Radiology meets archaeology: digital restoration and 3D printing using CT data

Radiologie trifft Archäologie: digitale Restaurierung und 3D-Druck anhand von CT-Daten

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ABSTRACT

Aim Archaeological objects are often recovered in blocks since highly porous materials and unstable and highly decayed objects cannot always be uncovered undamaged or time and resources for classic uncovering are lacking. Therefore, clinical computed tomography (CT) combined with freely available software solutions should be tested as a simple and fast method for visualizing and analyzing archaeological finds as an alternative to time-consuming restoration.

Materials and Methods As an example, a block with a shield boss was selected from a block excavation and examined by means of CT. Using the freely available software 3D-Slicer (https://www.slicer.org/), the shield boss and handle were segmented in the surrounding soil with different tools. They were then digitally reconstructed and then restored using Meshmixer (Autodesk Inc., San Francisco, CA). A 3D print was generated based on the reconstructed model of the shield boss.

Results The individual steps of CT examination of the block recovery, segmentation, reconstruction, and 3D printing were successfully performed. Based on the restored fragments of the shield boss, it was possible to date the object and to determine the initial properties of the find non-destructively without classic restoration.

Conclusion Radiological imaging combined with digital reconstruction and 3D printing makes it possible to determine decisive characteristics of the archaeological find before it is uncovered and restored, which is a time-consuming process. This opens up new opportunities for cooperation between radiology and archaeology for the evaluation and analysis of archaeological finds.

Key Points

- The transfer of medical technology, digital image processing and 3D printing to archaeology has been demonstrated.
- The digital restoration and reconstruction of archaeological objects using CT images is possible.
- Medical imaging could make a significant contribution to the investigation and reconstruction of archaeological objects.

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ZUSAMMENFASSUNG

Ziel Archäologische Funde werden oft am Fundort als Block geborgen, da stark poröse Materialen, instabile und stark zerfallene Objekte nicht immer unbeschädigt freigelegt werden können oder Zeit und Ressourcen für eine klassische Freilegung fehlen. Daher sollte die klinische Computertomografie (CT) kombiniert mit frei verfügbaren Softwarelösungen als eine einfache und schnelle Methode zur Darstellung und Analyse archäologischer Funde als Alternative zur zeitaufwändigen Restaurierung erprobt werden.

Material und Methoden Exemplarisch wurde aus einer Blockbergung ein Block mit einem Schildbuckel ausgewählt und mittels CT untersucht. Mit der frei verfügbaren Software 3D-Slicer (https://www.slicer.org/) wurden Schildbuckel und -fessel in der umgebenden Erde mit unterschiedlichen Werkzeugen segmentiert. Anschließend wurden diese mit Meshmixer (Autodesk Inc., San Francisco, CA) digital rekonstruiert und restauriert. Auf Basis des rekonstruierten Modells des Schildbuckels wurde ein 3D-Druck erzeugt.

Ergebnisse Die einzelnen Schritte CT-Untersuchung der Blockbergung, Segmentierung, Rekonstruktion und 3D-Druck wurden erfolgreich durchgeführt. Anhand der restaurierten Bruchstücke des Fundes konnte eine Datierung des Objekts vorgenommen und erste Eigenschaften des Fundes zerstörungsfrei ohne klassische Restaurierung ermittelt werden.

Schlussfolgerung Radiologische Schnittbildgebung kombiniert mit digitaler Rekonstruktion und 3D-Druck ermöglichen es, bereits vor der Freilegung und zeitaufwändigen Restaurierung entscheidende Eigenschaften des Fundstückes zu ermitteln. Damit ergeben sich neue Chancen der Kooperation zwischen Radiologie und Archäologie für die Befundung und Untersuchung archäologischer Fundstücke.

