a phenomenon described by the Beer–Lambert law, a single projection (or radiograph) shows the intensity of the transmitted signal. As X-rays interact with the electrons orbiting around an atom's nucleus, the more electrons there are the more X-rays are absorbed. This can be seen when atoms are packed closer together (increasing density) or when the material is made of heavier elements (hence containing more electrons). This explains, for example, why radiographs of bone (largely composed of calcium and phosphorus) appear more opaque than surrounding muscles which are made of lighter elements such as hydrogen, carbon, nitrogen and oxygen.

What is X-ray μCT good for?

For an object to be successfully analysed by X-ray μCT, three conditions have to be fulfilled:

(1) The object has to fit inside the CT chamber.

(2) The object must also fit within the scanning envelope (i.e. the volume that can be exposed to X-rays and that can be

offering an alternative to the physical handling of the object.

Limitations of X-ray μCT

X-ray μCT can be time-consuming. Data acquisition is relatively fast, from a few minutes to several days in extreme cases. If a specimen is large and/or dense, it attenuates X-rays more, therefore to get a good signal the exposure time is increased. However, the image processing and the separation of the subsets of the volume to represent the different components of the object is a time-consuming process that can take weeks, but the quality and relevance of the resulting information make this task worth the time and effort.

The data generated is often several gigabytes in size, making data storage and handling resource- and computationally-intensive.

The size of the object can be a problem. Firstly, most facilities with X-ray μCT systems will be able to investigate objects from a few millimetres to a few tens of centimetres; however, facilities suitable for the investigation of larger objects are rare. Secondly, the size limit is dependent on the composition of the object. For example, with a machine working up to 225 kilovolts (which is a common setup) one will be able to investigate, *inter alia*, a few tens of centimetres of wood, 10–20 cm for most fossils, 5 cm for rocks rich in metals or a couple of centimetres of stainless steel. Finding a facility with more energetic X-ray sources to extend the range and dimensions of the objects that can be analysed is possible but certainly less common.

It is a relatively but not prohibitively expensive technique: looking at the full economic costing alone (i.e. considering only the cost of running the equipment) a good ball-park figure is £500–1000 for a full day of usage.

Case study 1 – clay model of a Chinese man

A clay model from the museum collection of the Royal College of Surgeons, due to undergo conservation treatment, depicts a man with a conjoined twin attached to his chest and shows visible damage, mostly on the back of the head. Using X-ray μCT, it was possible to understand how this model was constructed and if there had been any previous intervention. The analysis revealed the texture of the unfired clay and detected invisible inner cracks and air bubbles. The imaging also showed that different parts of the model (legs, head, parasitic twin) had been sculpted individually and then attached to the torso (Fig. 2c). Furthermore, the model does not have a metallic armature inside, but three pieces of organic material (probably wood) in the legs and the head (Fig. 2b). The paint on the cassock and face also stands out in the data indicating the metallic content (which was confirmed separately by other techniques). The blue paint on the cassock does not show any contrast with the clay. Identified as ultramarine blue by Raman microscopy, the blue pigment has a density too close to that of the clay (both in terms of actual composition and mass/volume), which translates to similar grey levels in the data. Because of this lack of

