The role of radiology in provenance research - experiences from the collaboration between radiology and anatomy at the University of Rostock and future perspectives

Die Rolle der Radiologie im Rahmen der Provenienzforschung-Erfahrungen aus der Zusammenarbeit von Radiologie und Anatomie an der Universität Rostock und Perspektiven für die Zukunft

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ABSTRACT

Purpose Worldwide, the study and examination of human remains and the circumstances of their acquisition for anatomical collection have received great interest. As part of provenance research projects, a large number of collections are being investigated to determine whether the human remains have been acquired in a correct or unlawful way because the people could have been killed in order to be used as "anthropological objects" for research purposes and to become so-called "specimens". These topics have also been addressed by the Institute of Anatomy at the University Medical Center Rostock. The role of radiology in this interdisciplinary project will be presented using selected examples.

Materials and Methods The anatomical collection at the University of Rostock includes 40 human skulls, 14 plaster casts, 6 Egyptian mummy heads, and 1 full-body mummy. In addition to the examination by a historian, an anthropologist, and forensic pathologists, additional computed tomography was carried out on nine skulls and the full-body mummy. Micro-computed tomography was also carried out on seven skulls in order to enable a look behind the mummification material and tissue remains.

Results (Micro-)computed tomography was able to close diagnostic gaps and the results presented some rather unexpected findings.

Conclusion Due to interdisciplinary collaboration, individual fates could be determined, which provided information about the individual's life and death circumstances. None of the examined individuals showed evidence of colonial-era injustice or the use of violence that would have led to their inclusion in the collection. (Micro-)computed tomography was a valuable addition to this provenance research project.

Key Points

- Computed tomography enhances interdisciplinary provenance research projects.
- Computed tomography enables a non-destructive examination of human remains.
- The future of research and presentation of human remains will increasingly be virtual.

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ZUSAMMENFASSUNG

Ziel Die Erforschung der Erwerbsumstände von „human remains" in anatomischen Sammlungen erfährt derzeit weltweit große Beachtung. Im Rahmen von Provenienzforschungsprojekten wird in einer Vielzahl von Sammlungen untersucht, ob die darin befindlichen menschlichen Überreste einst unrechtmäßig erworben wurden und ob Menschen gezielt getötet worden sind, um sie anschließend als „anthropologische Objekte" zu Forschungszwecken zu benutzen und dann als sogenannte „Belegexemplare" in Sammlungen zu überführen. Auch am Institut für Anatomie der Universitätsmedizin Rostock widmete man sich diesen Fragestellungen. Die Rolle der Radiologie in diesem interdisziplinären Projekt soll im Folgenden anhand ausgewählter Beispiele vorgestellt werden.

Material und Methoden Die Sammlung der Anatomie der Universität Rostock umfasst 40 Schädel, 14 Gipsabgüsse, sechs ägyptische Mumienköpfe und eine Ganzkörpermumie. Neben der fachspezifischen Untersuchung durch Historikerin, Anthropologin und Rechtsmedizinerinnen wurde bei neun Schädeln und der Ganzkörpermumie eine ergänzende Computertomografie sowie von sieben Schädeln eine Mikro-Computertomografie durchgeführt, um einen Blick hinter Mumifizierungsmaterial und Gewebereste zu ermöglichen.

Ergebnisse Die (Mikro-)Computertomografie konnte diagnostische Lücken schließen und es sind ihr einige unerwartete Ergebnisse in diesem Projekt zu verdanken.

Schlussfolgerung Durch die interdisziplinäre Zusammenarbeit konnten Individualschicksale bestimmt und Hinweise auf die Lebens- und Todesumstände dieser Menschen erarbeitet werden. An keinem untersuchten Individuum wurden kolonialzeitliche Unrechtskontexte im Sinne von Gewaltanwendung nachgewiesen, die zu einem Eingang in die Sammlung geführt hätten. Die (Mikro-)Computertomografie war eine wertvolle Ergänzung im Rahmen dieses Provenienzforschungsprojektes.

