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INVESTIGATION OF THE CONTENT OF ANCIENT TIBETAN METALLIC BUDDHA STATUES BY MEANS OF NEUTRON IMAGING METHODS*

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Many important cultural and religious objects from Asia consist of outer metallic shapes, usually bronze, which fully enclose inner contents made of organic materials such as wood, bark, paper, textile, plants and others. Bronze and other metallic materials, such as copper and silver, are generally more transparent to neutrons than to X-rays. However, organic materials are less transparent to neutrons than to X-rays and therefore organic materials, enclosed by metallic materials, can be made visible with neutrons. Therefore, neutron imaging (radiography and tomography) was found to be an ideal tool for the inspection of objects that consist of metal outside and organic materials inside. This has been successfully demonstrated here with four metallic Tibetan Buddha statues, providing archaeometry with a powerful new tool. The first successful applications of this novel technique are described in this article. Further possible and useful applications of neutron imaging of cultural objects are outlined.

KEYWORDS: NEUTRON IMAGING, CULTURAL HERITAGE OBJECTS, BUDDHA BRONZES, NON-DESTRUCTIVE TESTING, TOMOGRAPHY, TIBETAN ORIGIN

INTRODUCTION

There is a class of metallic objects that contain objects made of organic materials. If the need arises to investigate the presence, the shape or the condition of the enclosed organic material, often this can only be done by destruction of the metallic enclosure and disturbing the arrangement of the organic substances. Therefore, we have developed a new, non-invasive technique that allows a direct, non-destructive, *in-situ* inspection of the organic content. The underlying principle is the fact that metals are more transparent to neutrons than to organic materials. Therefore, in the neutron beam, organic substances can become clearly visible while fully enclosed by metal.

One particular class of objects with an organic interior and a metallic exterior are ancient Tibetan bronze Buddha statues.

Neutron radiography investigations of cultural heritage objects have been done and reported before (e.g., Rant *et al.* 2006; Lang 2005), with different aims and success rates. Mostly film investigation using transmission radiography has been performed with 'frozen' information, without the option of image post-processing or quantification. Neutron tomography, however, has been available for non-destructive testing for about 5 years, but only in a few locations worldwide. Here we report on the application of state-of-the-art methods (digital neutron radiography

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and neutron tomography) for a unique application case, where the contrast and transmission advantages of neutrons can be utilized in the best possible way. The failure of common X-ray methods in this particular case was demonstrated with the same principal set-up.

TIBETAN BUDDHIST STATUES

Ancient metallic Tibetan Buddha statues are precious religious and cultural objects. They need to be treated with care and with respect. Without their inner organic content remaining undisturbed, they have no symbolic meaning and no religious power. In fact, Buddhists believe that it may be of negative influence or even dangerous to keep a statue if the inner content has been disturbed or removed by opening the metallic enclosure.

For art historians, opening a Buddha statue is a violation and partial destruction of an often singular or unique cultural relic and such destruction cannot be justified. Furthermore, for art collectors, originally sealed, i.e., not opened statues, are emotionally and financially more valuable than unsealed or empty statues. Unsealing or opening Buddha statues outside a religious context and proper ritual is therefore unscrupulous and is highly recommended against.

After the first millennium AD, when the second propagation of Buddhism in southern and central Tibet began to spread, Indian and Nepalese Buddhist statues cast of copper-rich bronze were taken across the Himalayas and carefully copied. Tibetan metallic Buddha statues can range in size from more than 2 m down to a few centimetres. Before they are placed on Tibetan altars, either in monasteries or in homes, all statues are consecrated using offers, relics, symbols and rituals in temple ceremonies. Tibetan metallic Buddha statues are generally less than a thousand years old. In eastern Tibet, a distinctive school of Buddhist bronze statue manufacturing flourished from the 12th century onwards. The first Buddha statue we investigate is from that school and its style indicates that it was made in the 14th or 15th century.

In southern and central Tibet the classic period of manufacture of Buddhist statues was from the 15th to the 17th century, when the highest artistic achievements were reached (von Schroeder 1981, 2001). The majority of the Buddhist statues investigated in the present work stem from that time and place.

We know about the inner contents of metallic Tibetan Buddha statues from at least two sources: accidental or unscrupulous opening, and the ritual text used for consecration. What is found upon opening has been described several times in the literature (Reynolds 1986; Huntington and Huntington 1990). An essential piece is a central wooden stick called '*tsog-sin*', literally 'life-stick' or 'soul-pole', sometimes compared to the human backbone. In addition, there are always Tibetan Buddhist religious texts on paper or silk, wrapped around the pole and also rolled up in separate bundles. (On one unfortunate day, when a large statue was not carefully handled, the bottom plate sprang open and a library of many large written rolls of religious Tibetan texts became visible!) Some statues contain series of numerous small paintings, so-called 'consecration pantheons' (Huntington and Huntington 1990). In addition, small statues, often made of clay (*tsha-tsha*), have come to light from inside larger statues.

