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Advantages and limitations of micro-computed tomography and computed tomography imaging of archaeological textiles and coffins

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Abstract
We have recently studied northern Finnish archaeological textiles extensively using computed tomography (CT) imaging. These textiles have been found in inhumation burials from the Late Medieval church of Valmarinniemi in Keminmaa and the Postmedieval church of Haukipudas. In this article we discuss the advantages and limitations of CT imaging based on three case studies. Based on the research objectives and the size of studied items, we utilised three different CT scanners: clinical systems and micro- and nano-scale X-ray microscopes. We were able to visualise a child's coffin and a doll inside, which is a larger scale sample. We were also able to study and reconstruct the complicated structure of a tablet-woven band, as well as identifying individual fibres when examining smaller textile samples with submicron resolution. Even though we observed some limitations in the image quality, we conclude that computed tomography has great potential in the research of archaeological textiles in both 3D and cross-sections and is often easier and more informative than conventional microscopic or other archaeological methodologies.

Keywords Textile archaeology, Archaeological fabrics, Computed tomography, Micro-CT, Late medieval textiles, Cotton, Funerary attire, Church burials

Introduction

Computed tomography imaging has great potential in the research of archaeological textile finds and other cultural heritage items. Research on mummified remains has a long history of utilising medical imaging techniques [1–6]. Computed tomography (CT) scanning is based on X-rays, which were discovered by Wilhelm Conrad Röntgen in 1895: as early as in 1896, Georg Walter König produced the first X-ray images of a mummified child and other Egyptian objects [7]. In the late 1960s, the first computerised axial tomography scanner was developed by Sir Godfrey Hounsfield, and the first research on Egyptian mummies was published in 1979 [8]. CT imaging has been extensively used on mummified remains in paleopathology [9–11], After successful research on mummies in paleopathology, CT imaging has found widespread usage in studying other archaeological finds such as pottery [12], statues [13], and coffins [14, 15].

Since the 1980s, μCT imaging has developed into a well-established technique to study mineralised bone structure [16–19], which has been widely utilised in bioarchaeology to, for example, evaluate the post-mortem interval [20], analyse vitamin D deficiency detected in teeth [21], and correlate bone porosity with preservation [22]. The technology has also proved to be highly useful in the study of archaeological textile remains [23, 24], and

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the anatomy of plant material in archaeological basketry [25] and lime bark [26]. Furthermore, the volumetric capabilities of high-resolution µCT modalities have been recently used in the study of other cultural heritage items to reveal internal structures unseen from the outside of precious objects such as papyrus [27], pottery [28], and coins [29]. In addition, µCT provides a unique 3D visualisation of the internal structures of the imaged object that is not possible with other methods. Lately, combining the µCT technique with further analysis such as chemical analysis as x-ray fluorescence to study the composition of investigated material together with structure has been growing in popularity [30]. It has been noted that a combination of µCT technique and x-ray fluorescence analysis may considerably help recording conservation history of both cultural heritage and paleontological items and making decisions on their future care [31].

In this article, we have used computed tomography imaging to study archaeological textile remains from northern Finnish inhumation burials. Depending on the imaged item, we have utilised different imaging techniques with scales varying from the macroscopic (millimetre range) scale used in clinical CT imaging to sub-microscopic scales achievable with µCT or X-ray microscopic imaging. In this article, we consider the advantages and limitations of the methodology as well as optimal scales of imaging in research on archaeological textile finds. The research is based on acquired images of two textile items and a child's coffin. These originate from two different church sites: the Late Medieval church of Valmarinniemi in Keminmaa and the Postmedieval church of Haukipudas (Fig. 1).

CT method and studied textiles

Imaged textiles and coffin

Based on the accelerator mass spectrometry (AMS) analysis and coin finds the inhumation burials at Valmarinniemi, Keminmaa, date from the late thirteenth century to the fourteenth century [32]. From the burials, two fabrics were scanned using µCT. One was a tablet-woven band found in three pieces (KM39304:1450) and the other was a piece of plain-woven cotton fabric (KM39304:1544). In addition, a small fragment of the cotton fabric was imaged with an X-ray microscope.

The woollen tablet-woven band was found on the pelvic area of the deceased in Burial 24. Due to the poor preservation of the remains, their sex and age could not be estimated [33]. The band is most likely the end of a belt and was preserved due to the spiral tubes attached to it (Fig. 2). The tubes were knotted to the end of the band and the warp yarns of the band were pulled through the tubes and again knotted with help of smaller tubes and left as tassels in the end of the band. The width of the band is 1.4 cm. The spirals are 0.3 cm in diameter and 0.7 cm in length [34]. Similar thirteenth and fourteenth century bands have been found in the Kekomäki cemetery in Kaukola, Karelia, and the Gaigovo barrows in the Southeastern Ladoga area (Fig. 1) [35, 36]. Similar spiral tube endings possibly attached to tablet-woven bands have been found in the Hiitola and Kaukola cemeteries in Karelia [36, 37].

Because of the acidic soil, plant fibre fabrics are rare soil finds in Finland [38]. The preserved fabrics are small fragments often made of bast fibres (flax or nettle). However, church burials with no soil contact suggest that it is likely that bast fibre fabrics were commonly used to cloth the deceased [38, 39]. Cotton, on the other hand, is an extremely rare find in archaeological contexts and the piece found in Valmarinniemi is so far the oldest found in Finland. It was found in Burial 101 which belonged to a woman ca. 20–30 years of age [33]. The fabric (size 2.8 × 2.4 cm) had been preserved on a bronze ring that is sewn on a tablet-woven belt (Fig. 3).

We have also CT-imaged three coffins from Haukipudas Church. All of them belong to newborns and the one studied for this article has been identified to belong to a three-week-old boy, Johannes Haustrammis, who died in 1747 [40]. Inside the coffin lid a text is written in ink in Swedish: "Johannes Haustrammis Johansson afsömnade den 22 et den 29 […] Christligen befordradet till det själs gum Gloria sit Deo Triuna!!!" which translates as "Johannes Haustrammis Johannes slept away the 22nd and the 29th […] with Christian ceremonies was promoted to soul's groom Glory to the Triune God!!!". According to the preserved church records only a few burials were made under the floor after rebuilding the church that took place between 1762 and 1764. When the old church was demolished, it is likely that many of the chambers and singular burials were covered with soil, and today only the most recent burials or chambers are visible above the ground. During the centuries, many of these have been opened by curious visitors. Because church burial tradition ended in the 1760s and the church books reporting the ages of the buried, other coffins that were CT-scanned belong to newborns who died most likely during the late 1750s and early 1760s. Because the coffin lids had been opened already in the 1996 inventory, in 2013, we visually inspected the state of preservation of the coffins, human remains, and textiles after they were CT-scanned. Then we noted that Johannes Haustrammis was buried wrapped in plant fibre fabrics that are today highly fragmentary and poorly preserved. The coffin linen, which has now mostly disappeared, was attached to the coffin edges with red sealing wax (Fig. 12A). The coffin is located right below the hatch that leads to the under-floor space, and it is likely that it was originally

