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Radiographic images

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Methods of recording radiographic images, film, X-ray paper, Xeroradiography, fluoroscopy, digital radiography; image quality; image processing; stereoradiography; computed tomography; practical radiography, image quality; problems; setting up and running a radiographic facility

RECORDING RADIOGRAPHIC IMAGES

As X-rays cannot be perceived by eye, the X-ray image must be registered on a suitable material to make it visible. The image may be recorded permanently on photographic film or paper. Images have also been recorded using xeroradiography plates or they can be viewed in real-time on fluorescent or sensitive screens, perhaps linked to a monitor or digital recording system.

Film

Characteristics of Film

Film is probably still the most common method of recording the image, although digital recording is increasingly being used. It is an integrating medium: the nature of the image depends not just on the intensity of the X-ray beam (determined by the tube current, in milliampere, for a given kilovoltage) but also on the duration of the exposure. For this reason, radiographic exposures are often expressed as the product of intensity and time (e.g. mAs or mAmin):

$$E = It \tag{2.1}$$

This relationship between exposure (E), intensity (I) and time (t) is known as the *reciprocity law*. Film is relatively cheap to buy and to process, does not require any expensive or complex equipment and provides a permanent record. Fortunately, sheet film is available in a variety of sizes, as the radiographic examination of antiquities frequently requires the use of sizes ranging from small dental films to large sheets. Occasionally, exceptionally large sheets have been made specially for radiographing statues. Film is processed using proprietrary photographic chemical solutions which must be handled and disposed of safely (see Box 1.2). Manual Processing in tanks is preferred by some as it is simpler to ensure a long fixing period (e.g. 15 min) and thorough rinsing for film longevity. Use of a film processor is convenient because it avoids mess and saves time, as the film emerges dry and ready for examination (see also Box 2.2). Detailed information concerning the use and processing of film to record radiographs is provided in several standard texts including that by Halmshaw (1995, pp. 76–95) and those produced by Kodak (Quinn and Sigl 1980, pp. 71–107) and Agfa (Halmshaw 1986, pp. 107–24). In this section we will consider briefly only some of the factors which may affect the quality of the radiograph obtained.

Industrial X-ray films usually have an emulsion containing a suspension of silver halide salts (usually of the order of 1–10 μm particle diameter) in gelatin attached by a thin layer of adhesive to both sides of the support film, with a thin coating layer to protect the surface. This double-sided emulsion effectively increases the speed of the film. The level of detail which can be recorded and subsequently developed generally depends on the grain size and thickness of the emulsion layer: a smaller grain size gives better definition and finer detail, but needs a longer exposure. The graininess of the image increases with the energy of the radiation and a γ-radiograph is usually grainier than an X-radiograph, which is one reason why X-radiation is often preferred. Graininess also increases with the length of the development time and the type of developer used.

For some applications, such as the electron radiography of paper, a double emulsion is not desirable and it may be preferable to use a single emulsion film (e.g. medical mammography film) or to take special precautions during processing to avoid development of the emulsion on one side of the film. This is discussed more fully in Chapter 5, where techniques for electron radiography of paper are described.

The photographic emulsion itself contributes to the unsharpness of the image. This inherent unsharpness (U_f) arises because the X-ray beam has sufficient energy not only to interact with the photographic emulsion, making the silver halide crystals developable, but also to produce some secondary electrons. These may have enough energy to move through the emulsion and interact with further nearby silver halide particles. These are also developed, so that the image shows gradual rather than sharp changes of density at edges and discontinuities. The magnitude of this effect increases with X-ray energy but Halmshaw (1971) has shown that the level of interaction is similar for different radiographic films.

Films are available with a wide range of characteristics. The choice of film is usually influenced by the subject and the type of investigation. Industrial direct-exposure films of moderate-to-fine grain size are most frequently used for archaeological radiography and are produced by well-known manufacturers, such as Agfa, Fuji and Kodak. The manufacturers supply details of the characteristics of their films and suitable processing regimes. More general information can be found in the various reference books listed at the end of this chapter. The European Standards Organisation has proposed a system of classification (CEN: prEN-584-1:2005-11); Table 2.1 (after Halmshaw 1995) provides information for some well-known films. For most purposes medium-to-fine grain film (e.g. C5) is used because it is faster, allowing shorter exposure times and providing good detail for most objects, but for the finest detail and highest image contrast a very fine-grained film (C3 or C1) is used, despite the disadvantage of requiring a longer exposure. When in doubt, both films can be used together in the same cassette.

This can also be a good way of capturing the radiographic image of an object which has a range of cross sections or is made from different materials.

Table 2.1. Data on some films suitable for radiography

CEN class	*Film*	*Manufacturer*	*CEN speed*
C.1	D.2	Agfa Gevaert	50–30
	IX25	Fuji	–
C.3	D.4	Agfa Gevaert	100
	MX	Kodak	125–100
C.5	D.7	Agfa Gevaert	400–250
	IX100	Fuji	–
	AX	Kodak	320–250

Data from Halmshaw (1995).

Metallic archaeological objects, for example, are often partially corroded; the corroded areas are much less dense than the sound metal parts, which are likely to be thicker and will also be denser. If only one grade of film is used, several exposures may be needed to show the detail in all areas (but see Digital Processing below).

Special high-resolution plates and film (e.g. Kodak high-resolution film DR (double sided) or FR (single sided)) have been used, in conjunction with X-ray sources normally used for X-ray diffraction, to study the microstructure of thin sections of minerals, composite materials and ceramics. The extremely high resolution of the plates means that they can be examined with a transmitted light microscope at useful magnifications of up to ×100 (Clark 1955; Niskanen 1959; Darlington and McGinley 1975). High-resolution film has also been used to examine cast structures (Williams and Smith 1952; Barkalow 1971), the distribution of inclusions or discontinuities by taking film stereopairs (see below and Chapter 3).

The degree of blackening of a film is known as its density; a densitometer can be used to provide a quantitative measurement of film blackening, relating the incident light intensity (I_0) to the intensity of the light transmitted through the film (I_t). The photographic density, D, of a film is defined as:

$$D = \log_{10}(I_0/I_t) \tag{2.2}$$

Clearly, the density is related to the exposure, E, received by the film and this relationship is conventionally shown by plotting density, D, against the logarithm of exposure ($\log_{10}E$). The resulting graph for a typical film is shown in Figure 2.1; this is known as the characteristic curve for that film. Figure 2.1 shows that control of the exposure can be used to