The ritual consecration of images in Indo-Tibetan tantric Buddhism, as well as the religious articles including the pole, the texts, the paintings and the figures that go into a bronze, are described in detail not only in Tibetan holy texts but also in English publications (Bentor 1996; Huntington and Huntington 1990; and partly in Reynolds *et al.* 1986).

Before a statue or a *Stupa* is consecrated, it is just considered a piece of metal and need not be treated respectfully. Only after consecration is it an empowered object and fit for ritual and meditation. This quality would be destroyed by opening the base plate that seals the religious articles and keeps them protected and in place. Thus it was our attempt to develop a non-invasive technique for studying the organic materials *in-situ*. Although some doubts were raised by O'Connor (2007), the authors believe the religious and ethical properties of the objects will remain unaffected and valid.

NEUTRON IMAGING METHODS—IN COMPARISON TO X-RAY TECHNIQUES

One of the standard inspection tools in material research is X-ray imaging, well known since its discovery by C. Roentgen. The radiation delivered from an X-source transmits the object under investigation more or less, depending on the attenuation properties and the thickness of the involved materials. An X-ray-sensitive two-dimensional detector converts the absorbed transmitted radiation into visible information (e.g., an image on a film, on a scintillation screen or as an array of numerical data). This is shown in principle in Figure 1.

X-ray interaction with matter takes place via Compton scattering, photo effect and pair production, all with the electrons in the atomic shells of the inspected materials. The common X-ray energy is too small to have an impact on the atomic nuclei. Therefore, the interaction probability is directly proportional to the number of electrons—and the atomic number. Light elements (like hydrogen) have little chance to absorb X-rays, whereas heavy elements absorb a lot. This has specific consequences for transmission and contrast: hydrogen is nearly invisible, but metallic layers absorb much of the X-ray beam before it can enter the detector (Mundry and Riederer 1988).

Neutron imaging is much less common and less often used than X-ray techniques due to its limited availability and because it is less well known. Worldwide there are only about 15 neutron

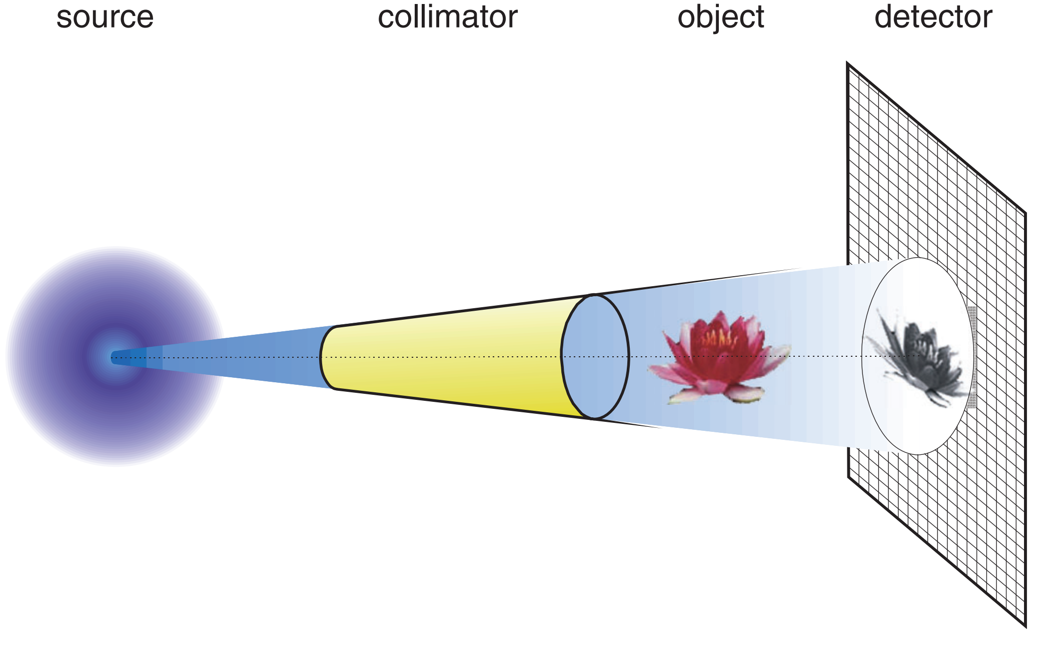


Figure 1 *Principle of sample transmission investigations: although a simple set-up, the real installations are much more complex and expensive. Neutron sources (reactors, spallation sources) are quite big facilities.*

