Eur Radiol Suppl (2005) 15[Suppl 4]:D74–D81
DOI 10.1007/s10406-005-0138-1

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Computed tomography in various fields outside medicine

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Abstract CT has been widely used for non-medical purposes, for which, as in medicine, it has the advantage of being non-destructive and having a high spatial and density resolution. CT may help to generate 3-D views which could otherwise be obtained only by dissecting the object. There is almost no limitation with regard to X-ray exposure and scanning time. Dedicated techniques, e.g., rotating the specimen between stationary tube and detector, have been developed. Micro-CT may provide a spatial resolution up to 1 μm. Fields where CT has been successfully applied are archaeology, soil science, the timber industry, biology, industrial X-ray inspection and aviation security.

Keywords Micro CT · Non-medical uses

Introduction

The first person to perform non-medical CT was Sir Godfrey Hounsfield himself [1], who, in his first experiment, successfully obtained a tomographic image of several objects – after an exposure time of 9 days, however (Fig. 1). His further studies were carried out with biological materials.

Not surprisingly, CT has been used for numerous purposes outside medicine, since its advantages for objects are basically the same as for patients. There is no superposition of objects, density measurements are possible to assess unknown materials inside the object, 3-D postprocessing can be done including generation of 3-D models and casts, and, most importantly, the objects need not be opened or probed. Other than in humans, however, neither time nor dose of X-ray exposure is of concern. Furthermore, scanners can be used where not the tube and detector rotate, but the object is placed on a twisting turntable between a stationary tube and detector. This spares many engineering problems of medical CT systems with their rotating tube-detector units. The fields where CT has been most used outside medicine are archaeology, soil science, the timber industry, biology, industrial X-ray inspection and, most recently, aviation security.

Sarcophagi and mummies

For decades, plain films have been used to non-destructively visualise the contents of sarcophagi and mummies. These are able to show the skull, jaws or spine, as well as the usually empty thorax (Fig. 2a). Prior to conservation, the brain, the abdominal and thoracic viscera had been removed, according to the custom. The advantages of CT compared to plain films are obvious on a CT cross-section through the skull and the sarcophagus [2] (Fig. 2b). The mortice dowl joints of the coffin base are visible as well as the skull of the mummy, which is filled with a resin-like substance, the surrounding soft tissue of the skull and the death mask covering the face and some adjuncts and gifts beside the skull. The 3-D reconstruction of the normal skull (Fig. 3a) impressively shows a complete set of teeth of this mummy; a 3-D reconstruction including skin and subcutaneous tissue visualizes the face of the deceased as it is today, i.e., as a result of preparation and the thousands of years which have

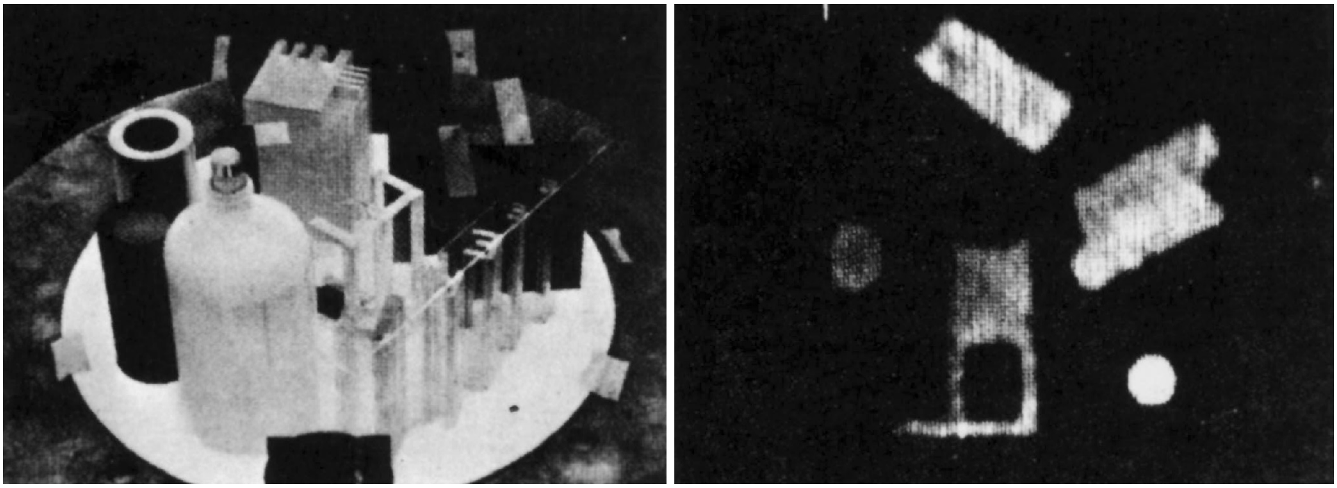

Fig. 1 Experimental setup used by Godfrey Hounsfield (*left*). Tomographic image (*right*) (from [1], with permission)