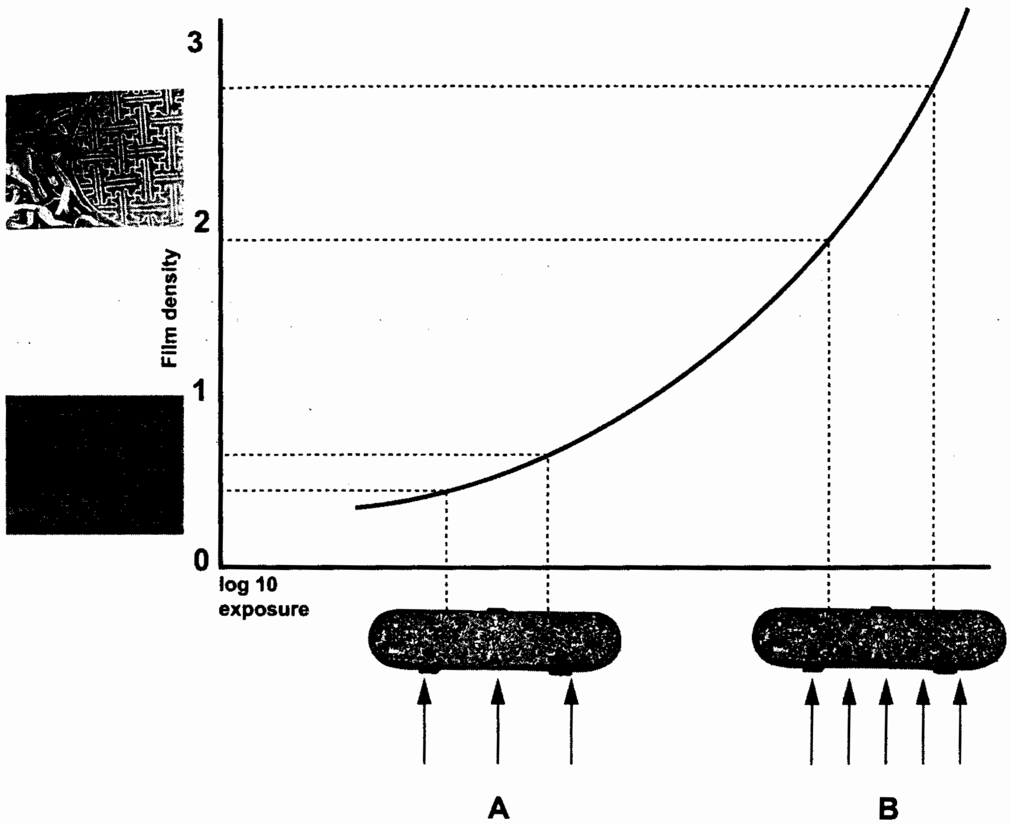


Figure 2.1. *Graph of film density versus log_{10} exposure (characteristic curve for a typical X-ray film) shows that a shorter exposure (A) gives a lower film density and less contrast (see also Figure 3.7(a), (c)) (after Halmshaw 1986).*

produce radiographs with more or less contrast as required. Film density measurements are used mainly in industry, where standardized conditions are important for comparing welds and in quality control. Typically, industrial codes and standards require values of between 1.8 and 4, when only 0.01% of transmitted light reaches the far side of the film. When films are digitized and processed, imaging of the detail is assisted by a slightly higher film density than would be needed for direct viewing. Monitoring film image quality is discussed below. Charts indicating appropriate exposures (mAs) for different thicknesses of various materials at various kilovoltage settings are used industrially, and may sometimes be applicable to archaeological material.

Cassettes and Screens

Film in sheet form is usually exposed in a light-tight cassette which allows it to be handled in the light without risk of exposure. A variety of cassettes is available. A simple black plastic envelope of the type used for film or photographic paper (*Note*: some bags produce distracting textured or striped images on the radiograph.) can be used with a light-tight closure is used when radiographing low-atomic number materials such as card or fabrics at low kilovoltage, or when a soft, flexible cassette is needed to fit a curved surface. At very low kilovoltage, when radiographing paper, for example, it may be necessary to dispense with a cassette altogether. The most commonly used cassette is rigid and designed to open like a book, being hinged at one side. It may be made of metal or plastic and has a front which is radiolucent and must face the X-ray set. The back is made from heavier material to make it radio-opaque. The cassette contains a pressure pad which ensures close contact between the film and intensifying screens when these are used. In very-low-energy applications, such as the radiography of paper, vacuum

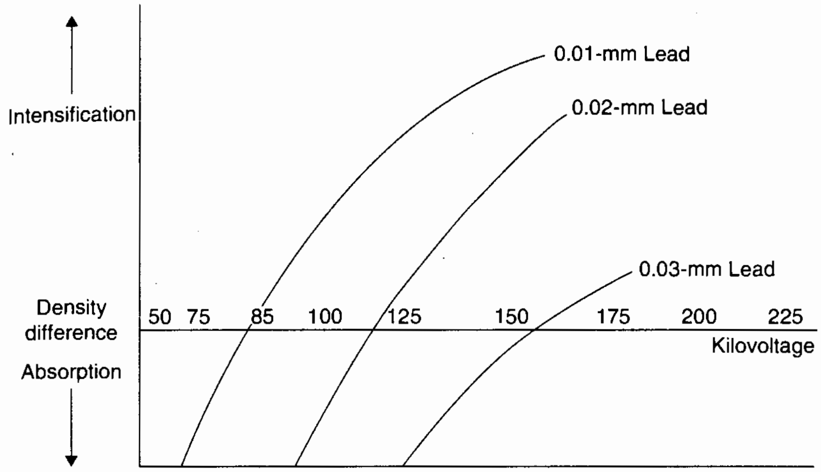


Figure 2.2. *Effects of kilovoltage on intensification properties of lead screens (after Quinn and Sigl 1980).*

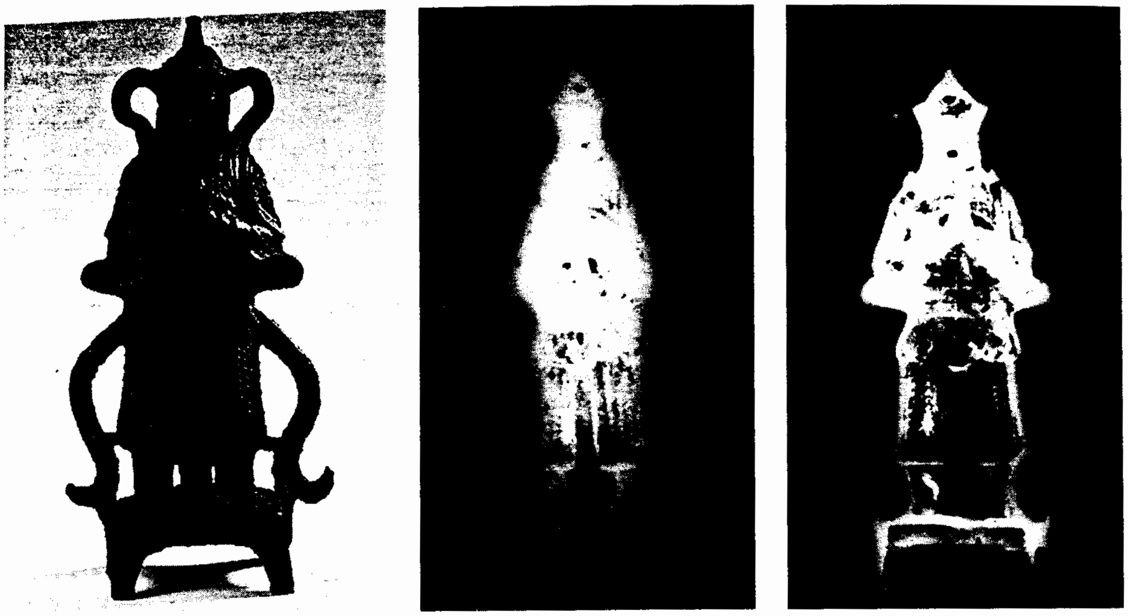
or helium-filled cassettes improve the contact between paper and film (Bridgman *et al.* 1958; Graham and Thomson 1980; Rendle 1993).