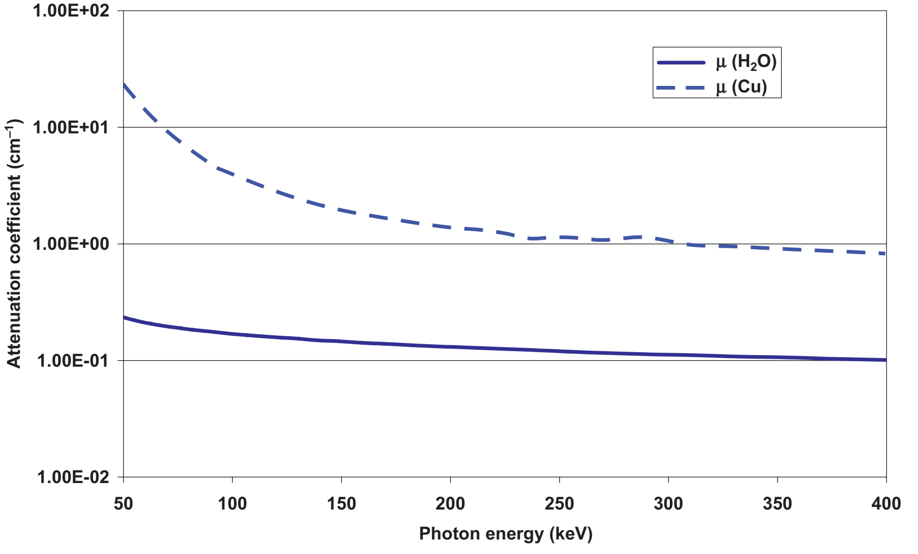


Figure 2 *Attenuation coefficients for X-rays of different energies for water and copper as a function of photon energy (source: NIST, Physical Reference Data, http://physics.nist.gov/).*

imaging facilities in operation at high-performance levels (Lehmann 2009). Nevertheless, there are many advantages to using slow neutrons for imaging purposes in a suitable way. Thermal and cold neutrons enable the visualization of very small amounts of hydrogenous materials, but are highly penetrable of heavy elements, such as many metals. This is caused by a different attenuation mechanism compared with X-rays: neutrons interact with the nuclei of the atoms only, whereas the electrons are neglected. There is no simple systematic rule as to how and why neutrons interact with matter in their specific way, although the interaction probabilities (interaction cross-sections, attenuation coefficients) are well known and tabulated (e.g., NEA Paris 1994). The experimental set-up for neutron imaging is very similar to that in Figure 1; only the source and detector are changed in an appropriate manner.

We thought that neutron imaging could be used to investigate the hidden contents of the statues. Neutrons can easily penetrate the metallic cover (copper or bronze) and detect small amounts of organic materials. This could be wood, paper, textile, plants, bark or cord, as discussed below. Both the size and the material combination of all four of our samples permitted successful investigation with thermal neutrons.

A study of these objects with X-rays would never deliver comparable results, even if the X-ray energy were to be varied over the whole range available. With low-energy X-rays, penetration of the objects is more limited; with high-energy X-rays the contrast of the organic matter is not high enough. This problem is illustrated in Figure 2 by a comparison of the attenuation behaviour of Cu and H_2O (used to represent organic materials because it is well reported; National Institute for Standardization and Technology, http://physics.nist.gov/PhysRefData/FFast/html/form.html). There is a factor of at least 10 between both values of attenuation coefficients (see below), with higher deviation towards lower energies. Even transmission of the object is possible with certain X-ray energy, the embedded material remains invisible. Reduction of the X-ray energy to raise the sensitivity for hydrogenous materials would result in a completely dark image of the metallic cover. Figure 3 confirms these statements by a comparison of the X-ray image (150 kV high voltage) and the corresponding neutron image of object A in Table 1.

The previously mentioned attenuation coefficient Σ is defined by Lambert's Law of exponential attenuation of an incident beam with intensities I and I_0 (behind and in front of the object) by a homogeneous object with thickness D, according to equation (1):

$$\Sigma = \ln\left(\frac{I_0}{I}\right)\Big/D \tag{1}$$

It holds for both X-rays and neutrons in a similar manner. The symbol of the attenuation coefficient, μ, is commonly used for X-rays, but Σ is used for neutrons. Whereas the ratio of this parameter for copper to water is more than 10 for X-rays (see Fig. 2), it is only 0.3 or less for thermal neutrons. This explains the findings in Figure 3 numerically.

FACILITIES AT PSI FOR NEUTRON IMAGING

The spallation neutron source SINQ is the Swiss national facility for research with neutrons (Bauer 2001). It is based on the principle of spallation where a collision of 590 MeV protons with the spallation target material (lead) delivers about 10 fast neutrons from one spallation act per proton. These fast neutrons are slowed down in a D_2O tank to thermal energies (around 25 meV) or in another vessel filled with liquid D_2 (at 25 K) to cold energies (around 3 meV).

