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Special application of computed tomographic imaging in the field of human paleoradiology

PhD Thesis

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1. Introduction and literature review

Although archaeology is a destructive discipline by nature as artefacts have to be dislocated for further exploration, the primary concern in the whole process—from the discovery, through the conservation, to the exhibition of the objects—is the non-destructive approach. This complex process requires the teamwork of archaeologists, paleopathologists and medical professionals as well. During the process the key imaging techniques are photography, endoscopy and last but not least, radiological imaging.

My research focuses on a small segment of the diverse field of paleoradiology: the CT examination of the human related paleopathological skeletal remains.

Paleoradiology

Etymologically the name paleoradiology means "ancient radiology", however, aligning it with paleopathology it is clear that it means the examination of bioarchaeological remains of past ages with radiological methods.

Brief history of human-related paleoradiology

In W. C. RÖNTGEN discovered the radiation named after him that has been used in medical X-ray imaging examinations since then. Paleoradiology is almost as old as medical radiological imaging, as in 1896, one year after the discovery of Röntgen radiation, C. G. W. KÖNIG carried out the first human-related paleoradiological X-ray examination of a child-aged Egyptian mummy's knee.

At the end of 19th and the beginning of the 20th century the X-ray examinations of the mummies from ancient times facilitated the development of paleoradiology.

The name paleoradiology originates from D. N. NOTMAN radiologist (1987), it covers the radiological examinations of various archaeological and anthropological remains and artefacts. Among the radiological examination modalities X-ray, computed tomographic (CT) and micro-CT examinations are generally employed; the role of magnetic resonance imaging (MRI) can be neglected.

The major directions in paleopathological studies are bone developmental variations, traumatological, inflammatory and oncological processes. The descriptions of metabolic disorders can also be found in the literature.

The review of bone developmental variations

Malformations may have been in existence since the beginning of human history, but up until the 20th century only a few descriptions can be found on the subject, presented as curiosities. At its 1979 annual meeting the American Paleopathological Society set out to focus on the research and publications on congenital defects. However, the initiative was unsuccessful, and even in 1983 it ended only with limited success. The causes of skeletal malformations examined in human paleopathology might be due to bone formation and bone developmental disorders, the formation of accessory ossicles and structures and the disorder of their interconnections. Classification of developmental disorders is difficult. According to certain theories, both the major anomalies that can be detected at birth and present serious clinical symptoms and the developmental variations and minor anomalies that may be clinically asymptomatic or occur only with mild clinical symptoms may belong to this group. There might be genetic causes and environmental factors in the background of these anomalies that may occur as a part of a syndrome or individually. The paleopathological research of life-affecting anomalies is difficult, because most of the infants who suffered from these conditions died due to their severe malformations and their immature and fragile bones were not maintained for posterity. The occurrence and epidemiology of anomalies considered as non-life-affecting can be examined in paleopathology, since these conditions did not cause the premature death of the individuals.

The review of traumatology processes

The lack of adequate clinical context is a significant disadvantage in human paleopathological research and in certain cases forming the proper diagnosis may be impossible. In cases of trauma without complications, the determination of the time of the fracture can be difficult. In trauma cases with complications, the multidisciplinary approach could help the differential diagnosis contributing to a possible diagnosis. In determining the time of the traumatic injury we can differentiate between antemortem, perimortem and postmortem injuries. In general it is easier to differentiate antemortem injuries from peri- and postmortem lesions due to the development of callus formation. The evaluation of the skull bones is even more challenging due to their poor healing tendency. In case of perimortem injuries, it can be difficult or even impossible to set the

time of the fracture if the callus formation hadn't started yet. The regeneration and callus formation starts immediately after the injury, but it can remain hidden in radiographic examinations even for two or three weeks.

The review of inflammatory processes

With the paleopathological examination of different bone lesions from a given geographical region, going beyond the individual differences, we may have an opportunity to obtain information on the epidemiology of certain infectious diseases. Among the skeletal lesions there can be found certain pathognomic lesions, which may characterize specific bacterial infections due to their unique morphological characteristics. Syphilis and tuberculosis are among these specific infections.