In order to reduce the exposure time it is possible to intensify the image by using an intensifying screen, which may be of the salt screen type or a sheet of lead metal. Salt screens produce fluorescent visible or ultraviolet light and have a high intensification factor. They are used in the medical field and also for paper (Chapter 5), but they are rarely used in industrial radiography because there is considerable loss of detail (Halmshaw 1995, p. 94). Lead screens have much lower intensification factors than salt screens but offer two advantages, both of which lead to a reduction in 'noise'. Firstly, they absorb the softer, lower-energy X-rays which have been scattered and would otherwise reduce the clarity of the image. Secondly, the intensification effect is greater for the primary radiation than for the scattered radiation. Intensification occurs because, as higher-energy X-rays (<120 kV) (or γ-rays) pass through the lead screens, electrons are emitted which augment the effect of the X-rays on the photographic emulsion, reducing the exposure time and improving the contrast of the image. The result is a high-quality image with the image contrast of low-kilovoltage images and the penetrating power and exposure latitude of high-kilovoltage images. The screens consist of sheets of polished lead foil, commonly between 0.02 and 0.15 mm thick, backed with stiff paper on one side. To maximize the effect of the electrons it is necessary to have the best possible contact between film and screen, so that the screen is normally used inside the cassette with the lead foil facing the film.

The intensification factor of lead is generally less than five (i.e. the exposure for a desired film density can be reduced by this factor) and it is most effective with harder radiation above c. 120 kV (Figure 2.2). However, lead screens are also used with softer radiation (Figure 2.3) to filter the scattered secondary radiation generated in the specimen. Thin sheets of lead have a greater intensifying effect than thicker ones, although the latter reduce scatter more effectively. For this reason front screens, lying between the film and the object, are between 0.025 and 0.15 mm thick to enhance the intensifying effect of the electrons, whereas back screens are thicker to reduce scatter and should be a minimum of 0.1 mm (for use up to 400 kV).

X-ray Paper

Special X-ray paper, produced by major film companies such as Agfa and Kodak for example, is about 10 times faster than the fastest film and is designed to provide rapid-access, low-cost radiographs. The emulsion is on one side of the paper only and contains developing agents. The paper is loaded into a rigid cassette with a salt intensifying screen in direct contact with the emulsion. A phosphor (calcium tungstate) coating on the screen converts the X-ray image to a pale blue light, which is photographically recorded by the paper's emulsion. The image quality is not as good as that of a fine-grained film. The paper can be



(a) (b) (c)

Figure 2.3. *(a) Cast iron Chinese figure, 16th century* AD *(OA 1990-5-20.1), (b) radiograph made at 7 mA, 3 min, 100 kV, no lead screens, and (c) radiograph at 7 mA, 7 min, 100 kV with lead screen back and front. (b) and (c) both at 1 m, Kodak AX film without filters. Adding lead screens increases the exposure time needed, but reduces scatter.*

processed with the same regime as X-ray film, but for permanence requires a final fixing with conventional black and white paper fixing solution.

Xeroradiography

Xeroradiography was developed as an alternative method of recording medical X-ray images (Boag 1973). The techniques used are similar to those used in the Xerox photocopying process but the recording medium (xeroradiography plate) consists of a layer of amorphous selenium, uniformly deposited on to an aluminium backing plate.

The main features of the xeroradiographic image are as follows:

- *Edge enhancement*, producing sharp delineation of boundaries, including those concealed by overlying structures, good resolution of fine details (e.g. fractures, voids and joins).
- *Wide exposure latitude*, allowing objects of widely varying density to be included in the same radiograph.
- The image is virtually *impervious to scatter* because scattered radiation, whilst reducing the overall charge slightly, has only a minimal effect upon the edge enhancement effect.
- The *image is reversed* with respect to the original and may also be made positive or negative, so that it is important to avoid any confusion in interpretation.

Several studies have been published comparing the results from xeroradiography with those obtained using film to radiograph archaeological materials (e.g. Alexander and Johnston 1982; Watts 1994). In many instances the two techniques have been found to be complementary.

Xeroradiography has been particularly useful for ceramic materials (Chapter 4), for human remains (Chapter 7) and for objects made of organic materials such as wood (Figure 2.4). Xeroradiography of the Winchester Reliquary (Keene 1987) revealed more details of the interior than conventional radiography, and the xeroradiograph of a 19th century Japanese Buddha (Figure 2.4) gives an admirably clear view of its construction. However, xeroradiography is now essentially obsolete because it is no longer used in the medical field and is not supported by the industry. For this reason we have omitted most

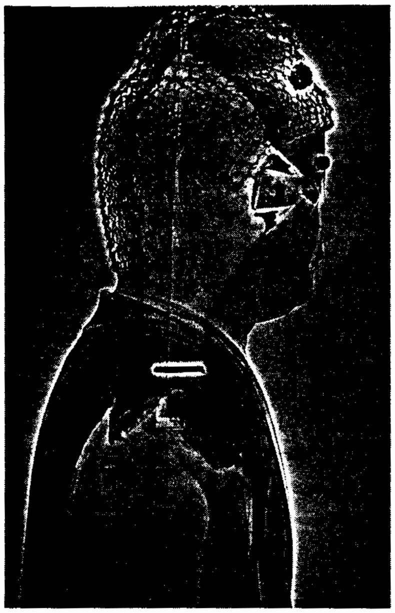


Figure 2.4. *Xeroradiograph of an 18th century* AD *Japanese wooden Buddha figure, showing the inserted stones in the forehead and hair, and the construction of the eyes, with some glue holding the eye block in position. A metal clip at the shoulder and the wood grain in the dowel at the shoulder can also be seen (OA 1945-10-17.309).*

of the technical details of the method (for these the reader is directed to the first edition of this book). Fortunately most of the features observable by xeroradiography can be achieved digitally by processing images scanned from conventional film radiographs (O'Connor *et al.* 2002) (Figures 2.5 and 2.6) (see below and also Figure 4.3).

The Sensitive Screen (fluoroscopy)

Observing the X-ray image on a sensitive screen is not a recent development. Röntgen himself used a fluorescent barium platinocyanide screen to detect X-rays in his experiments (Röntgen 1896). Fluoroscopy has been used both industrially and medically. In its simplest form, a system consists of a source of X-rays, a fluorescent screen and a means of viewing the screen, either through a lead glass window or by a mirror. If the X-ray tube has a fine focus (0.1–0.5 mm focal spot) the object can be moved away from the screen and an enlarged image obtained. Fluoroscopic systems can be 'stand alone', but the images obtained are often of rather low brightness. The image can be preserved by photographing the screen: this has the advantage that the film contrast can be chosen to enhance the image contrast. The integrating effect of a film exposure can also be advantageous.