Although most of the beams at SINQ are used for neutron diffraction experiments, there are also two facilities installed for neutron imaging purposes. Beam port 32 for thermal neutrons hosts the facility NEUTRA (Lehmann and Pleinert 1998), operational since 1998. On beam port 52, where a direct view on to the cold source is given, the facility ICON has been used since 2006.

In addition to its neutron performance, the NEUTRA station is equipped with a strong X-ray source with high voltages up to 320 kV. Therefore it was decided to perform the first trials with the Buddha statue objects at this facility so that there was a good chance for a comparison between neutron and X-ray imaging under identical detection and beam geometry conditions.

The first observation trials were done with imaging plates (Takahashi *et al.* 1996), delivering high spatial resolution (0.05 mm pixel size). Figure 3 shows how the metallic cover can easily be distinguished from the filling material. This radiographic approach can be performed from different perspectives, delivering projections with superposition of all layers along the whole beam propagation. One projection data set needs about 20 s of exposure time, 5 min for readout and some additional minutes for evaluation.

Neutron tomography was applied in a second sequence of investigations, where the full sample volume could be retained in a non-invasive way. The tomography approach is shown in Figure 4. In order to reconstruct the three-dimensional volume, single projection data are obtained during rotation of the object around its vertical axis over a range of at least 180°. The detection system is based on a cooled, high-sensitivity charge-coupled device (CCD) coupled optically to the neutron-sensitive scintillator. The field of view of 28.5 cm was observed with a 1024 × 1024 pixel sensor, corresponding to 0.28 mm pixel size in the images (and volumes). About 300 projections with about 20 s (corresponding to about 1.5 h) exposure are required for adequate image quality. The reconstruction of the volume data takes minutes to hours, depending on the computation power, the data volume and the algorithm. The visualization step is often more time consuming and needs an experienced operator to find the best possible settings to acquire the required information.

Figure 3 *Buddha sculpture (b), its X-ray image (a), and its neutron image (c).*

Table 1 *Data of the observed Buddha statues*

	A	*B*	*C*	*D*
Name of the object	Buddha Sakyamuni	Buddha Sakyamuni	Buddha Amitayus	Buddha Akshobhya
Origin	Bhumisparsa Mudra, West Tibet	Bhumisparsa Mudra, Central Tibet	Central Tibet	Central Tibet
Manufactured	14th–15th century	End 15th century	17th century	17th century
Height (cm)	17.1	17.2	19.5	20
Largest diameter (cm)	13.3	12.5	13.5	13.3
Weight (g)	769	1119	1042	1322
Material	Bronze	Bronze	Bronze	Bronze

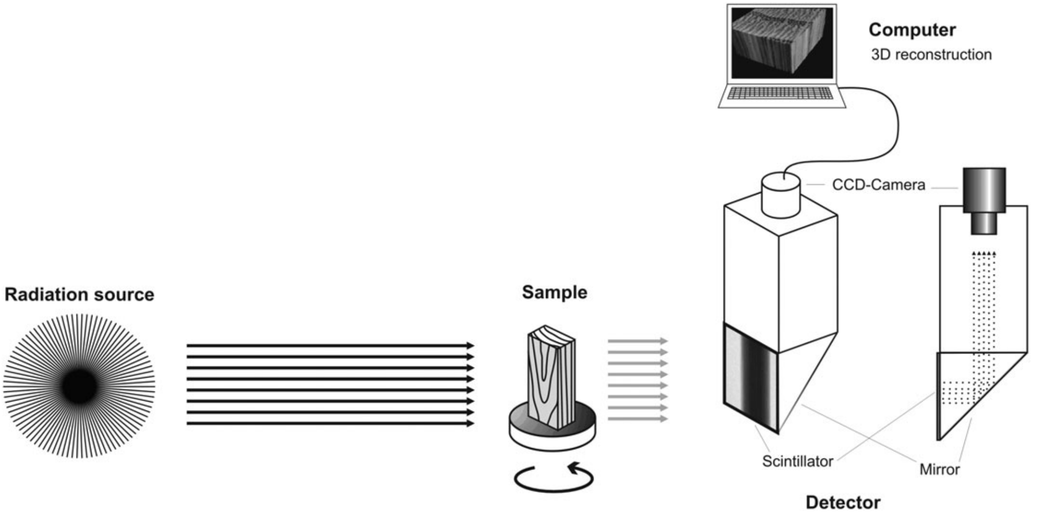


Figure 4 *Principle of set-up for tomography with neutrons using a charge-coupled device (CCD) camera detection system.*

The reconstruction into volume data has to be done with the help of a mathematical algorithm included in software tools (Dierick 2005). In principle, a matrix of attenuation coefficients $\Sigma(x, y, z)$ is obtained for the observed volume. Whether the involved materials become visible (Σ large enough) or different zones can be distinguished (Σ differs above the noise level) depends on their values. With the help of visualization tools it is possible to extract the inner properties of the observed objects, as shown below.