The review of oncological processes

The name paleo-oncology (the field of paleopathology dealing with oncology), known since 2004, comes from E. C. HALPERIN. The shorter life span, the different environmental factors and the lack of adequate therapy might have led to the death of the patient before the emergence of the malignant processes and bone lesions. The most frequent skeletal tumours are the secondary metastases that commonly occur as metastases of soft tissue tumours. The secondary bone lesions are non-specific, they might be similar in appearance regardless of the original tumour.

Mobile CT imaging in human paleopathology

Based on data from the international literature, CT scanners present the best two-and three-dimensional images in paleoradiological examinations, but their use in field-work is behind other imaging techniques, due to the difficulties in the transportation of the heavy scanners. The use of mobile CT scanners might be a compromise.

Databases

There has already been international initiatives to arrange paleoradiological images in databases. In 2012 the IMPACT Radiological Mummy Database was started exclusively to make materials of mummies available G. W. WEBER also reported on virtual anthropological databases.

To our knowledge there has not been made a multiparametric searchable database yet that contains both the basic data of the broad spectrum of human paleopathological studies and parameters of the paleoradiological examinations.

2. Aims

In my dissertation my objective was to demonstrate the potentials of the computed tomographic imaging and the relating clinical approach in the evaluation and processing of human paleopathological remains.

To overview the paleoradiological research process and the results obtained at the Institute of Diagnostic Imaging and Radiation Oncology of the Kaposvár University. With the help of the recognised conditions I aimed to draw attention to the medical historical background of certain pathological conditions as well as their diagnostic and clinical (e.g. neurological) aspects still relevant in the 21st century.

Aims

1. The introduction of the multidisciplinary approach and determining the role of CT imaging in human paleopathological case studies.

2. Introducing new opportunities in human paleoradiology: application of our currently accessible most advanced CT scanner (2 × 128-slice Siemens Somatom Definition Flash DSCT scanner) as well as the implementation of the mobile CT device in domestic human paleoradiological studies.

3. The presentation of different procedures of CT imaging (installed and mobile CT scanners), and the development of standard imaging methods and protocols.

4. Demonstration of the opportunities in the digital approach of the human paleoradiological examinations and the three-dimensional imaging.

5. Based on the data and results of the human paleoradiological examinations, developing a multiparametric database, applicable in everyday human clinical practice, where the radiological, anthropological and paleopathological basic data may serve as searchable parameters.

3. Materials and methods

The colleagues of the Institute of Diagnostic Imaging and Radiation Oncology of the Kaposvár University have been carrying out joint studies for several years with the colleagues of the University of Szeged Faculty of Science and Informatics, Anthropology Department; the Eötvös Loránd University, Faculty of Science, Anthropology Department; the Hungarian National Museum, National Heritage Protection Centre as well as the Hungarian Natural History Museum, Department of Anthropology. The multidisciplinary teamwork requires complex organization and background work of the archaeologists, historical anthropologists and radiologist professionals. The examinations were carried out scheduled and in an organized manner. The available data of the studied cases could be called "paleopathological history" by analogy with the clinical medical practice. Following the paleoradiological report, multidisciplinary consultation took place in order to reach a consensus opinion where the results of the anthropological, paleopathological and various diagnostic procedures are reflected. In addition to the importance of the multidisciplinary approach the multimodality feature should also be emphasized. The use of one imaging modality is not only unsuitable for answering all the arising questions, but in fact, the use of one single modality might increase the number of misinterpreted cases.

The paleopathological remains were provided, after detailed anthropological and paleopathological examinations, by the institutions being in relation with the Institute of Diagnostic Imaging and Radiation Oncology of the Kaposvár University. Those human skeletal remains (n=60) were included in my doctoral research in which non-destructive structural and spatial imaging and answering a differential diagnostic question was the goal. We carried out 100 paleoradiological investigations and 158 anatomic regions were depicted. Similar to the clinical radiology approach the ALARA principle (as low as reasonably achievable) should be considered in paleoradiology as well, meaning that the least amount of radiation dose should be applied in a given examination.