Kernaussagen
- Die Übertragung medizinischer Technik, digitaler Bildverarbeitung und des 3D-Drucks auf die Archäologie konnte gezeigt werden.
- Die digitale Restaurierung und Rekonstruktion archäologischer Funde anhand von CT-Aufnahmen ist möglich.
- Die medizinische Bildgebung kann einen bedeutenden Beitrag zur Funduntersuchung und Rekonstruktion in der Archäologie liefern.

Introduction

The recovery and restoration of archaeological finds include many challenges and possible complications. Objects cannot always be excavated without the risk of possible damage because of their condition. In particular, porous materials, unstable finds, highly decayed objects, and sensitive ceramic vessels with contents are excavated in blocks [1]. A lack of time and resources can also prevent conventional recovery and necessitate block excavation. In such cases, archaeological finds are recovered as a block together with the surrounding soil and can thus be removed from the soil and restored under laboratory conditions without time pressure.

Modern radiological imaging provides valuable tools for the exact visualization and analysis of an archaeological find still in a soil block [2]. In addition to conventional radiography for obtaining a general overview of the condition and position of a find in a block, examination with computed tomography (CT) allows three-dimensional investigation of the find while the object is still protected and surrounded by soil.

In combination with a CT examination of archaeological objects, 3D printing also offers new opportunities in archaeology. After segmentation of a find and possible further processing of the data, archaeological objects can be printed with a 3D printer. Using this method, archaeological finds can be examined and presented even before restoration. The goal of this study is to demonstrate the feasibility of using an uncomplicated approach combining readily available medical imaging, free software, and commercially available 3D printing technology. Moreover, the study will show that a digital reconstruction can be performed, and the time period of the find can be determined using such a technique without the need for time-intensive and expensive restoration.

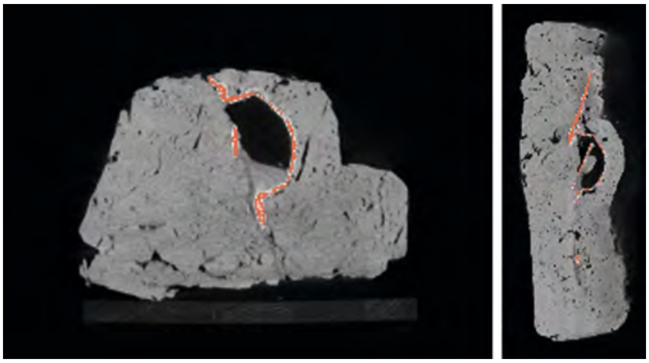
Materials and Methods

A 61.0 cm × 19.6 cm × 20.2 cm block of loess loam from the grave of a high-ranking individual from the Merovingian period (second half of the 5^{th} century to the middle of the 8^{th} century A.D.) was selected as an example. The block was excavated from a depth of approx. 1.50 m below the surface. Prior to examination, it was hypothesized that a metallic object was located in the block.

Excavating the block, creating a 3D model, and 3D printing a model included four steps: (1) Acquisition of thin-layer CT images, (2) segmentation of the object based on the CT data, (3) image processing for digital reconstruction of the find, and (4) 3D printing.

CT examination of the archaeological find was performed with a clinical CT scanner (SOMATOM Definition, Siemens, Forchheim). To prepare for the CT examination, the block of soil was wrapped in several meters of stretch film, was placed on a wooden board also wrapped in stretch film, and was wrapped again in stretch film. The CT scan was performed with a tube voltage of 120 kV, an effective current-time product of 360 $mAs_{eff.}$, a collimation of 64 × 0.6 mm, and a pitch of 0.9. Axial images with a slice thickness of 0.75 mm at an increment of 0.5 mm were reconstructed from the raw data using a medium-smooth kernel (B31 s).