Some sample activation can occur during neutron exposure. The activation level reached after exposure depends on the beam intensity, the kind of material and the amount of irradiated material. The activation cross-sections for thermal neutrons are well known and available (Weber 2008). In our samples, which contained mainly copper, tin, zinc or lead, the activation level after long-term exposure (some hours) in tomography with flux intensity of 3×10^6 cm^{-2} s^{-1} was in the order of 10 μSv/h. The decay down to a negligible dose rate took only a few hours or days, depending on the object's weight. It can be concluded that neutron tomography does not cause sample activation in this kind of object. A decay time of some days should be considered in a conservative manner before the samples can be returned to their origin.

RESULTS OF THE EXAMINATIONS

Due to the positive result with transmission imaging (see Fig. 3), a set of four Buddha statue samples (Table 1) were investigated using neutrons. Comparable X-ray images delivered no useful results for these objects.

Transmission neutron radiography

The radiography pictures (Fig. 5) represent a superposition of all layers of the object in the beam direction. Differentiation between front and back of the inside contents is not possible in this way. Nevertheless, the examples in Figure 5 show large deviations in the fillings and interesting details, in particular the materials used. The following conclusions can be derived from these image data:

- The cover material (bronze) of the hollow objects has a thickness of a few millimetres (or less in some places). It is relatively transparent for neutrons and can be measured comfortably. Statues B and D have some solid metallic parts—at least in the arms. Due to the homogeneity, this may be the same material as the cover.
- Another material can be found close to the inner wall of the cover in some objects. Due to the contrast values between bronze and air, some ceramic residuals are assumed. This finding is verified with tomography (see below).
- Two statues have point-like decorations imitating gemstones. However, these points show higher attenuation than the bronze regions, although their size is small. It is assumed that organic material is involved here, such as glue, wax or lacquer.
- The filling of each sample is very individual in terms of structure and composition. Sample A has a wooden stick in the middle, which is surrounded by a rolled textile or paper layer and fixed with a cable. Flowers or other plants with buds have been filled in the lower part of the sculpture. Due to the thickness and the considerable density of this layer, it is less transparent for neutrons close to the bottom. The sealing plate (wax, resin or gemstone) with a diameter up to 13 cm is more or less absorbent for neutrons in the 'sitting' positions. Sample B has a more homogeneous filling with maybe only one kind of plant material. This is confirmed after evaluation of the tomography data below. Sample C contains no plant material but small sticks (diameter about 1 cm, length 3–5 cm), which seem to be hollow in the middle. Some damaged material can be found separated on top of the bottom plate. Sample D also contains sticks (or tight rolls), of small diameter but longer length, and one goes up all the way through the head. Some material with a different structure is apparent in the lower part.

Neutron tomography is the right tool to provide the full structural information because the transmission is guaranteed for all possible projections. Only in the region close to the bottom sealing plate is there some limitation, which is not so important for structural studies on the content of the statues.

Neutron tomography

Tomography data cannot be visualized easily like the two-dimensional images (Fig. 5) because the whole three-dimensional volume is available as a matrix of attenuation coefficients. The following methods of representing the data are commonly used:

