Sci Int. 2011;205:15–28.
[79] Brough AL, Rutty GN, Black SM, et al. Post-mortem computed tomography and 3D imaging: anthropological applications for juvenile remains. Forensic Sci Med Pathol. 2012;8:270–279.
[80] Brough AL, Morgan B, Robinson C, et al. A minimum data set approach to post-mortem computed tomography reporting for anthropological biological profiling. Forensic Sci Med Pathol. 2014;10:504–512.
[81] Pasquier E, De Saint Martin Pernot L, Burdin V, et al. Determination of age at death: assessment of an algorithm of age prediction using numerical three-dimensional CT data from pubic bones. Am J Phys Anthropol. 1999;108:261–268.
[82] Telmon N, Gaston A, Chemla P, et al. Application of the Suchey-Brooks method to three-dimensional imaging of the pubic symphysis. J Forensic Sci. 2005;50:1–6.
[83] Dedouit F, Bindel S, Gainza D, et al. Application of the iscan method to two- and three-dimensional imaging of the sternal end of the right fourth rib. Technical note. J Forensic Sci. 2008;53:288–295.
[84] Barrier P, Dedouit F, Braga J, et al. Age at death estimation using multislice computed tomography reconstructions of the posterior pelvis. J Forensic Sci. 2009;54:773–778.
[85] Ferrant O, Rougé-Maillart C, Guittet L, et al. Age at death estimation of adult males using coxal bone and CT scan: a preliminary study. Forensic Sci Int. 2009;186:14–21.
[86] Grabherr S, Cooper C, Ulrich-Bochsler S, et al. Estimation of sex and age of "virtual skeletons" – a feasibility study. Eur Radiol. 2009;19:419–429.
[87] Pommier S, Adalian P, Gaudart J, et al. Fetal age estimation using orbital measurements: 3D CT-scan study including the effects of trisomy 21. J Forensic Sci. 2009;54:7–12.
[88] Dang−Tran K, Dedouit F, Joffre F, et al. Thyroid cartilage ossification and multislice computed tomography examination: a useful tool for age assessment? J Forensic Sci. 2010;55:677–683.
[89] Moskovitch G, Dedouit F, Braga J, et al. Multislice computed tomography of the first rib: a useful technique for bone age assessment. J Forensic Sci. 2010;55:865–870.
[90] Wade A, Nelson A, Garvin G, et al. Preliminary radiological assessment of age-related change in the trabecular structure of the human os pubis. J Forensic Sci. 2011;56:312–319.
[91] Chiba F, Makino Y, Motomura A, et al. Age estimation by multidetector CT images of the sagittal suture. Int J Legal Med. 2013;127:1005–1011.
[92] Chiba F, Makino Y, Motomura A, et al. Age estimation by quantitative features of pubic symphysis using multidetector computed tomography. Int J Legal Med. 2014;128:667–673.
[93] Lottering N, MacGregor DM, Meredith M, et al. Evaluation of the Suchey–Brooks method of age estimation in an Australian subpopulation using computed tomography of the pubic symphyseal surface. Am J Phys Anthropol. 2013;150:386–399.
[94] Lottering N, MacGregor DM, Barry MD, et al. Introducing standardized protocols for anthropological measurement of virtual subadult crania using computed tomography. J Forensic Radiol Imaging. 2014;2:34–38.
[95] Lottering N, Reynolds MS, MacGregor DM, et al. Morphometric modelling of ageing in the human pubic symphysis: sexual dimorphism in an Australian population. Forensic Sci Int. 2014;236: 195.e1–195.e11.
[96] Villa C, Buckberry J, Cattaneo C, et al. Technical note: reliability of Suchey–Brooks and Buckberry–Chamberlain methods on 3D visualizations from CT and laser scans. Am J Phys Anthropol. 2013;151:158–163.
[97] Villa C, Buckberry J, Cattaneo C, et al. Quantitative analysis of the morphological changes of the pubic symphyseal face and the auricular surface and implications for age at death estimation. J Forensic Sci. 2015;60:556–565.
[98] Villa C, Hansen MN, Buckberry J, et al. Forensic age estimation based on the trabecular bone changes of the pelvic bone using post-mortem CT. Forensic Sci Int. 2013;233:393–402.
[99] Wink AE. Pubic symphyseal age estimation from three-dimensional reconstructions of pelvic CT scans of live individuals. J Forensic Sci. 2014;59:696–702.
[100] Boyd KL, Villa C, Lynnerup N. The use of CT scans in estimating age at death by examining the extent of ectocranial suture closure. J Forensic Sci. 2015;60:363–369.
