Terahertz Imaging Modalities of Ancient Egyptian Mummified Objects and of a Naturally Mummified Rat

LENA ÖHRSTRÖM,[1] BERND M. FISCHER,[2,3] ANDREAS BITZER,[4,5] JAN WALLAUER,[4,5] MARKUS WALTHER,[4,5] AND FRANK RÜHLI[1]*

[1]Swiss Mummy Project, Centre for Evolutionary Medicine, Institute of Anatomy, University of Zurich, Zürich, Switzerland
[2]French-German Research Institute of St. Louis, Saint-Louis, France
[3]Physics Department, Philipps-Universität Marburg, Marburg, Germany
[4]Department of Molecular and Optical Physics, Albert-Ludwigs-University, Freiburg i Brsg., Germany
[5]Freiburg Materials Research Center (FMF), Albert-Ludwigs University, Freiburg i Brsg., Germany

ABSTRACT

During the last few years, terahertz (THz) imaging has been used to investigate artwork and historic artifacts. The application of THz imaging to mummy investigations is very attractive since it provides spectroscopic information over a broad frequency range and its radiation has proven to be harmless to human cells. However, compared with the current standard imaging methods in mummy imaging—X-ray and computed tomography (CT)—it remains a novel, emerging technique whose potential still needs to be fully evaluated. Here, ancient Egyptian mummified objects as well as a naturally mummified rat have been investigated by two different THz imaging systems: a broadband THz time domain imaging system and an electronic THz scanner. The obtained THz images are compared with conventional CT, X-ray, and magnetic resonance images. While the broadband THz time domain setup permits analyses of smaller samples, the electronic THz scanner allows the recording of data of thicker and larger samples at the expense of a limited spectral bandwidth. Terahertz imaging shows clear potential for mummy investigations, although currently CT imaging offers much higher spatial resolution. Furthermore, as commercial mobile THz scanners become available, THz imaging could be applied directly in museums or at excavation sites. Anat Rec, 298:1135–1143, 2015. © 2015 Wiley Periodicals, Inc.

Key words: paleopathology; mummy; diagnostic imaging; terahertz; computed tomography; magnetic resonance imaging

INTRODUCTION

Ancient mummies are immensely valuable in paleopathological research. They provide insights into the lives of our ancestors and the evolution of diseases (Aufderheide, 2000). Investigations of historic specimens should be as minimally destructive as possible to guarantee the integrity of these objects. Thus, noninvasive diagnostic imaging techniques such as X-ray, computed tomography (CT), and magnetic resonance (MR) imaging are

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*Correspondence to/Present address: F. J. Rühli, MD, PhD, Institute of Evolutionary Medicine, University of Zurich, Winterthurerstr. 190, 8057 Zürich, Switzerland. Fax: +41446350112. E-mail: frank.ruehli@iem.uzh.ch

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methods of choice (Aufderheide, 2000; Van Tiggelen, 2004; Rühli et al., 2007).

The feasibility of terahertz (THz) imaging of mummies, on the other hand, was just recently demonstrated (Öhrström et al., 2010; Fukunaga et al., 2011; Jackson et al., 2012). Its low energetic radiation is non-ionizing and thus harmless to human cells (Zeni et al., 2007). Broadband techniques are available, providing spectroscopic information in a broad frequency range (50 GHz to 3 THz), such as the THz time-domain approach (Bitzer et al., 2010). In this frequency range, many substances feature characteristic spectral absorption patterns, possibly permitting their identification. While spectral absorption features characterize the molecular composition of a sample, the phase and polarization of THz radiation transmitted through a sample rather reveal macroscopic structural details. Due to these favorable properties, THz imaging has been applied to recent studies of historical and cultural artefacts (Adam et al., 2009; Caumes et al., 2011; Bessou et al., 2012b).

In medical imaging, the strong absorption of water in the THz regime limits the penetration depth in human tissue to only a few millimetres, and thus applications are currently restricted to skin, tooth or thin tissue samples (Chen et al., 2011; Sun et al., 2011). The application of three-dimensional THz tomographic imaging of various isolated human bones has been shown recently (Bessou et al., 2012a). Water absorption, however, is not critical in the case of mummified tissue which usually has very low water content.

Two different technical approaches for THz imaging have been identified as being particularly well suited for these investigations: spatially resolved THz time-domain spectroscopy (TDS) and THz frequency modulated continuous wave spectroscopy (FMCW). The first technique, THz TDS, offers full access to the entire THz frequency band, but yet requires long scanning times. This approach is thus preferable for scanning smaller sample areas where the spectroscopic information or an overlap of results for different frequencies is expected to reveal important information. Terahertz frequency modulated cw spectroscopy imaging (THz-FMCW-imaging) is based on an electronic generation and detection of the signal. The system operates at a much narrower frequency band, which permits faster scan times at the expense of spectral information. This approach is thus better suited for scanning larger sample areas where the full spectroscopic information is expected to be less crucial. As FMCW measures both intensity and corresponding phase information, it provides information on the internal structure of the object under consideration, offering a potential data source for the inspection of artwork and historical objects. Further details of the technology and system specifications can be found elsewhere (Fischer et al., 2010).