Kernaussagen

- Die Computertomografie ist eine Bereicherung in interdisziplinären Provenienzforschungsprojekten.
- Die Computertomografie ermöglicht eine zerstörungsfreie Untersuchung menschlicher Überreste.
- Die zukünftige Forschung und Darstellung von „human remains" wird zunehmend virtuell sein.

Introduction

The study of people, their origins, their environment and their lives – both healthy and sick – has been the focus of numerous scientific disciplines for centuries. Especially in the late 19th and early 20th centuries, collections were created to help record people's phylogenetic development and their existence in different "races" and to provide specimens of "disappearing indigenous peoples" in the form of human remains and associated cultural objects.

Only recently has attention been devoted to researching the circumstances under which these collections were acquired, i. e., were they acquired legally or by exploiting injustice. The current focus in research projects is primarily on human remains of non-European origin, which can be found not only in ethnological collections, but also in a large number of "medical" collections, such as the collection at the Institute of Anatomy, Rostock University Medical Center. Here, between 2020 and 2022, a project was funded by the German Lost Art Foundation in order to conduct specific research of the origin, acquisition history, and origins of individuals of non-European origin in the collection. None of these individuals consented to body donation, as is customary today [1, 2, 3]. Considering the period in which the collection was created, however, this is not surprising. It should be noted that during that period countries such as Great Britain, France, the Netherlands, and Germany fought over areas of the world that they could include in their national territory as power territories. It was the time of colonialism.

In 1914, the German colonies together formed the third largest colonial empire in terms of area after the British and French. It included parts of today's People's Republic of China, Burundi, Rwanda, Tanzania, Namibia, Cameroon, Gabon, Republic of Congo, Central African Republic, Chad, Nigeria, Togo, Ghana, Papua New Guinea, and several islands in the Western Pacific and Micronesia. With the end of World War I, German colonial rule ended.

The populations living in the colonies were subjugated and often brutally exploited in order to produce goods for the colonial power. These populations were considered extremely interesting for the newly emancipating scientific disciplines of the European powers, such as ethnography, anthropology, anatomy, anthropology, and others. Through merchants, naval doctors, and others, graves were looted, skulls were bought from locals, or people were purposely killed in order to acquire interesting "specimens" for their collections. In one case, a letter is preserved in the Institute of Anatomy in Rostock which describes grave looting and thus indicates the origin of two of the 40 non-European skulls. In a few other cases, at least the consignors are named in the preserved transcript of the inventory book. Most of them were ship doctors who were directly connected to Rostock and even to the Institute of Anatomy in one way or another [4]. However, the circumstances of the acquisition remain unclear here. All other individuals came to Rostock via routes that are completely undetermined so far. It was, therefore, important that this project was carried out in an interdisciplinary manner. In addition to historical research into consignors, people, and old collection documentation, an anthropologist examined skulls that no longer had any preserved soft tissue. She was supported by forensic pathologists from the Rostock University Medical Center [5, 6].

However, special "fluoroscopy methods" were required for human remains in which soft tissue was still preserved and which "masked" bone features, e. g., the heads with skin and hair of people from pre-Hispanic Peru, the "Chilean mummy", and a New Zealander as well as a bandage-wrapped Egyptian mummy head. Some of the results of the radiological examinations are presented below.