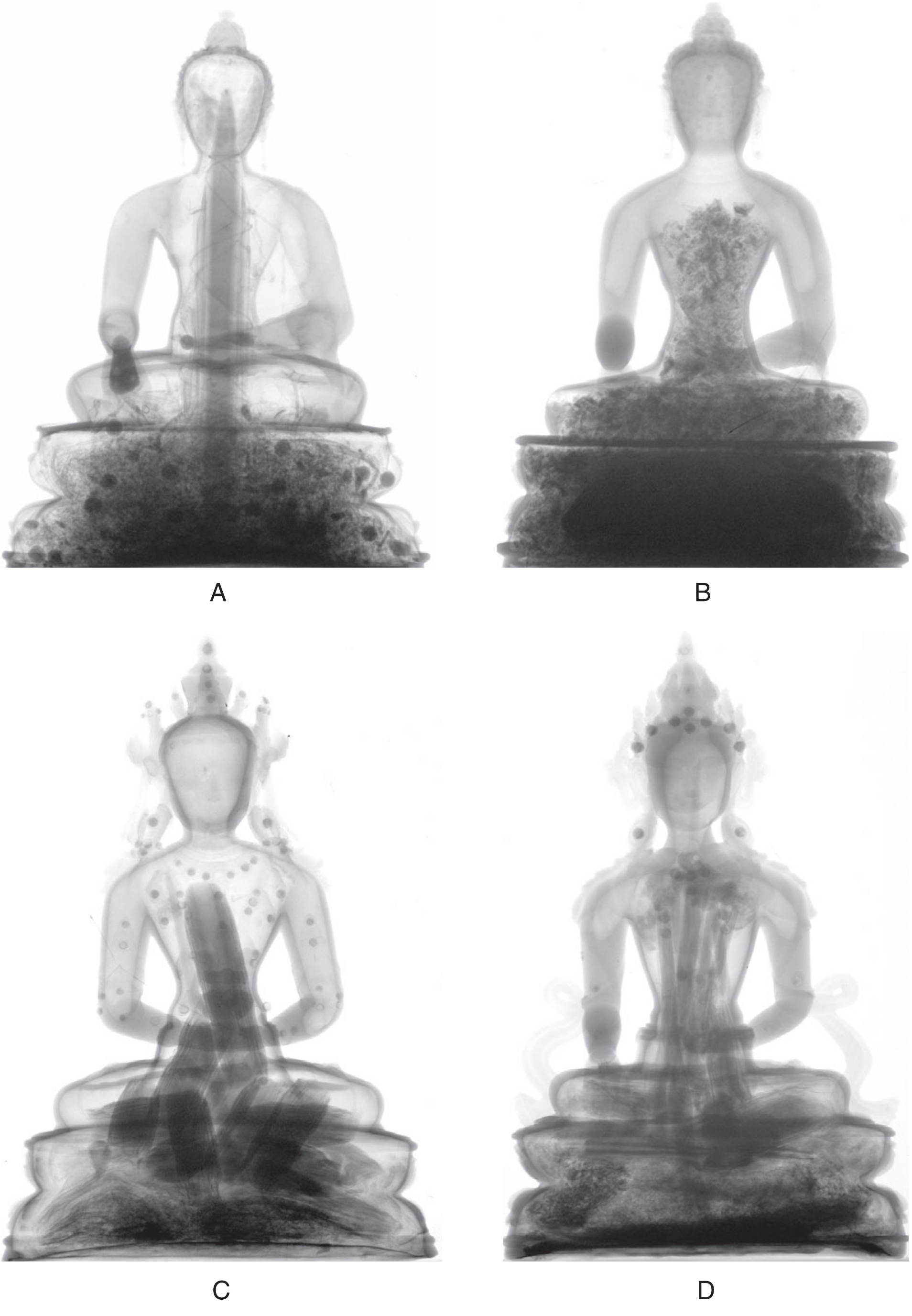


Figure 5 *Frontal transmission neutron radiography images of the four Buddha objects (see Table 1); the description as sample A–D is used consistently.*

- Virtual slices at relevant positions in all three directions and at arbitrary angles with respect to the main coordinates.
- Outer or inner views on surfaces of regions with the same material properties.
- Segmentation of outer and inner areas with the same density and separate visualization of these areas.
- Artificial transparency of outer regions to show inner details.
- Inversion of hollow regions as solid zones to show their distribution.
- Different illumination features to show surface properties adequately.

The dimensions of the structure, the outer or inner distances, can be measured directly with the precision of the voxel size (0.28 mm in this study).

Examples of several visualization options are shown in Figure 6 for statue A. A direct comparison between transmission radiography and virtual slices is given in Figure 7.

Although the spatial resolution in this tomography study was less than in the radiography measurements, more details are accessible with tomography data. Any position inside the samples can be observed, measured and visualized. The following new information was obtained from tomography data for statues A and B (see Fig. 7).

First, the contrast variation can be made more precise and suitable, when only one slice is involved. In this way, it becomes much easier to distinguish separate materials and structures with the same attenuation coefficient. Hollow areas can be determined much better in this way too.

For statues A and B it becomes clear that residual amounts of ceramic remains are present at the inner wall (sample B) or in broken pieces somewhere inside the bronze cover (sample A). Sample A clearly shows the wooden stick (*tsog-sin*), the rolled paper and the wire around, whereas the plants on the ground have reduced contrast. The radiography image of sample A delivers about the same grey levels for all the materials and has extremely high contrast for the plants in the lower region. Because the transmission is not very high in the lower region, only limited information can be derived for both radiography and tomography. This is also valid for sample B, where almost no details are visible below the sitting Buddha. Either the material density is higher than for sample A or some more attenuating material than just plants is present. This could be wax, oil, moisture or resin. It is interesting that the filling in statue B is quite heterogeneous in its composition, which is more visible in the tomography data than in the radiography. Further, the filling level obtained in the tomography data is surprisingly higher than ‘integral’ transmission would assume in the radiography. This clearly indicates the much higher sensitivity in the tomography data sets.