For segmentation from DICOM data for the find consisting of multiple parts, the open-source software 3D Slicer (Version 4.11.20210226, www.slicer.org) was used [3, 4]. Threshold segmentation with a threshold of 1998–3071 Hounsfield units (HU) was first performed. Then manual segmentation of the finds from the surrounding soil in the x-, y-, and z-directions of the image data was performed, see ▶ **Fig. 1**. The data was saved as a *.stl file. The further digital reconstruction of the digital model of the find was performed with the freeware modeling program Meshmixer (Version 3.5.474, Autodesk Inc., San Francisco, CA) [5]. In this software small irregularities and holes were first digitally improved in the model and the appearance of the shield boss was smoothed to correct changes caused by corrosion and blooming of the metal. Moreover, fragments that were independent of the



▶ **Fig. 1** Axial image of CT slices of the excavated block of soil containing the shield boss in 3D Slicer.

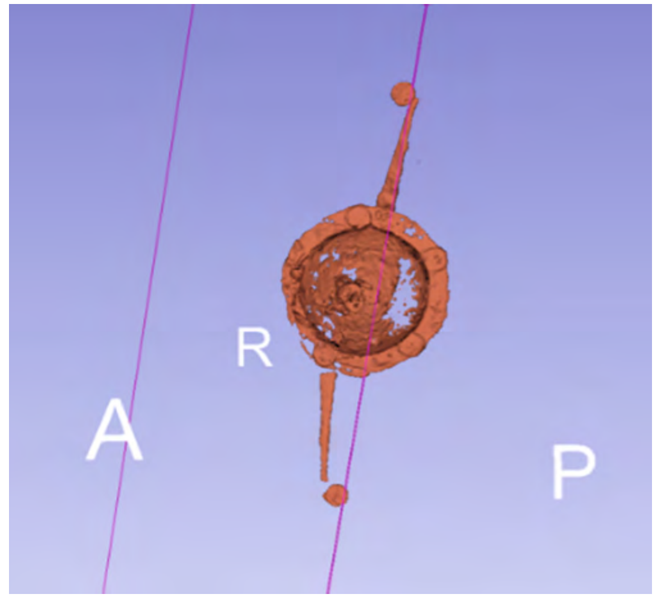
▶ **Table 1** Meshmixer tools used for the correction of three-dimensional models.

Tools	Intended use
Plain cut	Individual objects can be removed from the model
Inspector	Unrelated fragments can be removed and holes can be filled in
Select	Regions can be selected and holes can be filled in by removing the selected region and performing reconstruction with the Inspector
Sculpt	Using various tools, smoothing, edge enhancement, and planarization can be performed to varying degrees in a region
Make Solid	Provides an approximation of the original model in voxel form and small irregularities can be eliminated depending on the selected accuracy
Transform	Objects can be moved and rotated
Combine	Separate objects can be combined into one unit

find were removed. The highly decayed condition of the object and errors that occurred during segmentation were corrected digitally. ▶ **Table 1** lists the software tools used for processing, correction, and reconstruction of the model of the find.

After reconstruction of the largest fragment of the multi-piece find, the smaller fragments were processed in the same way. Once it became clear that the largest fragment was a shield boss, the four objects identified as the handles were rotated independent of the model, placed in the correct position, and digitally attached. Based on the 3D model available at the time, comparable objects from the literature were referenced. Images of similar objects from the same time period were used as a template for the further digital detailed reconstruction of the objects belonging to the shield. The flat button on the tip of the conical boss and the almost identical disc rivets on the rim, which are typical of the 6th and early 7th century, can be clearly seen. These features are also clearly visible here on the CT scan of the object [6].

The processed fragments were stored in various processing stages: After segmentation, after removal of the individual unrelated parts, after final processing with the shield boss in separate parts and in an assembled state.



▶ **Fig. 2** Image of the shield boss with substantial holes and irregularities after simple reconstruction from the CT data using a basic threshold method in 3D Slicer. A, P, and R indicate the spatial directions “anterior”, “posterior”, and “right”.

The printer Prusa i3 MK3S+ (Prusa Research, Prague, CZE) was used for the 3D printing of the individual components. Polylactic acid (PLA), a plant-based polyester (Prusa Research, Prague,CZE), was used as a filament for the printer [7].