Fig. 1 Map of Finland with the sites of the Valmarinniemi and Haukipudas churches. Similar tablet-woven bands as the one studied from the Valmarinniemi site have been found in Karelian cemeteries at Hiitola and Kaukola in the Southeastern Ladoga region (Map based on https://fi.wikipedia.org/wiki/Tiedosto:Finland_locator_map.svg)

Fig. 2 The tablet-woven band with spiral tubes was found in three pieces. The photograph has been taken after µCT scanning. The metric scale refers to cm (Photograph by S. Lipkin)

located somewhere else in the crypt. The length of the coffin is 62 cm and width at the head 22.5 cm, by the shoulders 26 cm, and at the foot 15 cm. The height of the pine coffin is 14 cm, and it has six lathe-made legs. On the body a wooden doll 25 cm in height, was found. However, former Vicar Timo Holma has said that the doll was originally in another coffin [41]. The newborn has a floral wreath on his head and shoulder, and he holds one in his hand.

Computed tomography

Computed tomography (CT) is a non-destructive imaging method that provides information about the internal structures of an object in three dimensions (3D). Non-clinical CT imaging systems have been designed for various sized objects with diameters ranging from centimetres to tens of micrometres, having respective resolutions from the millimetre range to a few hundreds of nanometres. In addition, X-ray energy and power need to be optimised so that part of the X-rays attenuate in the sample and cause intensity changes in the X-ray detector reflecting the structure and density of the imaged object. These images are called projection images, and they are typically collected over 180 or 360 degrees around the object. Combining all projections from multiple directions by employing a reconstruction algorithm, such as FDK [42], we can create a stack of cross-sectional slices and use it to create a 3D representation of the imaged object [16, 43–45].

Fig. 3 A piece of cotton fabric found on a bronze ring that was sewn on a simple tablet-woven belt. The photograph has been taken after µCT scanning. The metric scale refers to cm (Photograph by S. Lipkin)

The main advantage of CT imaging is that it is a non-disruptive imaging technique. It enables virtual visual inspection and slicing of the investigated object in any direction or making parts transparent to see the internal structures of the object non-destructively. This is important when investigating fragile items that should not be damaged or opened. Moreover, this volumetric 3D data from µCT can be used not only to visualise items qualitatively, but also to measure morphological features quantitatively [44–46].

We used three different CT modalities. Several factors need to be considered when selecting an appropriate imaging modality: the size of the object, any dose restrictions, the required resolution, and the material properties of the object. Conventional CT used in medical environments to take full-body scans of humans, typically producing datasets with a voxel size between 0.5–0.1 mm, while micro-computed tomography (µCT) devices generally are capable of achieving voxel sizes of < 100 μm and even < 1μm on nano-focus systems [43, 45, 46]. Most CT systems utilise geometric magnifications, which require placing the sample as close as possible to the source to yield the best attainable resolution. This can restrict the attainable spatial resolution with larger objects as the object needs to turn inside the machine around its axis without colliding with either source or detector [47]. A smaller voxel size usually results in a smaller field of view, meaning a smaller imaged area. A resolution of few micrometres is achievable with most μCT systems for samples with a diameter of a few centimetres. However, different devices have their own specific limitations on the size of scanned object you can fit inside the device, mostly due to the detector size and the geometry of the source and detector. Some devices have more freedom in the moving of source and detector closer or further, which allows fitting larger, even human head-sized objects and still retain high resolution. Furthermore, capturing the smallest of details with the highest resolution requires higher doses, longer imaging times and might even require multiple scans stitched together. In summary, larger, human-sized samples are most suitable for imaging with clinical CT, while smaller samples or ones that require high resolution need to be imaged with a μCT device or X-ray microscope. Once a suitable magnification is found, the X-ray energy needs to be optimised for the imaging studies. Hard or high-energy X-rays penetrate even denser objects such as metallic items more easily. On other hand, materials with low X-ray absorption such as textiles require lower imaging energies or softer X-rays. These aspects need to be considered when planning imaging protocols. While CT is non-destructive, high doses of X-rays can harm living tissue and break DNA [6, 48]. For this reason, it is advisable to take any needed ancient DNA or any other molecular samples before scanning. However, in the scope of archaeological studies and objects, radiation dose is not a similar limiting factor as with living patients or in vivo imaging and it is advisable to aim for higher image quality even if it increases the dose. Accurate, high-resolution scans of large volumes can take as much as over 24 h. Therefore, it is understandable that this kind of high-resolution imaging with long scan times is not yet applicable to living specimens similarly.

Results and discussion

Cotton fabric

Despite careful handling, many archaeological textiles are fragile and break down easily. In addition, most archaeological textiles have soil or corrosion products on their surface that may make it difficult to study them without cleaning. Moreover, cleaning can itself be damaging for such textiles. The cotton fabric we studied is fragile and every time it is taken out of its storage box, tiny pieces break down. One of the advantages of CT technology is that in the resultant images, extra dirt or substances may be digitally removed from the surface and fragile items can be easily and quickly viewed in 3D and cross-sections multiple times. In our research, the fabrics needed to be scanned in the vertical position. To prevent the fabric moving in the scanner, all the fabrics were first covered with parafilm and then carefully embedded in dental wax. Preparing fabrics for scanning and opening the wax pockets requires a gentle touch, and it was clear that some of the textile fragments we were interested in imaging were not sturdy enough to be prepared for scanning.

The main reason for choosing the cotton fabric for scanning was that initial transmitted-light microscope analysis suggested that the fabric was likely cotton [49]. We were interested in exploring the potential of both nano and μCT imaging to study weave, yarn, and fibre structures. The preserved fragment was suitable in size for the desktop μCT device we used (SkyScan 1272, Bruker microCT, Kontich, Belgium). The system was operated to produce softer X-rays by using a tube voltage of 50 kV and current of 200 μA. An anisotropic pixel size of 6.7 μm was selected to fit the wide sample in the μCT system with a 0.25 mm aluminium filter. The projections were acquired over 360° with 923 total projections, 4000 ms exposure time, and a frame averaging of 3. Cross-sectional images were reconstructed for the sample using NRecon, CT reconstruction software (v1.6.10.4, Bruker microCT). The same device and settings were used to image the tablet-woven band. The produced images were adequate for structural analysis and segmentation [24].