Experimental findings and their interpretation

The neutron radiography and tomography investigations have shown that all four of the Buddha statues detailed in Table 1 contain the religious organic articles indispensable for a genuine, consecrated Tibetan Buddhist statue. The *tsog-sin* central pole, with the religious text paper scrolls wrapped around it, is clearly visible in Figure 5, objects A, C and D. This conforms to the ritual requirements (Bentor 1996; Dorje 1996) and indicates that the statues are ‘empowered and thus fit for ritual and meditation’. This visualization is absolutely a ‘first’ in archaeometry and it can contribute positively to the important question of whether the statues are genuine or not. Figure 5, object B may have undergone an interior settling process and therefore requires further detailed study.

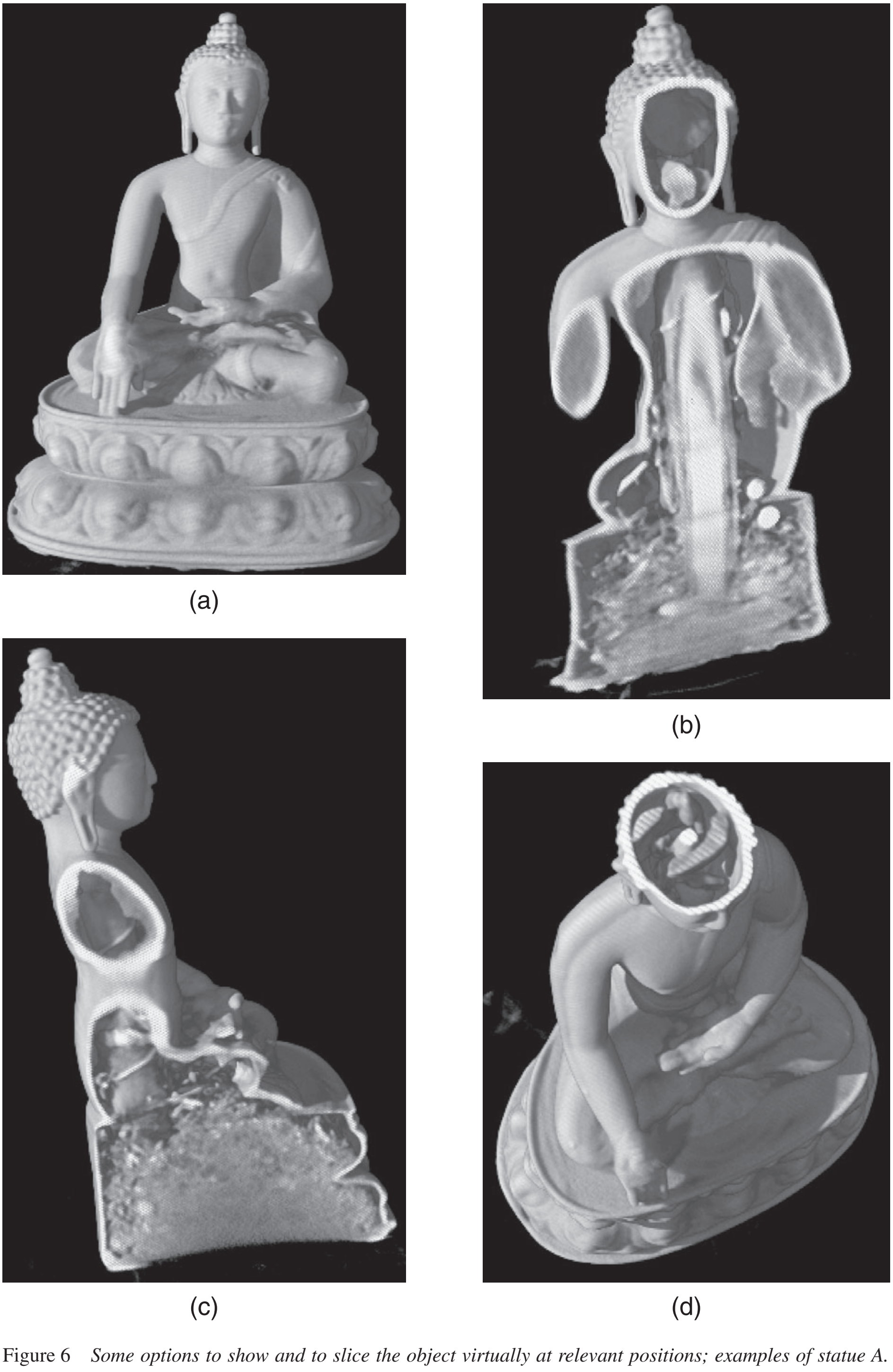
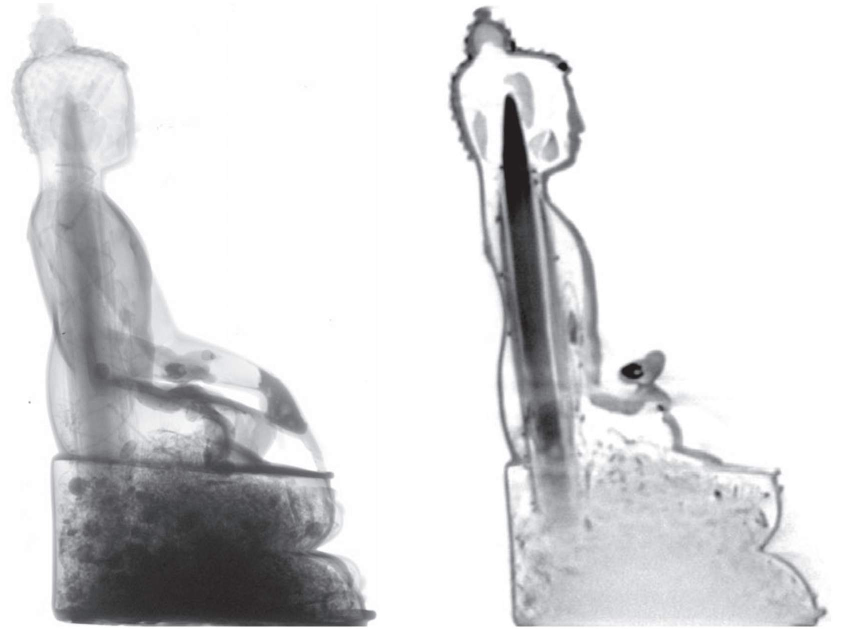
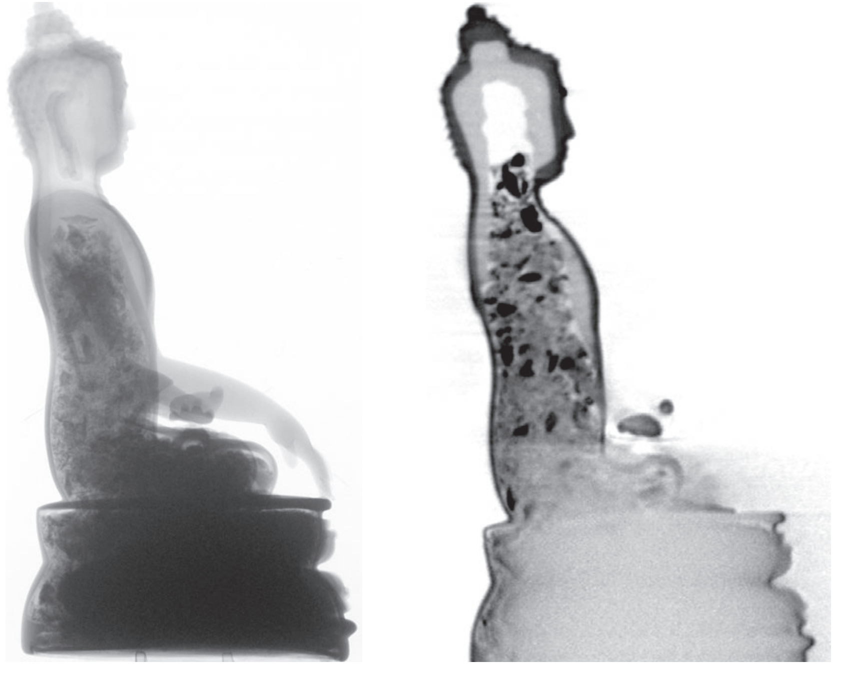