Here, we evaluate the potential of the different THz technologies for investigations of mummified samples and identify further technical improvements required in order to establish THz technologies as a complementary tool for current mummy imaging.

MATERIALS AND METHODS

Ancient Egyptian mummified objects including two artificially embalmed human hands and one embalmed and wrapped human foot from different individuals (ex-collection of the Musée d'Orbe, Switzerland, radiocarbon dated to ca. 1500–1100 BCE), an embalmed mummified fish (private collection, undated, ancient Egyptian time period); and a naturally mummified rat (private collection, estimated 17th–20th century) were examined by THz imaging. An electronic three-dimensional THz FMCW scanner (SynView GmbH, Germany) was utilized at the French-German Research Institute of Saint-Louis (ISL), France and at SynView GmbH, Bad Homburg, Germany. The system operates in the 230 to 320 GHz frequency range. A second emitter/detector set operating in the 70 to 110 GHz range was employed for comparison measurements. These measurements were compared with previously acquired data using a broadband THz TDS system in transmission configuration at the Freiburg Materials Research Center, Albert-Ludwigs-University, Freiburg im Breisgau, Germany (Öhrström et al., 2010).

The THz data were compared with conventional X-ray, CT, and MR images. X-ray and CT images (Philips Brilliance CT 40; imaging parameters: 0.67–2 mm slice thickness, 512 × 512 matrix size, 120–140 kVp tube voltage, 72–131 mA tube current) were performed in the Balgrist University Hospital, Zurich, Switzerland; MR images were realized using a three-dimensional ultra-short-echo time (UTE) sequence (Nielles-Vallespin et al., 2007) on a standard 1.5T clinical MR imaging system (256^2 matrix; 32,768 projections, nonselective radiofrequency pulses of 60 μsec duration; TR = 10 ms; minimum echo time: 70 μsec; acquisition time: 3 min–2 h; Magnetom Avanto, Siemens AG, in Erlangen, Germany).

Postprocessing of X-ray, CT, and MR image data was performed using OsiriX-64 bit version 3.9.4. The THz images represent the pure total THz transmission or reflected intensity at selected z positions. The terahertz pulse delay image illustrates the pulse time delay, which corresponds to the optical density of the investigated sample.

RESULTS

Prior research using broadband THz TDS on a mummified hand and fish (Fig. 4; Öhrström et al., 2010) and a mummified rat (Fig. 5a,b) found that the technology's long acquisition times (several hours) and limited penetration depth limited its suitability for analyses of larger objects. By employing the FMCW scanner, even thicker and significantly larger samples such as a mummified foot can be investigated in lateral and anterior-posterior projections (Fig. 3). Notably, the system permits simultaneous transmission and reflexion image acquisition.

Tissues were distinguishable in all samples. Bone and tendon can be discriminated from surrounding tissue. Nevertheless, especially in areas containing superimposed structures, differentiation between the skeletal elements can be challenging. For instance, a THz transmission image of an Egyptian hand at 100 GHz is shown in Fig. 1. Since the hand is in a cramped position clear differentiation of the anatomical structures remains difficult, even in the correlative X-ray image. However the outlines of several phalanges as well as remains of the superficial flexor tendons are visible.

Figure 2 depicts a THz image of the other Egyptian hand. The phalanges as well as the metacarpophalangeal joints of digits I and II are visible. Some metacarpal