However, the accuracy was not sufficient for individual fibre-scale analysis. For this reason, a small fragment of the same fabric that had fallen off the fabric while it was handled, sized about 1.5 × 1.5 mm, was imaged in a test tube with a high-resolution nano-scale X-ray microscope device (SkyScan 2214, Bruker microCT, Kontich, Belgium). The system was operated at a source voltage of 50kV and a current of 200 μA. An anisotropic pixel size of 700 nm was selected without additional filtering. The projections were acquired over 360° with 2401 total projections, 2700 ms exposure time, and a frame averaging of 2. Then the sample was computationally reconstructed into cross-sectional slices using the NRecon software (v1.7.5.9., Bruker microCT). This allowed us to confirm the cotton identification (Fig. 4). It is also possible to segment all fibres individually and inspect the fibre properties in detail [24]. The advantage of nano-scale imaging is that in one viewing you may see the fibres in both 3D and in 2D cross-sections. This saves time on extensive sample preparation. In addition, the reproduced still images

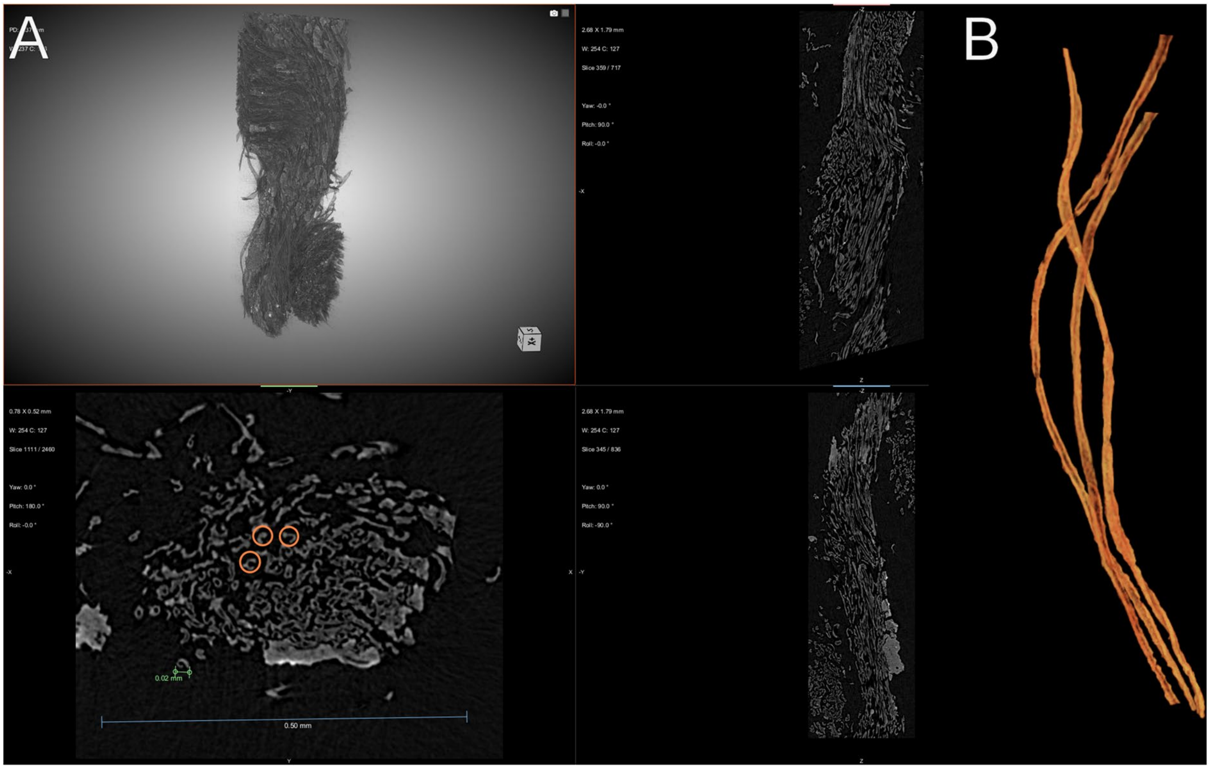

Fig. 4 **A** Nano-computed tomography scanned cotton. A single warp yarn of the textile is shown to be 0.5 mm thick with individual fibres having approximately 0.02 mm diameters. After a scan, we can see the sample in 3D or look at the different cross-sections from different planes. Cross-sectional image with orange circles indicates individually segmented fibres that also show the C-shape. **B** Internal segmented fibres can then be shown without the surrounding tissue to reveal the morphology of the fibre in more detail (Images by V-P. Karjalainen)

and videos are always viewable on the desktop and easily sharable. Today, desktop μCT systems are increasing in availability, with most of the European universities having some kind of CT device for research.

Tablet-woven band

Whereas the cotton fabric has a simple plain weave, the imaging of the tablet-woven band proved that one of the greatest benefits of μCT is in imaging complex textile structures. Tablet weaving is a method for weaving narrow fabrics such as ribbons. Weaving is done with thin often wooden or bone planks called tablets that have two to six holes in them. The warp yarns that will form the body of the ribbon are taken through the tablet holes. The warp yarns form an opening, the shed. Weft yarn is taken through the shed and the tablets are turned which forms a new shed and binds together the warp yarns and essentially form the band. Tablet-woven bands can be simple, but talented weaver can create colourful and patterned ribbons. A pattern can be woven, for example, by using warp yarns of different colours and turning the tablets to different directions. This lifts the warp yarns of different colours on top of the woven band in different sequences and forms the pattern. These turns can be seen even on top of a monochrome archaeological find. The most straightforward benefit of the μCT imaging of a fragment of a tablet-woven band is that it is possible to see the scan from different angles and from all sides (Fig. 5). We were able to reconstruct how the band was originally woven and weave a reconstruction (Fig. 6).

Handling the fragile fragment itself for a prolonged period is not possible without damaging it. The tablet-woven band was made from thin yarns (0.3 mm) that were packed close to one another (57 cm warp yarns/cm and 15–16 weft yarns/cm). It was exceedingly difficult to understand the characteristics of the yarns and the weaving pattern only looking them through a stereomicroscope or based on macro-scale photographs.