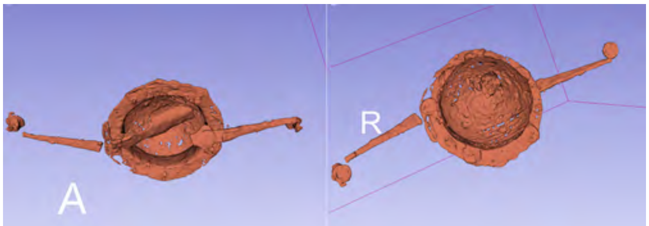
Results

The objects were able to be identified as part of a shield. The shield boss was comprised of multiple parts based on segmentation and initial post-processing. With the help of the indicated tools, the holes in the 3D model of the shield boss (▶ **Fig. 2**) were able to be filled in by the post-processing software and irregularities were able to be corrected (▶ **Fig. 3**).

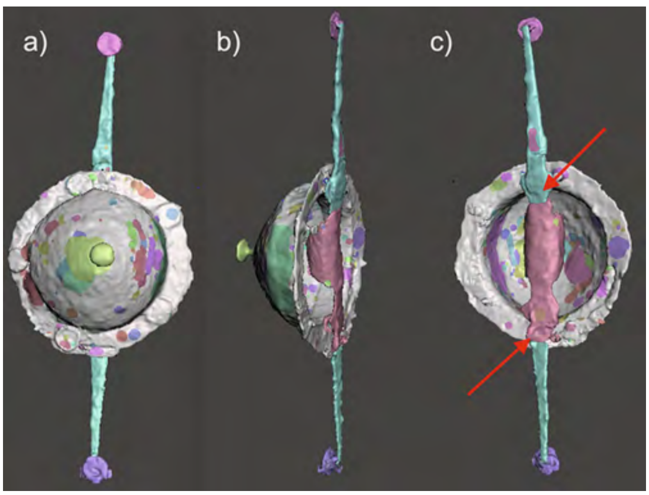
The final digital reconstruction created under consideration of comparable finds is shown in ▶ **Fig. 4**. The handles were also reconstructed in this step in Meshmixer. The finished 3D print in various configurations is shown in ▶ **Fig. 5**.

Discussion

The examined block of soil containing the shield boss with handles was excavated from the grave of a high-ranking person from the Merovingian period that lasted from approximately the 5th century to the mid-8th century A.D. The dating based on the digital reconstruction is so precise that the time period of the two parts can be narrowed down to the first half of the 6th century to the beginning of the 7th century [8] without having to first excavate the shield boss. Because the grave was approx. 1.50 m below the surface, it was not disturbed by modern agricultural equipment. However,



▶ **Fig. 3** After manual segmentation in 3D Slicer, parts of the defects visible in ▶ **Fig. 1, 2** were able to be corrected. The views from the front (right) and back (left) show the broken-off handles.



▶ **Fig. 4** The shield boss after correction and reconstruction in Meshmixer from various views, from the front (**a**), from the side (**b**), and from the back (**c**). The corrections performed in Meshmixer are shown in color. The red arrows in c mark the corrected positions of the handles broken off in the original.

▶ **Fig. 5** 3D-printed model of the shield boss in individual pieces (top) and assembled (bottom) with a scale

chemical processes in the soil did greatly affect the metal objects. To prevent further damage to the objects, they were not excavated on-site. Instead, the grave site was removed in blocks with the surrounding soil so that the objects could be subsequently excavated during restoration.

For three-dimensional visualization of the find, it must be segmented from the surrounding soil on the CT images. Particularly in the case of porous or highly fragmented finds, an image of the object as a whole can be created without jeopardizing the find. For example, the analysis of an archaeological find examined with CT because it was comprised of broken glass and could not be directly excavated due to its condition was published in 2006 [9]. Segmentation of a CT dataset can also provide essential information about the age, sex, and health of a person when examining bone in anthropology [10].