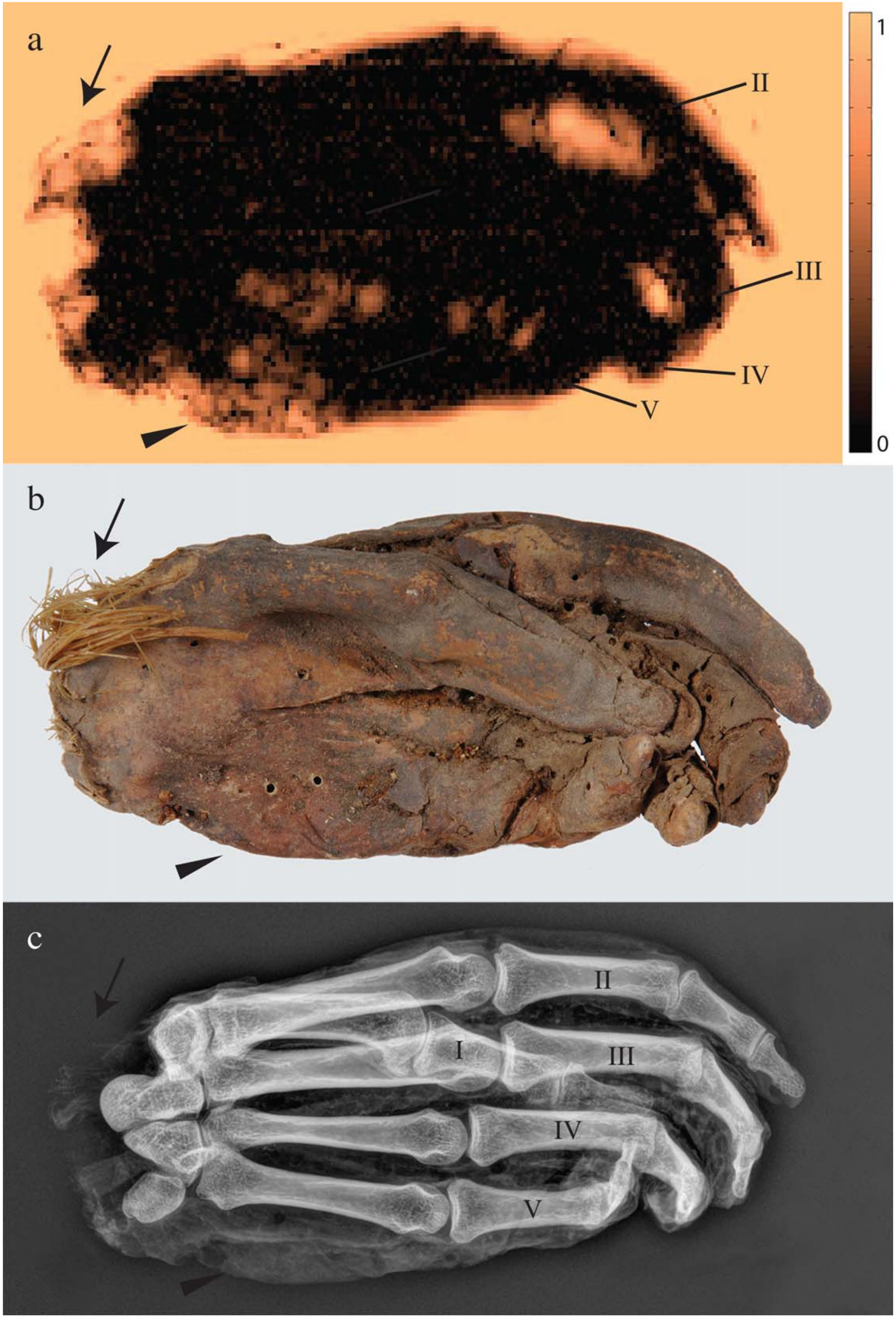


Fig. 1. Ancient Egyptian artificially mummified human hand (no. 1), unwrapped, **a**) Terahertz transmission image at 100 GHz; **b**) photo, **c**) corresponding X-ray image; roman numerals indicate the respective phalanges; arrows: remains of the superficial flexor tendons, arrowheads: skin soaked with embalming resin. THz System: electronic THz scanner.

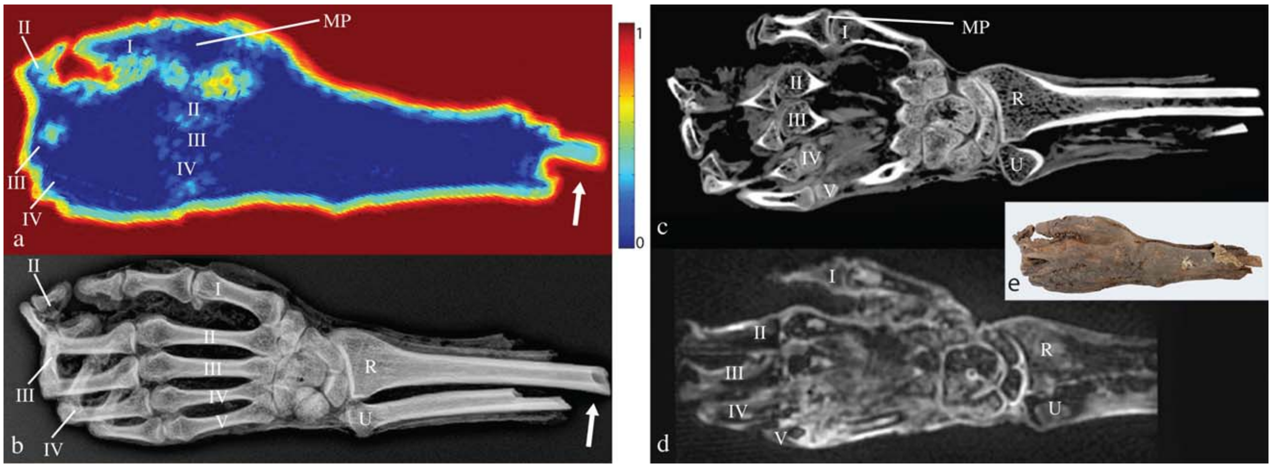


Fig. 2. Ancient Egyptian artificially mummified human hand (no. 2), unwrapped, **a**) THz transmission image at 100 GHz, **b**) X-ray, **c**) CT Image, **d**) MR Image, **e**) photo; arrow: note the clear differentiation of the radius in the THz image at the proximal unveiled edge, R: radius, U: ulna MP: metacarpophalangeal joint, roman numerals indicate the respective phalanges/metacarpal bones. THz System: electronic THz scanner.

