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Radiography and Computed Tomography for Works of Art

Maria Pia Morigi and Franco Casali

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58.1 Introduction

This chapter provides an introduction to the application of X-ray radiography and computed tomography in the analysis of archaeological finds and works of art. These powerful non-destructive techniques are capable of providing morphological and physical information on the inner structure of the objects studied; therefore, they are applied increasingly more frequently to Cultural Heritage assets, not only for conservation and restoration purposes, but also to increase the knowledge on the construction technique of a specific artefact or work of art. In fact, together with a variety of other scientific investigations, radiography and computed tomography can help answer the following main questions concerning the composition, dating, provenance, art technology, and conservation of an ancient object:

• What material is it made of?
• When was it made?
• Where was it made?

• How was it made?
• How can we preserve it for future generations?

Due to the large variety of sizes and compositions typical of Cultural Heritage objects, different X-ray sources, detectors, and setups are necessary to meet the different needs of various case studies. Moreover, as it is difficult to move the works of art from the place where they are kept, it is very important to develop equipment that is easy to move. This chapter provides a broad overview of radiography and tomography systems with different technical characteristics, accompanied by some examples of their application in the Cultural Heritage field. The last section will be devoted to neutron computed tomography and its application as a complementary technique to X-ray computed tomography (CT).

58.2 Radiography Applied to Cultural Heritage

Radiography has a long history of use in Cultural Heritage studies: within 2 years from the announcement of the discovery of X-rays by the German physicist Wilhelm Conrad Röntgen...
Easel paintings from the Middle Ages up to the nineteenth century have a complex multidimensional structure, created by superimposing different layers, as shown in Figure 58.1.

An easel painting consists typically of a wooden (poplar, oak, etc.), canvas (linen, hemp, cotton), metal (copper) or stone (obsidian) support, a ground layer, paint layers, and varnish. The ground layer provides a smooth surface for the execution of the painting and is generally made of chalk or gypsium and glue. An underdrawing can be executed directly either on the preparatory ground of the painting or on the priming layer (ot imprimatura, i.e., a second thin layer made of a pigment, such as lead white, in a medium and applied over the first ground), by using charcoal, chalk, a metal point, ink or water-based black paint. The painting is then built up by superimposing layers of organic or mineral pigments suspended in organic media. The palette used by European painters contains relatively few variations up until the nineteenth century, when a number of new pigments, such as Zinc White and Prussian Blue, were developed thanks to progresses made in science. In order to protect the painting and saturate colors, a varnish layer is added (Alfeld and Broekaert 2013).

Thanks to their high depth of penetration, X-rays have the capability to cross through all the layers of an easel painting: therefore, radiography enables us to obtain insight into the entire structure of the painting. The X-ray differential absorption when rays pass through the object studied produces the contrast in the radiographic image. In fact, according to the Beer–Lambert law, the degree of absorption of a monochromatic X-ray beam depends on both the thickness and the attenuation coefficient of the material through which the radiation passes. Elements with high density and high atomic number absorb X-rays more than light elements, so metal nails or pigments containing high-Z elements will contrast well with wood or canvas, while organic pigments will be almost “transparent” to X-rays. Table 58.1 shows a rough classification of the radiopacity of the materials generally used in paintings.

### TABLE 58.1

<table>
<thead>
<tr>
<th>Radiopacity</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Canvas (linen, hemp)</td>
</tr>
<tr>
<td></td>
<td>Thin wooden supports (up to 2 cm)</td>
</tr>
<tr>
<td></td>
<td>Binders (oil, egg, glues)</td>
</tr>
<tr>
<td></td>
<td>Organic pigments</td>
</tr>
<tr>
<td>Medium</td>
<td>Thick wooden supports (over 2 cm)</td>
</tr>
<tr>
<td></td>
<td>Calcium carbonate</td>
</tr>
<tr>
<td></td>
<td>Calcium sulfate (preparatory layer)</td>
</tr>
<tr>
<td></td>
<td>Light mineral pigments</td>
</tr>
<tr>
<td>High</td>
<td>Ochre and iron oxides</td>
</tr>
<tr>
<td></td>
<td>Zinc white ([\text{ZnO}])</td>
</tr>
<tr>
<td></td>
<td>Mineral pigments with medium atomic number</td>
</tr>
<tr>
<td>Very high</td>
<td>Lead white ([\text{PbCO}_3]); Red lead (minium) ([\text{Pb}_3\text{O}_4])</td>
</tr>
<tr>
<td></td>
<td>Lead tin yellow ([\text{Pb}_2\text{SnO}_4])</td>
</tr>
<tr>
<td></td>
<td>Vermilion (cinnabar) ([\text{Hg}_2\text{S}_2])</td>
</tr>
<tr>
<td></td>
<td>Metallic components (nails, etc.)</td>
</tr>
</tbody>
</table>

Radiography and Computed Tomography for Works of Art

In particular, the X-ray examination of a painting is able to provide us with information on:

- The kind of pigments used by the painter (organic or mineral)
- The possible existence of changes in the paint layer and/or underlying paintings (see, for example, Figures 58.2 and 58.3)
- The state of degradation of the materials used (for example, galleries and holes caused by woodworms in wood panels)
- The assembly of different components in a work of art
- The presence of previous restoration work (Figure 58.4)
- The characteristic “touch” of a certain artist and the authenticity of a work of art

Figure 58.5 shows a typical setup for the performance of X-ray tests on paintings: the X-ray source is mounted underneath a lead-plated table with a rectangular opening through which the diverging X-ray beam passes. Paintings are laid horizontally on this table and can be examined in a few minutes with the X-ray source working at a voltage between 30 and 50 kV, depending on the kind and thickness of the support. As an image detector, classical X-ray films have been used for decades, but nowadays they are increasingly being replaced by a variety of digital imaging solutions, among which photostimulable phosphor plates and flat panel detectors are worthy of mention.

58.2.1 Film Radiography

Generally speaking, X-ray films are covered with an emulsion containing a suspension of silver halide salts (usually with a

![Figure 58.2](image1)

Light photograph (left) and X-ray image (right) of the panel painting *Madonna with Child* by Domenico Beccafumi (National Gallery, Pisa, Italy). (Reproduced with permission from Aldrovandi, A. and M. Picollo. 2007. *Metodi di documentazione e indagini non invasive sui dipinti*. Saonara (Pd), Italy: Il Prato.)

![Figure 58.3](image2)

particle diameter of around 1–10 µm) in gelatin; a thin layer of adhesive is used to apply this emulsion to both sides of the support film, while a thin coating layer protects their surfaces. The level of detail that can be recorded depends on the grain size and thickness of the emulsion layer: a smaller grain size affords better definition and finer details, but requires a longer exposure (Lang et al. 2005). Film is quite cheap to buy and process and it is an integrating medium; in fact, the degree of blackening of a film, known as its optical density, depends not only on the intensity of the X-ray beam, but also on the length of exposure. For this reason, the radiographic exposure, \( E \), is generally expressed as the product of intensity, \( I \), and integration time, \( t \):

\[
E = It
\]  

(58.1)

A correct exposure is important to produce a reliable image on the film. Over- or underexposure will result in a loss of contrast and, therefore, possibly in a loss of information.

The proper film exposure can be obtained from the so-called characteristic curve of the X-ray film, which describes the relationship between the optical density and exposure.

The optical (or radiographic) density, \( D \), of a film is defined as:

\[
D = \log_{10} \frac{I_0}{I_t}
\]  

(58.2)

where \( I_0 \) and \( I_t \) are the intensities of light incident on and transmitted through the exposed film after its development with chemicals.

The characteristic curve (an example is given in Figure 58.6) has three distinct regions with different contrast transfer characteristics. The portion of the curve associated with low exposures is called the toe, while the upper portion is called the shoulder. When the exposure of a film falls within these two regions, little or no contrast is transferred to the image.

In the central part of the curve, the relationship between optical density and the logarithm of exposure is approximately linear. To achieve the best contrast, the film must be exposed in such a way that the object studied causes film doses which are in the central portion of the characteristic curve.