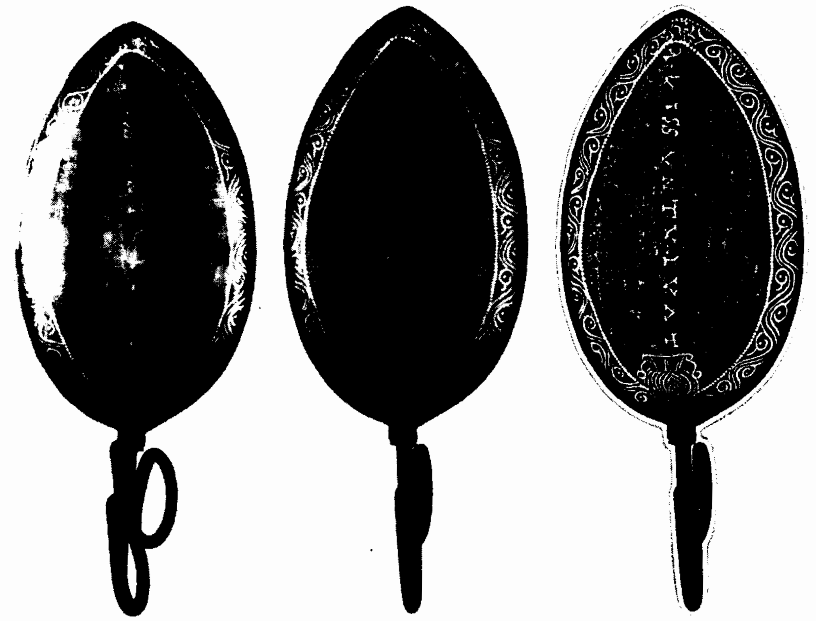
In more sophisticated systems, a remotely controlled manipulator allows the object to be moved while it is in the X-ray beam, allowing a 'real-time' examination. The advantages of such real-time viewing systems are obvious: a large complex of objects (e.g. material from excavation) can be surveyed quickly, allowing rapid assessments to be made for micro-excavation and conservation or for identifying the optimum position for conventional radiography. Moving an object in the X-ray beam produces an almost three-dimensional (3-D) effect; the relative speed with which the components move past each other on the screen allows the observer to form an impression of their relative positions in three dimensions.

Various changes have improved the basic systems; the image intensifier has been developed to give a brighter image, which is usually captured with a CCD camera. The image is transmitted by the camera to a monitor and can be viewed in real-time; the image may be simultaneously recorded on a video recorder, digitized for image processing, or digitally archived.

The criterion of the number of line pairs per millimetre (lp/mm) is commonly used to compare the resolution of different imaging systems: it is the smallest gap between pairs of wires which can be distinguished. For instance, a typical aluminium window/cesium iodide phosphor intensifier is quoted as having a resolution of 4.6, 5.4 and 9 lp/mm for fields of view of 220, 160 and 120 mm, respectively; the resolution of film, similarly expressed is typically 200 p/mm. There is some additional loss of quality as the image is transferred through the camera to the recording medium. Film is therefore better for an accurate representation at high resolution, but the convenience and versatility of image intensification, combined with digital recording and processing has some advantages especially for excavated block complexes. The introduction of microfocus tubes for some applications has improved image quality.

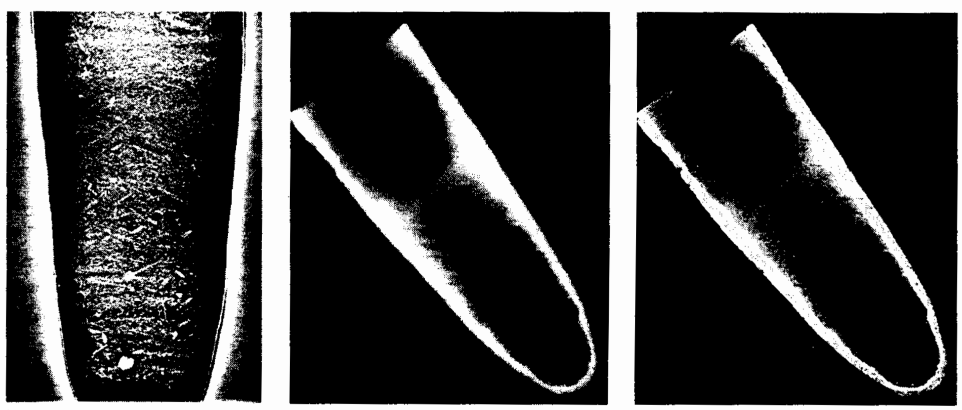
Digital Radiography

Traditionally, radiographic images have been collected on various forms of film or paper, but there



(a) (b) (c)

Figure 2.5. *The Roman* cygnus *spoon no. 103 from Hoxne shows an inscription and decorated border, but the geometry and variable thickness makes it difficult to see the details (see also Figure 3.26, Plate 3.3). It seems to have been deliberately abraded. The radiographs show the decoration and the inscription QVIS SVNT VIVAT, written as a single word. Two different exposures are shown at the same source-to-film distance (1 m): (a) exposure at 7 mA, 90 kV, 20 min, front and back lead screens, Kodak MX film, no filter and (b) exposure at 7 mA, 10 min, 100 kV, front and back lead screens, Kodak AX film, 0.6 mm copper filter. In (a) the contrast is greater because the kilovoltage was lower, and the scrape marks on the bowl show mossre clearly. In (b) the contrast is reduced because a copper screen was used to reduce the low-energy component of the beam. A shorter time was used because the film was faster. Curved objects like these spoons with shallow designs and variable thickness may need several exposures to extract all of the details. In (c) the image (b) has been processed with a high-pass filter and contrast adjustment to make the design more visible and the longitudinal scrapemarks can be seen on the bowl. The appearance is similar to a xeroradiograph.*



(a) (b) (c)

Figure 2.6. *Radiographic images of an Egyptian pottery ibis case. (a) xeroradiograph, (b) unprocessed film radiograph, and (c) digitally scanned and processed film radiograph. To achieve this effect, the image was manipulated using the* unsharp mask *feature of Adobe Photoshop, a software package readily available to most users.*

is an increasing move towards the use of digital images. It seems likely that radiography will follow the pattern shown by photography and move with increasing speed in this direction. As with all forms of computing the equipment and programs available in this field change with bewildering speed, both in terms of what is possible and in cost, so it is not intended to go into great detail here. This section is instead intended as a brief overview of the characteristics of this format and the ways in which such images can be gensenerated; those with a particular interest in this topic are advised to consult manufacturers and recent literature as to what is available within their budget. At the time of writing, Jones *et al.* 1998; O'Connor & Maher 2001 and O'Connor *et al.* 2002 provide a good starting point for such an investigation.