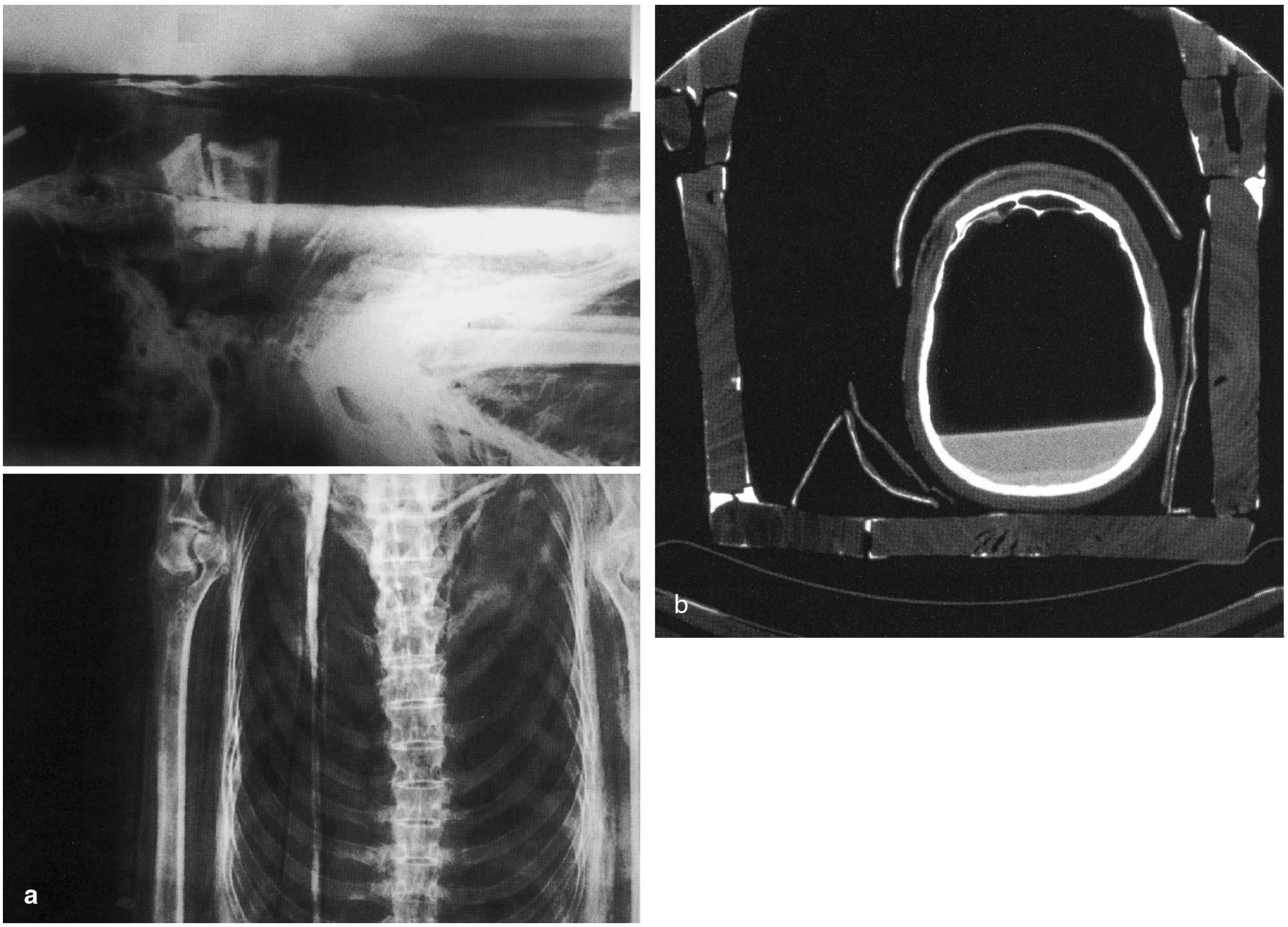

Fig. 2a,b Egyptian mummy dated to the period of Echnaton about 1300 P.C., exhibited in the archaeological museum of the city of Constance. Plain films (**a**) and CT examination (**b**) (from [2], with permission)