The CT scanners:

1. Siemens Somatom Emotion 6
2. Siemens Somatom Sensation Cardiac 16
3. Siemens Somatom Definition Flash
4. Siemens Somatom Emotion 16 (mobil MDCT)

4. Results

Paleoradiological examination protocol

In designing the protocols the following factors were taken into consideration: adequate spatial resolution (hard algorithm kernels /60-90 in value/ and the use of the thinnest possible slice thickness /0.40 to 1.25 mm/), as well as the preparation of images suitable for post-processing.

Case studies

During the examination process of the paleoradiological findings we have found lesions indicating tumour in 24 cases, including three cases of benign lesions. In nineteen cases we detected the secondary signs of bone inflammation, in eleven cases traumatic lesions were suspected.

1. Bone developmental variations

I. **Unilateral coronal suture synostosis.** The remains of a 30-35 years old woman from 9th century Zalavár area belongs to the collection of the Anthropology Department of the Hungarian Natural History Museum (No. 2014.2.7.). The skull shows unilateral coronal suture synostosis on the right side. During the examination we performed 3D VRT CT reconstructions making possible the virtual removal of the calvaria and thus the spatial representation of the intracranial structures. Based on the CT examination we prepared the three-dimensional virtual cast of the endocranium (endocast), which well depicts the deformity of the intracranial space.

II. **Paracondylar process.** In 2008 the archaeologists of the Field Service for Cultural Heritage uncovered the skeletal remains of a 39-44 years old man (10-12th century, M6 TO67, grave 1758.) during the Lánycsók, Gata-Csotola excavations. A CT images well depicted the 16 mm long bony process originating from the skull base and its articulation with the right transverse process of the atlas. The multiplanar reconstructions showed the resulting torticollis.

III. **A possible case of Eagle syndrome from the Middle Ages.** The Lánycsók, Gata-Csotola excavations were carried out by the archaeologists of the Field Service for Cultural Heritage in 2008. The CT examination of the skeletal remains of a middle aged (40-45 years old) man (10-12th century, M6 TO67, grave 1801.) clearly shows the anatomy and the spatial geometry of the elongated styloid process. A slight axial

deviation and contour roughness can be observed on the elongated left styloid process (41 mm).

2. Traumatic lesions

I. **Healed skull base fracture from the Iron Age.** In 2011, near Pócspetri, the archaeologists of the National Heritage Protection Centre uncovered the remains of a 35-39 years old woman (Object number: 80, stratigraphic unit: 179) from the late Iron Age. In addition to the multiple postmortem injuries, the traces of a healed skull base fracture could be observed. The results of the CT examination confirmed the preliminary paleopathological opinion, that the case represents a survived and healed fracture of the posterior skull base.

II. **Symbolic skull trepanation from the 11-12th century.** In 1884, during the Pusztapáka–Nándorhalom excavation, the remains of an adult woman (aged 40-60 years) from the 11-12th century were uncovered (grave 90.). The CT examination clearly showed the ovoid superficial bone defects and signs of healing of the skull bones, in correspondence with healed symbolic trepanations.

3. Inflammatory processes

I. **Skull lesions caused by syphilis.** The excavations in the area of the former Castle of Szeged started in 1999 while the examination process of the human remains started in 2004 at the Anthropology Department of the University of Szeged. Pathognomic bone lesions indicating treponematosis could be observed on the skull of the 18-20 years old woman uncovered from ossuary 16 (16/4. finding). The indicators of late syphilis such as multiple nodular bone destruction occurring with frontoparietal dominance could be observed in the CT scans.