The μCT scanning enabled us to see the internal structure of the textiles. Such features include the tubular selvedges, where the weft goes around the outermost warp yarns, turning them towards the centre of a band, forming a looped edge (Fig. 5C). The looping structure of the weft and warp yarns becomes clear and visible when individually segmented yarns are viewed in 3D and horizontal cross-sections [24]. In the case of the Valmarinniemi

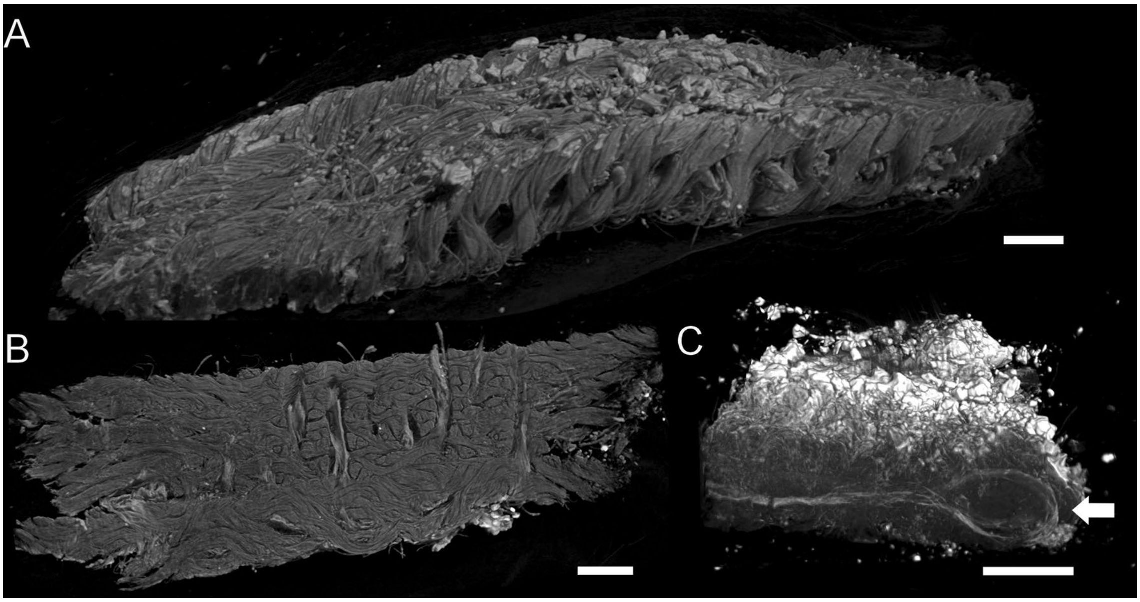

Fig. 5 **A** 3D micro-computed tomography image of a tablet-woven band. **B** Cross-sectional image shows how yarns intertwine inside the band. Looking at the cross-sectional images from different depths and orientations can show us the whole internal structure of the sample. **C** The looping structure of the weft yarn is visible, indicated with an arrow. Scalebars 1 mm. (Images by V-P. Karjalainen)

Fig. 6 Reconstruction of the band woven by Hanna-Leena Puolakka. The metric scale refers to cm (Photograph by S. Lipkin)

band, the µCT scanning helped to establish that there was only one 14 mm wide band broken in two, with tubular selvedges on both edges of the band. In addition, it was easy to see that there was only one weft running continuously from side to side within the band. This helped to establish that the band was not used as a finishing band for a fabric, which would include more weft yarns, which would not travel continuously within the band. The diagonal pattern is also easier to observe in the µCT images than in photographs. Also, it is possible to follow the path of each singular warp yarn within the band. Especially in cases where the outer surface of the band is somehow distorted or not visible, this gives greatly beneficial information on the weaving technique used, such as the number of cards, how many warp yarns were used per card, the turning sequence of the cards, and a possible pattern. This requires new ways of thinking from a weaver, since it is not usually possible to see within the band and weavers are not used to envisioning the inner structure in this manner.

When observing the band with the naked eye, the weft yarn was almost completely invisible. On the broken edges, it was only possible to see the fractured end of the bluish-green weft in a few spots. The µCT scan revealed its thickness, spin direction, and weave density. Based on the image, it was also possible to view the yarn's preservation. The weft had poorer preservation than the warp yarns. This may be due to different dyeing processes. In the scanning, the weft is lighter in colour, suggesting that due to preservation of the dye solution's metal component, the weft is of denser material than the warps. It is possible that a different kind of metal mordant (such as iron, copper, aluminium, tin, or zinc) or more of it was used in the dyeing process than in the red, blueish-green, and yellow/white warp yarns. The colours are not visible in the scanning and were observed under the stereomicroscope at the broken edge of the band (Fig. 7).

Because different colours of warp yarns usually play the key role in forming a tablet-weaving pattern, knowledge of the structure alone is not usually enough to reconstruct a whole pattern. Together with even partial colour information for the warp yarns, understanding the structure can however give important clues and in the end enable the reconstruction of the pattern. This was the case with the tablet-woven band from Valmarinniemi, where the µCT images together with the presence

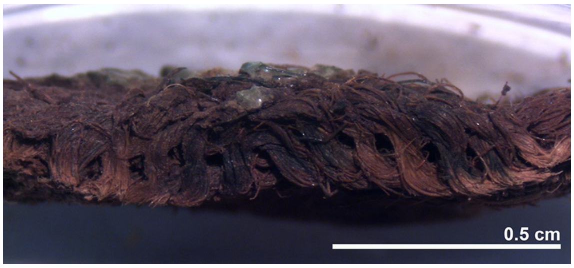

Fig. 7 In the tablet-woven band different colours of the warp yarn were visible in the broken edge when viewed under the stereomicroscope (Photograph by S. Lipkin)

of some colour information on some of the strands were crucial in reconstructing the turning sequences of the tablets and, in the end, the pattern itself.

In addition to two fragments of the tablet-woven band, we also scanned the textile piece attached to the spiral tubes (Figs. 2 and 8). As most CT devices are based on the attenuation of X-ray by material to generate the projection images and the X-ray intensity is closely related to the atomic number and concentration of that element [46], there was a large contrast difference between the spiral tubes and the textiles. If the difference between materials of interest is too great, as, in this instance, textiles and metal, the textile is not well visible. Furthermore, metal can cause streaking artefacts that further distort the textile image quality, as seen in Fig. 8A as streaking shadows coming from the metal spirals. Thus, different imaging protocols for each material should be used to attain accurate information on both and the results combined in post-processing for the best result. While the spirals were clearly visible (Fig. 8B), the technology used did not allow us to review the fabric around spiral tubes to a detail (Fig. 8A). Therefore, it should be further noted that while imaging varied materials together can prove difficult and lead to only adequate results, mostly for the less-attenuating material, it can be sufficient depending on the required application of the sample imaging.

Newborn's coffin

The newborn's coffin was CT-scanned at Oulu University Hospital using a Somatom Definition Flash dual source CT scanner (Siemens Healthcare, Forchheim, Germany) at 100kV and 140kV with a tube current of 205mAs and 157mAs, respectively, an in-plane resolution of 0.68×0.68 mm, a slice thickness of 0.5 mm, exposure time 285ms, focal spot size 1.2, and a convolution kernel l31f\3. The dual source CT scanner setup halves the time required for each scan, while also reducing imaging artefacts from metal objects, such as metal implants [50]. Furthermore, it is possible to record dual energy information for further material analysis, when the two tubes are operated at different voltages. This kind of dual source CT device is beneficial in-patient care, where short imaging times are crucial. While dual source CT is not necessary for archaeological studies when compared to a more conventional CT, the artefact reduction and shorter scanning times are beneficial. In this study, we used the dual source CT scanner as it was the one available to us at the time. Within the archaeological context, this medical imaging device is suited for acquiring full-body images of human remains. The acquired images are also suitable for studying coffin structures and metal items but studying lighter ones such as textiles is more challenging (see also [51]). The images were studied using Osirix MD (version 12.5.3) and Dragonfly software, (Version 2020.2, Object Research Systems (ORS) Inc, Montreal, Canada).