X-ray films are available with a wide range of characteristics and sizes, even though the format used most often is 30 × 40 cm². Many separate radiographs are necessary in the case of paintings...
larger than 30 × 40 cm²: films in black envelopes are positioned on the surface of the painting, with sufficient overlap between individual plates. The final image is obtained as a mosaic of single radiographs, but there are a number of problems associated with this method: for instance, the presence of tonal differences in adjacent images and the impossibility of aligning adjacent images perfectly if the position of the X-ray tube is different for the various radiographs. A number of museums overcome many of these problems by using large-format X-ray films (up to 1.37 m wide and 30 m long). The radiographic film is cut and then sealed inside a black plastic envelope that is also used for the film processing: after the exposure, developing, fixing and washing solutions are introduced through a valve at one end of the envelope, so that the film can be developed on-site, without a specially equipped darkroom. It is also possible to digitize the original X-ray plates by using adequate scanners with a large imaging area and high resolution. Generally speaking, sufficient information is captured from the original X-ray film by scanning at a resolution of 300 dpi, but, sometimes, in order to obtain more manageable image files, a lower 150 dpi resolution is used when there are a large number of plates to be assembled together in a single mosaic image (Padfield et al. 2002).

58.2.2 Computed and Digital Radiography

Digital systems are traditionally split into two broadly defined categories (Körner et al. 2007): Computed Radiography (CR) and Digital Radiography (DR). CR systems use photostimulable phosphor (PSP) plates with a separate image readout procedure (see Section I, Chapter 12), that is, an indirect conversion process, while DR detectors can use either a direct or an indirect process for converting X-rays into electric charges.

PSP imaging uses reusable imaging plates and the associated hardware and software to acquire and display digital projection radiographs. PSP (e.g., BaFBr:Eu²⁺) stores absorbed X-ray energy in crystal structure “traps” and is sometimes referred to as a “storage” phosphor. This trapped energy can be released if it is stimulated by additional light energy of the proper wavelength in the process of photo-stimulated luminescence (PSL). The light emitted is captured by a photodetector and then converted into a digital image (Rowlands 2002).

Different kinds of digital detectors are available on the market for digital radiography: the most frequently used are charge coupled device (CCD) or complementary metal-oxide semiconductor (CMOS) cameras optically coupled to a scintillator screen and direct or indirect flat panel detectors. Direct-conversion flat panels have an X-ray photodetector, such as amorphous selenium (a-Se), which converts X-ray photons directly into electric charges. Indirect conversion systems use a two-stage technique for conversion. In the first step a scintillator layer, such as cesium (a-Se), which converts X-ray photons directly into electric charges. Indirect conversion systems use a two-stage technique for conversion. In the first step a scintillator layer, such as cesium (a-Se), which converts X-ray photons directly into electric charges. Indirect conversion systems use a two-stage technique for conversion. In the first step a scintillator layer, such as cesium (a-Se), which converts X-ray photons directly into electric charges. Indirect conversion systems use a two-stage technique for conversion. In the first step a scintillator layer, such as cesium (a-Se), which converts X-ray photons directly into electric charges. Indirect conversion systems use a two-stage technique for conversion. In the first step a scintillator layer, such as cesium (a-Se), which converts X-ray photons directly into electric charges. Indirect conversion systems use a two-stage technique for conversion. In the first step a scintillator layer, such as cesium (a-Se), which converts X-ray photons directly into electric charges. Indirect conversion systems use a two-stage technique for conversion. In the first step a scintillator layer, such as cesium (a-Se), which converts X-ray photons directly into electric charges. Indirect conversion systems use a two-stage technique for conversion. 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of a pair of orthogonal lightweight and dismountable axes that make the translation of the digital detector with a stroke of 1.5 m possible. Two different detectors have been used for on-site measurements: a CCD camera (Apogee Alta U9000, 3056 × 3056 array, 12 μm pixel size) optically coupled to a structured CsI(Tl) screen (useful area: 12 × 12 cm²) and a flat panel Hamamatsu C10900D (photodiode area: 12.48 × 12.48 cm², 1216 × 1232 active pixels, 100 μm pixel size, 12 bit digital output). The X-ray tube (Gillardoni MHF 200D, air-cooled, adjustable voltage from 30 to 200 kV, 900 W maximum power) is placed opposite the work of art at a proper distance, in order to irradiate the whole area to be scanned (roughly 3 m for an area of 1.5 × 1.5 m²).

Another scanning device for the investigation of paintings of size up to 2 × 2 m² with a spatial resolution of about 100 μm has been designed and constructed at the Larix Lab of the Department of Physics and Earth Science in Ferrara University. The system, shown in Figure 58.8, can be disassembled and transferred on-site to perform X-ray scans. The X-ray tube (a mammographic unit, Varian M147) and the detector (RadEye100 image sensor, featuring a 1024 × 1000 pixel image area with 96 μm pixel size for a roughly 10 × 10 cm² active area) are mounted specularly on a motorized double aluminum arm at a fixed distance of about 60 cm. The short distance between X-ray tube and detector requires a small focal spot size in order to minimize the so-called penumbra effect (Casali 2006). This setup provides the best detector-source stability. Arm movements are induced by two motorized scanning systems, one for X and one for Y direction. The painting is locked in a central frame. The movement of the source-detector system, X-ray emission and image acquisition are synchronized and remotely controlled by a dedicated PC (Albertin et al. 2013).

In both devices, the so-called tile scanning technique is used to perform DR of works of art: radiographic images are acquired on the basis of a grid that ensures an overlap of a few centimeters between images. Several commercial or open-source software programs, such as PTGui, PanaVue ImageAssembler, ImageJ or Adobe Photoshop, are used in processing to merge single images.

Within the framework of the neu_Art Project (Re et al. 2012), a new DR system has been recently developed and installed at the “La Venaria Reale” Center for Conservation and Restoration near Turin (Italy). This instrument provides high quality radiographic images of paintings (and other works of art) with sizes up to 4 × 3.5 m² by scanning horizontal portions of their surface with an X-ray linear detector. The painting is positioned vertically in front of a motorized mechanical system that makes it possible to select the height to be scanned. A horizontal axis, with an accurate speed control, synchronizes the detector movement with the image acquisition software. The X-ray source is a General Electric Eresco 42MF4, with a Tungsten anode and a peak current of 4.5 mA at the maximum voltage of 200 kV. The focal spot size of the source is 3 mm and the emission of X-rays takes place in a cone of elliptical section (40° vertically and 60° horizontally). A linear X-ray TDI (Time Delay Integration) camera (Hamamatsu C10650), coupled with a fiberoptic plate and a scintillator, is used to acquire the radiographic images. It features a 22 cm long CCD array (4608 × 128 pixels, 48 μm pixel size) and is designed for operation with X-ray energies lower than 95 keV. This radiographic system has been used, for example, within the framework of a scientific campaign of analyses on a series of House of Savoy portrait paintings on canvas from Racconigi Castle (Buscaglia et al. 2013).

Conventional transmission radiography is able to visualize clearly the spatial distribution of pigments containing high atomic number elements, but, in the case of lead white-based preparatory layers, imaging problems may arise because of the dominant contribution of the ground. Various alternative techniques have been proposed to overcome the shortcomings of traditional radiography, such as X-ray fluorescence mapping (Dik et al. 2008; Alfeld et al. 2013), neutron activation autoradiography (Alfeld et al. 2015), electron emission radiography (Bridgam et al. 1958, 1965; Schalm et al. 2014) and energy-resolved X-ray radiography (Krug et al. 2006; Albertin et al. 2009; Cabal et al. 2015), but their application is still limited. A good overview of the possibilities of these imaging techniques is provided in Alfeld and Broekaert (2013).

