Cone Beam Computed Tomography vs. Multi-Slice Computed Tomography in paleoimaging: where are we?

Abstract

Objective: Paleopathology and anthropology are fields of research which have benefited from the use of diagnostic imaging since its introduction in clinical setting. The deriving discipline, that is, paleoimaging, has effectively employed several diagnostic techniques. However, while Multi-Slice Computed Tomography (MSCT) has found its role in paleoimaging, Cone Beam Computed Tomography (CBCT), despite its several advantages with regards to MSCT, still struggles to find a clear position in this field. The aim of our study is to evaluate the possible advantages CBCT could bring to paleoimaging.

Materials and Methods: We describe the characteristics and role of CBCT in clinical applications, in forensic and legal medicine, and in paleopathology. We report the study of an ancient mandible using CBCT and MSCT, in order to compare the quality of the images obtained in terms of spatial resolution.

Results: CBCT provides good quality images of mineralized tissues, and the possibility of imaging also metallic manufacts makes the technique suitable for the study not only of bony remains, but also of museum and archaeological artifacts.

Conclusions: CBCT has a great potential to become a valid imaging technique for the study of ancient bone remains, and we encourage an increasing use of CBCT in paleoimaging.

Significance: Our work revises the current uses of CBCT technology, and highlights the possible role CBCT can cover in bioarchaeological studies.

Limitations: Further evaluation is needed in terms of the possible applications to paleopathology of the technique, being the use of CBCT for the study of bioarchaeological samples still an uncharted territory.

Suggestions for further research: We strongly encourage the use of CBCT in paleoimaging, and suggest broader application of this imaging technique to the study of archaeological samples.

Introduction

The study of bioarchaeological materials using diagnostic imaging is called paleoradiology (Chhem, 2008), or more broadly, paleoimaging (Beckett and Conlogue, 2009). Paleopathology and anthropology benefit from the use imaging methods since their introduction in clinical practice. One of the first studies reporting the application of X-rays on ancient human remains, namely an Egyptian child mummy, was performed in 1896 by the physicist Walter König (König, 1896), a few months after the discovery of X-rays by Wilhelm Conrad Roentgen in November 1895. Radiography was then applied to the study of dry bones, to detect possible pathological changes (Eaton, 1916). Over the years, paleoimaging has become increasingly important for the investigation of skeletons and mummies. After the introduction of computed tomography (CT) in the 1970s, the first CT examination of ancient Egypt mummified tissue was performed by Lewin and Harwood-Nash in 1979 (Harwood-Nash, 1979).

Attempts were made to use Magnetic Resonance (MR) in paleoimaging, but relevant limitations were observed in the study of desiccated mummies (Notman, 1986). Rehydration of the mummified tissue specimens prior to scanning (Piepenbrink, 1986) and the use of dedicated pulse sequences (Giovannetti et al., 2016) were tested, without achieving completely satisfactory results.

More recently, MSCT has been effectively employed for non-invasive diagnosis of ancient human remains, thank to its high spatial resolution and panoramic exploration.

Interestingly, a less expensive and widely available X-ray based imaging modality such as Cone Beam Computed Tomography (CBCT) has not yet found a definite place in paleoimaging. In fact, CBCT has been employed in the analysis and restoration of archaeological samples (Rossi et al., 1999; Morigi et al., 2007) and for the study of human remains for forensic purposes (Du et al., 2011). Some authors even adopted CBCT for bioarchaeology (*sensu* Buikstra, 1977) or “human osteology” (Cappella et al., 2013; Vasil'ev et al., 2014; Demiralp et al., 2018), but only six papers reported the use of CBCT for paleopathological studies *sensu stricto* (Ceperuelo et al., 2015;

Kendall et al., 2015; Woo et al., 2015; Riccomi et al., 2018; Riccomi et al., 2018; Gaeta et al., 2018).

The aim of this paper is to contribute to find the appropriate position CBCT in the general field of paleoimaging, in particular evaluating its strengths and weaknesses with respect to MSCT.

Cone Beam Computed Tomography

Characteristics of CBCT

CBCT substantially differs from MSCT in beam geometry (Figure 1). While MSCT uses a fan-shaped X-ray beam, CBCT uses a cone-shaped X-ray beam with the apex localized at the source of radiation and the base on the detector (Pauwels et al., 2015) (Figure 1-2).

The shape of the X-ray beam influences image acquisition and reconstruction. In MSCT, the fan-shaped beam allows the acquisition of the considered volume by means of a rotating gantry, where the patient is moved through at constant speed (in helical acquisition modality). From the acquired volume, multiple axial sections can be reconstructed depending on the acquisition parameters.