As seen in the cross-section image of the coffin, the CT has captured the year rings of the wood used for the coffin (Fig. 9). The coffin structure, bone and mummified tissues are also easy to observe. Fabrics such as that of the wooden doll can be seen as layers.

Due to the chosen imaging protocols, in 3D, making fabrics visible poses considerable difficulty as their density is close to that of air. They therefore remain mostly transparent. However, with optimizing the image parameters, we were still able to visualise the mostly transparent clothing in the coffin. We observed the layers of fabric on the feet of the newborn but did not see any signs of stockings. The filling of the pillow seems to be made of hay. Some of the newborn's organs have been preserved, and the soft tissues confirm that he was a boy. It is easy to study the details of the metal structures of the floral accessories and see how wooden and iron coffin nails were used to construct the coffin as well as how sealing wax and pins were used to attach fabrics (Figs. 10 and 12). There were some ring artefacts around the coffin that appear as half transparent circles around the middle of sample due bad detector pixels and beam hardening artefacts due to selective attenuation of polychromatic beam that appear as dark streaking bands on the nails. However, these were only minor and did not significantly reduce the image quality. With different reconstruction software and skills of the software users, it is possible to reconstruct a variety of images that provide complementary information.

For this article we decided to concentrate on the wooden doll lying on the body (Figs. 11 and 12). The doll is dressed in a roughly sewn coarse plant fibre fabric shirt that looks like it may have been made by a child (Fig. 11B). The shirt has sleeves, but as the CT images reveal, underneath, the doll has no arms (Fig. 12). In the CT images the surface of the wood is clear, and it is

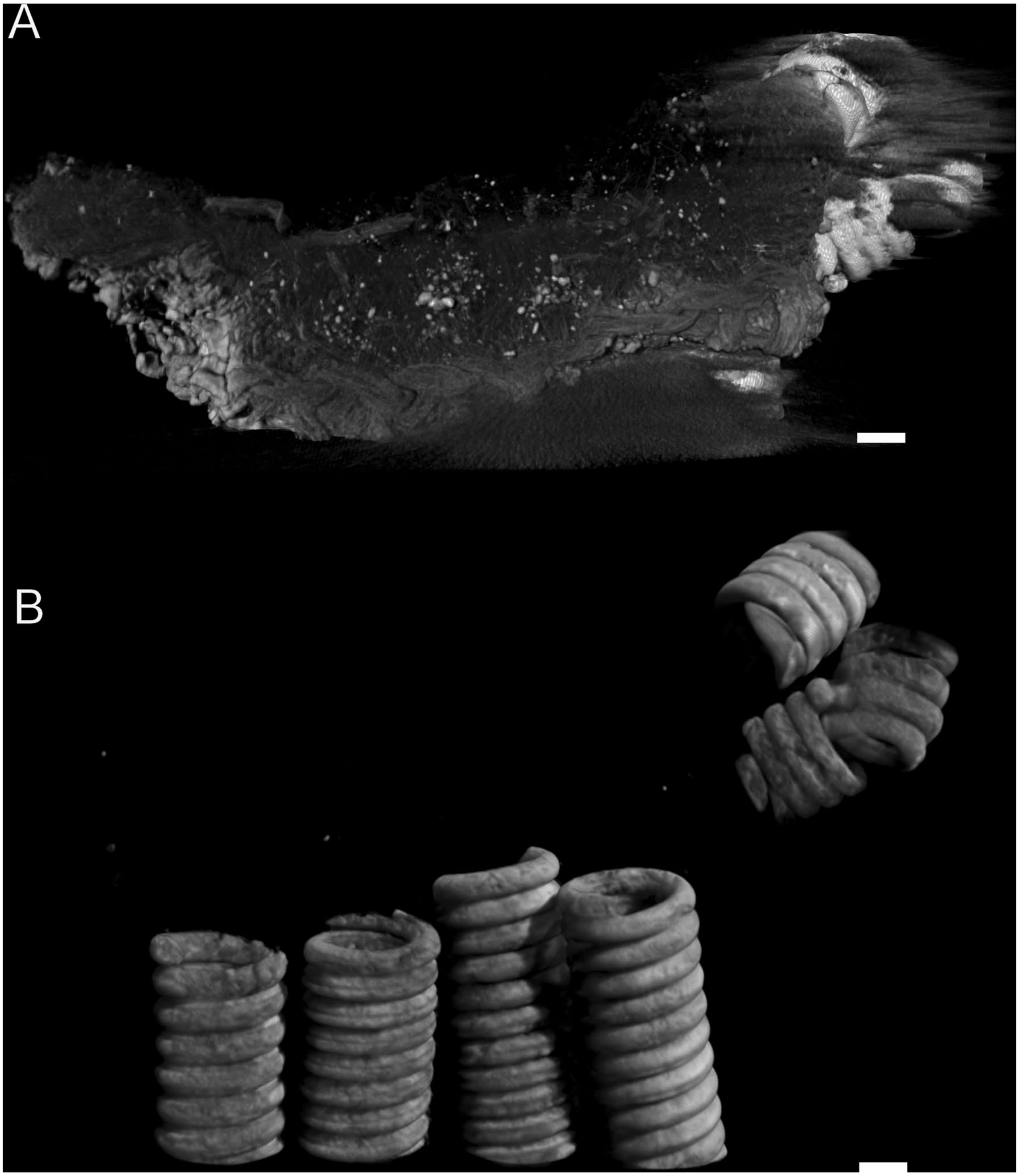

Fig. 8 A 3D micro-computed tomography image of the dense spiral material with textiles around it. The low energy required to capture the details of the textile causes streaking artefacts around the denser spiral material, reducing the image quality of the textile. **B** The denser spiral material is clearly visible after removing the low-attenuating textile around it by simple image thresholding. Scalebars 1 mm. (Images by V-P. Karjalainen)

possible to see what the face of the doll looks like. The doll is carved from one branched piece of wood and on the body has two small holes with pins beaten inward from the back (Fig. 13). The purpose of the pins remains unknown, but grooves around the doll's body suggest that the pins probably attached some sort of strings around the body.

Denser materials are lighter in CT images. Already while looking through the holes, it was apparent that something made of metal was inside them.