58.3 Computed Tomography Applied to Cultural Heritage: General Considerations

While radiography has been used for decades in the analysis of paintings and other works of art, only recently has X-ray CT been introduced in the field of Cultural Heritage diagnostics. This kind of technique is the natural evolution of radiography and is able to provide morphological and physical information on the inner structure of the objects studied, while preserving their integrity. In particular, CT is able to overcome an important limit of radiography: the superimposition of elements belonging to different layers of the object (see Section III, Chapter 32). In fact, in conventional radiography, the 3D structure of the object is projected onto a 2D detector and each point of the resulting image provides a measure of the overall attenuation of the X-ray beam as it crosses through the subject. Consequently, while the lateral dimensions (height and width) of the specimen—those perpendicular to the direction of the radiation travel—are retained in...
the radiograph, the third dimension (depth) is lost. Generally speaking, in the case of essentially 2D works of art such as paintings, this is not a crucial issue, but it may create problems when the case study is a 3D object.

The first attempts at overcoming this limitation were made by introducing X-ray stereoradiography, a technique based on the acquisition of two radiographs from slightly different positions; their viewing through an appropriate apparatus gives a 3D image (Lang et al. 2005). In addition to the application in medicine, stereoradiography has also been applied for Cultural Heritage study and diagnostics, being particularly useful for ceramics (Middleton 2005), human remains (Davis 2005) and wooden statues (Lang et al. 2005). Stereoradiography, however, has become essentially obsolete after the introduction of tomography (CT or CAT scans) in the medical field.

The method on which CT is based was conceived and developed for the first time in the 1960s by English engineer Godfrey Hounsfield and South Africa-born physicist Allan Cormack (naturalized a US citizen in 1966). They worked independently of each other and, thanks to their discovery, were jointly awarded the Nobel Prize for Medicine in 1979. The first clinical CT scan on a patient took place on October 1, 1971 at Atkinson Morley’s Hospital in London, England. The patient, a woman with a suspected frontal lobe tumor, was scanned with a prototype scanner, developed by Godfrey Hounsfield and his team at the EMI Central Research Laboratories in Hayes, West London. The scanner produced an image with an 80 × 80 matrix, taking about 5 minutes for each scan, with a similar time required to process the image data. Since then, continued progress in this technique has brought the development of new generations of medical tomographic scanners with faster image acquisition and reconstruction times (Hsieh 2002). Even though CT is primarily used as a diagnostic tool in the medical field, in recent years its importance and potential when applied to other areas, for example industry and Cultural Heritage, have become increasingly evident.

The successful use of CT as an efficient and powerful non-destructive tool for the study of archaeological findings and works of art has been reported on by a growing number of authors (Mazansky 1993; Rossi et al. 1999, 2001; Jansen et al. 2002; Applbaum and Applbaum 2005; van Kaick and Delorme 2005; Casali 2006; Freeth et al. 2006; Morigi et al. 2010; Hughes 2011; Re et al. 2012, 2015; Pintus et al. 2016). The 3D reconstruction of the objects makes it possible to obtain a large amount of information on the manufacturing and assembly techniques, as well as on the conservation status and inner morphological features. This knowledge is very useful for determining adequate maintenance and restoration procedures. Information can be retrieved as either 2D cross-section images (the so-called slices) or 3D full-volume images, thus allowing for the inspection and the classification of the different materials making up the object studied. In fact, through the use of sophisticated computer programs, it is possible to manipulate 3D renderings, by making virtual cuts on the reconstructed volume or selectively removing some layers to reveal additional information. Moreover, by processing tomographic data, a 3D numerical model of the sample can be obtained for virtual reality applications, digital archives storage or the creation of replicas using laser stereolithography or 3D printing (Laycock et al. 2012; Zhang et al. 2012; Doney et al. 2013).

Most of the studies on archaeological findings and works of art reported in the literature have been conducted using medical scanners or, less frequently, CT systems set up inside shielded cabinets, generally used for the X-ray inspection of industrial components (Karl et al. 2014). In particular, medical scanners have been used for the analysis of human mummies (Dawson and Gray 1968; Marx and D’Auria 1986; Baldock et al. 1994; Hughes 1996; Previgliano et al. 2003; Taylor 2004; Davis 2005; Lynnerup 2010), human and animal bone materials (Lynnerup et al. 1997; Wu and Scheppartz 2009) and clay and ceramic archaeological artifacts (Anderson and Fall 1995; Jansen et al. 2001; Minozzi et al. 2010; Harvig et al. 2012). However, the geometrical setup and X-ray beam energy of medical CT scanners are optimized for the human body, so their application to Cultural Heritage assets is characterized by strong constraints with regard to the maximum size, shape, and density of the object to be analyzed. Moreover, the spatial resolution is usually limited to 0.5 mm, even though special CT scanners devoted to particular anatomical regions can arrive at around 0.2–0.3 mm (Logan et al. 2013).

In order to overcome these limitations, especially in the past few years, several research groups have designed and developed customized CT systems (Bettuzzi et al. 2004; Brunetti 2007; Tuniz et al. 2013; Re et al. 2014), expressly conceived for analyses in the Cultural Heritage field. In addition, as it is usually difficult or even impossible to move the works of art from the place where they are located, sometimes the CT analysis has been performed inside museums or restoration laboratories by means of transportable equipment (Casali 2006; Morigi et al. 2010).

Due to the large variety of size, density, and materials typical of Cultural Heritage assets, different X-ray sources, detectors, and setups are necessary to perform CT studies on a broad range of archaeological findings and works of art. In the following sections of the chapter, we present an overview of CT systems with different technical characteristics, along with various examples of applications in the Cultural Heritage field.

### 58.4 CT Systems with X-ray Tubes up to 200 kV

The great majority of CT studies in the Cultural Heritage field have been carried out by using laboratory or transportable CT systems with X-ray tubes of up to 200 peak kilovoltage (kVp). Depending on the object to be analyzed and the desired spatial resolution, different setups are necessary; however, in any case, the main components of a CT system are the following:

- A radiation source
- A digital detector
- Equipment to make the object or source-detector system rotate, in order to acquire a sequence of X-ray projections at different angles
- One or more computers to manage image acquisition and perform tomographic reconstruction and 3D rendering

The objects of cultural interest cover a wide range of sizes; therefore, it is necessary to develop and use different kinds of equipment in order to meet the varying requirements of the
Cultural Heritage field. We can distinguish three main categories of CT systems that use X-ray sources of up to 200 kV:

- Micro-CT systems
- CT systems for medium-sized objects
- CT systems for large works of art

The following pages provide descriptions of the typical setups for each category, together with some examples of applications on archaeological objects and artworks.

### 58.4.1 Micro-CT Systems

X-ray micro-CT scanners are available on the market from several companies (for example, Bruker MicroCT [formerly known as SkyScan], Scanco Medical, RX Solutions, North Star Imaging, GE Measurement and Control Solutions and Nikon Metrology), but some research groups have developed in-house modular systems, with spatial resolutions varying from sub-micrometer for millimeter-size objects to tens of micrometers for 10–20-cm size objects (Rossi et al. 2001; Massaehle et al. 2007; Tuniz and Zanini 2013; Dierick et al. 2014) (see Section III, Chapter 36). A microfocus or nanofocus tube, with a micrometric or submicrometric focal spot size, is used as the X-ray source in order to take advantage of magnification in cone beam geometry, so the spatial resolution can be increased while limiting the so-called “penumbra” effect. In fact, the relationship between the magnification, \( M \), the unsharpness (or penumbra), \( U \), and the focal spot size, \( S \), of the X-ray source is described by the equation:

\[
U = S(M - 1)
\]  

with \( M \) given by:

\[
M = \frac{SDD}{SOD}
\]

where SDD is the Source-Detector-Distance and SOD is the Source-Object-Distance.

Obviously, the geometric unsharpness should be smaller than the features of the object to be visualized; therefore, it is clear from Equation 58.3 that only with a microfocus or nanofocus tube can high magnifications be possible without a significant loss of image quality.

A magnification stage (e.g., a motorized axis) is generally integrated into the setup to change the position of the sample with respect to the source and detector.

Another stage can be used to change the SDD and, consequently, the X-ray flux reaching the detector for a given voltage and current. Small SDDs permit short exposure times, but can also cause more cone beam artifacts (Dierick et al. 2014), while an increased SDD is sometimes used to perform phase-contrast micro-CT measurements.