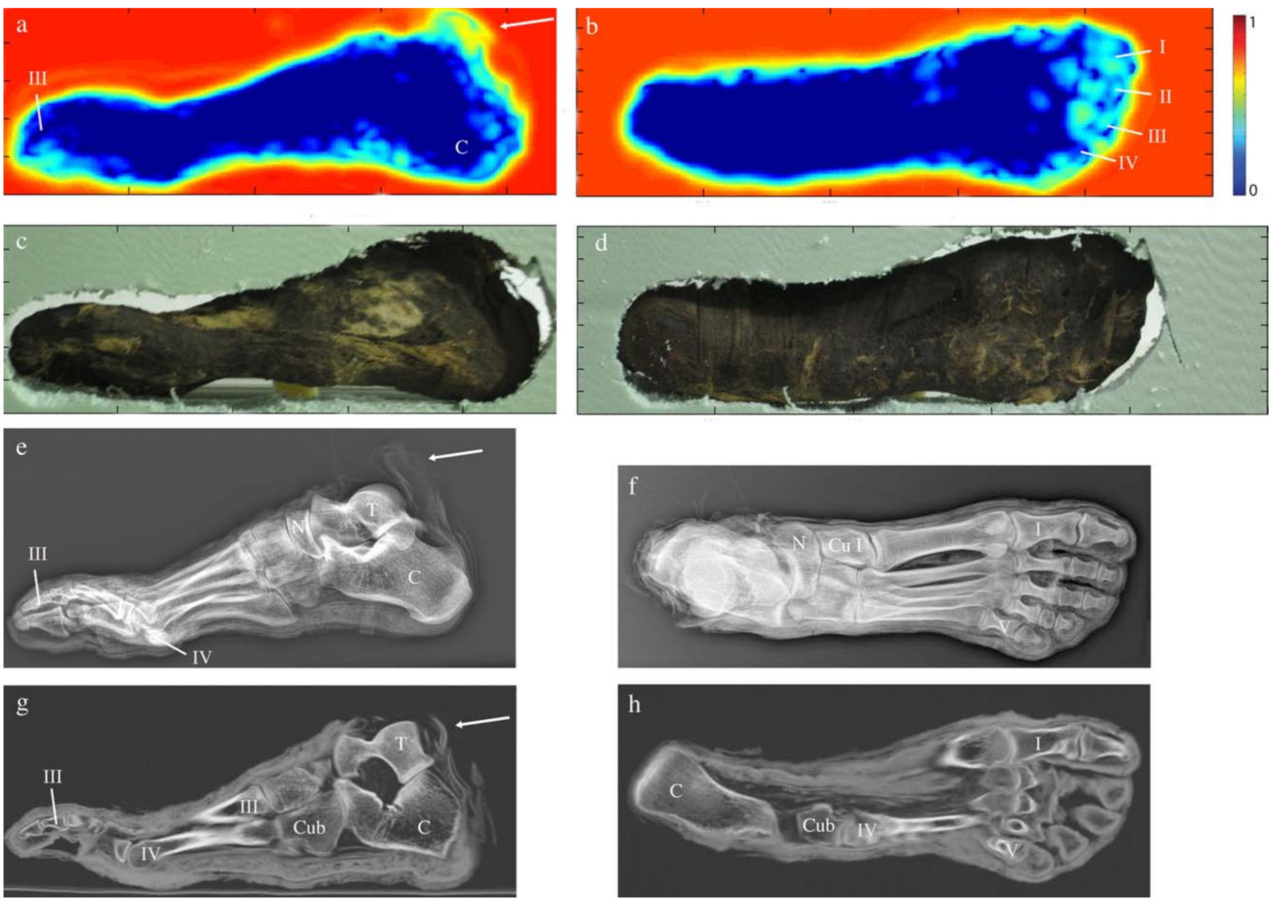


Fig. 3. Ancient Egyptian artificially mummified human foot, wrapped, side view, **a**) THz transmission image at 100 GHz, side view and **b**) bottom view, **c**), **d**) foot as seen in THz setup; fixed in polystyrene, **e**) X-ray side view, **f**) X-ray bottom view (X-ray image is flipped vertically, for better comparison with THz images) each with indication of window setting; **g**), **h**) correlative CT images; arrows: remains of Achilles tendon, C: calcaneus, T: talus, N: navicular bone, Cub: cuboid bone, Cu I: cuneiform bone (medial cuneiform bone), Cu III: cuneiform bone III (lateral cuneiform bone), roman numerals indicate the phalanges/metatarsal bones. THz system: electronic THz scanner.