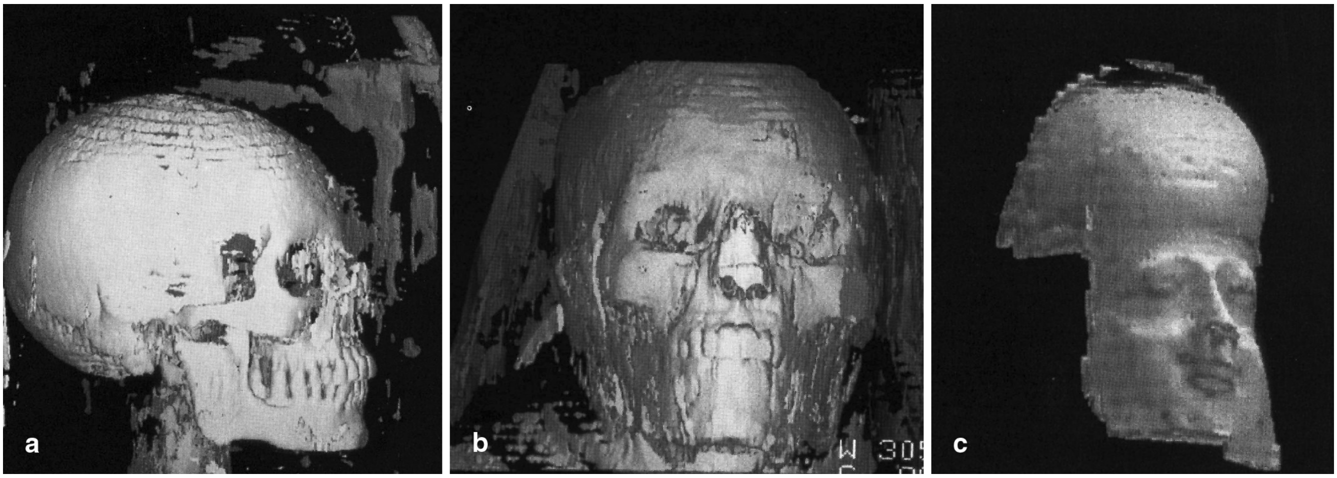

Fig. 3a-c 3-D reconstruction from the CT data obtained from the mummy shown in Fig. 2. **a** Shaded surface display (SSD) with the skin and death mask clipped away. **b** SSD showing the skin surface, but the death mask removed. **c** SSD of the inner surface of the death mask (from [2], with permission)

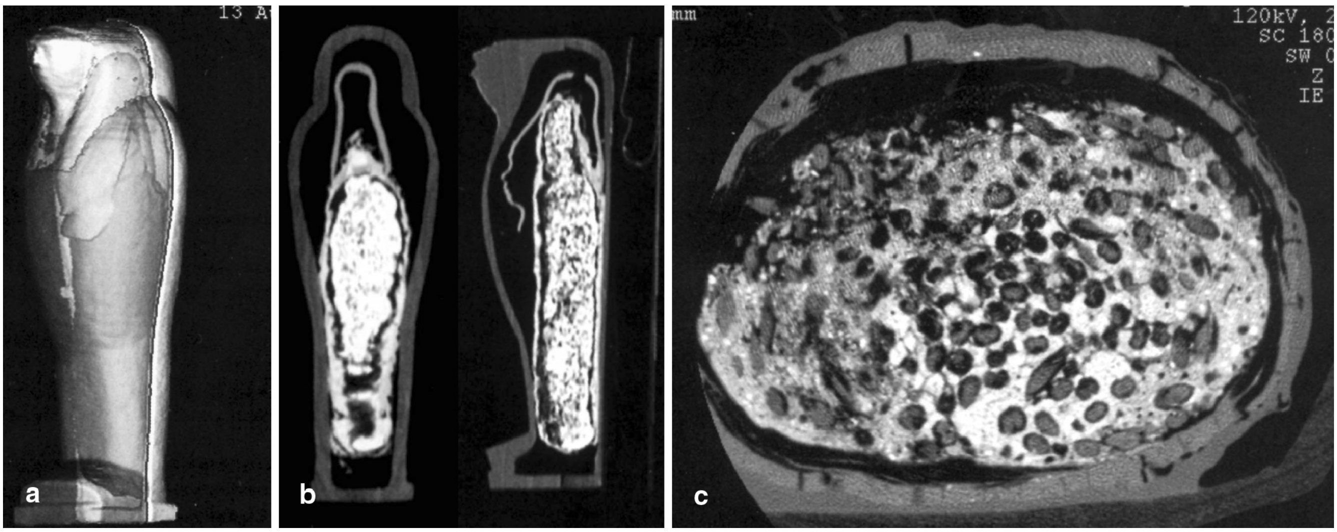

Fig. 4a-c SSD of a corn mummy (**a**). Coronal (*left*) and sagittal (*right*) reconstructions from a whole-mummy CT (**b**). In a single transverse slice (**c**), the grains are visible with which this artificial mummy is filled (from [3], with permission)

elapsed since (Fig. 3b). Reconstructing not the outer surface of the face, but the inner surface of the overlying death mask, however, which was at that time prepared by a papyrus-like substance, gives an impression of the shape the face had at the time of preparation – it is the face of a young woman, almost appearing alive (Fig. 3c).