In micro-CT analysis, the number of 2D radiographs acquired at different angles is quite high (typically from 1000 to 4000), while tomographic images are generated by using specific mathematical algorithms for slice reconstruction (Feldkamp et al. 1984; Kak and Slaney 1987), which are implemented in commercial or in-house software programs. 3D rendering, segmentation and manipulation of the reconstructed volume are generally performed by means of advanced imaging software such as VGStudio Max (http://www.volumegraphics.com), Amira (http://www.fei.com/software/amira-3d-for-life-sciences), 3D Slicer (http://www.slicer.org), OsiriX (http://www.osirix-viewer.com) or Mimics (http://biomedical.materialise.com).

Micro-CT is a versatile technique which can be successfully applied to a great variety of materials, such as fossil (and non-fossil) teeth (Macchiarelli et al. 2006; Zanoll et al. 2012) and bones, small metal objects, jewelry, ceramics (Sanger et al. 2013), prehistoric pottery, stone (Yang et al. 2011), and organic materials such as wood (Haneca et al. 2012), charcoal (Bird et al. 2008), textiles, and archaeological food remains (Coubray et al. 2010).

Figure 58.9 shows a typical cone beam micro-CT system, developed at the Department of Physics and Astronomy of Bologna University.

The setup is based on a microfocus X-ray tube (maximum voltage: 130 kV; maximum current: 0.5 mA; minimum focal spot: 5 μm) and a Photonic Science CCD camera (4008 × 2672 pixels, 9 μm pixel size) with a 36 × 24 mm² field of view (FOV). This camera features a high resolution phosphor screen directly coupled to the CCD by means of a fiber-optic plate that protects the sensor against radiation damage. The sample manipulator consists of a high precision rotary table, on which the object to be analyzed is positioned, and a tip-tilt platform to assure the correct alignment between the vertical rotation axis and the detector’s pixel matrix. The sample manipulator is mounted on a vertical translation axis that makes it possible to analyze, in successive steps, objects with a vertical size larger than the CCD camera’s FOV. This system has recently been applied to the study of human remains (Belcastro et al. 2014) and to home-made ceramic samples to study the effects of firing temperature on pottery microstructure (Ricci et al. 2015).

It is possible to find a very similar setup in the so-called TOMOLAB station at the ELETTRA Synchrotron Light facility (Trieste, Italy), operational since 2006 and implemented thanks to the cooperation between ELETTRA and the University of Trieste. TOMOLAB, too, is a micro-CT system based on a cone beam geometry that makes it possible to achieve a spatial resolution close to the focal spot size of the 130 kV microfocus source (5 μm). A low-noise water-cooled CCD camera providing a good combination between a large field of view (49.9 × 33.2 mm²) and a small pixel size (12.5 μm) is used as a detector. It is also

![FIGURE 58.9 Scheme of the micro-CT system developed at the Department of Physics and Astronomy of Bologna University, Italy.](http://www.fei.com/software/amira-3d-for-life-sciences)
possible to perform scanning with a large area detector (a flat panel with an active area of 120 × 120 mm²). This instrument has been designed to be complementary to the SYRMEP beamline setup for micro-CT (described in Section 58.6.2). Thanks to the property demonstrated by Wilkins et al. (1996), for which the radiographs obtained by using a polychromatic X-ray beam from a microfocus source may reveal phase jumps, at the TOMOLAB it is possible to perform phase-contrast micro-CT measurements (even if with limited spatial coherence compared to a synchrotron X-ray beam). This system is currently used for 3D imaging on a wide range of materials for many different applications, including objects of archaeological interest. For example, worth mentioning is the micro-CT analysis carried out on a Neolithic human tooth (Bernardini et al. 2012), which revealed the use of beeswax as a dental filling: this could be the earliest known direct evidence of a therapeutic-palliative dental filling. Another interesting example of micro-CT investigation is that performed on the Divje Babe “flute,” made from a juvenile cave bear left femur and found in the Middle Paleolithic layers of the Divje Babe I Cave in Slovenia in 1995. The micro-CT study was performed to characterize the morphology of the two holes in the bone that had been interpreted by some scholars as a possible Neanderthal “flute.” Other researchers did not agree with this hypothesis, suggesting a carnivore origin for the holes. The results of the micro-CT analysis, shown in Figure 58.10, demonstrated that there were originally four holes, possibly man-made by means of pointed stones or bone tools. Moreover, a thin bone layer was removed around one of the holes, probably for facilitating perforation. The results of micro-CT showed that a Neanderthal manufacture of the object cannot be ruled out (Tuniz et al. 2012).

ELETTRA-Sincrotrone Trieste S.C.p.A. has also been involved in the development of another micro-CT system in collaboration with the Multidisciplinary Laboratory (MLAB) of the “Abdus Salam” International Center for Theoretical Physics (ICTP) located in Trieste (Italy) (Tuniz et al. 2013). This is part of a project funded by the Friuli Venezia Giulia Region (Italy), which aims at developing advanced portable/transportable X-ray instruments for the study of Cultural Heritage materials. The micro-CT system, shown in Figure 58.11, is set up at the MLAB and has been designed for the study of relatively large objects with a lateral measurement of up to 20 cm and a weight of up to 15 kg, with a voxel size of 50–100 μm. In the case of smaller samples, it is possible to achieve a voxel size of 5–10 μm. The system is equipped with a 150 kV microfocus X-ray tube and a Hamamatsu CMOS flat panel coupled to a fiberoptic plate under a gadolinium oxysulfide (GOS) scintillator. High precision horizontal and vertical stages permit fine movements and the precise alignment of the sample. In the ICTP laboratory, the CT system operates inside a lead-shielded cabinet, but the various components can be easily disassembled in order to be transported and mounted in museums and other locations to perform on-site studies.

Several modular micro- and nano-CT scanners have also been developed at the “Centre for X-ray Tomography” of the Ghent University in Belgium (UGCT), an interdisciplinary research facility that performs research on the X-ray micro- and nanotomography technique and its applications in a scientific context. UGCT designs and integrates its own scanners by purchasing their basic components and assembling them to obtain versatile systems that can be modified ad hoc and optimized afterwards. Thanks to
its modular structure, it is possible to adapt the setup to obtain optimum experimental conditions as well as to install additional devices, if necessary. The CT facility houses four high resolution CT scanners (called HECTOR, Nanowood, EMCT, and Medusa) with different X-ray sources and detectors and a combined micro-CT/micro-X-ray fluorescence (XRF) system (Herakles). Detailed information can be found on the website of the facility (http://www.ugct.ugent.be) and in various papers (Masschaele et al. 2007, 2013; Dierick et al. 2014). In particular, worth mentioning is the EMCT system (Environmental Micro-CT), which is rather unique in the context of micro-CT scanners because of its gantry-based setup with the X-ray source and detector assembly rotating around the sample, which remains static. Among their numerous applications, these systems have also been used for the analysis of archaeological materials (Haneca et al. 2012), art objects (De Witte et al. 2008), wooden musical instruments (Van den Bulcke et al. 2016), and building stones (to understand, for example, the mechanism by which salt crystallization can damage building materials) (Raneri et al. 2015).