Expressed in the most simple terms, a digital image is best defined as an image made up of tiny picture elements (pixels), each of which is represented in binary code. A computer is necessary to view this information as an image. In general, the more processing power and faster the computer used the better, particularly in the case of digital radiography, where large file sizes are required to get good images (around 120 mb for a standard 43 × 35 cm plate). Large and good quality monitor screens are also an obvious requirement.

Factors Determining Digital Image Quality

Three factors need to be taken into account when considering digital imaging systems; the resolution, the bit depth and the dynamic (optical density) range. To optimize imaging, all of these factors need to be as large as possible. Unfortunately, any increase in quality tends to be accompanied by an even more dramatic increase in price:

- The *resolution* is defined by the number of pixels per inch present on the image. At the time of writing the best quality digital radiography equipment operates at around 500 pixels per inch. This is the equivalent of approximately a 50 μm grain size in conventional film; a high resolution, but not yet equal to the finest-grained film stock (*c.* 1–10 μm).
- *Bit depth* is a rather more difficult concept to grasp, but controls the number of colours (or in the case of radiographs, shades of grey) which each pixel can represent. The higher the bit depth, the larger the number of shades of grey that the digital image can contain. An 8-bit system can display 256 shades of grey, a 12-bit system 4096 and a 16-bit system 65,536. Given that the human eye can only distinguish between around 50–60 different shades of grey, the advantages of a digital system are immediately obvious. At present, most purpose designed digital radiography systems operate at a bit depth of 12.
- *Optical density* is a term used to define the darkness or lightness of a grey shade held on a radiograph. *Dynamic range* defines how wide a range of optical densities can be recognized in the digital image. Industrial radiographs tend to have a wider dynamic range, with a larger range of near blacks and near whites, than those produced in medical facilities, where the dose rate to the patient is the main consideration. Digital radiographic systems designed for medical purposes therefore tend to have a lower dynamic range than those designed for industrial systems. Again, the wider the dynamic range available the better (but also the greater the expense).

Production of Digital Images

There are currently three methods by which digital radiographic images can be produced: by digitizing the film image with a scanner, by indirect capture, or by direct capture. Each has advantages and disadvantages. These are summarized below in the light of the current state of technical development of the various methods, but, given the speed with which all computer-based facilities develop, these should be treated as a 2004 snapshot. Any potential user should contact manufacturers for current information.

- *Film digitization* is used with film produced by conventional methods. This is scanned to give a digital file. Scanning can be carried out using a wide range of equipment, from a fairly simple, non-specialized, flatbed scanner (providing that it is fitted with a transparency adaptor) through a range of specialized radiographic scanners of either flatbed or roller design. Non-specialist scanners are limited in usefulness because of poor dynamic range and limited physical size, and the use of specialist equipment is strongly recommended. Of the specialized equipment, industrial style scanners tend to be the best suited to work on cultural materials, as they have the greatest dynamic range, but this is achieved at considerably increased cost. Scanning is probably the digital technique most readily available to those involved in work on cultural material; it is the cheapest option, can be used to record pre-existing film stocks, and can be easily outsourced to a number of extant facilities. Used carefully it can produce extremely good images with all the advantages that the digital format supplies (see below). It is, however, an indirect method and offers none of the savings of time or chemical-free properties of purely digital radiography. Digital cameras and video cameras used in conjunction with a light box are sometimes used for details but the image quality is likely to be less satisfactory than small, purpose-built industrial scanners.

- There are currently two methods of *indirect capture* (frequently termed computed radiography or CR) available, involving the use of either flexible phosphor films or flat panels. These are used in place of the films in conventional radiography. Here exposure to an X-ray beam generates a light emission which is then collected electronically to form the image. The exposures required are considerably shorter than those needed to generate images on standard films and the latitude of exposure is higher. The inclusion of a light-dependent stage does mean however that a degree of scatter is generated. No chemicals are needed, with savings in both time and disposal costs. Phosphor films have the advantage of being flexible, so that they can be shaped around objects, but have the disadvantage of requiring a separate plate reader. Flat panels do not require a reader, but are rigid. Both phosphor films and flat panels can be cleared and reused numerous times.
- The final option is *direct capture*, (also known as direct radiography or DR) where the object under examination is placed onto a flat plate and exposed to an X-ray flux. The image is generated directly in the dielectric plate and converted immediately into a digital file. This method produces by far the best image, instaneously, with no light scatter and at high resolution. Again, exposure times are very much shorter than those used with conventional film and there is a wide-exposure latitude, together with no requirement for chemicals. Unfortunately, direct capture is also by far the most expensive of the options available and is unlikely to be generally available within the field of cultural materials for many years. Other disadvantages include a rigid plate which cannot be repositioned to suit the object. The plate is also susceptible to extremely costly damage if treated roughly.

Viewing Digital Images

However the digital image is collected, a suitable computer with a large and high-quality viewing screen will be needed, together with an appropriate image manipulation program. These things will generally be considered with the purchase of any digital radiography equipment and will often be supplied by the same manufacturer, but if it is intended to use only scanned images produced at an outside facility, it is quite possible to use some of the standard, commercially available image manipulation programs such as Adobe PhotoShop (see also Image Processing, below). In any case, for ease of use and storage, programs which are capable of producing images in standard file formats should be selected. Currently TIFF or DICOM (most frequently used in medical environments) are probably the file types of choice. Lossy file formats such as JPG should be avoided during interpretation or for long-term storage and used only for final publication or display purposes (see below).

Digital Radiography; Advantages and Disadvantages

After all the discussion above, and given the costs involved, the obvious question arises as to whether digital radiography is worthwhile. That question is probably best answered by the increasingly rapid movement towards digital format in every part of the radiographic field, as clearly exemplified by the recent announcement that the British National Health Service now intends to move to completely digital format.

File formats

The choice of file format to use with digital radiographs is particularly important. To save storage space, most file types are compressed before being written to a disc. This compression can be *lossy* or *non-lossy* (or lossless), with the description referring to the effect on the data of the compression process. Fairly obviously, in lossy formats, the compression is achieved at the cost of some loss of data (but with the advantage of considerably reducing file sizes). This effect is cumulative, with further losses occurring every time a file is saved in a lossy format. Lossy compressions exist for good reasons, being primarily designed to minimize the disc space and processing time required for an image whilst retaining as much sharpness as necessary for simple viewing, but are obviously not suitable for radiography, where the whole aim of the process is to collect and retain as much information as possible. For this reason lossy formats should be avoided for all purposes except simple display and publications. At the time of writing the most common non-lossy formats available are TIFF, DICOM (which can be compressed in either lossy or non-lossy format) and PNG (normally used for colour images). The most common lossy format, useful for publication, web display or widespread distribution, is JPG.