It should be mentioned that with the help of laser sintering techniques, real models and casts can be created based on such datasets, which are helpful for archaeologists and archaeological museums.

Another example of the exactness of modern CT examinations in this field is given by several pictures of a so-called corn mummy [3]. Corn mummies were not real mummies but artificial ones, which were part of the cult for the god Osiris, who, according to the myth, was killed by his brother but brought to life again by his beloved wife (Fig. 4a). The internal bag of this pseudomummy is filled with shooting barley corns and mud from the river Nile. By enveloping this bag, a mummy-like figure was prepared (Fig. 4b). The shooting barley corns are symbols for a new life arising from the dead body. CT brilliantly visualizes the shooting corn with a transversal diameter of 3 and a longitudinal diameter of 7 mm (Fig. 4c).

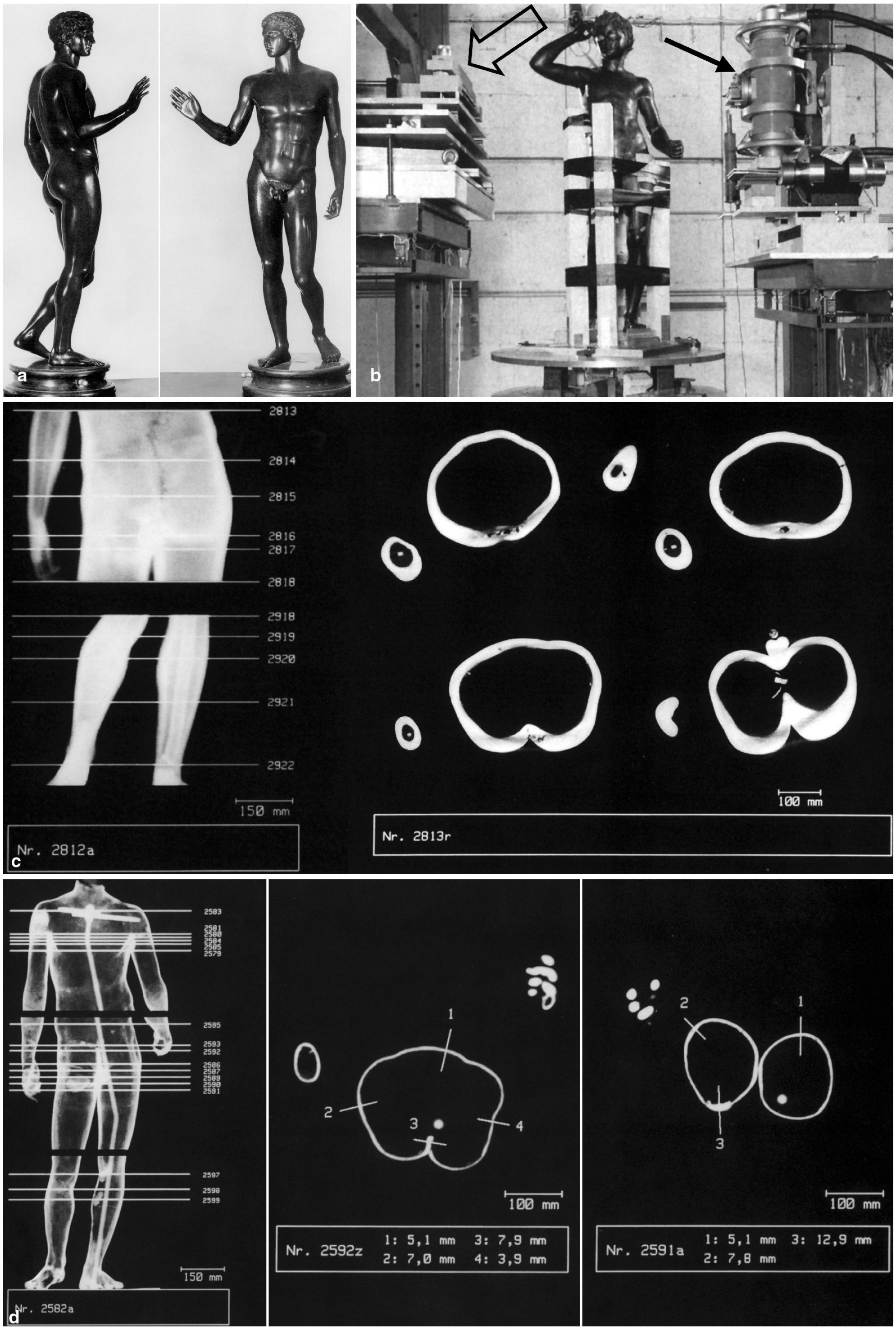

Fig. 5a-d The Youth of Magdalensberg (**a**). CT arrangement with the stationary tube (*arrow*) and detector (*open arrow*), and a different statue (Agon of Mahdia [5]) placed on a turntable in between (**b**). Scout view (*left*) and transverse sections of the Youth of Magdalensberg at the level of the lower