Materials and Methods

The collection of non-European human remains at the Institute of Anatomy at the Rostock University Medical Center currently includes 40 skulls (China, Polynesia, Central and South America, Namibia, Egypt, New Zealand), 14 plaster casts, 6 Egyptian mummy heads, and 1 full-body mummy from Chile. In addition to collecting individual data such as age, gender, and presumed pathologies, possible causes of death and, most importantly, the origin of each individual were to be determined. An anthropologist initially determined gender and age at the time of death, collected craniometric measurements and dental status, and recorded individual abnormalities and cultural transformations [7]. Detailed questions arose about individual skulls with post-traumatic changes, which were then examined by forensic pathologists. Since anthropology is classically dedicated to the study of skeletal material, radiology was consulted to study bandaged and mummified human remains and also to clarify detailed questions, such as the treatment of the dead and the effects of violence. At the Institute for Diagnostic and Interventional Radiology, Pediatric and Neuroradiology at the Rostock University Medical Center, the human remains of nine skulls and the full-body mummy were examined using the "Revolution" computed tomography scanner from GE Healthcare (256 × 0.625 mm) (▶ **Table 1**). To evaluate the image data, reconstructions in axial, sagittal, and transverse planes as well as illustrative 3D models were created using volume rendering technology.

At the Institute for ImplantTechnology Rostock, seven non-European skulls were scanned using a micro-CT/X-ray microscope (Bruker SkyScan1273) and 3D data sets were created for further analysis (▶ **Table 2**). An isotropic resolution (voxel size) of approx. 52 µm could be achieved, which exceeds the resolution of a clinical CT scanner by three times and thus allows analysis of even the finest intracranial features and intraosseous structures. In micro-CT, the sample is usually rotated up to 360° in defined steps while the X-ray source and detector do not move.

Acquisition of images of the entire skull was made possible by adding several individual scans together. Depending on the condition of the sample (e. g., bone density, presence of soft tissue), individual scans lasted 2 to 15 hours (with single image exposures of 575 ms) and thus, depending on the sample dimensions, total scan times of 6 to 40 hours were necessary.

Similar to clinical CT examinations, the captured individual images are converted into a voxel-based 3D volume using the appropriate device software, which can be further processed or

▶ **Table 1** List of human remains examined by CT with inventory number and origin.

Computed tomography	Origin
Skull Cd 1	Egypt
Skull Cd 2	Egypt
Skull Cd 3	Egypt
Skull Cd 4	Egypt
Skull Cd 5	Egypt
Skull Cd 6	Egypt
Skull Cd 7	Egypt
Skull Cd 8	Egypt
Skull Cd 10	Egypt
Skull Cd 11	Egypt
Skull Cd 12	Egypt
Skull Cf 22	New Zealand
Skull Cf 23	New Zealand
Mummy mod. b 9	Chile

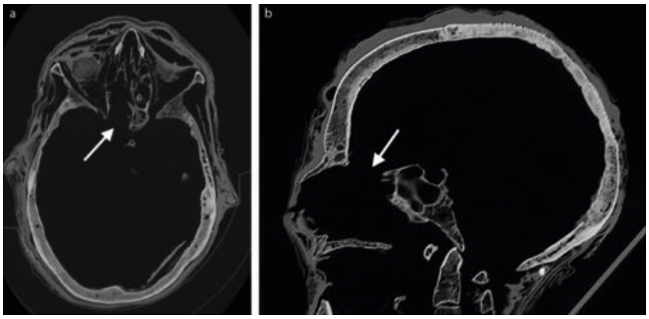
▶ **Table 2** List of human remains examined by micro-CT with inventory number and origin.

Micro-CT	Origin
Skull Cd 20	Namibia or South Africa
Skull Cd 24	Namibia or South Africa
Skull Cd 35	Namibia
Skull Ce 27	Ancient Peru
Skull Cf 1	Java
Skull Cf 12	Yap
Skull Cb 28	Rostock, Germany