Figure 6 *Some options to show and to slice the object virtually at relevant positions; examples of statue A.*



A



B

Figure 7 *Comparison between transmission radiography (left) and tomography virtual slice across the centre (right) for statue A above and B below.*

CONCLUSIONS AND OUTLOOK FOR FURTHER STUDIES

This neutron radiography and tomography experiment has successfully shown how easily organic materials fully enclosed in metals can be investigated. The results are convincing as they show both the outer cover structure and most of the details of the filling materials.

As shown above, the experimental effort for radiography and tomography is reasonably small, justifying a larger number of tests with other similar objects of relevance. Starting with simple transmission images, it can be decided case by case whether a more demanding tomography run will be justified.

Objects of dimensions up to 30 cm can be observed in one single frame; larger objects can be studied in scanning mode by changing the sample position. A final object size limitation will be given by the sample thickness and the attenuation power of the contained materials.

Our successful investigations have shown that neutron imaging is a new and powerful tool that can be used in archaeometry, whenever the presence, shape and arrangement of organic contents, wrapped in metal, need to be investigated *in situ* and in a non-invasive way. There is the potential not only to help decide if the object is genuine or fake, but eventually, with the build-up of a database, to find out when it was made.

Combination with other neutron inspection techniques, like neutron activation analysis (NAA) or prompt-gamma activation analysis (PGAA), can help to analyse the material composition non-destructively. Once irradiated using tomography, the residual activity can be used to perform gamma spectroscopy to identify the material composition, at least in a qualitative way.

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