abdomen and the buttocks (*right*) (**c**) reveal a considerable thickness of the wall. For comparison, a CT of the Youth of Salamis, a statue confirmed to be of Roman origin (**d**), shows how much thinner the Romans made the walls of their statues. This is a scout view, a section at the level of the buttocks (with the right forearm and the fingers of the left hand also included), and of the upper thighs, together with the fingers of the right hand (from [5, 6], with permission)

Bronze statues

Radiography and CT have been extensively used for examining antique figures or statues. The Youth of Magdalensberg was found in 1502 near the Magdalensberg (Austria) by a farmer while ploughing his fields [4]. This famous Roman bronze statue was manufactured about 50 BC following Greek prototypes. The statue came into the possession of the prince-bishop of Salzburg, where it remained for many years. King Ferdinand I, however,

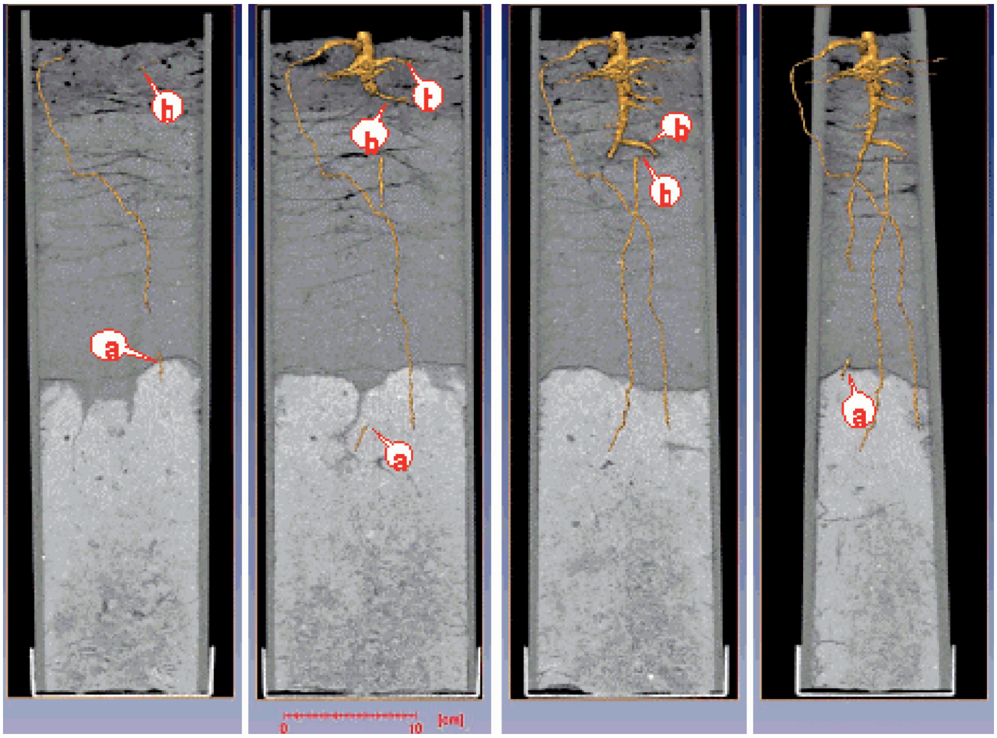

Fig. 6a,b Canola root system behaviour in a non-ripped soil visualized with CT 16 weeks after sowing. A 3-D image of root superimposed on longitudinal slices through the soil shows the root penetration into clay horizon (**a**) and roots following a layer of organic matter (**b**) (from [8], with permission)