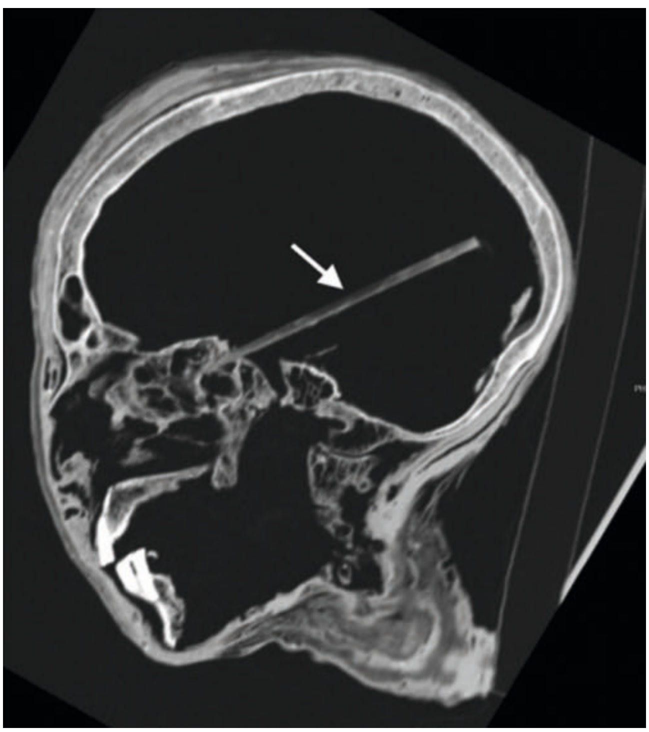
exported as an image series. With specialized software it is possible, in addition to the overall representation as a volume model, to segment individual tissue components and intraosseous structures manually or using AI algorithms and to reconstruct them as surface or volume models [8, 9, 10].

Results

In all Egyptian heads, the stages of the ancient Egyptian mummification process were visible. In particular, the destruction of the walls of the paranasal sinuses (▶ **Fig. 1a**) and the floor of the anterior cranial fossa was visible (▶ **Fig. 1b**). This artificial access to the brain was created by the embalmers in ancient Egypt in order to remove the brain through the nose for successful mummification. One CT scan showed a straw-shaped object in a mummy head (Cd 6), lying between the sphenoid sinus and the cranial cavity. Presumably, it



▶ **Fig. 1** Removal of the brain was part of the mummification process. CT is able to visualize the destruction of the skull base occurring as a result of the removal of the brain through the nose. **a** Axial CT of the skull showing destruction of the posterior wall of the sphenoid sinus (arrow). **b** Sagittal CT of the skull showing destruction of the rhinobase (arrow).



▶ **Fig. 2** Sagittal CT of the skull shows a tubular foreign body that may have been inserted to remove brain tissue and got stuck in the base of the skull (arrow).

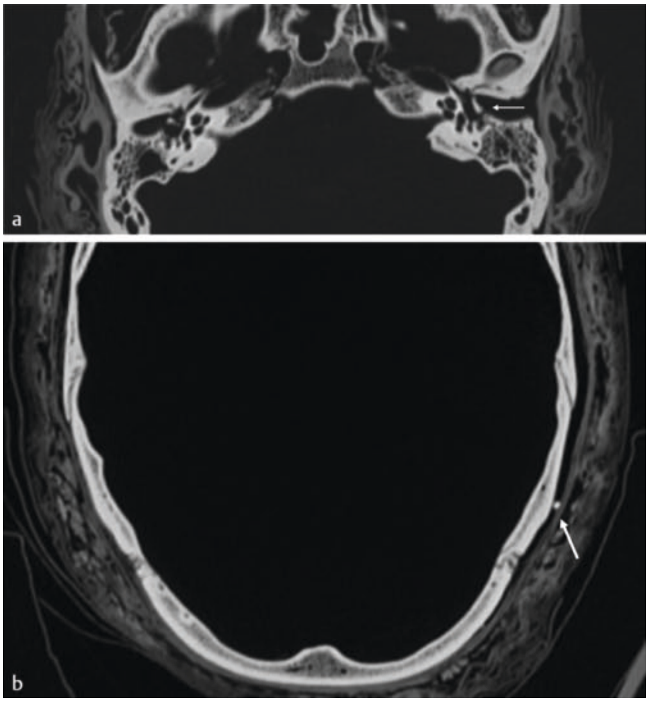
had been used as a tool and got stuck there during the mummification process (▶ **Fig. 2**).