58.4.2 CT Systems for Medium-Sized Objects

For the analysis of medium-sized objects (maximum size equal to a few tens of centimeters), it is possible to use either a medical scanner—if the density of the material is not too different from that of the human body—or a 3D-CT inspection system for industrial non-destructive testing (see Section IV, Chapters 45 and 46). The latter type of equipment makes it possible to expand the range of materials that can be analyzed, thanks to the higher X-ray energy source. A wide range of systems are available on the market (see, for example, the following websites: www.gemeasurement.com/inspection-and-non-destructive-testing, www.4nsi.com, www.yxlon.com or www.nikonmetrology.com), which are equipped with different X-ray tubes and digital detectors of various formats. The instrumentation, provided with a sample manipulator that assures several degrees of freedom, is generally set up inside a shielded cabinet. These CT systems have the advantage of a fully automated execution of the CT scanning and image reconstruction; however, they are very expensive and the cabinet is not easy to transport outside the laboratory. As previously pointed out, on-site studies are frequently required in the Cultural Heritage field: for this reason, there is a need for transportable CT systems, like that illustrated in Figure 58.12, which was developed by our research group within the framework of a national research project, carried out in collaboration with a team of paleoanthropologists. The system consists of the following items:

- A microfocus portable X-ray tube with a maximum voltage of 130 kV
- A flat panel detector with an active area of $19.5 \times 24.2 \text{ cm}^2$ (Varian PaxScan 2520D, CsI conversion screen, $1536 \times 1920$ pixels, $127 \mu\text{m}$ pixel size)
- A couple of orthogonal translation axes by Physik Instrumente for moving the detector, in order to obtain a field of view of about $50 \times 50 \text{ cm}^2$
- A tip-tilt platform and a turntable on which the object to be analyzed is positioned

When it is not necessary to achieve a very high spatial resolution, a standard source may be used instead of a microfocus tube, in order to increase the X-ray flux and reduce scanning time. Examples of CT studies carried out with this system can be found in Mariotti et al. (2015) and Belcastro et al. (2014), while
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Figure 58.13 shows the 3D rendering of the tomographic data obtained from the scanning of a human skull from the Anthropology Museum of Bologna University. The virtual cut of the reconstructed volume and the detail of a slice, visible in Figure 58.14, reveal the high spatial resolution of the CT system, which makes it possible to clearly visualize the trabecular structure of the bone.

Another interesting example of CT analysis performed with the same setup is the tomographic examination of four animal mummies (a cat, a small falcon, and two ibises) belonging to the Egyptian Collection of the Archaeological Museum in Bologna, which have recently been restored. The reconstructed volume of the falcon mummy is visible in Figure 58.15, together with the 3D rendering of the bird’s skeleton inside, after the linen wrappings of the mummy have been virtually removed by means of the software for 3D visualization.

A CCD-based detector may be used instead of a flat panel: a simple scheme of this kind of detector is shown in Figure 58.16. It is made of a scintillating screen (for example, either CsI(Tl) with needle structure or gadolinium oxysulfide), on which the X-ray beam generates the radiographic image of the object, optically coupled to a CCD camera (scientific grade, usually cooled to reduce thermal noise), through a lens and a 45° mirror, which is used to avoid the direct irradiation of the CCD by the primary X-ray beam. The camera, mirror, and scintillator are positioned in a light-tight box. The pixel size in the radiographic images depends on the number of pixels of the CCD chip as well as on the FOV captured by the camera, which can be modified by changing the focal length of lens and/or the camera-to-scintillator distance.

58.4.3 CT Systems for Large Works of Art

Sometimes the size of the work of art to be analyzed is very large (more than 2 m), thus making it impossible to use a medical scanner or a CT system similar to those described in the previous paragraphs. Moreover, it could be very difficult or even impossible to move large artworks from the place where they are located. In these cases, it is necessary to transfer the equipment inside the museum or restoration laboratory and perform the acquisition of CT data on-site. The tomographic survey of large objects is a challenge in terms of both data acquisition and image reconstruction, because of the large number of Gigabytes to be managed and processed. Moreover, this requires the development of custom setups, such as that shown in Figure 58.17, which was designed by our research group and used for the first time in 2004 for the on-site complete tomography of Egnazio Danti’s Globe located inside the Palazzo Vecchio in Florence (Italy). The diameter of this terrestrial globe, characterized by an iron inner structure, exceeds 2 m, and its full tomographic analysis was a true challenge, which required the acquisition of over 31 000 partial radiographs taken from different angles (Casali et al. 2005; Casali 2006).
Several years later, the same system, with an upgraded detector, was transferred to the “La Venaria Reale” Conservation and Restoration Centre (Turin, Italy) for a CT of two Japanese wooden statues, known as Kongo Rikishi (over 230 cm in height) and Tamon Ten (about 125 cm in height), dating back to the thirteen and seventeenth centuries, respectively (Morigi et al. 2010). On the same occasion, our research group also carried out the complete tomography of a precious and very large (350 × 109 × 68 cm3) writing cabinet by Pietro Piffetti (the most famous cabinet-maker in Piedmont in the eighteenth century), owned by the Accorsi-Ometto Foundation in Turin.

The transportable CT system, expressly conceived for the study of large objects, consists of:

- A directional X-ray tube that operates at up to 200 kV (Gilardoni MHF 200) and moves on a motorized vertical axis.
- A rotating platform, on which the work of art is positioned.
- A CCD-based detector that can be translated both horizontally and vertically by means of two motorized axes. The detector consists of a structured Caesium Iodide scintillating screen (1 mm thick, 45 × 45 cm2), optically coupled to a cooled CCD camera (Apogee Alta U32, 2184 × 1472 pixels). With a FOV of 45 × 30 cm2, at maximum resolution (binning 1 in the CCD chip), the pixel size in the radiographic images is about 200 µm, while the voxel size depends on the magnification which, however, in the case of large works of art, is usually close to 1.

As the FOV of the detector is smaller than the size of the artwork, it is necessary to operate in the so-called tile-scanning mode: the entire area of the object’s radiographic projection is divided into a certain number of frames, according to the size of the scintillating screen. Each frame corresponds to a different position of the detector. In this way, the work of art is virtually split into several horizontal portions that are reconstructed separately. For each frame, the object is rotated over 360° with fixed angular steps (typically 0.5° or 0.25°), while the detector acquires the set of radiographic projections at different angles. After a full rotation, the motorized axes move the detector into a new position and the procedure described above is repeated. Some overlap between adjacent frames is required in order to assure a good stitching together of the radiographs in the reconstruction phase, which may be quite long because of the high number of radiographic projections acquired (some tens of thousands).

Figure 58.18 shows three different CT slices of the Kongo Rikishi statue. The pixel size is about 0.4 mm.

The CT analysis was very useful for increasing our knowledge of the construction technique of this statue, which was created by assembling numerous pieces of Japanese cypress wood following an ancient technique called yosegi-zukuri. In fact, for the first time, CT made it possible to understand how the different pieces were assembled, revealing the types of joints, the empty spaces between them, and the presence of stucco, nails, and fastening elements (Casali et al. 2008a; Ravera 2008; Morigi et al. 2010).

Even if transportable, the CT system described above requires the help of porters for its transfer on-site, because of the size and weight of the motorized translation axes. For this reason, we have recently developed a new setup with shorter and lighter
axes and a compact flat panel detector. It is essentially the same equipment described in Section 58.2.2, except for a rotary stage and a vertical translation axis for the X-ray tube that have been integrated into the system, as shown in Figure 58.19.

The CT system depicted in Figure 58.20 has a slightly different setup: in this case, the X-ray tube is in a fixed position, while the CCD-based detector moves along a motorized horizontal axis at the same height as the X-ray source. The object is placed on a rotation stage and can be shifted vertically by means of a translation axis. In this case too, the CT acquisition is performed step by step with the tile-scanning technique.

Two interesting examples of CT investigation carried out with this system can be found in Casali et al. (2008b) and Morigi et al. (2007).

Another system capable of performing CT investigations on large objects has been developed within the framework of the aforementioned neu_Art Project: the mechanical system and the X-ray tube are the same as those described in Section 58.2.2, with the addition of a high precision rotary stage (Newport RV PE 350) which is mounted on a carriage to adjust the distance between the object and the detector. The rotary table has a diameter of 160 cm and can support a maximum load of 500 kg. To overcome the energy limitations of the detector used in DR, a Hamamatsu X-ray Line Sensor Camera C9750-20TCN, capable of operating with an X-ray energy of up to 200 keV, is used for CT. It has an active area 51.2 cm long and consists of a scintillator coupled with a linear array of vertically arranged CCDs (2560 pixels of 200 µm). The tomographic system, which is described in detail in Re et al. (2013), has been applied to the analysis of several archaeological findings (Re et al. 2015) and works of art (Re et al. 2014).

As outlined above, the CT analysis of large works of art is also particularly challenging with regard to the time necessary for the reconstruction of tomographic images, due to the large amount of data to be processed.