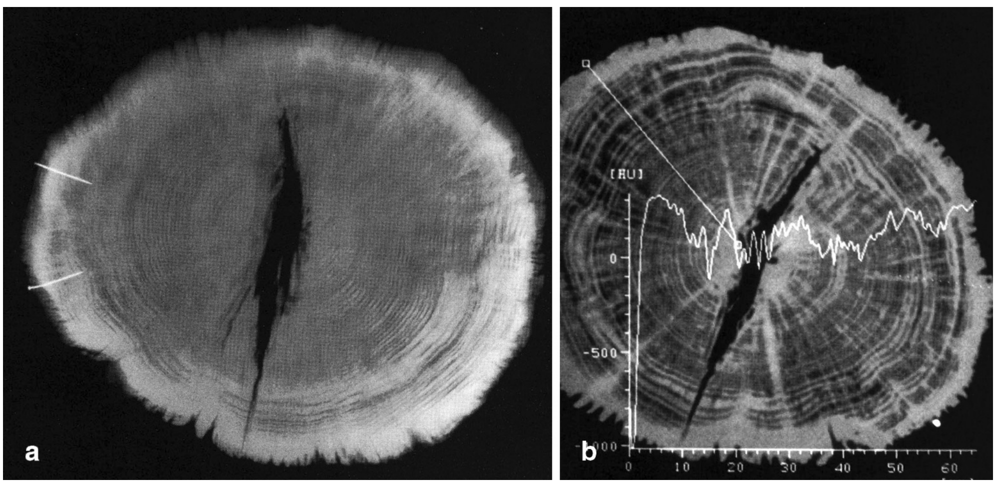

Fig. 7a,b Plain film of a thin slice of a 5000-year-old oak, found as wet wood, and stabilized with glucose solution (**a**). Two pins (*left side* of the slice) served for fixation of a label. The CT image (**b**) reveals the annual rings with their typical structure, and the values of density measurements (from [2], with permission)

claimed the statue, and it was given to him. Its further whereabouts are not clear. The statue which is now in the museum of Vienna was for long thought to be the Roman original (Fig. 5a). However, several archaeological observations and especially CT examinations proved it to be a new casting, a copy manufactured in the Renaissance.

For the CT examination of bronze statues special techniques [5] had to be developed and installed (Fig. 5b). The CT cross-sections (Fig. 5c) revealed a wall thickness of 3 cm on average, corresponding with the casting techniques used during the Renaissance. A typical Roman statue has a thin wall of about 0.5 cm (Fig. 5d) [6]. As a consequence, a CT examination carried out 20 years ago contributed essentially to clarifying that the Youth of Magdalensberg exhibited in the museum of Vienna is not the Roman original.

Soil science

CT has been increasingly used to examine samples of sand or soil [7]. Meanwhile, soil experts and biologists use CT for evaluating soil fertility. The cylinders, cores