In CBCT, the dataset is acquired as an entire volume during a single gantry rotation around the patient by means of a two-dimensional digital array providing an area detector and a three-dimensional x-ray beam with circular collimation. The x-ray source and a digital Flat Panel Detector (FPD) rotate synchronously while performing repeated exposures at fixed intervals, generating basis images forming the projection data. Feldkamp-Davis-Kress (FDK) algorithm is applied to projection data in order to reconstruct the volume through filtered back-projection in three orthogonal planes (axial, sagittal, and coronal) (Pauwels et al., 2015).

CBCT produces a volumetric dataset from which the voxels are extracted. CBCT volume acquisition consistently obtains isotropic voxel resolutions, while anisotropic voxels are often obtained in MSCT depending on the model and/or field of view chosen. The isotropic nature of the volumetric dataset allows multiplanar reformation (MPR) on non-orthogonal planes.

CBCT images are characterized by sub-millimetre voxel size, ranging from 0.4 mm to as low as 0.125 mm. However, spatial resolution (that is, the ability to perceive two adjacent points with different degrees of attenuation as distinct) of CBCT units can vary depending on several factors. Dillenseger et al. (2015) report that spatial resolution is influenced by the physical characteristics of the detector (unitary elements number and size), geometrical characteristics of the beam (focal spot size, beam collimation), and acquisition mode (incremental, helical, number of projections, rotation duration time). Moreover, reconstruction parameters, such as kernel type, pixel reconstructed size, and reconstruction algorithm, have an impact on image resolution (Pauwels et al., 2012; Carrino et al., 2014)

Brüllmann and Schulze (2015) reviewed the two main methods of assessment of CBCT spatial resolution. Visual method employing line-pair (lp) measurements reported values below 3.0 line-pairs per millimetre, while using automated assessment through modulation transfer function (MTF) values ranged between 0.1-2.65 cycles per millimetre.

CBCT provides improved spatial resolution of high-contrast structures such as bone versus air, whereas MSCT performs better in analyzing soft tissues (Nardi et al., 2017). CBCT employs CsI scintillators, which are characterized by lower quantum efficiency and slower response compared to ceramic detectors used in helical MSCT. The nature of the FPD therefore limits contrast resolution due to reduction in temporal resolution and dynamic range, compared to standard MSCT detectors (Orth et al., 2009; Gupta et al., 2006).

Reduced temporal resolution decreases image quality and impairs low-contrast detectability, causing artefacts (image ghosting, “after-glow”, memory effects, streak artefacts) (Schulze et al. 2011). Zhang et al. (2007) employed a direct projection modification method to minimize metal artefacts by localizing and segmenting the metallic object through a thresholding method, and replacing metal shadow with boundary values.

Dynamic range is directly related to improvement in contrast resolution, as it qualifies the range of incident signals effectively captured and transmitted as image data; the larger the detector dynamic range, the better contrast resolution (Koong, 2010).

Due to the low contrast-to-noise ratio (CNR), CBCT is unsuitable for the imaging of soft tissues, where MSCT remains the gold standard (Koong, 2010). However, since anthropological studies mainly focus on human skeletal remains and mummified specimens, CBCT could be a valuable diagnostic technique in paleopathology.

CBCT in clinical imaging

Cone Beam Computed Tomography (CBCT) is a three-dimensional (3D) X-ray imaging technology, which was developed in the early 1980s (Robb 1982). CBCT was initially applied to angiography, and subsequently introduced for otorhinolaryngology, musculoskeletal, breast, respiratory, and cardiac applications (Ejima et al., 2010; Cakli et al., 2012; Sun et al., 2017; Nardi et al., 2018; Posadzy et al., 2018). The introduction of CBCT to maxillofacial imaging in the late 1990s led to fast diffusion of the technique, which now finds application in implantology, maxillary bones fractures, temporomandibular joint disorders, periodontology, and endodontics (Horner et al., 2015). Technological improvement in detector systems with the introduction of the Flat Panel Detector (FPD), along with the need of lower power requirements for the X-ray tube compared to multi-slice computed tomography (MSCT), favored the diffusion of CBCT. Moreover, CBCT allows 3D image reconstruction by using dedicated or general purpose algorithms. In head and neck imaging CBCT provides high spatial resolution with a relatively lower radiation dose with respect to MSCT (Nardi et al., 2017).

CBCT in legal medicine and forensic anthropology

CBCT currently finds primary application in oral and maxillofacial diseases (Kiljunen et al., 2015; Mandelaris et al., 2017). Apart from clinical purposes, CBCT has been applied to forensic medicine in post-mortem investigations (Sarment et al., 2014). 3D imaging allows precise depiction of anatomy without the limitations of projection 2D imaging.

