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REVIEW ARTICLE

'Virtual anthropology' and radiographic imaging in the Forensic Medical Sciences

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Abstract Technological advancements in forensic imaging have had tremendous flow-on benefits to the professional practice of forensic anthropology, not only in respect of case-work analyses, but in facilitating empirical research that has validated and/or improved existing, and introduced novel, methods into the discipline. Some of the pioneering practical examples of radiographic imaging being applied in the forensic analysis of human skeletal remains date to the initial introduction of radiography in the late 19th and early 20th centuries. Subsequent modern applications have developed concurrent to the use of computed tomography in the forensic morgue for autopsy procedures by pathologists; virtopsy (as it is now termed) represents a powerful non-invasive supplement/alternative to traditional autopsy practices where dissection may not be allowable due to religious objection (amongst other reasons). The present review considers a brief history of skeletal radiographic imaging and the specific modalities typically employed. Forensic applications of 'virtual anthropology' are then discussed, as are applications of the latter in DVI and other case-work scenarios. Throughout the review we emphasise the research importance of virtual modelling and conclude with some thoughts for future directions.
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1. Introduction

Deeply rooted in physical anthropology, the cognate discipline of forensic anthropology, based on the application of theory and method from the former in a medico-legal context, has evolved considerably over the course of the last half-century. The discipline as it now stands is very different to the one first admitted into the American Academy of Forensic Sciences (AAFS) as a recognised section in 1972 – then it was known as the 'physical anthropology' section, which was amended to 'Anthropology' in 2013.[1–3] Irrespective of the considerable evolution of the forensic anthropological discipline, its core basic functions still remain largely unchanged, that is to facilitate estimations of biological attributes towards ascertaining identity in unknown human remains (both living and deceased). Determinations of human origin also continue to be a task frequently referred to the anthropologist, in addition

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to assisting in the interpretation of skeletal trauma and pathology, most frequently at behest of the forensic pathologist working within a coronial system.

Recent publications in both leading international journals and books from reputable publishers clearly highlight diversity and technological advancement in the practice of forensic anthropology, but also the solidification of inter-disciplinary approaches relevant to answering questions of an anthropological nature. Molecular and bone chemical approaches are able to assist in the determination of sex,[4–6] age,[7] likely ancestry,[8] and even geographical provenancing,[9,10] not to mention the potential identification of disease and/or other illnesses.[11,12] When available and practical (e.g. there are limitations in relation to expense and expertise required) the latter all have obvious investigative power. There are other interesting advancements, especially in relation to the use of medical imaging modalities to either enhance, or as a substitute for, the direct physical analysis of bone specimens. Whilst it is legitimate to indeed argue that radiographs are not anything new nor novel (having been first discovered in the late 19th century[13]), the manner in which they are now obtained and processed (e.g. multi-detector computed tomography) and the computer software available for the visualisation and analysis of those structures, sits at the cutting edge of technological innovations being developed for medical and forensic applications alike.

In considering the purpose and scope of the present review, it is perhaps now opportune to revisit the development and application of novel visualisation approaches in the forensic medical disciplines and consider their impact in the specific field of forensic anthropology. To achieve the latter, the research foundations of virtual anthropology will be discussed, in addition to its present multi-faceted applications; we conclude the review with some remarks on the future of virtual anthropology in the forensic sciences.

2. A brief history of skeletal radiographic imaging

2.1. Modalities using ionising radiation

2.1.1. Radiography

The inception of non-traditional applications of virtual technology occurred in the early 20th Century when paleoanthropologist Gorjanovic-Kramberger[14] used newly discovered X-ray technology to investigate the internal bone structure of the Kapina Neanderthals in an attempt to determine specimen age; remarkably this occurred only eight years after the discovery of X-rays by Wilhelm Roentgen in 1895. The development of radiographic techniques allowed researchers to visualise the internal structure of remains without the requirement for dissection, which importantly is non-destructive to the specimen of interest (whether living or deceased); this was previously unachievable using traditional morphological approaches. Furthermore, studies utilising X-ray technology were less arduous (e.g., time consuming; labour intensive) and thus facilitated research projects that involved a larger number of specimens than previously possible; this not only generated novel insights, but also concurrently increased the quantitative value of the associated research output(s).

This breakthrough initiative, combined with a growing awareness of its importance and applications in the medical and allied sciences, foreshadowed the use of radiography throughout the disciplines of archaeology and physical anthropology for the specific purpose of investigating fossilised skeletal material of early hominids – a topic of great scientific (and political) interest in the late 19th century to the present day.[15–17]

Whilst X-ray technology allows the non-invasive investigation of the internal structure of fossils and bones, its application is not without caveats. The technique discharges electromagnetic radiation and depending on the structure and density of the object, a variable proportion of X-ray particles are absorbed before passing into a radiation sensitive film. The resultant image is a two-dimensional superimposition of the internal structure of the object.[18] When fossilised remains are subjected to X-ray imaging however, the matrix in which they are embedded can often distort the image, especially if the sediment is of a similar density or more radio-dense than the surrounding skeletal tissue. Spoor, Jeffery and Zonneveld[18] thus suggest that plain film radiography is most appropriately suited for application in postcranial skeletal elements[19] and the dentition.[20]

With specific reference to questions of a medico-legal nature, Culbert[21] is amongst the first documented example of the application of radiography for victim identification. The case reports on a man who was positively identified based on a series of cranial ante-mortem X-rays taken as part of chronic sinusitis treatment. Those radiographs were compared to post-mortem X-rays taken of the remains and supposedly unique characteristics were matched. This use of X-rays for the purpose of personal identification highlighted the potential value of virtual technologies within the field of forensic science.

A transition from film to filmless (or digital) radiography began in the 1980s with the increased 'domestication' of computers in the laboratory and/or home office context. Film radiography is generally more expensive, time consuming and less manipulable (in terms of contrast) than its digital counterpart.[13] One of the advantages of digital radiography is the relative ease of data storage. With the latter new medium came an associated management system for electronic data; Picture Archiving and Communication Systems (PACS databases) that are readily accessible by clinicians and researchers alike.[13,22]

2.1.2. Computer tomography

Efforts to correct distortion and superimposition factors, and improve the versatility of radiographic techniques when applied to more complex bone structures, occurred throughout the 1970s and 1980s in the form of pluridirectional tomography. This technique requires both the X-ray film and source to move in opposing directions during exposure, thus causing erroneous details to become distorted, and only the focal point of the investigation (i.e. the piece of anatomy under investigation) to become clearer and sharper.[18]

As for previous radiographic approaches, computerised tomography was developed as a medical diagnostic tool, however its use within the field of forensic anthropology has since become comprehensive and significant (see below). CT scanning is a form of tomography (imaging using sections) that is a combination of multidirectional X-ray images, computer processed to produce cross sectional images of a desired object.[23] Specimens can, therefore, be viewed as 2D, or as a

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