[101] Mahfouz M, Badawi A, Merkl B, et al. Patella sex determination by 3D statistical shape models and nonlinear classifiers. Forensic Sci Int. 2007;173:161–170.
[102] Kharoshah MAA, Almadani O, Ghaleb SS, et al. Sexual dimorphism of the mandible in a modern Egyptian population. J Forensic Leg Med. 2010;17:213–215.
[103] Ramsthaler F, Kettner M, Gehl A, et al. Digital forensic osteology: morphological sexing of skeletal remains using volume-rendered cranial CT scans. Forensic Sci Int. 2010;195:148–152.
[104] Uysal Ramadan S, Türkmen N, Dolgun NA, et al. Sex determination from measurements of the sternum and fourth rib using multislice computed tomography of the chest. Forensic Sci Int. 2010;197: 120.e1–120.e5.
[105] Decker SJ, Davy-Jow SL, Ford JM, et al. Virtual determination of sex: metric and nonmetric traits of the adult pelvis from 3D computed tomography models. J Forensic Sci. 2011;56:1107–1114.
[106] Uthman AT, Al-Rawi NH, Al-Naaimi AS, et al. Evaluation of maxillary sinus dimensions in gender determination using helical CT scanning. J Forensic Sci. 2011;56:403–408.

[107] Bilfeld MF, Dedouit F, Rousseau H, et al. Human coxal bone sexual dimorphism and multislice computed tomography: geometric morphometric analysis of 65 adults. J Forensic Sci. 2012;57:578–588.
[108] Bilfeld MF, Dedouit F, Sans N, et al. Ontogeny of size and shape sexual dimorphism in the ilium: a multislice computed tomography study by geometric morphometry. J Forensic Sci. 2013;58:303–310.
[109] Bilfeld MF, Dedouit F, Sans N, et al. Ontogeny of size and shape sexual dimorphism in the pubis: a multislice computed tomography study by geometric morphometry. J Forensic Sci. 2015;60:1121–1128.
[110] Zech WD, Hatch G, Siegenthaler L, et al. Sex determination from os sacrum by postmortem CT. Forensic Sci Int. 2012;221:39–43.
[111] Karakas HM, Harma A, Alicioglu B. The subpubic angle in sex determination: anthropometric measurements and analyses on Anatolian Caucasians using multidetector computed tomography datasets. J Forensic Leg Med. 2013;20:1004–1009.
[112] Kim DI, Kwak DS, Han SH. Sex determination using discriminant analysis of the medial and lateral condyles of the femur in Koreans. Forensic Sci Int. 2013;233:121–125.
[113] Mokrane F, Dedouit F, Gellée S, et al. Sexual dimorphism of the fetal ilium: a 3D geometric morphometric approach with multislice computed tomography. J Forensic Sci. 2013;58:851–858.
[114] Djorojevic M, Roldán C, García-Parra P, et al. Morphometric sex estimation from 3D computed tomography os coxae model and its validation in skeletal remains. Int J Legal Med. 2014;128:879–888.
[115] Franklin D, Cardini A, Flavel A, et al. Morphometric analysis of pelvic sexual dimorphism in a contemporary Western Australian population. Int J Legal Med. 2014;128:861–872.
[116] Rodríguez S, González A, Simón A, et al. The use of computerized tomography in determining stature and sex from metatarsal bones. Leg Med (Tokyo). 2014;16:252–257.
[117] Dong H, Deng M, Wang W, et al. Sexual dimorphism of the mandible in a contemporary Chinese Han population. Forensic Sci Int. 2015;255:9–15.
[118] Petaros A, Sholts SB, Slaus M, et al. Evaluating sexual dimorphism in the human mastoid process: a viewpoint on the methodology. Clin Anat. 2015;28:593–601.
[119] Hishmat AM, Michiue T, Sogawa N, et al. Virtual CT morphometry of lower limb long bones for estimation of the sex and stature using postmortem Japanese adult data in forensic identification. Int J Legal Med. 2015;129:1173–1182.
[120] Michel J, Paganelli A, Varoquaux A, et al. Determination of sex: interest of frontal sinus 3D reconstructions. J Forensic Sci. 2015;60:269–273.
[121] Savall F, Faruch-Bilfeld M, Dedouit F, et al. Metric sex determination of the human coxal bone on a virtual sample using decision trees. J Forensic Sci. 2015;60:1395–1400.
[122] Torimitsu S, Makino Y, Saitoh H, et al. Estimation of sex in Japanese cadavers based on sternal measurements using multidetector computed tomography. Leg Med (Tokyo). 2015;17:226–231.