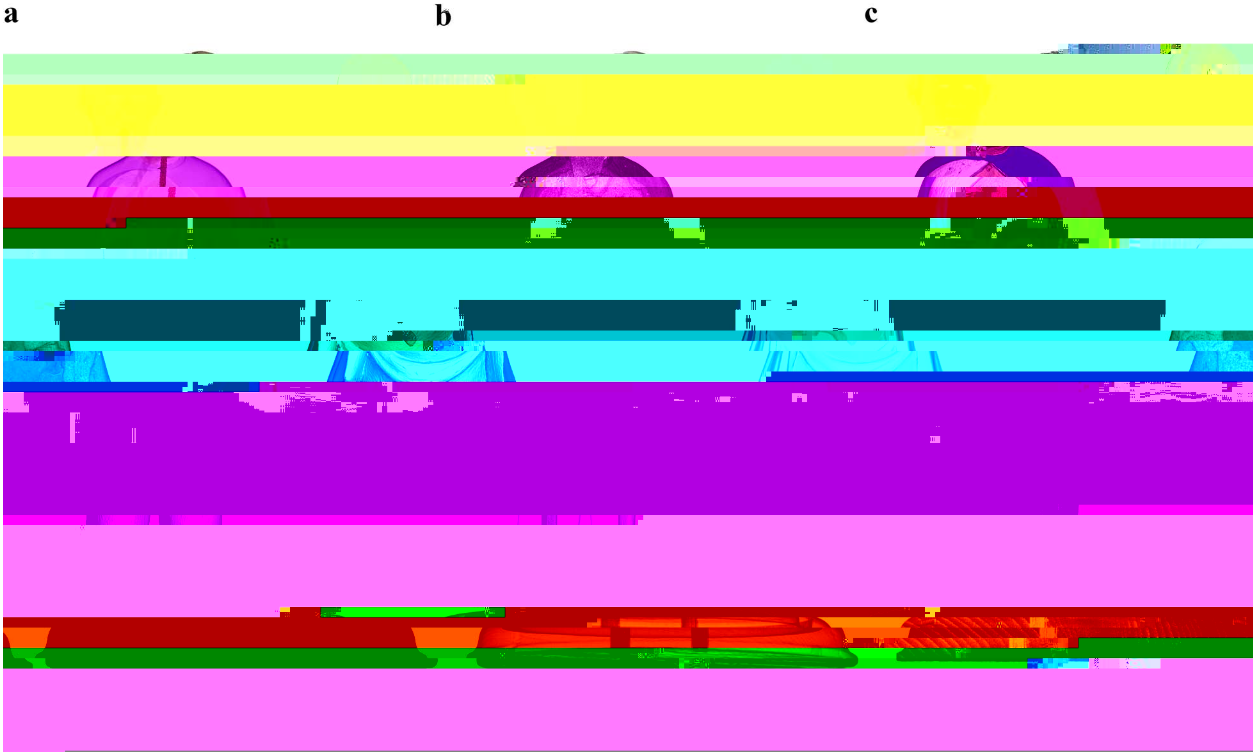

Fig. 2 Digital 3D rendering of the figurine. (a) Artificially coloured rendering; (b), semi-transparent figurine revealing the organic material supporting the legs and head; (c), vertical section through the dataset showing the different parts of the model. © Natural History Museum and Royal College of Surgeons.