In order to reduce the reconstruction time, our research group has chosen an approach based on the parallelization of the reconstruction algorithm in a Microsoft HPC environment. This approach has proved very effective and easy to use, reducing the reconstruction time by almost two orders of magnitude on a 32-core cluster (Brancaccio et al. 2011).

58.5 CT Systems with Medium and High Energy X-rays

58.5.1 Sources of Medium and High Energy X-rays

As already stated, the field of interest of Cultural Heritage is very broad. It ranges from very small archaeological findings (e.g., prehistoric teeth and old jewellery, for which micro-CT is necessary), to large artifacts and metal or stone objects of considerable size and/or thickness.

The tomographic analysis of the objects belonging to the last category requires a very penetrating and high power X-ray source, in combination with a detector capable of providing good resolution images for this type of radiation.
As sources, it is possible to use:

- Orthovoltage X-ray tubes with voltages of up to 450 kV and 600 kV (medium–high energy)
- LINACs (Linear Accelerators) from 2 up to 15 MeV (high energy)
- Betatrons from 2 up to 7.5 MeV (high energy)

Orthovoltage X-ray tubes are often used for non-destructive testing in the industrial field. Portable X-ray generators are generally limited to a maximum voltage of 300 kV, while X-ray tubes capable of working at higher voltages are usually heavy instruments, which are difficult to move for on-site analysis.

LINACs are electron accelerators which, used in industrial bunkers, can work at up to 25 MeV or more. LINACs of this category, with high power, are very heavy and difficult to use on-site. LINACs with a mobile head are being studied.

Betatrons are a type of equipment within which electrons are accelerated along circular orbits with suitable combinations of electric and magnetic fields. Once the electrons have acquired the desired energy, they are made to hit a heavy metal target producing, in the process, a beam of photons by bremsstrahlung. Modern betatrons can be constructed in very compact dimensions so that they can be used on-site and even be supported in order to rotate around the object to be analyzed (for an example of portable betatron, see the website: https://qsa-global.com/product/portable-x-ray-betatron/).

The energy distribution of the photons produced by X-ray tubes, LINACs and betatrons is of "white" type, that is, it is not monoenergetic. The “rule of thumb” tells us that, from the standpoint of the penetration through an object, “white radiation” is equivalent to a monochromatic X-ray beam of energy equal to about 1/3 of the peak voltage. For example, the radiation produced by a 3 MeV LINAC (or betatron) is equivalent to a monoenergetic beam of about 1 MeV (like the gamma rays emitted by a ⁶⁰Co source).

In the past, instead of electron accelerators, radioactive sources (mainly ⁶⁰Co and ¹⁹²Ir) have been used for the radiography of bronze or marble statues. Despite the advantage of providing easier handling, this type of source has the drawback of producing a photon flux much lower than that of LINACs or betatrons and with a larger focal spot size, thus resulting in a lower spatial resolution of the image. Moreover, owing to their low photon flux, these sources are not suited to performing CTs of statues and columns.

### 58.5.2 Examples of CT Systems with the Object Rotating on a Mobile Platform

As for low-energy tomographic systems, medium and high energy CT scanning can be performed either by rotating the object between the source and the detector or by rotating the acquisition system and the source around the immovable object.

A tomographic system of the first type is used at the Getty Conservation Institute (GCI) in Los Angeles. It is equipped with a 450 kVp industrial X-ray tube and a CCD-based detector. As an example of application of this system to Cultural Heritage diagnostics, we can mention the 3D CT of a 67 cm tall Roman bronze statue of Cupid, one of the few examples of a bronze statue of this size to be totally scanned. Figure 58.21 shows some images related to the tomography of this statue, dating back to the first century A.D. and belonging to the collection of the J. Paul Getty Museum (Bettuzzi et al. 2015). The CT scanning revealed details that are invisible with conventional radiography, such as chaplet holes and deformation, metallurgical joints, casting flaws, and repairs. The possibility to measure the bronze thickness at all heights was very important for studying the casting and construction techniques used by Roman foundry workers.

![FIGURE 58.21](image-url) 3D-CT scan of a Roman bronze statue of Cupid: picture of the statue (left); interior view of the statue obtained from the CT data (center); interior of head, showing filled core bubbles (right). The arrow indicates a neck joint, possibly metallurgical. (With kind permission from Springer Science+Business Media: Applied Physics A, Computed tomography of a medium size Roman bronze statue of Cupid, 118, 2015, 1161–9, Bettuzzi, M. et al.)
A tomographic system, with the X-ray source and detector similar to that of GCI, has also been developed at the Swiss Federal Laboratories for Materials Science and Technology (EMPA) in Dübendorf (Switzerland), within the framework of the European project DETECT ("New Product Design and Engineering Technologies Based on Next Generation Computed Tomography"), funded under the Sixth European Community Framework Program for Research, Technological Development, and Demonstration. The main components of the prototype, shown in Figure 58.22, are the following:

- 4-axis manipulator (3 translation, 1 rotation axis), consisting of a RHENOCAST® mineral casting base and an Object Positioning Unit (OPU) suitable for objects up to a weight of 50 kg
- Detector box consisting of a 2-mm thick CsI scintillator (active area: 428 × 280 mm²), a high reflectivity front surface mirror (670 × 470 mm²) and a 16-bit CCD camera (Apogee Alta U32 with 2148 × 1472 pixels)
- X-ray source YXLON MG452 (450 kV, 2 mA, 2.3 mm spot size), a source collimator in front of the tube window (not included in the sketch)

Worthy of note is the presence of a Scatter Reduction Device (SRD), that is, a special device consisting of collimators and filters with the function of reducing the scattered radiation, which is produced in considerable amount in this range of energies, thus consequently degrading the contrast and spatial resolution of CT images (Miceli et al. 2007). Monte Carlo simulations were used to optimize the parameters of the device. With this system, especially tailored for industrial applications, a tomography has been performed of a mock-up of a clay pot containing some bronze coins (Berdondini et al. 2011).

At EMPA another CT system is also used, which adopts a portable LINAC (HESCO PortaMeV-6) as the X-ray source. The LINAC has been specially designed to work for several days without interruption, which makes it particularly suitable for performing the CT scanning of significantly sized objects. It can operate in dual energy mode (6 and 4 MeV) and it has a small target focal spot (2 mm maximum size) and good pulse frequency (300 pulses/s at the maximum). Without the removable lead shield, which attenuates the X-ray radiation emerging from the sidewalls of the accelerator head, it weighs only 61 kg, making it easily transportable. The LINAC is combined with a detector made of a CdWO₄ photodiode linear array with 2880 scintillator channels at 0.5 mm pitch. Figure 58.23 (Flisch et al. 2014) shows the tomographic image of a Celtic excavation block (~100 BC) with iron findings inside (pixel size: 1.0 × 1.0 mm²), obtained by means of this system.

A second example of high energy CT performed with the object rotating on a mobile platform is the tomographic analysis of a marble cylinder, used as a mock-up of David’s left ankle. In fact, Michelangelo’s David, the famous statue carved from Carrara marble and standing in the “Galleria dell’Accademia” in Florence (Italy), presents some critical crack patterns in the left ankle, in the area of attachment between the left heel and the base, and in the so-called “broncone,” the marble tree stump on which the right leg rests. In order to obtain a good knowledge of the crack pattern, some ultrasonic tests using specific
instrumentation and experimental procedures have recently been carried out (Pascale and Lolli 2015); with current technology, however, it is not possible to measure the depth of cracks accurately. In fact, this would require a system which, used on-site, could perform a CT of the damaged area. In order to evaluate the feasibility of using X-ray CT for the inspection of leg fractures, a 23-cm Carrara marble cylinder mock-up of the thinner ankle of the statue was prepared. The cylinder was cut on a transversal section and, on one of the two faces, cuts were made on the marble in order to simulate several cracks. The Lawrence Livermore National Laboratory (LLNL, Livermore, CA) carried out a series of tomographic tests on this mock-up with a VARIAN 9 MeV LINAC, coupled to a THALES Amorphous Silicon panel that also used an extensive “graded-collimation” to reduce scatter. Figure 58.24 shows that the CT performed with such a system is able to characterize the details in artificial cracks completely. In addition, novel extraction techniques from the 3D-CT volumetric data enabled the inspection of micro-cracks and voids in the marble.