II. **POTT's gibbus.** In case of the remains of a 30-40 years old woman (grave 483.), uncovered during the excavations of the Castle of Szeged, the ossification of seven vertebrae of the thoracolumbar region could be observed, morphologically corresponding to POTT's gibbus deformity caused by tuberculosis. The CT examination showed the structure of the ossified vertebrae and the virtual cast of the spinal canal showed directly its localized stenosis.

III. **Differential diagnostic challenge on the mandible.** A thoroughly deformed mandible of a 9-11 years old child from the 16-17th century (grave 316./a) was uncovered during the excavations at Ják. The right side of the mandible is

asymmetrically broadened, bone destruction and cavity formation could be observed with the surrounding sclerosis. The cavity opens to the mandible's buccal surface. The bone lesions are well depicted in the CT images.

IV. **Tibiotalar ankylosis.** During the excavations of the Castle of Szeged the remains of a 50-60 years old man was uncovered from grave 291. The thickened cortex could be observed in the CT scans, along with an irregular cavity in the bone, opening to the surface with several fistulas. The talus is completely ossified with the tibia. The overall morphological and radiological appearance corresponded to distal fracture of tibia with consecutive chronic osteomyelitis and tibiotalar ankylosis.

4. Oncological processes

I. **Craniofacial osteosarcoma from the 11-12th century.** The remains of an adult woman (11-12th century, aged 40-60, grave 90.) were uncovered during the 1884 Pusztapáka-Nádorhalom excavation. The CT scans depicted the pathologic mass protruding to the left orbit, showing bone destruction and spiculated pathologic new bone formation and intracranial propagation. The lesion was replicated with 3D printer.

II. **A possible case of femoral osteosarcoma.** The remains of a man (aged 25-35 years) from the 16-17th century were uncovered during the Budapest Lovasút excavations (grave 72.). In the CT scans extensive, irregular bone lesions, peri- and paraosteal sclerotic lesions could be observed. The multidisciplinary approach assumed probable femoral osteosarcoma with possible pathological fracture in the background of the lesions, but the possibility of a chronic inflammatory process could not be completely excluded.

III. **Possible metastatic bone processes**

   a) **Osteoplastic- osteolytic bone lesions from the Roman period.** The skeleton of a 45-49 years old woman was uncovered (grave 284.A) during the Esztergom Roman excavations. In the CT scans multiple sclerotic, osteoblastic and lytic, radiolucent lesions could be observed. Based on the findings possible metastatic process arose as a potential diagnosis, which corresponded with the preliminary paleopathological opinion.

   b) **Lytic skull lesions from the Avarian Age.** During the excavation of the Tiszafüred-Majoroshalom cemetery, the remains of an elderly woman (grave

761., 7474. finding) were uncovered. On the basis of the multiplicity, the lesions' lytic and destructive nature and their variations in size detected with the CT examination, lytic metastatic process was suspected.

c) **Osteoplastic bone lesions from the Árpádian Age.** In the CT scans of the remains of an adult woman from the 10-13th century, found nearby Kaposvár (grave 2250.) multiple, destructive sclerotic bone lesions were observed, with assumed metastatic process in the background.

IV. **Fibrous dysplasia.** The remains of an elderly woman (grave 864.) from the 17th century were uncovered during the Ják excavations. In the CT scans osseous lesion was detected bulging the bony contour of the right maxilla, with mostly irregular sclerotic internal structure and smaller radiolucent areas. Based on the radiological images fibrous dysplasia arose as a possible diagnosis.

New potentials of CT imaging in paleoradiology

Dual-energy imaging (DECT). CT scanners capable for DECT can make tissue characterization possible on the basis of the different absorption maps. Taking advantage of this, we have the opportunity to investigate the different characteristics and absorption maps of the findings and the different materials deposited on them as well as to perform virtual mono-energetic image reconstructions.

Mobile CT. In January 2015 the first human paleoradiological CT examinations were performed with a mobile CT scanner in Budapest. The digital images were forwarded to the institute server. On the basis of the concept "not the archaeological findings travel" we think that the mobile CT scanners with minimum installation needs may facilitate the examination process of the remains. If the CT scanner is transported to the frequently priceless artefacts, we can minimize the risk of damage due to their transport.