Image manipulation and enhancement

The greatest advantage of digital format is that it makes accessible evidence which has always been recorded onto film, but which was previously unavailable because of the limitations of human vision. As discussed above, a 12-bit system can distinguish between 4096 different shades of grey, in contrast to the 50 or so which can be differentiated by the human eye. Manipulation of the grey levels shown on the screen, accomplished with extreme ease by a few key strokes or movements of the mouse, can make these additional greys visible to the person reading the radiograph and allow the recognition of previously unseen features. Similarly, magnification is no longer a case of holding a lens close to a film balanced on a light box, but becomes a simple mouse movement, making detailed examination far more straightforward. Even if these were the only advantages of the use of digital radiography, they would make it more than worthwhile.

Image enhancement is also possible. Images can be sharpened, edges and voids clarified and artefacts removed using a wide range of filters. Which filters are appropriate is heavily dependent on the equipment being used and the purposes of the examination, and this is discussed in more detail below. An example of what can be achieved is given in Box 2.1, which describes how the details of the Ur helmet complex (Figure 2.7) were elucidated by digital processing of a scanned radiographic image.

Most proprietary radiography programmes also include a range of other features, such as on screen measurement tools, and some allow for more complex procedures, such as the addition of false colours to bring up certain features (Clogg and Caple 1996). Similarly, software exists to enable the mosaicing of several separate images together to produce a single image of large objects. At the time of writing, an image processing package (VIPS) used by many museums and galleries is available at www.vips.ecs.soton.ac.uk.

Figure 2.7. *Ur helmet complex (BM ANE 121414).*

Archive and storage

One of the possible advantages of digital format radiography widely hailed at the early stages of development was that it could provide a permanent and space efficient method of archiving. Film, however well processed and stored, does have a finite-lifespan and is bulky, requiring large areas of dedicated storage space. As with most such novel equipment, this initial promise has proved to require some qualification. With increasing usage it is becoming apparent that forms of storage such as CD or DVD are not as permanent as once hoped, and may in fact have a lifespan equivalent to or less than that of film stock. Additionally, the file formats used to store images are constantly evolving and being superseded and even such widespread file types as TIFF and DICOM must be expected to be replaced in time, while the proprietary formats associated with some equipment are far more ephemeral. Unfortunately, archaeology is full of examples of databases constructed in now defunct file types, or stored on media, which are no longer readable. Such problems can be minimized

Box 2.1 Processing the image of the Ur helmet complex

Figure 2.7 shows the skull of a young adult male wearing a copper helmet, excavated by Leonard Woolley from one of the Royal Graves in the ancient city of Ur in modern day Iraq (Irving and Ambers 2002). Despite the early date of these excavations (in the 1920s), Woolley block lifted many of the objects found at Ur, including this (see Chapter 8 for an explanation of this technique). In this case the block was never fully excavated. Instead it was prepared for museum display supported on a board and with only the top surface cleaned, revealing the skull and helmet as found in the ground. Radiography was required to reveal more details of the helmet construction and to visualize the roots of the teeth, which are used to estimate the age at death. This presented a number of problems, most notably because of the wide range of radiographic densities present. The conventional approach here is to take a number of plates at a range of different exposures. An alternative can be to take a more limited number of exposures but to examine them in digital format, taking advantage of the increased range of visible greys. Figures 1 and 2 give an idea of the versatility of this method. Here a single conventional film has been scanned to produce a digital file. This is presented in two ways; in Figure 1 the visible greys have been optimized to show features with similar radiographic density to bone, while in Figure 2 the visible greys are optimized to show the metal helmet. From Figure 2 it is finally possible to make sense of the shape of the helmet; one of the twin earpieces has slipped forward over the front of the skull, giving the impression of a strange nose piece. The parallel lines across the image are due to the corrugated plastic layer on which the entire block sits.

Figure 1. *Visible greys optimised to show bone and material of similar density*

Figure 2. *Visible greys optimised to show metal helmet*

by the storage of images on network drives, where data is subject to frequent backup, and reformatting as required, but a strong argument can be made for the retention of hard copies.

Dissemination and publication

One area where the use of digital equipment has proved to be truly innovative is in the dissemination and publication of images. It is virtually impossible to produce a true copy of a film radiograph, containing precisely equivalent detail. Each one is therefore unique and a precious resource holding in it the time and effort used to produce it. In the situation where an object is conserved, altered or lost, a film radiograph may also be completely irreplaceable as a record. Films also tend to be a very popular resource, in demand by conservators, archaeologists and other specialists, not to mention the owner or curator of the object in question. Films are quite fragile things, easily damaged by handling, scratched (particularly when used to produce measurements) or quite simply lost. Once an image is in a digital format however, endless numbers of identical copies can be produced and disseminated with ease, in hard copy, on CD or by electronic means. Similarly, the publication of radiographic images becomes much simpler. Rather than having to photograph a film on a light box to produce a publishable picture, images can be collected or transferred directly into the form required by the printers and any labelling, arrows, etc. added simply by the radiographer.

IMAGE PROCESSING

What is Image Processing?

Image processing involves the application of a process or series of processes to an image so as to make it more amenable to human or computer interpretation. Simple examples of processing include such operations as changing the brightness and contrast or sharpening an indistinct image; more complex operations might involve pattern recognition or the comparison of two or more images in order to detect subtle differences.

Image processing can be divided into several non-exclusive groups that include: capture, enhancement, restoration, reconstruction, analysis and compression. *Capture* is the process by which digital images are obtained and also embraces such topics as image resolution and how many colours or shades of grey are to be used to represent the image (see also above p. 28). *Enhancement* is the process of improving the visibility of the image and also making the image 'look' better; it includes the adjustment of brightness or contrast, and edge enhancement. Enhancement is usually an interactive process and the results are often judged subjectively. *Restoration* is used to improve images. In some cases, images may have been degraded so that they are virtually unusable without processing. Degradation may result from geometric distortions in the optical system used to obtain the image. It may also be caused by electronic noise added at source or through transmission or by aberrations arising from the combination by the mosaicing of several separate images (*reconstruction*). *Image analysis* involves the quantification of features within an image but falls beyond the scope of this chapter. *Image compression* deals with the storage and transmission of images and is discussed more fully above.

Processing the Image

When an image is digitized, each pixel is assigned a value to represent the grey level at that point of the image; in a 12-bit image, the values lie between 0 (conventionally black) and 4096 (conventionally white). When the image is displayed on a screen the value of the pixel is converted into an appropriate amount of light. It is a simple matter to change the image so that what was black appears white, in rather the same way that there is a reversal of contrast when a photographic positive print is prepared from a negative. The mechanism for designating the display value of each pixel is called the look-up-table (LUT). Changes to the LUT can be used to modify the appearance of the image, including display in false colour, and on some systems changes can be made so quickly that they appear instantaneously, so that the process can be interactive.