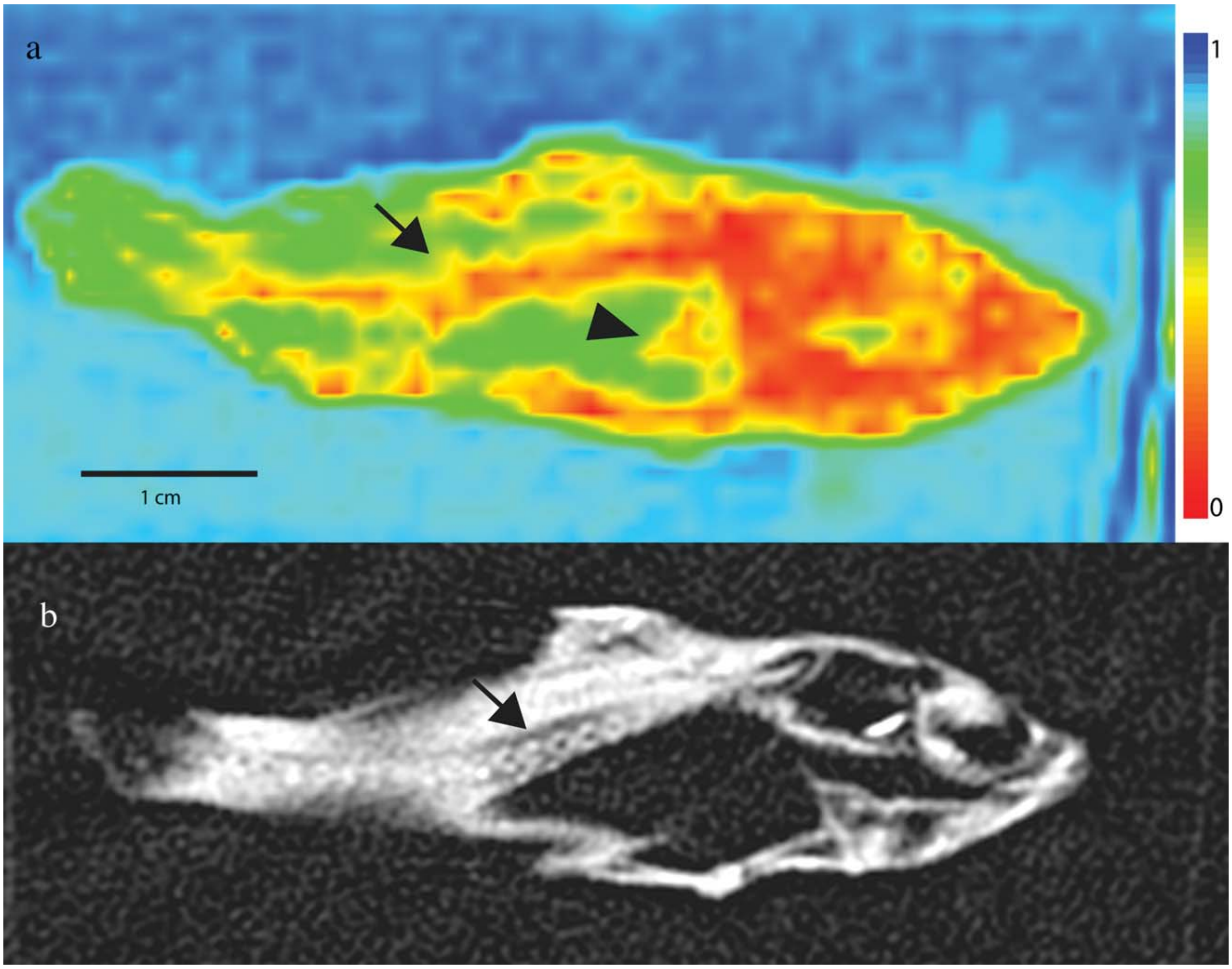
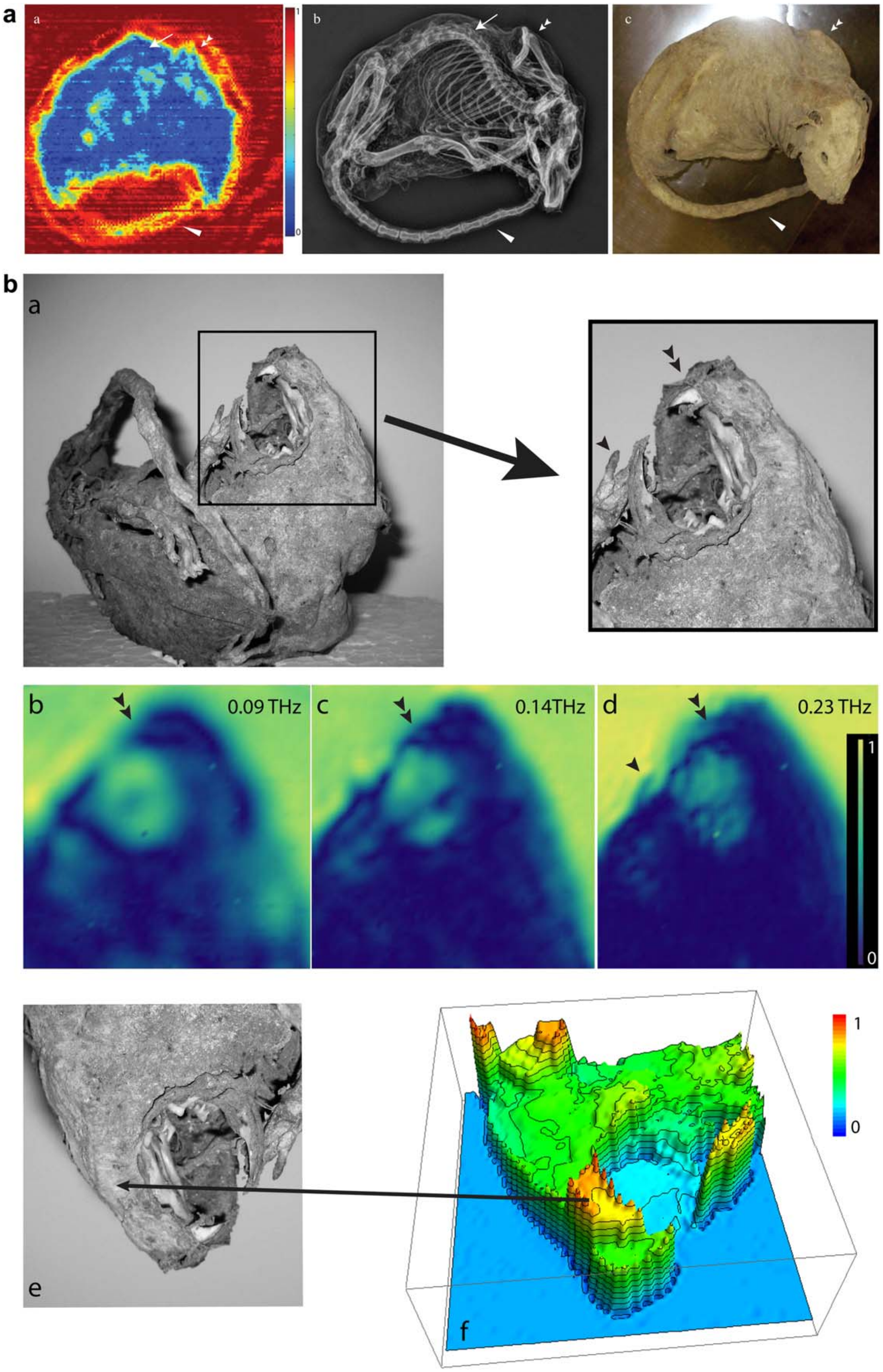