After removing all water-containing organs such as the brain and those from the abdominal cavity, the body was dried, covered with bitumen, and then wrapped with the bandage wrap, as is typical for Egyptian mummies. It was believed that the dead person would then be granted eternal rest as an intact body for life after death. Centuries later, in the time of grave robbers and Europeans traveling to Egypt, the belief in life after death was still known, as was the curse of the mummy, supposedly killing anyone who disturbed that peace. Grave robbers tried to protect themselves out of fear of these "still living" individuals and their power over those living in this world. They did this through what 21st-century researchers initially thought was a "post-mortem defect": a hole hacked into the skull. The grave robbers believed that this hole allowed the spirit of the dead to escape. The corpse would thus be "empty" and inanimate so that no curse could harm the living (▶ **Fig. 3**).

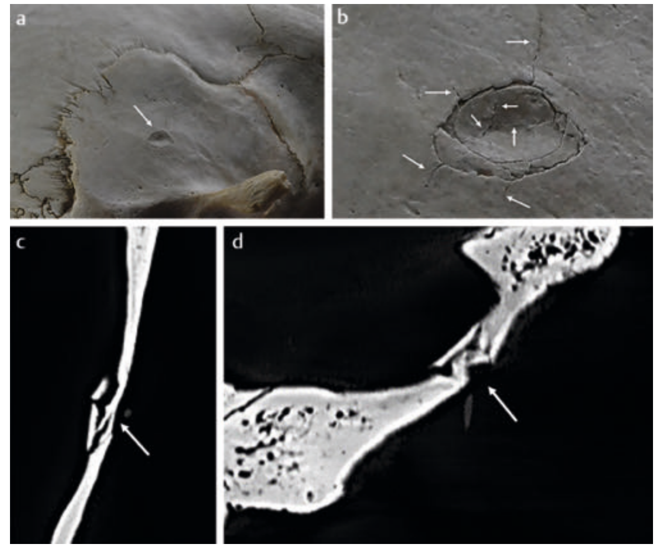
▶ **Fig. 3** Axial CT of skull Cd 8 shows the remains of a bees' nest (arrow) and a hole (star) carved into the skull by grave robbers to allow the mummy's spirit to escape.

A head (Cd 8) indicated the place of its storage after its removal from the grave by a "subtenant". After extensive interdisciplinary discussions as to whether this was a postmortem or intravital finding act, a partially calcified foreign body on the inside of the skull turned out to be a bees' nest. Remains of straw which trickled into the skull through the hole made by the grave robbers, indicated that the head had presumably been wrapped in straw after it was taken from the grave and that a bee had found shelter in it and built a nest (▶ **Fig. 3**).

In the search for postmortem moving of the human body after its removal from the grave and until entering the collection of the Institute of Anatomy, evidence was also found in the head (CD 2) of another Egyptian mummy. In the area of the middle ear of this skull, an asymmetrical configuration of the auditory ossicles was found. The 3D reconstructions showed bilateral incomplete ossicles in the middle ear (▶ **Fig. 4a**). The hammer was missing on the right and the incus and stapes on the left. Upon closer inspection of the CT data, the "lost" ossicles were found in the cavities between the bones, skin, and mummy bandages, while the intact incus on the left was clearly visible (▶ **Fig. 4b**). This finding is not uncommon in Egyptian mummies [11] and is related to the drying process, which destroyed the structures of the connective tissue



▶ **Fig. 4** During mummification, the drying process led to a loss of connective tissue between the ossicles, allowing them to dislocate, e. g. during transport. In the paraaxial CT examination of skull Cd 2, the incus and the stapes on the left cannot be depicted (**a**, arrow). The incus was dislocated between the calotte and the skin during improper transportation (**b**, arrow).