Creating a human paleoradiological database

The size of the data set, and its potential further growth supported the claim for a database. The data related to the examinations: (1) anthropological, paleopathological data, (2) CT scanners and their parameter settings, (3) data obtained during the evaluation of the paleoradiogical images and (4) data of the participating institutions and individuals. Designing the paleoradiological database included: (1) data cleaning, (2) data integration, (3) data selection, (4) data definition and (5) display of the resulting data set.

5. Conclusions and discussion

Besides the paleopathological examinations the paleoradiological approach provides opportunity to examine the archaeological remains and artefacts in a non-invasive and non-destructive way. From our paleoradiological research, ongoing for several years, I have chosen to present those cases where the imaging provided additional information either to the differential diagnosis or to the internal structural and spatial representation.

Discussion of the reviewed cases

Analysis of skeletal bone remains is a priority matter in paleopathology. Since the cranial bones are the hardest bones of the skeletal system, they are preserved in the soil for future generations therefore I discuss the skull lesions in my dissertation emphatically.

Dual-energy imaging (DECT)

Dual-energy imaging has been successfully applied in earlier mummy studies to characterize textiles, embalming materials and body tissues. By mono-energetic reconstructions we can create virtual density curves that represent the characteristics of the different kinds of materials in addition to the representation of the internal structures of the materials. With the help of these specific density profiles the characterization of the soil is possible without geological identification. After proper standardization, the curves of the soil covering an artefact can be compared to the soil layer profile data set of the given archaeological site, which may make it easier to conclude which stratigraphic layer did the particular artefact belong to originally. I am convinced that in the future the paleoradiological and geological imaging studies will find their place in an even more complex approach.

To carry out CT examinations with mobile CT scanner, the device is transported to the findings. The scanner installation requirements are minimal, the organization and logistics may cause difficulties.

Practical utilization of the results

The number of studies carried out indicate that there is a demand for paleoradiological examinations in the domestic paleopathological researches. We approached the background pathology and clinical aspects in connection with the presented cases, with

up-to-date instruments of modern medical imaging. With our paleoradiological studies we draw attention to the pathological conditions and their bone manifestations occurring even in the 21st century, emphasizing the importance and the versatility of diagnostic imaging. The paleoradiological examinations in addition to possibly giving answers to the arising paleopathological questions, with the digital morphological archivation of the findings may, with some exaggeration, create a priceless protection for the artefacts. Utilizing the opportunities of telemedicine, the standard formatted digital images can be transmitted electronically, viewed anywhere in the world and are eligible for teaching and demonstration purposes. The models created with 3D printing technique are suitable for exhibition and educational purposes. Beyond the general advantages of CT examinations the DECT technology allows the characterization of various structures and with mono-energetic reconstructions post-processing of the images is possible without having to re-examine and re-exposing the findings to further radiation. Using the mobile CT scanner in paleoradiology makes the radiological examination of those artefacts possible that earlier could not be transported.

6. New scientific results

1. The unified documentation of the human skeletal paleoradiological examinations performed at the Institute of Diagnostic Imaging and Radiation Oncology of the Kaposvár University.
2. The introduction of dual-energy imaging in the human paleoradiological studies in our country. We were the first to use mobile CT scanner for examining human paleopathological findings in Hungary.
3. Development of protocol systems for Siemens Somatom Emotion 6, Siemens Somatom Sensation Cardiac 16, Siemens Somatom Definition Flash and Siemens Somatom Emotion 16 CT scanners, based on more than six years of experience in human paleoradiology in Hungary.
4. Application of the infrastructure of modern human medical diagnostics and telemedicine in the fields of paleoradiology and utilizing their opportunities.
5. The creation of the world's first human skeletal paleoradiological-paleopathological database based on citable publications.

7. Publications, abstracts and presentations

Publications

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