Fig. 4. Ancient Egyptian artificially mummified fish, **a**) THz transmission image at 0.43 THz, **b**) correlative CT image; arrow: vertebral column, arrowhead: note the visibility of the pectoral fin in the THz image. THz System: broadband THz TDS system.

bones can be distinguished, though only very vaguely. Whereas the distal ulna and radius are not visible, the unveiled proximal end of the fractured radius is clearly identifiable as it attenuates THz radiation only slightly while uncovered. This implies that not only bone is responsible for the high attenuation of THz waves, but also skin and probably the embalming resin. In correlative X-ray, CT and MR images most of the anatomic structures can be easily seen. In MR imaging however, the resolution remains unsatisfying.

Figure 3 shows transmission images of the Egyptian foot at 100 GHz. The phalanges as well as some of the interphalangeal joints and remains of the Achilles tendon can be identified. The shape of the calcaneus is vaguely visible, whereas tarsal and metatarsal bones are not distinguishable. As the metatarsal bones (in contrast to the metacarpal bones) are in oblique position, the distance for THz waves is longer (which leads to higher attenuation of THz waves), possibly causing diffraction.

While at 100 GHz tissue differentiation in thicker samples such as the investigated hand and foot is possible, the resolution is limited due to the large refraction-limited focal spot size at such long wavelengths in the order of 1 mm. At higher frequencies, however, the transmission decreases significantly, and at 300 GHz nearly all the radiation is absorbed in the thicker samples. Depending on the sample thickness, a trade-off between frequency, i.e. resolution, and transmittance needs to be considered. Figure 4 shows transmission images of a mummified fish obtained with the conventional TDS system. The resolution can be significantly enhanced at higher frequencies. Figure 5a shows a THz image of a naturally mummified rat obtained with the electronic imaging system at 300 GHz. Areas of high transmission can be identified, but the resolution is still very limited. The TDS system thus allows further inspection of these areas; for example, Fig. 5b depicts further investigation of anatomical details such as teeth in the mouth. Terahertz images over a broad frequency range are provided in Fig. 5b–d, again at higher frequency spatial resolution increases, allowing identification of smaller details such as a claw (Fig. 5d), but at the cost of overall transmission decreases. Figure 5f shows a THz pulse delay image, where red indicates a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large time delay of the pulse maximum compared with blue (no delay). This corresponds to the optical density of the investigated specimen. Here the upper jaw with high optical density is clearly pronounced compared with the rest of the rat head (green part).

Figure 6 presents a reflection image of the same hand as shown in Fig. 2 recorded in the 100 GHz band. The total reflectance, i.e. the radiation reflected from all interfaces on and in the sample, is depicted in Fig. 6a. However, the technology enables to selectively record the reflectance at different depth layers within the sample, which is shown for two selected layers in Fig. 6b (−6 mm) and Fig. 6c (−9 mm), respectively. Depending on their position within the sample, different internal structures, for example of the radius and ulna, are observed. For comparison, a metal coin was placed next to the sample, that is, the lowest layer, which thus only appears as a clear and strong signal in the picture of the total reflectance, yet only phantom artifacts appear in the images of the other layers. It is noteworthy that due to current technical constraints, mainly the surface structure of the hand is depicted (see below).