While purely threshold-based segmentation is known to be error-prone even in the medical field, manual segmentation can also result in deviations between the original object and the model of the archaeological object since clear segmentation is not possible in all regions. This applies primarily for regions in which the find is corroded, has attenuation properties very similar to those of the surrounding soil, or in the case of very significant decay of organic materials. Particularly in the region of rust bubbles, the surrounding soil is difficult to separate from the find. Moreover, how true the model is to the original object depends on the processing in the post-processing software. Therefore, as a result of smoothing, the filling in of holes, as well as reconstructions, the created model can differ from the original to varying degrees. However, during reconstruction, a reasonable assumption as to how the find once looked can be made with the help of already known archaeological finds. As a result of digital restoration and reconstruction with the option of saving the various steps, it is possible to examine the different stages and reconstruction variants of the find without putting it at risk and to go back as needed and use a different reconstruction approach. Conventional manual reconstruction does not allow this option. In contrast to conventional excavation and reconstruction, the object can thus be corrected and assembled in various ways without putting the find at risk. Process errors can thus be corrected without any lasting consequences for the find.

3D Slicer and Meshmixer were used for post-processing and segmentation since, in contrast to the CT scanner's own post-processing tool, these programs provide the *.stl files needed for 3D printing. Moreover, they allow the individual pieces to be adjusted for reconstruction and digital repair.

Using 3D printing, authentic replicas of skulls, crowns, inscriptions, and mummies have already been able to be displayed as exhibits [11–13]. As a result of this technique, objects can be displayed to the public even before restoration is complete. In anthropology, such reconstructions have been able to be used in select cases as evidence in court [14].

In block excavation it is not always clear what the block contains until after restoration. It can take years for the find to be restored. However, with CT examination and subsequent segmentation, the object can be viewed quickly and easily. Compared to simple X-ray examination, CT provides more detailed visualization. Therefore, in the future, new finds could be examined significantly faster after recovery. Thus, it is also easier to decide which objects have priority for manual excavation and reconstruction. The creation of a digital model prior to excavation also makes it possible to secure against possible damage or loss. By saving CT data digitally, archaeological finds can be additionally digitally documented, analyzed, and made globally available without putting the find at risk.

CT scans of archaeological finds have many additional advantages for the field of archaeology. Prior to excavation and restoration, finds can be analyzed on a monitor and the condition and position of the find can be evaluated. This noninvasive method makes it possible to examine properties of a find that otherwise would only be visible by destroying the object. Therefore, the structure and manufacturing technique of ceramic can be evaluated without having to damage the object. Although the creation of digital models and digital reconstruction offer many possibilities, it is not possible to draw any conclusions about the color and pattern of a find based on cross-sectional imaging [15].

CT examination also has its limits. Not every find can be scanned with a clinical CT scanner. The block of soil must be small enough to fit in the gantry of the CT scanner. In addition, enough radiation must be able to penetrate the block to acquire a suitable CT image. An industrial CT scanner could be used for scanning very large finds since these scanners are more powerful than clinical scanners [16]. The described method is generally suitable for all objects that have different attenuation coefficients than the surrounding material. Compared to other three-dimensional visualization methods for archaeological finds such as laser scans in which only the surface of an object is scanned without contact, CT can also visualize the interior of an object. In some cases, insight into the manufacturing process of an object can thus be acquired [16]. Therefore, CT scans can be performed on the block of soil while laser scans can only be performed on the excavated object. For regular application of CT imaging with post-processing, the method must be quick and convenient.

Conclusion

The present study shows that analysis, documentation, and reconstruction of archaeological finds from an excavated block of soil is possible using available medical infrastructure and free software. As a result of the good digital visualization of the shield boss, sufficiently exact dating between the first half of the 6th century and the beginning of the 7th century A.D. can be performed based on reference images. Close collaboration between radiology and archaeology provides new opportunities for the examination of archaeological finds prior to excavation and restoration. Further improvements of the method, particularly completely automated and precise segmentation based on the cross-sectional images, are needed.

Conflict of Interest

The authors declare that they have no conflict of interest.

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