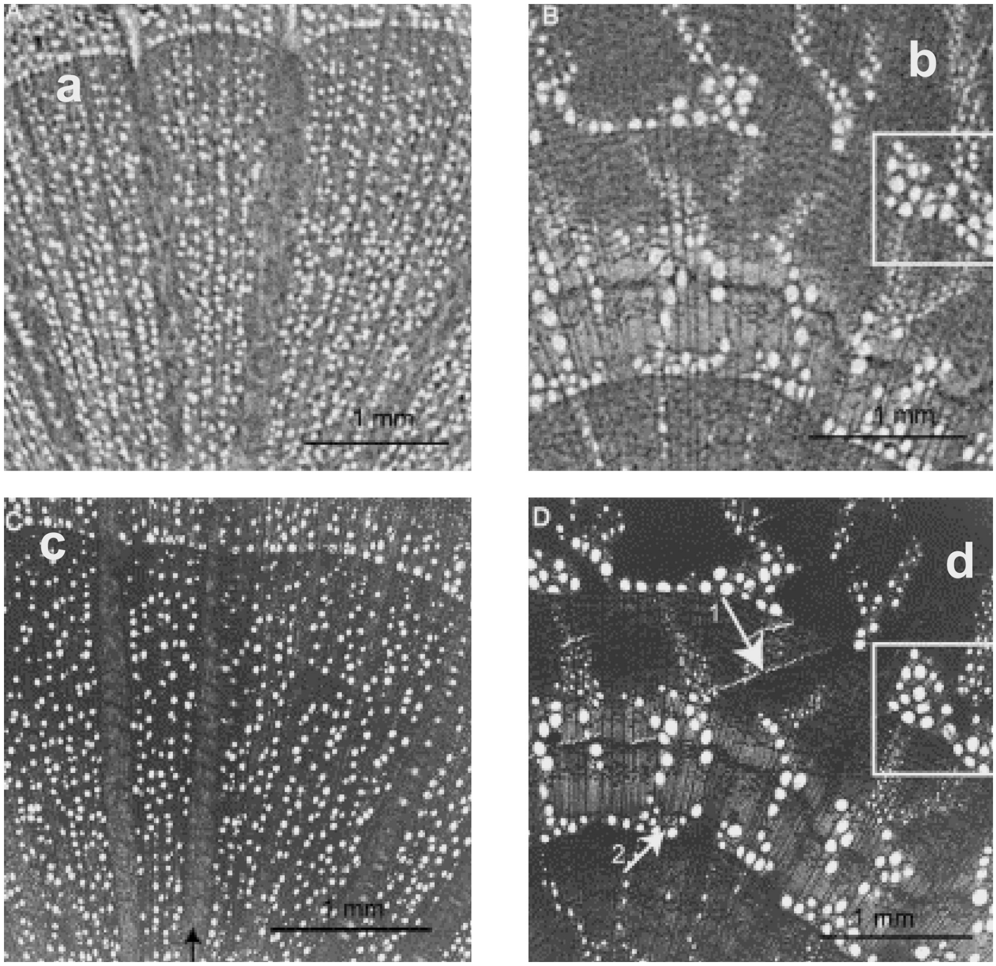

Fig. 8a-d Micro CT slices of a beech (**a**) and an oak sample (**b**), respectively, together with the corresponding optical micrographs (**c**, **d**). Small wood cubes of 5 x 5 x 25 mm were examined. *Arrow 1* shows an example of a crack, an artefact caused by microtomy (from [11], with permission)

of soil measuring 15 x 50 cm, are placed in a CT scanner. CT imaging revealed the architecture and morphology of root systems in situ, e.g. layers of organic matter in the sand, clay domes at the interface with the sand, old root channels, calcium deposits and stones (Fig. 6) [8]. Even the burrowing characteristics of several earthworm species could be studied [9, 10].

The timber industry

The timber industry has also benefited from CT technology. Special mobile CT scanners are designed to scan logs or trees, making it possible to test the quality of wood, to detect rottenness, knots, fungal decay and etc. CT is able to non-destructively image details of the stem which would otherwise only be revealed by inspection of the transversely cut surface, or a radiography of a transverse slice (Fig. 7). The axial CT sections therefore can also be used for non-destructive dendrochronology [2].

Biology

Quantitative analysis of anatomical characteristics of wood is usually performed using classical microtomy, yielding optical micrographs of stained thin sections. This procedure, however, is time-consuming, and, as in microscopic sections of human material, sectioning artefacts, like crumbling, folding or cracks, are a common problem. X-ray-computed microtomography (micro CT) can be used for non-invasive imaging of wood anatomy (Fig. 8). Micro CT has already found application in several biological research disciplines [11, 12]. As for the statue described above, the sample rotates inside the gantry, while the tube and detector are fixed. The resulting images are as impressive as optical micrographs.

Industrial X-ray inspection

For the inspection of electronic assemblies, 2-D X-ray systems serve most needs. More advanced systems also offer the ability to inspect for defects by rotating the part that is being inspected. The target area can thus be viewed from multiple directions. Modern devices consist of an X-ray source, a fixture for holding and manipulating the sample and the detector (Feinfocus, Garbsen, Germany, personal communication). Special tubes can provide a spatial resolution up to 1 μm with geometrical magnifications up to 2400. The manipulator is a device for x, y and z positioning and rotating or tilting of the sample with high precision (Fig. 9). The most notable advantage of 3-D X-ray inspection is the fact that it results in a complete picture of the object, or a detail thereof. The sample can be viewed from all sides and defects can be identified more easily (Fig. 10).