Lessons learned, new modalities, and future visions

Our case studies show that computed tomography has a significant potential in the study of archaeological

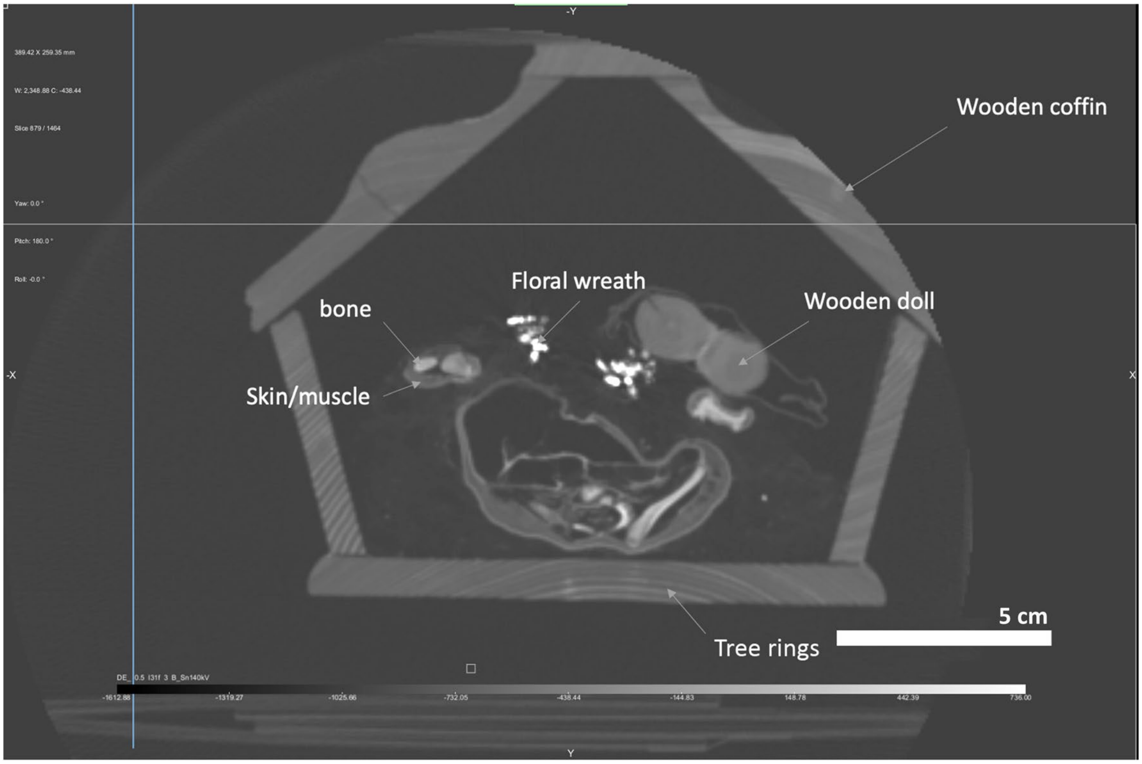

Fig. 9 Cross-section of the newborn's coffin imaged with clinical computed tomography (CT) device. Denser materials are coloured more brightly white in the image. This tells us that the floral wreath seen in the image includes some high-attenuating material such as bronze or iron inside it. Bones are another highly attenuating material easy to see inside the coffin. Less-attenuating materials such as wood and skin share similar attenuating profiles. Reconstructed with Dragonfly ORS software (Image by V-P. Karjalainen)

textiles. It is important to choose the optimal technology and imaging protocol for each piece of fabric to acquire images that are adequate for research purposes. Depending on the research questions, it is possible to image the whole sample at a lower resolution (both CT and μCT) or focus on a single area for high-resolution imaging with a small voxel size (μCT). In addition, it is possible to use quick, low-dose protocols to scan multiple items or focus on fewer items with higher resolution.

As a different option to normal CT imaging, phase-contrast imaging is a method based on measuring the phase difference in photons instead of attenuation when the photons interact with the material. This technique could provide a preferable method in the future for imaging low-attenuating materials, and has already been used to some extent with archaeological textiles [52]. However, phase-contrast imaging has usually been done in synchrotron facilities. These may be challenging to access and laboratory CT devices capable of similar image quality were sufficient for these studies.

Conclusions

In this paper we have outlined some benefits and limitations of CT methodology in research on archaeological textiles. CT provides the possibility to non-destructively visualise challenging objects in 3D with a richness of internal features that is not otherwise visible or researchable using conventional 2D microscopy methods. Furthermore, archaeological textiles may be covered with dirt that makes the analysis of their properties difficult, and the fragility of these textiles can prevent cleaning. It is possible to digitally remove dirt and patina virtually from the surface of the fabrics, or in the case of coffins, digitally "cut" the coffin lid or wall from the image and observe the internal space. This enables easy and quick reconstructions of, for instance, how textiles were woven, or clothes made. As the image intensity reflects the apparent density of the object, adjacent items are easily separated based on their varying densities. Segmentation of individual fibres, yarns, or items makes visualisation even easier. The images have no colour information.

As rule of thumb, clinical CT can be used for imaging human-sized objects, such as coffins and mummies,