From the experimentation at LLNL it was also possible to ascertain that the level of X-ray radiation for a limited number of inspections does not affect the original color of the marble. While the scanning performed demonstrates the initial feasibility of the X-ray CT, the next challenge consists of fielding this skill at the “Galleria dell’Accademia” (Berdondini et al. 2009). The system will necessarily be a “gantry-type” scanner, where the source and detector rotate around David, leaving the statue untouched (Figure 58.25). Such a system would also be of invaluable use for the inspection of marble columns (for instance by earthquakes) and equestrian statues (with corrosion inside the legs of the horse). Recently developed systems for the gantry scanning of High Power Feeder cables are one example to Cultural Heritage objects is being actively considered, since gantry-type scanning is particularly strategic when the work of art cannot be manipulated.

**FIGURE 58.25** Sketch of a gantry-type scanner for the CT study of immovable Cultural Heritage assets.

(see next paragraph). The design and experimental work for evaluating and fielding this type of scanning is ongoing.

### 58.5.3 Examples of CT Systems with Source-Detector Rotation

As highlighted above, the use of medium to high energy sources for CT scanning makes it possible to inspect a wide range of objects. High peak energies yield a robust signal through large dense objects. In this regard, one drawback is the size of the detector. Consequently, a variety of scan geometries are in use to make the most of detectors that are smaller than the object. Figure 58.26 shows some different scanning techniques in this context. In particular, the upper right image in Figure 58.26 refers to the so-called half-scan or offset-scan technique, in which the center of the beam divergence is positioned at one end of the detector, as well as the center of the rotation table.

One application of this scanning technique, using high energy sources, is in the scanning of High Power Feeder cables (Schneberk et al. 2016). These objects are large, long, unwieldy, and include both relatively high attenuating components (copper conductors and steel outside) and low attenuating components (insulation and conductor positioning supports). The 3D properties of both high and low attenuating components are important for the inspection. At VJ Technologies Inc. (Bohemia, NY), the scanning of these objects is being performed with a 7.5 MeV betatron coupled with a PerkinElmer 40-cm amorphous silicon panel. The source and detector are attached to a gantry-type scanner, while the source-detector rotates around the object. In this case, the pipe is held on a stand with rollers and the gantry can be positioned in arbitrary positions along the length of the pipe. Figure 58.27 shows the betatron and flat panel in the offset-scan configuration, as well as a cross-sectional slice from the 3D volumetric scanning acquired by the gantry-type scanner. Results show the ability of this technique to inspect the entire feeder cable assembly: conductors, pipe, structural hardware, insulation, ground wires, foil, staples, and possible fluid in the feeder cable pipe.

At the present time, the application of this type of scanning to Cultural Heritage objects is being actively considered, since gantry-type scanning is particularly strategic when the work of art cannot be manipulated.
58.6 CT with Synchrotron Radiation

58.6.1 General Considerations

Synchrotron radiation is generated by large equipment where ultra-relativistic charged particles, usually electrons, are guided along circular orbits by magnetic fields. The emitted radiation has a very high intensity, which is orders of magnitude greater than that produced by X-ray tubes (allowing for fast measurements), and characteristic polarization properties (linear and circular), while the associated frequency can range over a wide portion of the electromagnetic spectrum, from infra-red (IR) to hard X-rays. The high flux makes it possible to use monochromators to select some specific energy bands of photons, while maintaining a sufficient flux for imaging. In this way, it is possible to fine-tune X-ray energy to the characteristics of the specimen and to obtain tomographic images unaffected by the so-called beam hardening artifacts, which are of much better quality than those obtained using conventional sources. In addition, the high spatial coherence of the X-ray beam makes phase-contrast imaging possible.

Thanks to these features, synchrotron radiation is increasingly frequently applied as a radiation source for micro-imaging in medicine and industry. Moreover, the possibility to have a parallel and monoenergetic beam, associated with a detector of high spatial resolution, makes the synchrotron radiation a source of great interest for diagnostics in Cultural Heritage (Creagh 2007; Quartieri 2015).

There are several accelerators in the world that produce synchrotron radiation. They are large storage rings with a circumference of several hundred meters. These dedicated “light sources” produce radiation via “ad hoc” insertion devices with different characteristics, which are installed on electron trajectories in correspondence with light extraction beam lines, thus “feeding”...
58.6.2 Phase-Contrast X-ray CT with Synchrotron Radiation

As X-ray CT (XCT) is based on the different degrees of absorption of X-rays, it is particularly suitable for the analysis of objects made of materials that have absorption cross-sections very different from each other. Conversely, whenever it is necessary to discriminate between low-Z materials with similar attenuation coefficients and, therefore, poor absorption contrast, the most suitable diagnostic technique is X-ray Phase-Contrast Tomography (XPCT) (see Section IV, Chapter 49). This non-destructive technique is based on the observation of the phase shifts produced by the object on a monochromatic incoming wave, while passing through it; since the mid-1990s, it has grown in importance, with the creation of dedicated lines in modern synchrotrons.

Figure 58.28 shows the basic principle of Phase-Contrast X-ray Imaging (PCI): the formation of interference patterns between diffracted wave (phase-shifted) that passes through the object of interest (defined detail in the figure) and unperturbed wave beyond it. This interference effect takes place along the border of the detail inside a narrow angular region (about 10 µradians), and, if the sample-to-detector distance is large enough, it gives rise to an edge-enhancement effect (see the two peaks in the intensity detected), improving the visibility of thin and small details that are usually invisible on absorption images (Arfelli et al. 2000; Olivo and Castelli 2014).

Figure 58.29 shows a typical experimental setup for absorption and phase-sensitive micro-CT at the SYRMEP beamline of ELETTRA Synchrotron Radiation facility (Trieste, Italy). (Reprinted from Nuclear Instruments and Methods in Physics Research A, 548, Abrami, A. et al., Medical applications of synchrotron radiation at the SYRMEP beamline of ELETTRA, 221–7. Copyright 2005, with permission from Elsevier.)

In order to compare synchrotron results with a state-of-the-art conventional system, the same analysis was repeated at the TOMOLAB facility, using “cone beam” geometry. As already stated in Section 58.4.1, TOMOLAB is a micro-CT system with a microfocus X-ray tube (energy range from 40 kV up to 130 kV) and a CCD camera with a small pixel size (12.5 × 12.5 µm²) and a field of view of 49.9 × 33.2 mm². In this case, the tomographic scan used a pixel size of 20 µm², with a tube voltage of 45 kV. The source-to-sample distance was 45 cm and the source-to-detector distance was 55 cm. Thanks to its geometry, this setup...
also permits the performance of phase-contrast measurements. With this arrangement too, it was possible to obtain some satisfactory data concerning wormholes and the presence of larvae (Figure 58.30).

The second example concerns a new and truly interesting application of X-ray volumetric scanning, followed by segmentation, surface generation and surface unfolding, as a non-destructive method for revealing inaccessible texts in damaged books and scrolls that are fragile and cannot sustain physical manipulation without serious risk of further damage. This approach has been described in several papers (see, for example, Seales and Lin 2004; Samko et al. 2014; Albertin et al. 2015; Pintus et al. 2016) and has also been recently applied on a carbonized papyrus discovered in the so-called “Villa dei Papiri” at Herculaneum (Italy). In 1752, hundreds of papyrus rolls were brought to light in this villa, charred by the eruption of Mount Vesuvius, which took place in 79 AD. It is virtually impossible to read them, owing to their fragility when trying to unroll them. Furthermore, since the ink used for their writing is based on carbon—which possesses an absorption coefficient very similar to that of the papyrus—any attempt to read them by means of conventional CT is totally in vain. Recently, using the XPCT technique, it has been possible to read some Greek letters on a papyrus, without unrolling it, by measuring the protrusion of the ink (about 100 μm).