[123] Torimitsu S, Makino Y, Saitoh H, et al. Morphometric analysis of sex differences in contemporary Japanese pelves using multidetector computed tomography. Forensic Sci Int. 2015;257:530.e1–530.e7.
[124] Torimitsu S, Makino Y, Saitoh H, et al. Sex estimation based on scapula analysis in a Japanese population using multidetector computed tomography. Forensic Sci Int. 2016;262:285.e1–285.e5.
[125] Torimitsu S, Makino Y, Saitoh H, et al. Sexual determination based on multidetector computed tomographic measurements of the second cervical vertebra in a contemporary Japanese population. Forensic Sci Int. 2016;266:588.e1–588.e6.
[126] Torimitsu S, Makino Y, Saitoh H, et al. Sex determination based on sacral and coccygeal measurements using multidetector computed tomography in a contemporary Japanese population. J Forensic Radiol Imaging. 2017;9:8–12.
[127] M Didi AL, Azman RR, Nazri M. Sex determination from carpal bone volumes: a multi detector computed tomography (MDCT) study in a Malaysian population. Leg Med (Tokyo). 2016;20:49–52.
[128] Zhang K, Cui JH, Luo YZ, et al. Estimation of stature and sex from scapular measurements by three-dimensional volume-rendering technique using in Chinese. Leg Med (Tokyo). 2016;21:58–63.
[129] Zhang K, Luo YZ, Chen XG, et al. Sexual dimorphism of sternum using computed tomography – volume rendering technique images of Western Chinese. Aust J Forensic Sci. 2016;48:297–304.
[130] Koterova A, Veleminska J, Dupej J, et al. Disregarding population specificity: its influence on the sex assessment methods from the tibia. Int J Legal Med. 2017;131:251–261.
[131] Karakas HM, Celbis O, Harma A, et al. Total body height estimation using sacrum height in Anatolian Caucasians: multidetector computed tomography-based virtual anthropometry. Skeletal Radiol. 2011;40:623–630.
[132] Giurazza F, Del Vescovo R, Schena E, et al. Stature estimation from scapular measurements by CT scan evaluation in an Italian population. Leg Med (Tokyo). 2013;15:202–208.
[133] Torimitsu S, Makino Y, Saitoh H, et al. Stature estimation in Japanese cadavers using the sacral and coccygeal length measured with multidetector computed tomography. Leg Med (Tokyo). 2014;16:14–19.
[134] Torimitsu S, Makino Y, Saitoh H, et al. Stature estimation based on radial and ulnar lengths using three-dimensional images from multidetector computed tomography in a Japanese population. Leg Med (Tokyo). 2014;16:181–186.
[135] Torimitsu S, Makino Y, Saitoh H, et al. Stature estimation in Japanese cadavers based on scapular measurements using multidetector computed tomography. Int J Leg Med. 2015;129:211–218.
[136] Torimitsu S, Makino Y, Saitoh H, et al. Stature estimation in Japanese cadavers based on pelvic measurements in three-dimensional multidetector computed tomographic images. Int J Legal Med. 2015;129:633–639.
[137] Zhang K, Chang YF, Fan F, et al. Estimation of stature from radiologic anthropometry of the lumbar vertebral dimensions in Chinese. Leg Med (Tokyo). 2015;17:483–488.
[138] Lorkiewicz-Muszyńska D, Przystańska A, Kociemba W, et al. Body mass estimation in modern population using anthropometric measurements from computed tomography. Forensic Sci Int. 2013;231: 405.e1–405.e6.
[139] Elliott M, Kurki H, Weston DA, et al. Estimating fossil hominin body mass from cranial variables: an

assessment using CT data from modern humans of known body mass. Am J Phys Anthropol. 2014;154:201–214.
[140] Jung GU, Lee UY, Kim DH, et al. Selecting best-fit models for estimating the body mass from 3D data of the human calcaneus. Forensic Sci Int. 2016;262:37–245.
[141] Robinson C, Eisma R, Morgan B, et al. Anthropological measurement of lower limb and foot bones using multi-detector computed tomography. J Forensic Sci. 2008;53:1289–1295.
[142] Verhoff MA, Ramsthaler F, Krähahn J, et al. Digital forensic osteology – possibilities in cooperation with the Virtopsy® project. Forensic Sci Int. 2008;174:152–156.
[143] Franklin D, Cardini A, Flavel A, et al. Concordance of traditional osteometric and volume-rendered MSCT interlandmark cranial measurements. Int J Legal Med. 2013;127:505–520.