One important method used to describe an image is to present the distribution of grey levels within it, normally in the form of a *histogram*. Figure 2.8 shows the grey level histograms of two areas of the same image. Clearly the distributions are not the same: the histogram of the darker area is concentrated towards the lower (left-hand side) end of the graph, whereas the histogram of the lighter area is concentrated at the higher (right-hand) end. Just as informative is the shape of the distributions. For instance, the histogram for the dark area is quite narrow which shows that the image is made up of pixels which all have rather similar values (i.e. a limited range of grey levels). One technique which can be used is histogram equalization: a new LUT is calculated which 'stretches' the histogram so that most of the available levels of dark to light are used. The result is an image in which more detail is seen (Figure 2.9(a)). The new grey level histogram is shown as Figure 2.9(b). A useful approach with histogram manipulation and included with all image processing software, can be to work only in the areas which are of immediate concern. Treating an image as a series of small sections, and individually optimizing each, will frequently give better results than applying a single approach to the whole image.

Spatial Filtering

Spatial filtering of an image is traditionally performed by applying a *filtering element* to the top

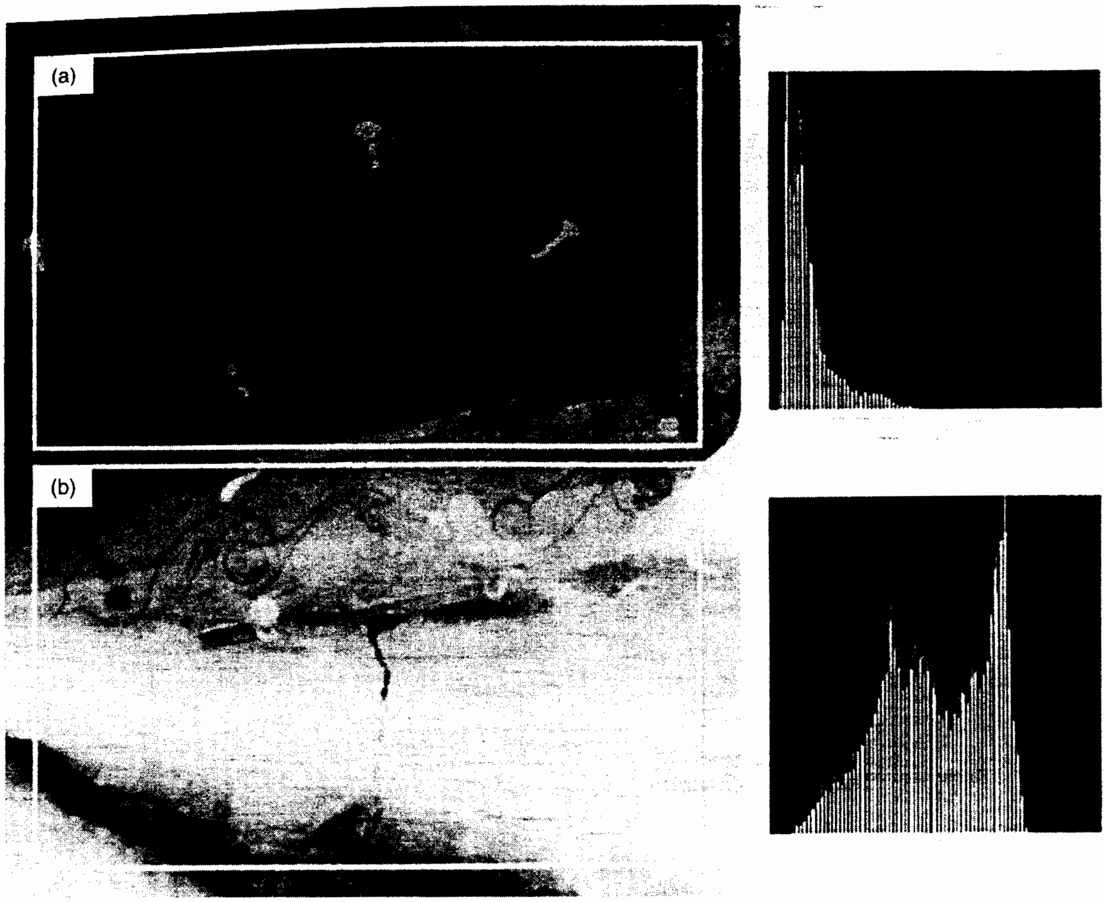


Figure 2.8. *Detail of a digitized radiograph of a shield complex from Essendon, Hertforshire which contains a dark area labelled 'a' and a light area labelled 'b'. An intensity histogram is shown alongside each area.*

left-hand corner of an image and moving it successively one pixel at a time until the bottom right-hand corner is reached. The filtering element is just a simple array of numbers which, in part, defines how the filter works. This type of processing is localized in that the result depends only on the value of neighbouring pixels. For example, a 3×3 filtering element is 3 pixels wide, 3 pixels high, and the result is returned to the middle pixel. The simplest spatial filters blur or sharpen an image, as one might alter the focus of a camera lens. *Blurring* involves the simple averaging of the neighbouring pixels and is suitable for removing noise from an image, although this also tends to remove detail as well. *Sharpening*, the most likely to be of use within the interests of this book, increases the difference between a pixel and its neighbours, the effect depending on the magnitude of the difference. This is a very effective way of enhancing the appearance of details and edges but it also tends to increase the noise within an image. Figure 2.10 shows the effects of sharpening an image. The edges of features within the images have been subtly heightened. Although it may be possible to use sharpening and blurring filters in succession, first to sharpen the image and then to reduce the amount of noise by blurring, there is a risk that vital information may be lost and unwanted artefacts introduced. Caution must therefore be exercised in the successive application of sharpening and blurring filters as there is no guarantee that anything new will be revealed or that the image will be improved.

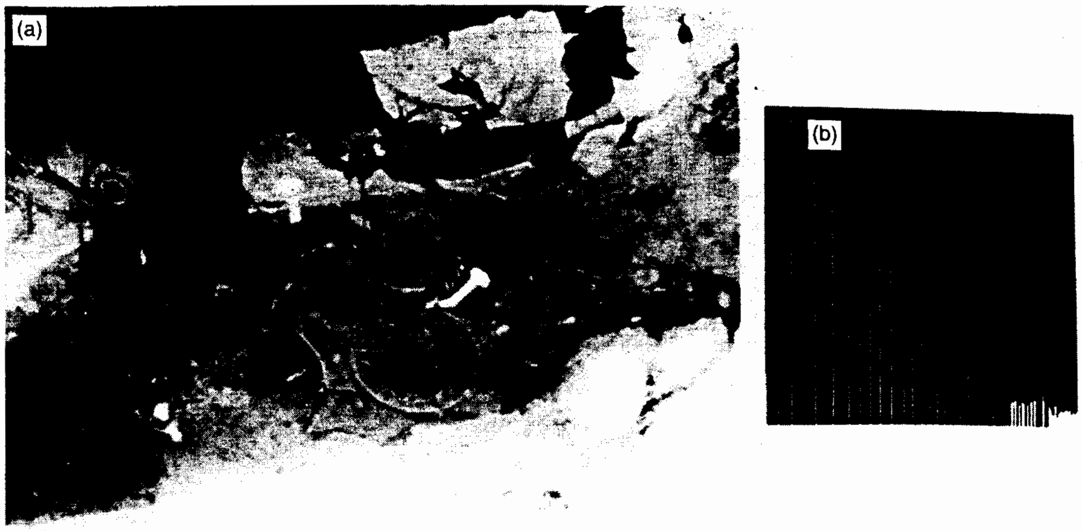


Figure 2.9. *Upper part of Figure 2.8 (a) showing the effects on the image and (b) of equalizing the brightness by manipulating the histogram.*