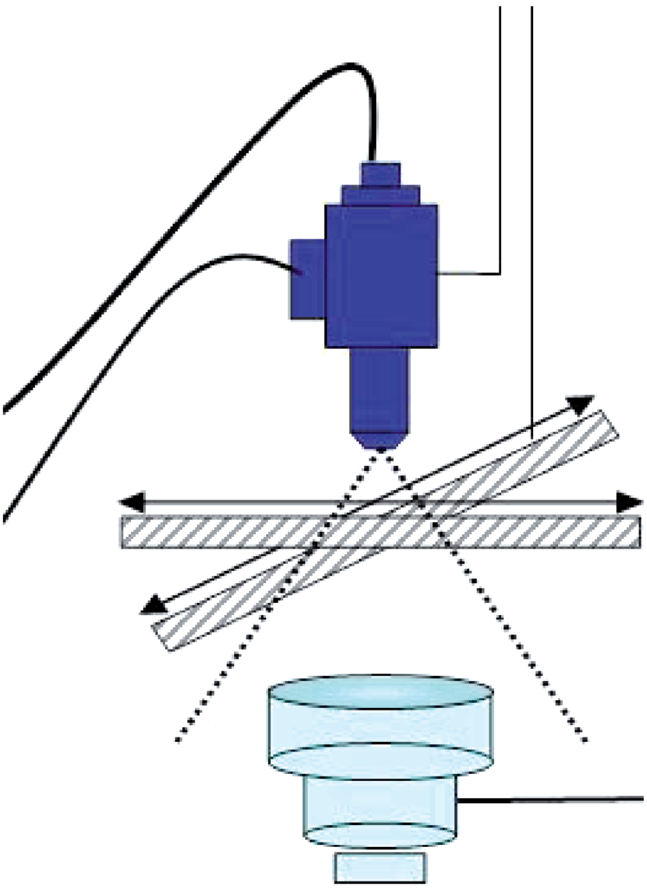

Fig. 9 Sketch drawing of an industrial micro CT with tube and detector, and the rotating object in between. (Courtesy of Feinfocus AG, Garbsen, Germany)

Aviation security

Recently, the protection of passenger flights against terrorist attacks, as well as hazards from dangerous goods, brought on board in good faith, is of growing concern. With more than 570 million air travellers flying inside the USA and nearly 1 billion pieces of checked baggage passing through American airports every year, improving

Fig. 11 Explosives Detection System (Turner Construction Company, USA), a CT scanner for detecting suspicious object in checked flight baggage (http://www.turnerconstruction.com/aviation/content.asp?d=3247&p=3245, with permission)

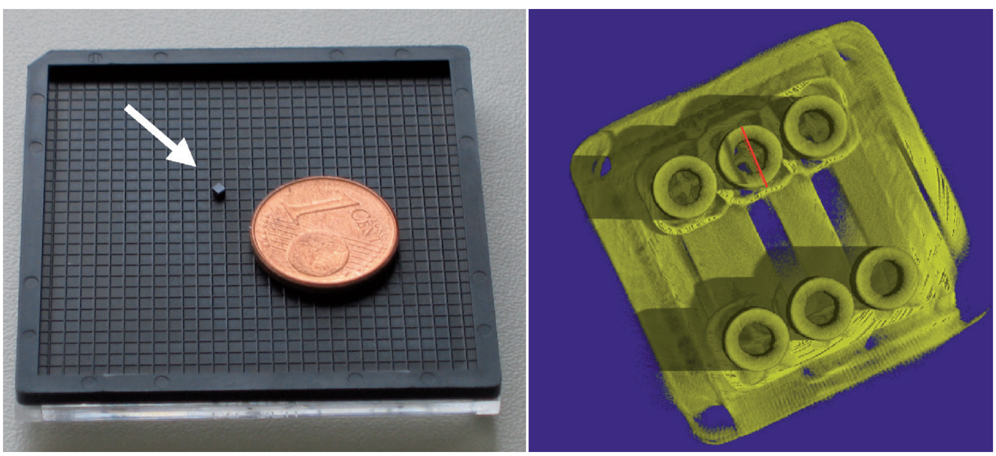

Fig. 10 Microchip (*arrow*) with a 1 cent coin for comparison (*left*). 3-D image of the same chip (*right*). (Courtesy of Feinfocus AG, Garbsen, Germany)

air safety has become a national strategy of great importance.

In January 2002 the Transportation Security Administration (TSA) began screening all checked passenger bags using several methods, of which one is to scan the luggage in large automated, so-called Explosives Detection Systems (EDS) that use computed tomography similar to that used in medicine (Fig. 11). In other terms, the potential of CT to resolve small structures three-dimensionally and to measure densities will probably play a valuable role in aviation security. The TSA has contracted two well-known experts in the field – the Boeing company and the Siemens corporation – to install 1100 EDS and to train the personnel [13, 14]. One must be aware, however, that the plethora of images which clutter the reader's working place may become a problem for the security personnel as it already is for the radiologist. The future will tell how realistically 3-D CT datasets of all checked luggage can be not only acquired but also read within the tight time schedule in a large, international airport.

Concluding remarks

Godfrey Houndsfield, when he developed the concept of computed tomography, could hardly have imagined how, beyond the field of medicine, CT would achieve importance in research and technology. The above outline of applications is by far not exhaustive – some authors report also using CT in geoscience, grading of meat and for several other purposes. Nowadays, CT is part of the repertoire of non-destructive material testing. Whenever the size of samples is similar to that of the human body, medical CT devices can be used and are widely available. Some specimens, however, will warrant dedicated CT technology. Whether CT will gain in importance in non-medical fields to the same degree as in medicine, however, remains open.

Acknowledgement The authors are indebted to Martin Spannagel, Heidelberg, for his valuable advice and assistance in the field of archaeology.

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