In legal medicine, CBCT has been effectively employed for forensic applications in the study of bone remodeling, to investigate the inner structure of fractures and calluses on dry bone (Cappella et al., 2013). Forensic anthropology often relies on the analysis of skeletal trauma on dry bone. The age of a fracture or a bone callus may provide useful information for victim identification, assessing the nature of injuries which occurred prior to death. In these cases, CBCT can effectively visualize the trabecular structure of the bone, with higher sensitivity compared to MSCT. Moreover, CBCT can be a more versatile technique than micro-CT and peripheral Quantitative CT (pQCT), as it is not limited by sample dimension (Van Dessel et al., 2013; Klintström et al., 2016). Several authors report the use of CBCT in this field, mostly for the study of bone and dentition (Gaudio et al., 2014; De Angelis et al., 2015; Kabak et al., 2017; Przystańska et al., 2017).

Trochesset et al. (2014) also hypothesize a possible role for CBCT in cases of mass disasters, due to reduced scanning time, the use of metal-artefact reduction algorithms in presence of metallic dental restorations, quicker reconstruction time, and possibility to obtain diagnostic images even with suboptimal head positioning.

CBCT in paleoimaging

In the study of bioarcheological materials the is a distinct advantage of CBCT: its reduced vulnerability to metal artifacts that can be extremely damaging in MSCT (Zhang et al., 2007). For instance, it is possible to reliably evaluate metal manufacts with CBCT. We report an example of study of an ancient metal garment accessories belonging to a sepulcher in central Italy. Such evaluation is possible thanks to Metal Artifact Reduction (MAR) algorithms, which allow to image metallic objects reducing streak artifacts and beam hardening. In this specific case, CBCT images allowed to discriminate between the metal of the garment and rust (which appeared slightly more radiolucent with respect to the structure of the garment), providing a guide to the restoration process without damaging the sample (Figure 4).

In the paleopathological literature, we found only six papers that deal with the use of CBCT to describe diseases or malformations. Ceperuelo et al. (2015) illustrated a case of hyperdontia in a middle-aged Chalcolithic male from Spain and the CBCT was used to highlight the supernumerary molar. Kendall et al. (2015) reported a CBCT scan of an exostotic maxillary sinus lesion, probably of odontogenic origin, in a Roman-British (3rd to 4th century AD) adult male from Newport, Lincoln. 3D reconstructed CT images of a cranium were described by Woo et al. (2015) for a case of dwarfism-related skeletal dysplasia in a Late Joseon Dynasty (South Korean) individual.

Riccomi and colleagues described two cases of frontal sinus osteomata (2018) from the Collatina necropolis of the Roman Imperial Age (1st–3rd centuries AD) (Rome, Italy) and a very rare case of skull osteoblastoma (2018), a benign bone tumour dated between the 10th and 12th centuries, found in the skeletal remains of a young man aged 25–35 years, buried in the cemetery of Pava, Siena, Italy.

Gaeta et al. (2018) for the first time reported the use of Cone Beam not for a pathological condition related to the skull, but for a disease, the atherosclerosis, which affected the abdominal arteries of an 18th century Italian mummy. Because of the disease, the arterial vessels were completely replaced by calcific tissue, so it was possible to validly employ CBCT.

MSCT and CBCT scanning of an ancient human mandible

To the best of our knowledge no comparison was made between the imaging results on ancient human remains obtained by MSCT and CBCT. We had that opportunity while studying an ancient mandible, belonging to a child from an archaeological site in Northern Italy. The scans were performed at the Diagnostic and Interventional Imaging Department, University Hospital, Pisa, using two different CT techniques. MSCT was performed using CT Discovery CT750 HD-VEO 128 Slices equipment (GE Healthcare, Chicago, Illinois, US). The images were processed through iterative algorithms increasing image sharpness and definition. Two scout acquisitions were performed in antero-posterior (AP) and latero-lateral (LL) orientation. Image acquisition was performed at the following parameters: 1.25 mm slice thickness, 120 kV, 350 mA. Standard and bone algorithm were applied, and 3D reconstructions were performed.

CBCT was performed with Planmeca Promax 3D Classic (Planmeca Oy, Helsinki, Finland) equipment (Figure 3). Image acquisition was performed at the following parameters: 8 cm FOV, 90 kV, 14 mA, 12 s. Synapse 3D software (Fujifilm, Minato, Tokyo, Japan) was used for image post-processing.

In Figures 5-7 it is possible to compare the quality of the images obtained with CBCT and MSCT in terms of resolution.

Volume rendering reconstructed from the CBCT dataset allowed to highlight surface details and micro-fractures, and discriminated between tooth and alveolar bone better than MSCT volume rendering (Figure 5). Panoramic and cross- sectional reconstructions (Figures 6-7) showed higher resolution compared to MSCT, and allowed to recognize the inner structure of teeth and mandibular bone.