DISCUSSION

Our results demonstrate the potential for THz imaging to detect external and internal structures of mummified objects. The THz images provide contrast data, providing supplementary information to other imaging modalities. Multiple images of the same object at different frequencies as well as time-dependent images can be obtained. The technique also provides spectroscopic data, which could potentially yield information on chemical substances like the ingredients of the embalming material in Egyptian mummies. However, chemical investigations using THz spectroscopy remain complex, as substance concentrations can be low and the development of a spectroscopic reference database will be required.

Reflection-mode imaging with the three-dimensional electronic imaging systems are promising particularly for ancient remains, as it provides information on the internal structure of the sample. The signal is partly reflected at interfaces with different refractive indices, permitting the visualization of reflective objects at various interface layers through the comparison of the phase of the emitted and detected reflected signals. Nevertheless, the electronic FMCW imaging system employed for this study was optimized for industrial applications at normal incidence—the emitted radiation is focused on the sample and the reflected light collected using the same optics and later deviated via a beam splitter on the detector. This implies that the contribution of radiation, which is reflected at an angle (e.g. on a nonorthogonal surface) or scattered, is not considered in the analysis of the signal, partly accounting for the limited penetration depth.

Therefore, the surface structure of the hand is well-resolved due to the particular setting. As the light reflected from all curved areas will be reflected in different directions, it will not be detected by a detector in normal incidence. Thus these areas appear darker on this image. The inner structure of the hand is not clearly visible, probably due to a superposition of the strong signals of the surface reflection combined with significant diffraction and attenuation losses. Metallic objects—such as a coin placed next to the sample—act as very strong reflectors, but they appear as dark spots in transmission images as THz radiation cannot penetrate this material. This could be helpful in discovering metallic objects such as scarabs or amulets placed between the bandage layers in a mummy.

The resolution and penetration depth remained problematic in all the experimental set-ups. This is partly due to bone dense areas and scattering effects at fibril structures. Additionally the density of embalming resin could be partly responsible for the impenetrability of THz waves in certain areas (Fig. 2). The interpretation of the acquired images remains difficult. The main reason is the lack of reference data as well as the scattering effects, which can occur at the edges of the investigated sample. Thus the danger of misinterpretation should be considered. More powerful sources as well as integrating the scattered radiation in the detection scheme can certainly help to increase the penetration depth.

It should be noted that the systems employed here were optimized for material quality investigations and not social scientific studies. The aim of the study is therefore to evaluate the potential of the technology in general, in particular to estimate the advantages and disadvantages of this new complementary technology in relation to the more established methodologies. To optimize the results the system should be customized for this particular purpose of mummy imaging.

Broadband THz TDS imaging provides multiple images at different frequency ranges, which leads to long acquisition time. As an alternative, the all-electronic FMCW system operating in defined frequencies can be used. This restriction of frequency bandwidth significantly decreases the acquisition time and thus even larger objects can be scanned on a reasonable time scale. Using our system an area of 50 × 50 cm is typically scanned in a few minutes. The penetration depth could be augmented, so that even samples in the size of the Egyptian mummified foot could be penetrated at certain areas. Again, more powerful electronic THz sources and improvement of the optic system would be needed to increase the penetration depth further.

Currently, CT is clearly superior to THz and MR imaging for mummy investigation (Fig. 2). CT imaging reveals detailed information, based on its intrinsically high spatial resolution. MR imaging remains problematic due to the low water content in mummies. Accordingly the quality is lower than that obtained in the clinical setting.

Fig. 5. a: Modern naturally mummified rat, undated, a) THz transmission image at 100GHz, b) X-ray, c) photo of rat mummy as seen in setup, arrow: vertebral column, double arrow: bent front leg, arrowhead: tail. THz System: electronic THz scanner. **b**: Modern naturally mummified rat, a) photo of rat mummy as placed in setup, b-d) THz transmission images at selected frequencies, e) photo, f) THz pulse delay image, corresponding to THz optical density of specimen. Double arrow: note the visibility of the upper jaw and the claw (arrowhead): THz System: broadband THz TDS system.