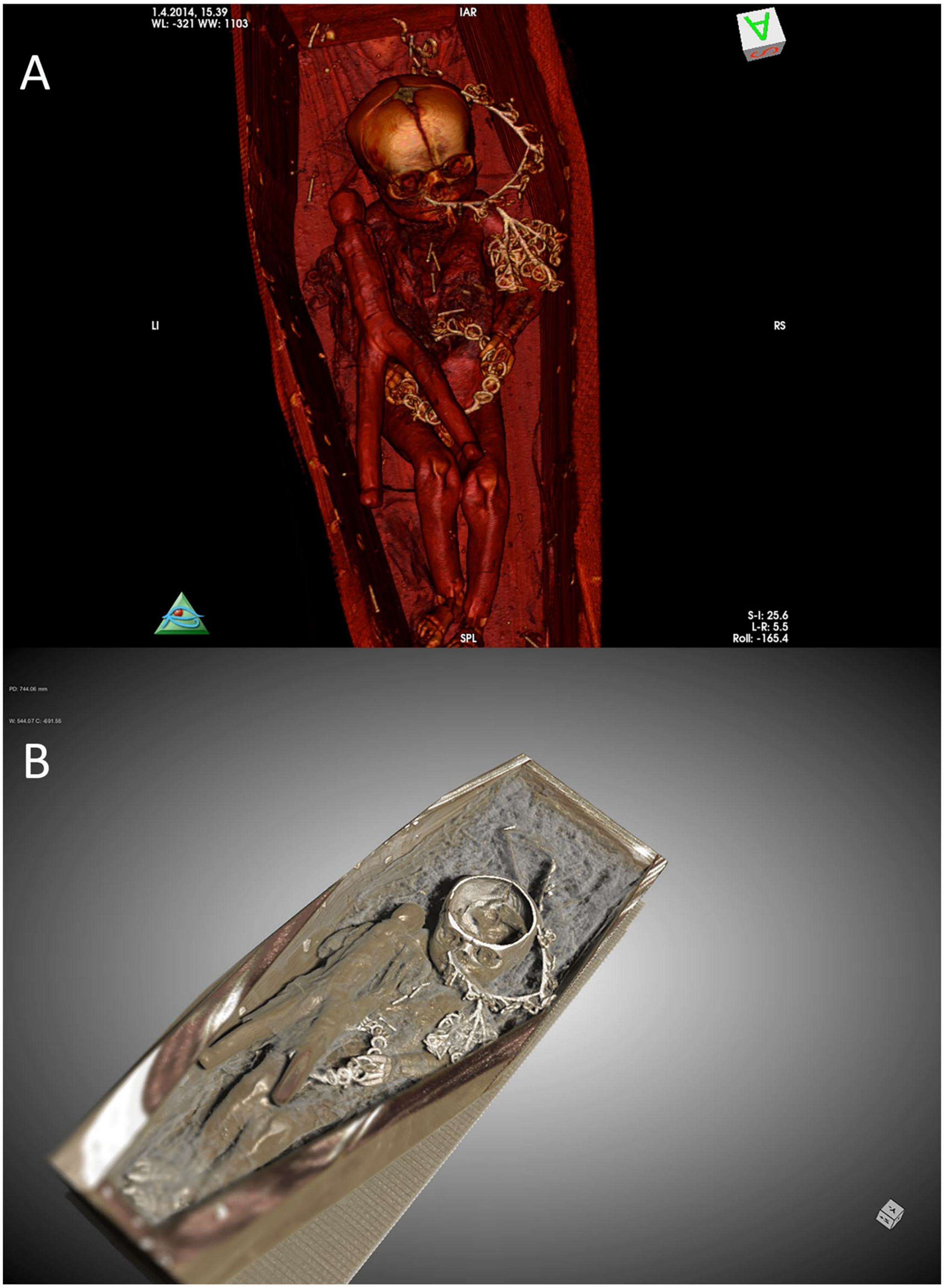

Fig. 10 Different views of the newborn's coffin. **A** With Osirix-software it was generally more difficult to view fabrics and other organic remains, but mummified human remains, and metal accessories are easily seen (Image by S. Lipkin) **B** With Dragonfly software the pillow hay were observable, but the fabrics still remained largely invisible, probably also because they were poorly preserved (Image by V-P. Karjalainen)

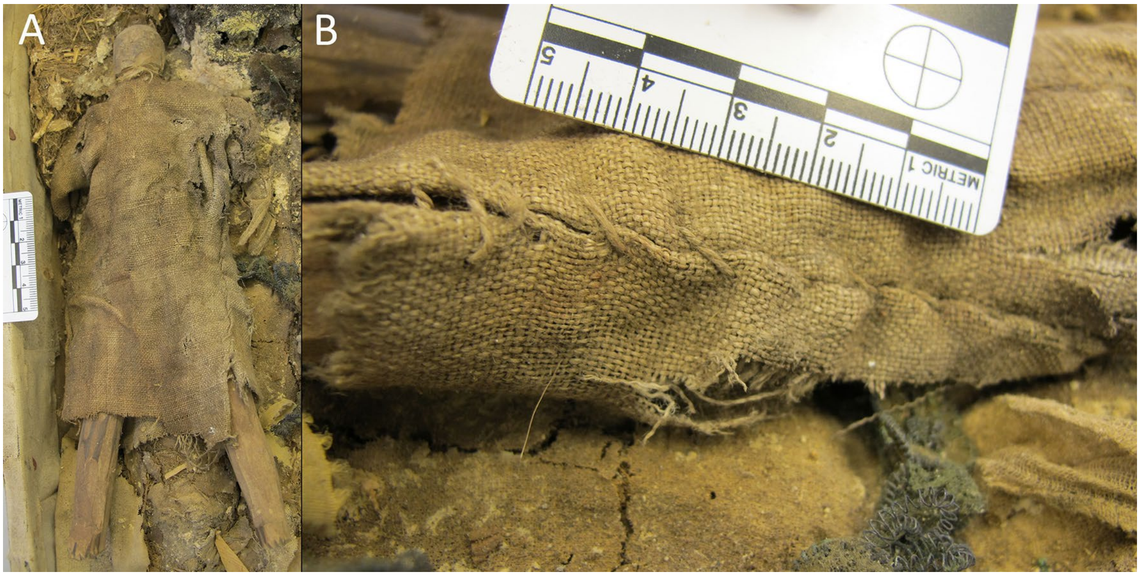

Fig. 11 **A** The wooden doll was found on the body of the newborn. **B** Its shirt is made from a piece of coarse fabric and the sewing stitches are long. The metric scale refers to cm (Photograph by S. Lipkin)

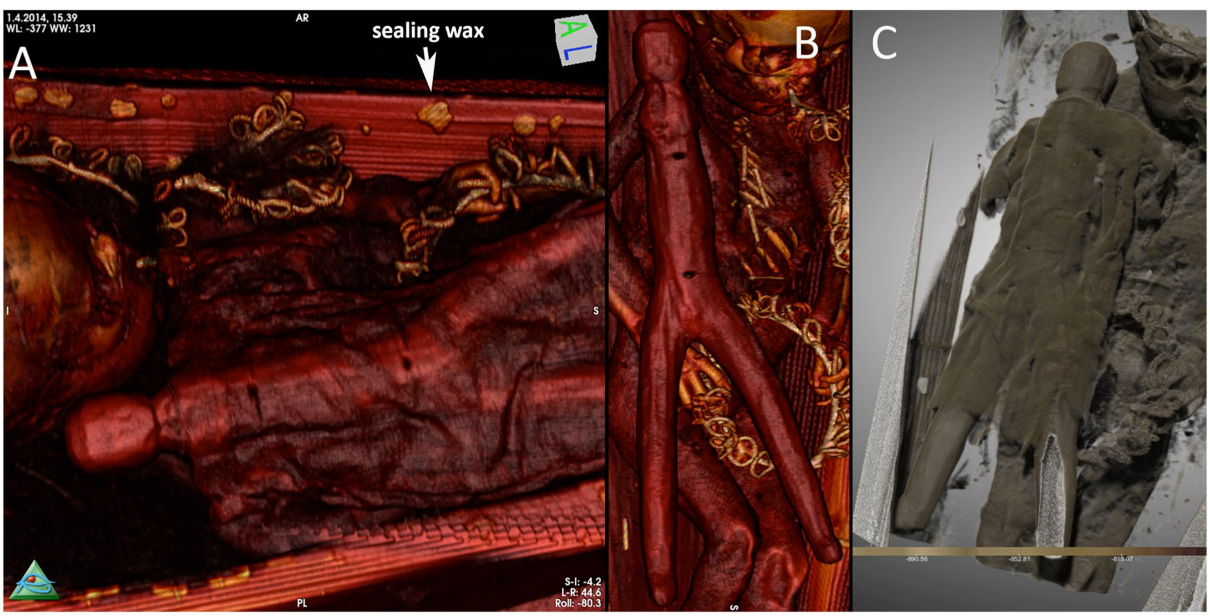

Fig. 12 The rectangular coarsely sewn fabric on the doll's body has sleeves, but the CT images reveal that underneath, the doll does not have any arms. Two holes and grooves on the body are visible in all these images. Sealing wax is indicated with an arrow. **A** and **B** Images are reproduced with Osirix software (S. Lipkin). **C** Image is produced with Dragonfly software (V-P. Karjalainen)