[144] De Froidmont S, Grabherr S, Vaucher P, et al. Virtual anthropology: a comparison between the performance of conventional X-ray and MDCT in investigating the trabecular structure of long bones. Forensic Sci Int. 2013;225:53–59.
[145] Brough AL, Bennett J, Morgan B, et al. Anthropological measurement of the juvenile clavicle using multi-detector computed tomography – affirming reliability. J Forensic Sci. 2013;58:946–951.
[146] Lorkiewicz-Muszynska D, Kociemba W, Sroka A, et al. Accuracy of the anthropometric measurements of skeletonized skulls with corresponding measurements of their 3D reconstructions obtained by CT scanning. Anthropol Anz. 2015;72:293–301.
[147] Richard AH, Parks CL, Monson KL. Accuracy of standard craniometric measurements using multiple data formats. Forensic Sci Int. 2014;242:177–185.
[148] Stull KE, Tise ML, Ali Z, et al. Accuracy and reliability of measurements obtained from computed tomography 3D volume rendered images. Forensic Sci Int. 2014;238:133–140.
[149] Uthman AT, Al-Rawi NH, Al-Naaimi AS, et al. Evaluation of frontal sinus and skull measurements using spiral CT scanning: an aid in unknown person identification. Forensic Sci Int. 2010;197:124.
[150] Christensen AM. Assessing the variation in individual frontal sinus outlines. Am J Phys Anthropol. 2005;127:291–295.
[151] Christensen AM. Testing the reliability of frontal sinuses in positive identification. J Forensic Sci. 2005;50:18–22.
[152] Ruder TD, Kraehenbuehl M, Gotsmy WF, et al. Radiologic identification of disaster victims: a simple and reliable method using CT of the paranasal sinuses. Eur J Radiol. 2012;81:e132.
[153] Schmeling A, Grundmann C, Fuhrmann A, et al. Criteria for age estimation in living individuals. Int J Legal Med. 2008;122:457–460.
[154] Schmeling A, Garamendi PM, Prieto JL, et al. Forensic age estimation in unaccompanied minors and young living adults. In: Vieira DN, editor. Forensic medicine: from old problems to new challenges. Rijeka: InTech; 2011. p. 77–120. doi:10.5772/19261
[155] Black SM, Aggrawal A, Payne-James J (eds.). Age estimation in the living: the practitioner's guide. Oxford: Wiley-Blackwell; 2010.
[156] Schmeling A, Reisinger W, Wormanns D, et al. Strahlenexposition bei Röntgenuntersuchungen zur forensischen Altersschätzung Lebender. Rechtsmedizin. 2000;10:135–137.
[157] Mahesh M. MDCT physics: the basics: technology, image quality and radiation dose. Philadelphia (PA): Lippincott Williams & Wilkins; 2012.
[158] Schmeling A, Schulz R, Reisinger W, et al. Studies on the time frame for ossification of the medial clavicular epiphyseal cartilage in conventional radiography. Int J Legal Med. 2004;118:5–8.
[159] Schulz R, Mühler M, Mutze S, et al. Studies on the time frame for ossification of the medial epiphysis of the clavicle as revealed by CT scans. Int J Legal Med. 2005;119:142–145.
[160] Kellinghaus M, Schulz R, Vieth V, et al. Forensic age estimation in living subjects based on the ossification status of the medial clavicular epiphysis as revealed by thin-slice multidetector computed tomography. Int J Legal Med. 2010;124:149–154.
[161] Kellinghaus M, Schulz R, Vieth V, et al. Enhanced possibilities to make statements on the ossification status of the medial clavicular epiphysis using an amplified staging scheme in evaluating thin-slice CT scans. Int J Legal Med. 2010;124:321–325.
[162] Mühler M, Schulz R, Schmidt S, et al. The influence of slice thickness on assessment of clavicle ossification in forensic age diagnostics. Int J Legal Med. 2006;120:15–17.
[163] O'Brien JJ, Battista JJ, Romagnoli C, et al. CT imaging of human mummies: a critical review of the literature (1979–2005). Int J Osteoarchaeol. 2009;19:90–98.
[164] Uldin T. Virtual anthropology: the forensic approach [dissertation]. Geneva: University of Geneva; 2016.
[165] Conlogue G. Considered limitations and possible applications of computed tomography in mummy research. Anat Rec (Hoboken). 2015;298:1088–1098.
[166] Cox SL. A critical look at mummy CT scanning. Anat Rec (Hoboken). 2015;298:1099–1110.