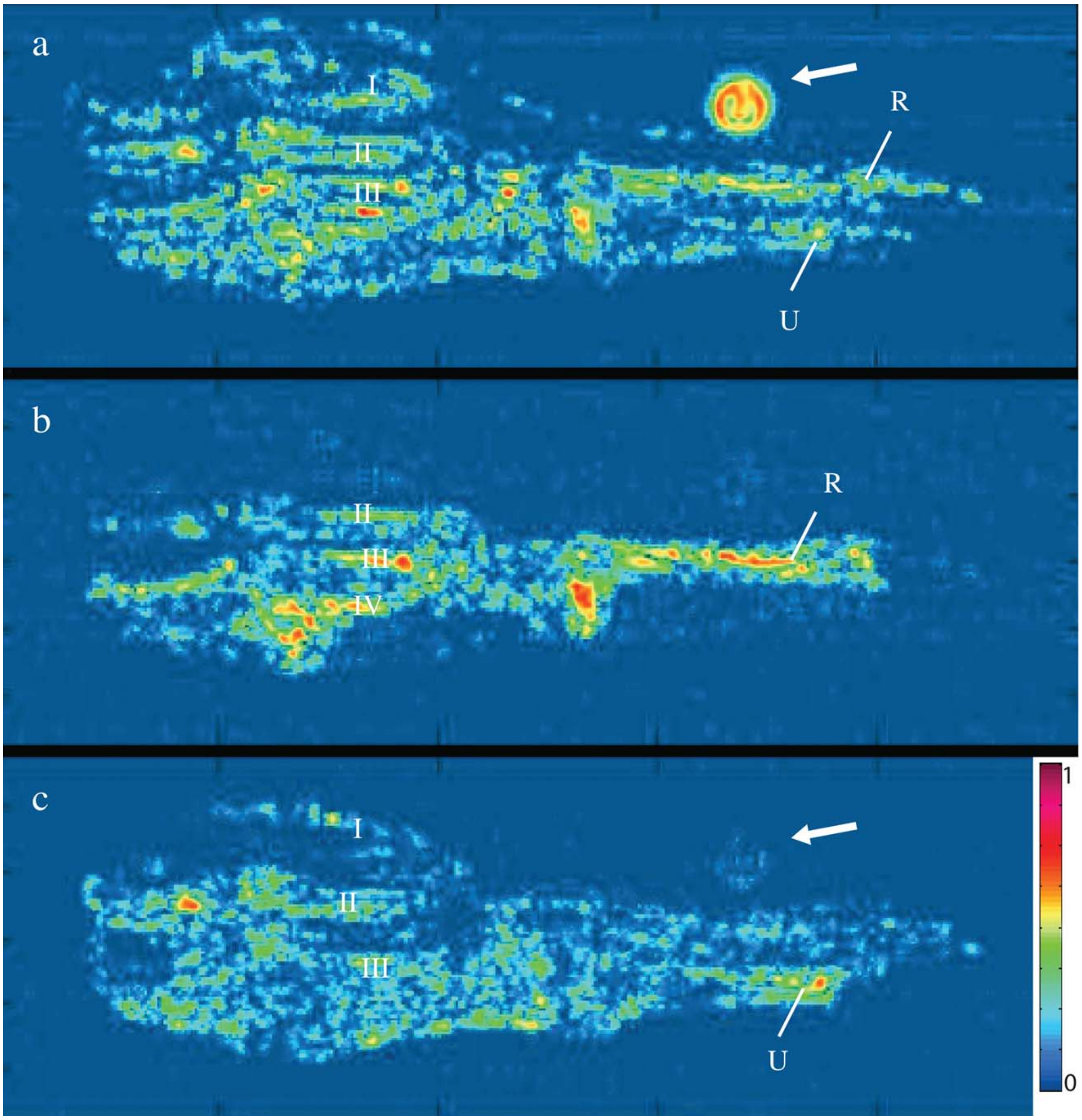

Fig. 6. Ancient Egyptian artificially mummified human hand (no. 2), unwrapped, **a**) THz reflection image, total reflectance, i.e. the radiation reflected from all interfaces on and in the sample, **b**) THz reflection image at 100 GHz layer at −6 mm, **c**) THz reflection image at −9 mm; arrow: coin, R: radius, U: ulna, roman numerals indicate metacarpal bones. THz System: electronic THz scanner.

Resolution remains a substantial limitation in the investigation of mummified objects with THz imaging modalities. As the absorption increases with increasing frequency, in most objects the frequency range will be limited to values of few hundreds of GHz. Nevertheless, a very fast contact-free, non-invasive image acquisition with a mobile low-frequency scanner will allow to obtain a rough estimate of areas of interest for more detailed investigations of these areas with specific, customized approaches. For example, another frequency range might be used for investigating the areas of high transmission for increased spatial resolution, or THz spectroscopy may be applied if a conglomerate of a specific substance of interest have been detected by the fast imaging approach.

In conclusion, THz imaging shows potential for its application in mummy imaging. Specifically, reflexion measurements are most promising, as it allows three-dimensional reconstruction of the image. New approaches such as dark field imaging might help to significantly enhance the image contrast. However, even with an improved system, THz radiation will hardly penetrate an entire body of a mummy, as scattering effects would probably be even stronger in thicker or denser samples. Nevertheless it could become feasible to image a whole mummy since certain areas are less dense. The use of THz imaging could be particularly interesting for the application in museums or at excavation sites since commercial mobile THz scanners are available. A quick view could reveal basic data and help determine whether further investigation using CT imaging or THz spectroscopy is necessary. However the benefit of portable THz scanners needs to be evaluated first, until then portable X-ray scanner can serve as an alternative.

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