The experiment was conducted in December 2013 at the biomedical beamline ID17 of ESRF (Mocella et al. 2015). The scheme of experimental setup is shown in Figure 58.31. The image, formed on a gadolinium oxysulfide screen by the X-rays that pass through the papyrus, was read by a Fast Readout Low Noise (FReLoN) 2k charge-coupled device camera with a 90 × 90 mm² field of view and an effective pixel size of 46 × 46 μm². The sample-to-detector distance was set to about 11 m, while the energy of the X-ray beam used was 70 keV. In general, the letters stand out in slight relief from the papyrus surface and, thanks to this morphological feature, it is possible to highlight them by XPCT. In fact, the relief of the letters (at least 100 microns above the surface of the papyrus fibers) is sufficient to produce appreciable phase-contrast. The numerical elaboration of the tomographic images has made it possible to distinguish several Greek letters and small segments of writing.
According to the authors, once the XPCT technique is tuned up, it could be very useful for reading many papyri still unopened or not yet discovered, “perhaps including a second library of Latin papyri at a lower, as yet unexcavated level of the Villa.”

58.7 Neutron Computed Tomography

58.7.1 General Considerations

In addition to electromagnetic radiation, which makes it possible to examine objects by IR, visible, UV, X-ray, and gamma radiations, in some cases it may be useful to use nuclear magnetic resonance (NMR) and neutrons. In the following section, we will focus our attention on the complementarity of neutron and X-ray radiation for non-destructive studies of Cultural Heritage assets.

Neutrons are particles with no electric charge, which interact with the atomic nuclei in different ways depending on their energy and type of nucleus. The most important interactions are elastic and inelastic scattering, absorption (with subsequent emission of other particles and/or photons) and fission. Light materials (such as hydrogen, deuterium and carbon) remove neutrons from a beam primarily by scattering; other materials (such as boron, cadmium and copper) remove neutrons mainly by absorption. Some heavy elements, highly opaque to electromagnetic radiations (such as lead), can be easily penetrated by thermal neutrons. In general, metals are more transparent for neutrons than for X-rays, while hydrogenous materials like leather, wood or textiles give much higher contrast with neutrons than with X-rays.

From these brief considerations, it is clear how neutron radiation, from the standpoint of imaging, can be seen as complementary to X-rays, in particular when the examined object has a composite structure made of metal and organic materials. However, it should be mentioned that neutron radiography (NR) and tomography are far less used than X-ray imaging for the examination of cultural objects. In the last few years, however, the possibility to use these techniques in the field of Cultural Heritage has remarkably improved due to the development of small mobile neutron sources and also thanks to the accessibility of high performance NR facilities, located for example at research reactor sites. A drawback is the potential risk for radioactivity, due to the fact that neutrons are able to activate materials by capture. In the case of a long irradiation (as for neutron CT), the object may remain radioactive for a time that cannot be considered negligible. As a general rule, bronze objects will decay below the detection level within a few days of exposure (Van Langh et al. 2009).

58.7.2 Examples of the Complementarity of Neutron and X-ray Imaging for Non-Invasive Investigations of Cultural Heritage Objects

The first example of a combined use of neutron and X-ray computed tomography for the investigation of Cultural Heritage objects concerns an ancient short sword found in Lake Zug, Switzerland (Mannes et al. 2015). The object is made of organic material (mainly the wood of the sword hilt) and metal and this feature makes it an ideal case study for demonstrating the complementarity of neutron and X-ray imaging.

Neutron and X-ray tomography studies were conducted at the NEUTRA beamline at the spallation neutron source SINQ of the Paul Scherrer Institute (PSI), in Villigen, Switzerland. NEUTRA, a facility for neutron radiography and tomography of medium-to-large-sized objects, uses a thermal neutron energy spectrum (Lehmann et al. 2001). A 320 kV X-ray tube is also available on the beamline to perform X-ray imaging with the same geometry of neutron measurements. The X-ray tube, in fact, can be positioned in line with the standard neutron setup, which allows a direct comparison of the two types of images that are produced by neutrons and X-rays on a CCD-based detector. Two different scintillating screens are available: a 100 µm thick 6LiF:ZnS screen for neutrons and a CAWO OG 8 converter foil for X-rays. A CCD camera with 2048 × 2048 pixels focuses onto a field of view of 307 × 307 mm², resulting in a pixel size of about 150 µm.

The overall length of the sword is 61 cm; hence, it was necessary to carry out tomographic scans in three height steps to ensure that the entire object was covered within the recorded images. For each height level, 625 neutron projections were acquired with an exposure time equal to 20 s. After neutron tomography, the procedure was repeated with the X-ray tube operating at 150 kV, with an exposure time of 4 s.

Figure 58.32 shows clearly that only the combined use of the two types of radiation (neutrons that highlight the intimate structure of the wood and X-rays that provide information about the metallic part) made the exhaustive examination of the sword possible, providing complete information on the manufacturing process of this object.

Another interesting example of the complementarity of neutron and X-ray imaging regards the analysis of archaeological objects in blocks of soil. Very often during archaeological excavations, objects of cultural interest are extracted, together with the soil around them. For study purposes, the items must be freed from the soil, but this procedure is usually very time-consuming; in fact, the conventional unearthing and documentation of a block of soil can take weeks or even months. Therefore, it is necessary to find new methods for a faster identification and study of the objects in blocks of soil, in order to avoid them remaining stored for a long time without providing useful information for archaeologists. X-ray 3D Computed Tomography (XCT) has been used several times for this purpose (Jansen et al. 2006;
Re et al. 2015) as a non-destructive alternative to conventional methods. In addition, in order to better visualize the presence of organic materials, it is possible to perform radiography or computed tomography with neutrons (NCT). This approach has been followed, for example, by Stelzner et al. (2010) in a Deutsche Forschungsgemeinschaft (DFG)-funded study that systematically studied, by XCT and NCT, various objects lifted “en block” from the medieval cemetery of Lauchheim in Baden-Württemberg.

X-ray examinations of the blocks of soil were carried out with a cone beam 3D-XCT system with a 225 kVp microfocus tube and a 1024 × 1024 a-Si flat panel detector with a Gadox scintillator, while neutron radiography and tomography were performed at the FRM II research reactor in Munich-Garching at the ANTARES facility. The detector used was a CCD camera with 2048 × 2048 pixels, optically coupled to a ZnS+LiF(Ag, Au, Cu) scintillation screen.

The results of the study show that, with the combination of the two imaging techniques, it is possible to visualize all types of materials: metal, glass and ceramics, bone, and textiles. In particular, NCT can be very useful when organic materials are in direct contact with a dense metal like bronze.

Other examples of the complementary use of neutrons and X-rays for the non-destructive investigation of archaeological findings and other objects of cultural interest, such as ancient musical instruments, can be found in Deschler-Erb et al. (2004), Triolo et al. (2010), Festa et al. (2014), Masalles et al. (2015) and in Nguyen Hai-Yen’s Master’s thesis (2011).

58.8 Conclusions

Scientific studies and diagnostic techniques are being applied increasingly frequently in the quest for knowledge on all the “tangible” characteristics of archaeological finds and movable and immovable heritage assets, for the purpose of obtaining information on constituent materials and construction techniques and/or defining the state of preservation, and eventually designing specific conservation interventions.

One of the main requirements in the study of ancient and precious materials is that the selected techniques be non-destructive (or, at most, micro-destructive). X-ray radiography and computed tomography fully comply with this requirement, as they are able to provide morphological and physical information on the inner structure of the objects studied in a completely non-destructive way. A peculiar feature of archaeological finds and works of art is that they are often heterogeneous and complex in shape and composition (pottery, glass, metals, pigments, wood, textiles, etc.); consequently, several different X-ray sources and detectors, as well as flexible setups, are necessary to meet the different needs of various case studies. This means that a specific technical and scientific background is necessary for researchers working in the field of Cultural Heritage diagnostics. Another important factor is a strong interdisciplinary approach, which entails a close cooperation between scientists, on the one hand, and archaeologists, art experts and restorers, on the other.

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