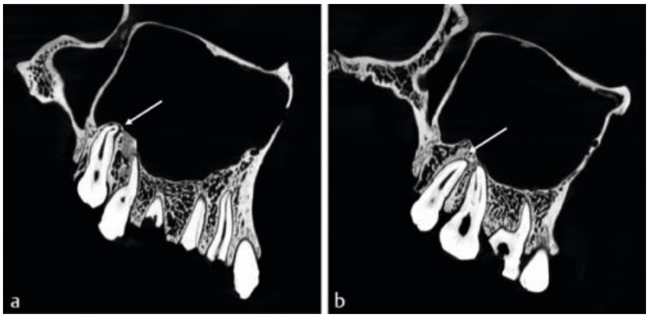
▶ **Fig. 5** Skull Cd 20 shows a triangular defect/impression fracture on the right temporal bone (**a**, arrow), with several small fissures/fractures extending from its center and outer edge into the temporal bone (**b**, arrows) photos: Ute Brinker. In the axial (**c**, arrow) and sagittal (**d**, arrow) planes of micro-CT, it can be seen that the impinging object has not completely penetrated the skull bone. The tabula externa, diploe, and tabula interna are imprinted. Parts of the internal tabula have been blasted off. Fractures that completely penetrate the bone are clearly recognizable. There are no signs of bone healing.

between the ossicles and the tympanic membrane. This resulted in the loss of the connection between the ossicles which then dropped out and came to lie, largely loose, in the middle ear. When the mummies were removed from their resting place and moved, vibrations might have occurred that caused the ossicles to fall out of the external auditory canal. However, the bandages, the "mummy wrap", prevented them from being completely lost. Due to the high density of the ossicles, they can also be easily recognized by X-ray-based imaging in locations other than the middle ear. Occasionally they are found in the Eustachian tube.

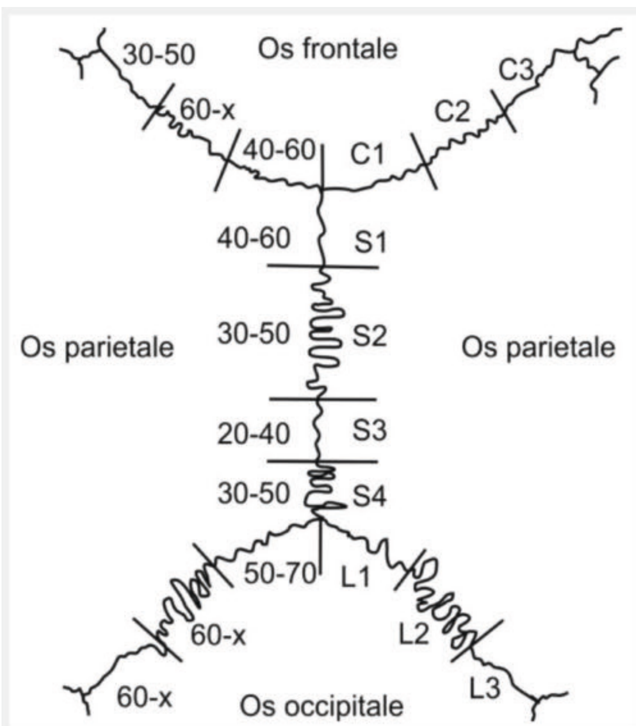
The two Maori heads in the collection of the Institute of Anatomy in Rostock (Cf 22 and Cf 23), a mummified head and a skull, were also examined using CT. In particular, heads such as the former were popular "souvenirs" from New Zealand in the late 19th and early 20th centuries. The question now was whether the Maori skull was once a mummified head which was macerated due to a lack of fluoroscopic methods at the time it entered the collection, or whether it came from a burial context and was defleshed in the natural decomposition process. The CT scan did not show any morphological differences in the bone substance of the two heads, nor did it reveal any changes in the bone structure that may have occurred during the mummification process of the head with preserved soft tissue, e. g., like heat exposure (sphere fractures/tabula externa avulsions) or the use of caustic chemicals.