in a sub-millimetre resolution. Clinical CT is suited for visualising fabric layers and observing how they were used, for example, inside a coffin. Furthermore, it is possible to observe fabric properties, but detailed yarn-based analysis is not possible. In our research, medical CT was more suitable for studying denser materials than textiles, which remained transparent. μCT, on the other hand, is adequate for yarn scale analysis, as it provides a more focused resolution option. μCT is most beneficial while studying complex fabrics, such as tablet-woven bands, fabrics covered with dirt, or those that are found in multiple layers. Nano-scale, a sub-micrometres resolution, is the option for smaller items, such as for studying the morphology of an individual fibre.

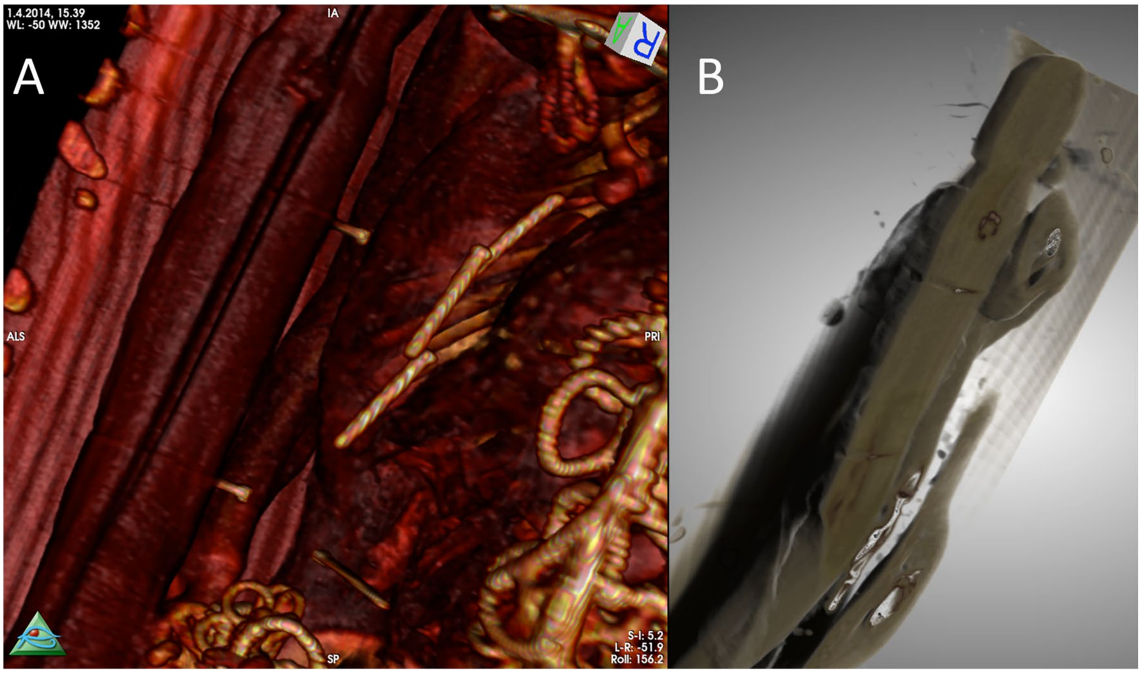

Fig. 13 **A** When the doll was inspected from the side, it was noticed that small pins were placed in the holes. Similar pins were used to attach the funerary attire to the deceased. Such pins were observed for instance below the doll (Image by S. Lipkin). **B** In the cross-section, the holes and the metal pins were also visible. In addition, the wood of the doll seems to have been split on one side; a place of a branch on the "elbow" of the doll is also visible (Image by V-P. Karjalainen)

CT is quicker and less laborious than conventional methods. For instance, fibre sample preparation is not needed and after scanning the items are readily available for viewing on a desktop. There is no need to take fragile textiles from their boxes. For colour information and coffin textiles, photographs aid interpretation. As CT technology is based on reconstructing visualisations, the produced images are influenced by the individual's software usage skills and visual perception of optimal viewing angles and settings.

Understanding the technical details of archaeological textiles is not irrelevant. Our case studies all provided information that is important in the reconstruction of wider cultural connections and social realities. Our knowledge of the medieval textiles from Northern Finland is very limited as there are only a few that have preserved. Most of them are from Valmarinniemi, where fabrics are preserved in only eleven burials and are as fragmentary as the μCT-scanned specimen. Because the fabric remains are small, they are suitable for μCT scanning and the benefits are unquestionable. Without the scanning, we would not have been able to study and reconstruct the pattern of the tablet-woven band and understand the characteristics of the yarns and pattern. The reconstruction of the band helped us to identify that the fragment we were researching was a piece of a belt, and we know that such belts have previously been found on the Karelian Isthmus. This may be the region where the belt from Valmarinniemi was made.

In addition, identifying cotton fibre in the plain-woven fabric was easy and fast and enables studying the fibre structure both from cross-sections and in 3D, which is not simultaneously possible with any other technology. To date, this fragment remains the earliest piece of cotton fabric from an archaeological context in Finland and shows that Asian luxury products were used at the far end of the European continent. This information is relevant when considering the lives of people in Late Medieval Northern Finland, how they related to the rest of the world, and from which trade routes they benefitted.

Imaging an entire coffin provides information on the full context and enables examination of the coffin structure and how it was prepared for burial. In addition to viewing the fabrics and other items that are visible when the coffin lid is opened, CT enables seeing below the upper textile layers. For this reason, we were able to study the sex of the newborn, see if he was wearing stockings, and above all, for this article, view the structure of the doll lying on the newborn's body.

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Author contributions

SL Conceptualised the research, reconstructed the clinically imaged data, conducted textile archaeological analysis based on the computed tomography, as well as wrote the original manuscript. V-PK Reconstructed and segmented the micro-scale CT images and wrote, reviewed, and edited the manuscript. H-LP Analysed the weaving structure of the tablet-woven band, wrote, reviewed, and edited the manuscript. MAJF Conceptualised the research, provided the micro-scale computed tomography scanning and wrote, reviewed, and edited the manuscript.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

The authors declare no competing interests.

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