Discussion

Computed Tomography has supported paleopathological investigations since its early introduction in clinical setting. Although some research centers have dedicated CT equipment for paleopathological and forensic purposes, such equipment may not include state-of-the-art MSCT. Huges (2011) reports the difficulties in terms of costs and maintenance of MSCT equipment exclusively for archaeological purposes, which may not always be justified if the volume of examinations is limited. In most cases, collaboration with clinical centers may be therefore needed for most paleopathology research groups. In this scenario, the potential use of CBCT is much more feasible than having access to MSCT that are often overloaded with clinical studies.

In fact, by using CBCT whenever possible (in relation to sample dimension) the access to MSCT can be dramatically reduced. As shown by our comparison, CBCT may achieve an image quality that is equivalent or even superior to MSCT.

In cases of human remains exceeding the dimensions of the FOV, stitching can be applied (Fotouhi et al., 2018).

Stitching is a 3D volume reconstruction resulting from merging two or more small FOV volumes to image a wider region (Fotouhi et al., 2018). In clinical settings, few studies investigated the accuracy of stitching in dental applications (Kim et al., 2012; Kopp and Ottl, 2010; Ozemre and Gulsahi, 2018). Stitching needs an analogic confirmation with calipers or probes, due to slight differences in measurement of distances from vital structures (Egbert et al., 2015). In case of paleopathology, stitching can be effectively used to overcome the limits in field of view (FOV) dimensions, as the purpose of imaging is to obtain further information on mineralized tissues, without damaging or compromising the integrity of the specimens analyzed. Therefore, in paleopathological research, stitching allows the study of specimens of various dimensions without jeopardizing the quality of the images.

The possibility of post-processing the dataset obtained with CBCT provides the creation of 3D reconstructions of the specimens analyzed, producing large amounts of data. At present time, a major issue in paleoimaging is the storage of a huge quantity of data deriving from CT acquisition of human remains. Although 3D reconstructions of CBCT datasets could help long-term storage and sharing of bioarchaelogical data among the scientific community (Ulguim, 2018), problems arise in terms of intellectual property protection when data are shared on open databases, and of homogeneity of image format when Dicom format is not used (Nelson et al., 2015).

In some clinical applications, mostly regarding diseases involving both hard and soft tissues at the same time, CBCT cannot replace conventional MSCT due to limited contrast resolution. However, for anthropological, forensic and paleopathological studies mainly focused on bony human remains, CBCT can be successfully used.

In summary, the advantages of Cone Beam Computed Tomography are:

- high spatial resolution with a comparatively low X-rays dose;
- reconstruction of 3D sections in any plane;
- rapid scan time;
- use of metal-artefact reduction algorithms;
- no limitation by sample dimension with the use of stitching technique;
- smaller CBCT equipment with reduced acquisition and maintenance costs;
- reduction of the workload on MSCT scans, which are necessary for the study of routine clinical cases.

Conclusions

Indeed, we believe that for its qualitative characteristics mentioned above, CBCT is the most appropriate imaging technique for the study of ancient bone remains and we encourage an increasing use of this technique. CBCT could therefore support research in paleopathology, giving insight on several possible applications. CBCT could substitute MSCT in biomechanical analysis of long bones, thus adding functional information on the complex relationship between bone structure and probable function (Jüngers et al., 1979; Navega et al., 2017). Moreover, the investigation of archaeological and museum manufacts could benefit from CBCT application, supporting restoration processes also in case of metallic samples. CBCT could also detect breakages of the manufacts and fractures in bony remains, allowing to perform targeted restoration interventions on the samples, and also avoid accidental damages to areas of minor resistance.

Acknowledgments

Authors wish to thank Prof. Gino Fornaciari for the critical revision of the manuscript and Giulia Feriani from Diagnostic and Interventional Radiology for her help in the acquisition of radiological images.

Disclosures.

This manuscript represents original work, and it is not under consideration for publication elsewhere.

All of the authors participated in the preparation of the manuscript. We have permission to reprint any figures or tables that were initially printed elsewhere.

The authors declare no conflict of interest.

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Figure key

Figure 1. CBCT operating principle. From the X-ray source a cone-shaped beam is generated, allowing the acquisition of a full three-dimensional dataset through a single rotation.

Figure 2. Positioning of a dry skull in the CBCT scan. Red lasers allow to centre the region of interest inside the 8x8 cm FOV.

Figure 3. The CBCT equipment (Planmeca Promax 3D Classic, Planmeca Oy, Helsinki, Finland) employed for the study of the ancient child mandible

Figure 4. CBCT study of a metallic garment accessory.

Figure 5. 3D reconstruction of the mandible.

Figure 6. Panoramic reconstruction of the mandible.

Figure 7. Cross sectional reconstruction of LR6.