The micro-computed tomography scans carried out at the Institute for ImplantTechnology in Rostock were used in particular to analyze traces of injury, with the high-resolution scans making it possible to obtain better information about a possible healing status and to clarify whether detected injuries had occurred a long time ago and had or had not healed, or if they were the cause of death or at least related to it. This was the case for one skull (Cd 20), which shows an almost oval or triangular, funnel-shaped, tapering defect (approx. 6 × 4 mm) on the right temporal bone, from which several radial fractures and fissures extending in the surrounding bones were detectable (▶ **Fig. 5a** and **5b**). Micro-CT analysis showed that the causative object hit the bone from the outside of the skull but did not penetrate the bone itself. On the inside of the skull, broken bone fragments were visible, which still showed partial continuity with the bone surface (hinge fracture) (▶ **Fig. 5c** and **5d**). There were no signs of bone healing. Anthropological experience led to the interpretation of a perimortem injury (i. e., occurred around the time of death) which, due to its defect characteristics [12, 13], was most likely caused by the penetration of a projectile [14], but did not cause a brain injury due to the shallow penetration depth and was, therefore, not immediately nor necessarily fatal. However, the lack of healing tendencies might also suggest that other causes associated with this injury could have ultimately led to the individual's death.

For skulls with preserved soft tissue, (micro-)CT was used to estimate the individual's age at the time of death based on tooth development [15, 16]. On the CT scan of Cd 20, the complete closure of the roots of the two third molars was detectable, one of which is in eruption (▶ **Fig. 6a**) and the other in occlusion (▶ **Fig. 6b**) which indicates an age at the time of death of approx. 18–20 years [17].

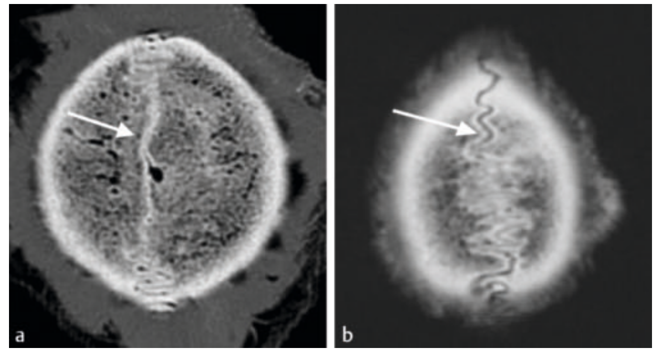


▶ **Fig. 6** The age at death can be determined on the basis of tooth development with the aid of (micro-)CT. The micro-CT examination of the maxilla of skull Cd20 shows in sagittal plane complete root closure of both third molars in eruption (**a**, arrow) and occlusion (**b**, arrow). The age at death could be narrowed down to 18–20 years.



▶ **Fig. 7** Scheme for determining the age of death based on the ectocranial suture closure according to Herrmann.

Another method for determining the age of at the time of death beyond adolescence is the analysis of the ectocranial suture closure – with CT helping in cases where soft tissue or bandages mask bone structures. According to Herrmann's scheme, the suture frontalis and the suture lambdoidea were divided into three sections and the suture sagittalis into four sections [18]. Based on the ossification stage of the respective sections, the individual's approximate age at the time of death can be derived (▶ **Fig. 7**) (▶ **Fig. 8a** and **b**). Furthermore, sex determination was carried out using anatomical landmarks such as the shapes of the orbit, the jaw, the forehead, and bony protuberances of the skull [19]. The assessment of the dental status was a standard part of



▶ **Fig. 8** Axial CT of a skull with completely ossified sagittal sutura in a senile individual (**a**, arrow) and partial occlusion of the sagittal sutura in a 30–50 year old individual (**b**, arrow).

the diagnosis in this research. Here, the consequences of a diet of hard grains could be clearly seen in the wear and tear of tooth structure and defects in the Egyptian skulls. Consecutively, small osteolyses were found at the tooth root tips as an indication of past apical periodontitis. [20, 21].