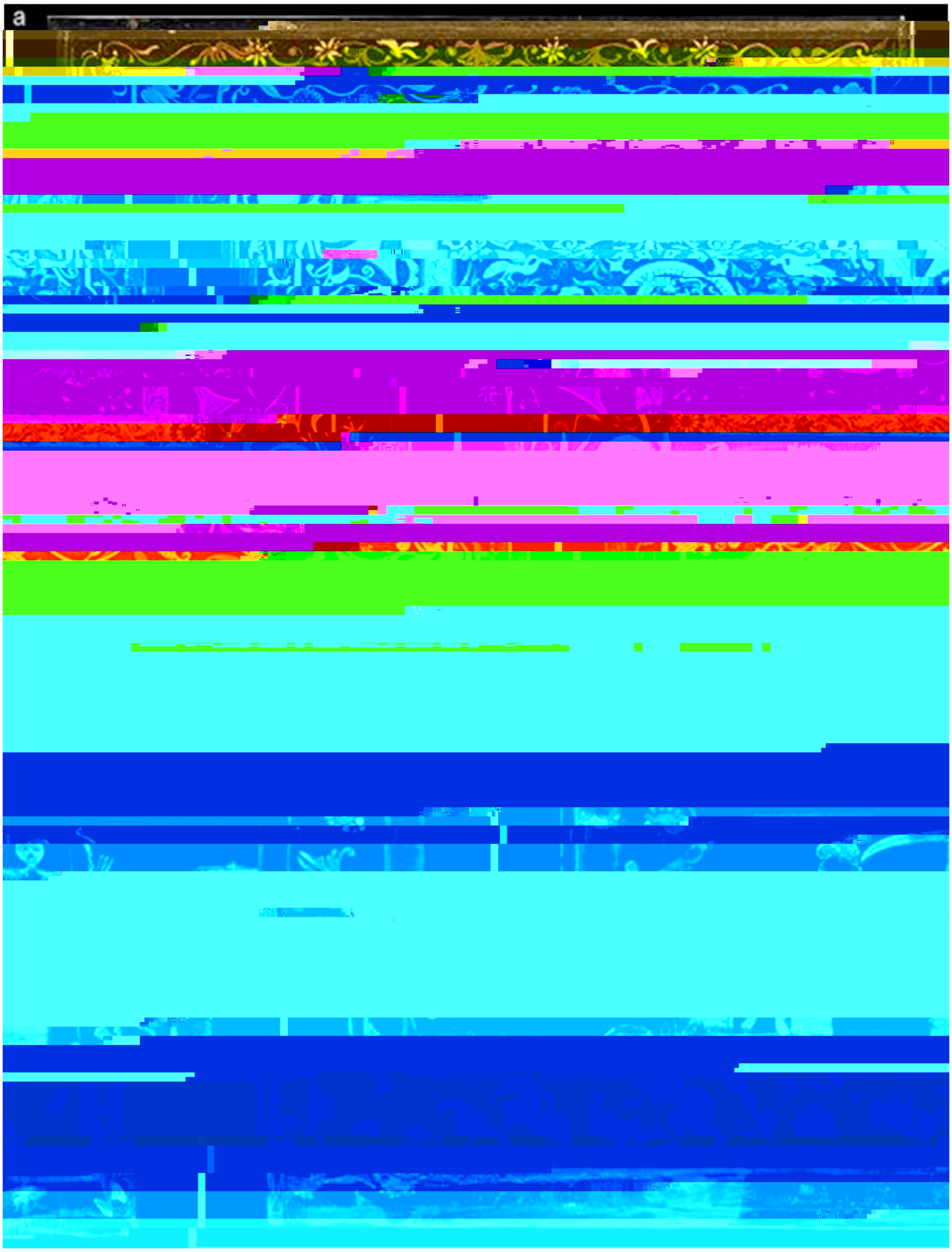

Fig. 3 (a) Photograph of the inner surface of the V&A cabinet's lid showing a 20th century paint scheme; (b) digital rendering of the original mercury-based decorative scheme, hidden below the surface. © Victoria and Albert Museum and Natural History Museum.

contrast the software could not differentiate between the two different materials. It is however possible to select manually just the first few voxels (voxels are the 3D equivalent of 2D pixels) at the surface of the model, attribute them to the coat, and paint them virtually in blue (for more information, see ref. 1).

Case study 2 – Barniz de Pasto table cabinet

The lid from a rare 17th-century table cabinet from South America, from the Victoria and Albert Museum collections (Fig. 3), was analysed by X-ray μCT to visualise the original decoration hidden under a 20th-century paint scheme. The analysis facilitated visually 'peeling off' the modern surface paint to reveal the original pigments. The latter contained mostly mercury and were therefore easily distinguishable from the wooden substrate and the other organic components of the paint (for more images see ref. 2). See ref. 3–5 for further examples of where X-ray μCT has successfully been used in heritage science.

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Further Reading

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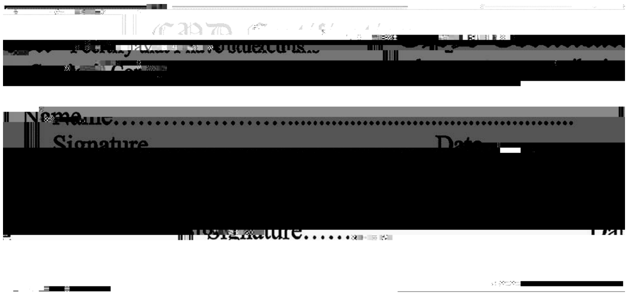

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