Conclusion and Perspective

Provenance research attempts, firstly, to detect all possible information on the individual whose human remains are in a collection, i. e., his/her origin and circumstances of life and death, and, secondly, investigates the acquisition history.

Exposure to direct colonial-era injustice such as the use of violence to kill the individual to be able to incorporate his/her remains into the collection could not be found for any of the individuals examined in this provenance research project. Most remains showed remnants of sand and natural decomposition, which indicates extraction from graves.

However, through interdisciplinary collaboration, individual fates could be determined, thus providing information about the circumstances of the life and death of individuals, even if these took place before the colonial period. The context of injustice lies primarily in grave robbing in the early 19th century and the inclusion of these human remains in collections such as in Rostock.

The future of the collection, as in other collections with human remains worldwide, remains a "matter of negotiation" for the Institute of Anatomy at the Rostock University Medical Center. The aim is to establish a dialogue with the descendants of the communities of origin and with representatives of victim groups.

However, Egypt has not yet reclaimed any human remains from its pharaonic era. Things look different in the efforts with New Zealand. In general, the Federal Republic of Germany is always trying to find descendants or representatives of communities of origin worldwide in order to start a dialogue about the future handling of collections that were created in the colonial period. Some countries and groups have already achieved the return of the bones of their ancestors several times in this process, especially the indigenous peoples of North America and descendants in New Zealand, Australia, and Namibia, whose bones are or were present in the Rostock collection. Repatriation to the

Maori/Moriori descendants in New Zealand has not yet taken place. However, this could happen for both Maori heads, as repatriation to New Zealand is the current standard procedure in Germany.

In general, noninvasive methods are to be preferred in provenance research in order not to violate the dignity of the dead and, on the other hand, to respect the wishes of the communities of origin regarding how to deal with their dead. Corresponding noninvasive visualization and "dissection options" are now used in many places and thus offer specialists the opportunity to examine the human remains without having to treat them again or examine them directly.

In the future, three-dimensional reconstruction techniques may provide a solution for further management after an initial CT scan. Basically, there are currently two main procedures. The rather simple surface rendering, in which a contour of the body is defined using the density value and then displayed in three dimensions. In contrast, with volume rendering, with the individual density of a pixel determining its representation, all structures can be displayed transparently and in different colors at the same time. With this procedure it is possible to selectively display the different structures of the CT-scanned body and thus to systematically dissect the person virtually. The layer thickness determines the quality or realism of the 3D reconstruction. Optimal results are achieved with an isotropic voxel resolution of a maximum of 1 mm^3.

In addition to viewing the 3D objects obtained in this way on a screen, it is possible to create a so-called holographic projection. The basic principle was first presented in 1862 at a theater performance in London by John Henry Pepper. To achieve this, an individual was attired as a ghost and positioned beneath the stage, concealed from the audience's view. Through the utilization of a sizable, segmented, semi-transparent, and slanted mirror, this individual's image was projected onto the stage. The mirror reflected a portion of the incident light while allowing the remainder to pass through. Consequently, spectators perceived the 3D object in the room behind the mirror, akin to a ghost appearing to float freely in space.

In addition to the stage construction involving a large dividing mirror or dividing film, which is still used today, there are also 3- and 4-sided pyramid constructions in various sizes, ranging from 6 inches up to an edge length of 2 meters, enabling life-size representation as a hologram. For each side, a projection coming from a vertical direction can be viewed horizontally across the sloping glass surface. The size of the holographic object is freely scalable and depends on the geometry of the projection surface and the pyramid used [22, 23].

VR/AR glasses have already been successfully utilized for direct interaction. The 3D data is manipulated using joysticks or simply by finger and body movements. When operating online, these systems also enable direct and limitless interactive work by different people or work groups on a dataset without needing the original. The future lies in the virtual realm, both for researchers and museum visitors.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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