Figure 2.10. *Upper part of Figure 2.8, showing the effects of enhancing the edges of objects within an image; the decoration is more clearly visible.*

Another useful technique is to arithmetically subtract the processed (blurred) image from the original. In the resulting image the edges of features appear against a black background, somewhat similar to a drawing or etching which has been printed as a negative. There are several filters which have been designed to show different aspects of this type of information. Figure 2.11 shows the image after processing with a set of filters known as gradient filters (Gonzalez and Woods 1992, pp. 414–29). Here, the

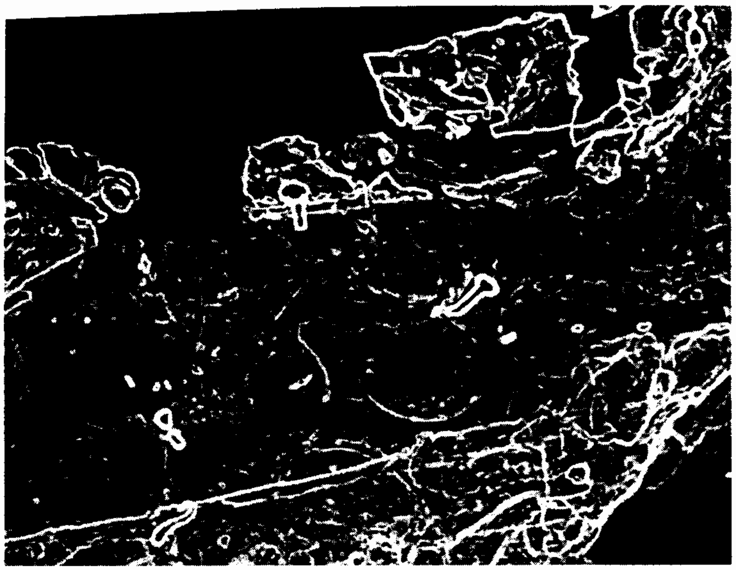


Figure 2.11. *Part of Figure 2.8, showing how the edges have been emphasized by processing the image using gradient filters.*

edges of features stand out, with the thickness of the outline being proportional to the difference between adjacent areas in the image. Complex structure is revealed, but the information given is quite different from that produced by simply sharpening the image or by altering the contrast or brightness.

Morphological Filtering

One way to look at an image is to imagine it as consisting of details superimposed on a background of broad features which cover the entire surface of the image. If the pixel intensity is plotted as a height value, the image can be presented as a topographic map with hills and valleys. A set of image processing filters grouped together under the common title of *mathematical morphology* have been developed to process the shape of objects within an image. Originally these were developed for binary images which contain only black and white pixels (i.e. with no intermediate shades of grey) but their use has been extended to include greyscale images. In the case of greyscale images, the morphological operators do not act upon the shape of a feature as in binary images but on the shape of the *terrain* (the hills and valleys). This type of processing allows the separation of broad features from detail (Serra 1982; Sternberg 1986).

Morphological filtering involves two fundamental operations: erosion and dilation. *Erosion*, as its name suggests, refers to the shrinking of a feature, while *dilation* refers to an increase in the size of a feature. These two operations are usually performed sequentially: an erosion followed by dilation is called an *opening*, and dilation followed by erosion is called *closing*. The enhancement of watermarks will be used to illustrate the power of greyscale morphological filtering.

Watermarks are a rich source of information for the art historian and much can be gleaned from the design of a watermark, from evidence of repairs and also from the spacing of the wire mesh on which the watermark was supported (see Chapter 5; also Higgins and Lang 1995). Figure 2.12(a) shows the scanned image from a β-radiograph of the watermark from a drawing by Rembrandt. In this image it is quite difficult to see the whole of the watermark as there is a dark vertical band at the top, right-hand part of the image. This arises partly from the radiographic technique but mainly from the uneven thickness of the paper. What is required is to mathematically remove the dark band so that the whole watermark can be seen. The filter used to process an image should be one roughly equal in size to the feature that is to be enhanced. In this case, a filter of size 41 × 41 pixels was selected as this was the width of the dark band. Two processed images were produced, one derived from opening the image, the other from closing the image. The resultant image (Figure 2.12(b)) was derived by arithmetically subtracting the opened and closed images from the original.

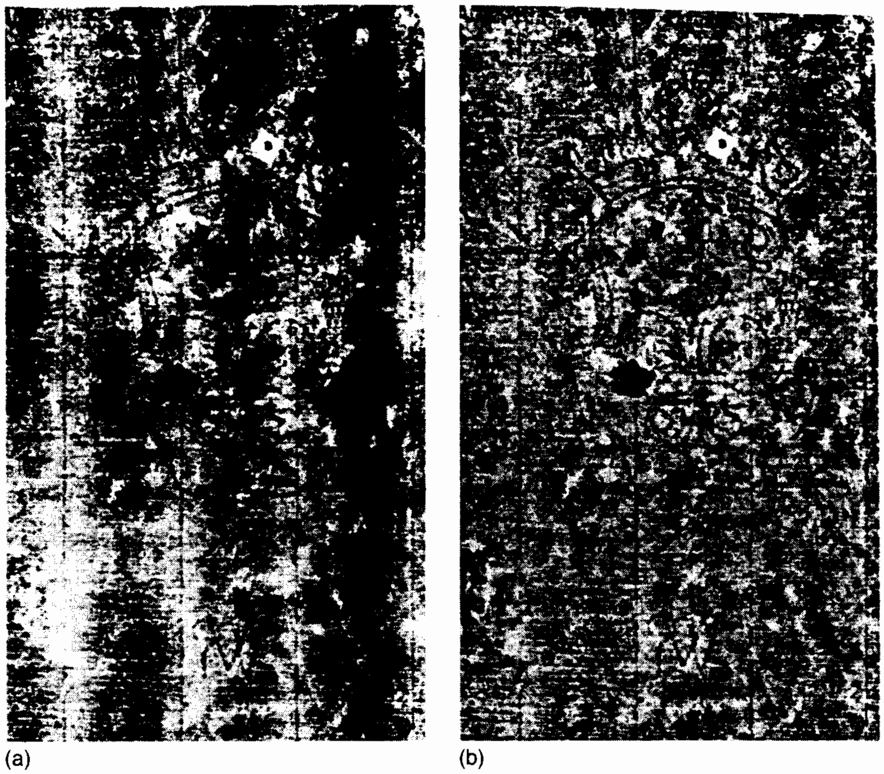


Figure 2.12. *β-radiograph of a watermark from an etching by Rembrandt showing (a) broad dark vertical bands caused by the method of production, which obscure the watermark image; and (b) the same image after processing with morphological filters.*

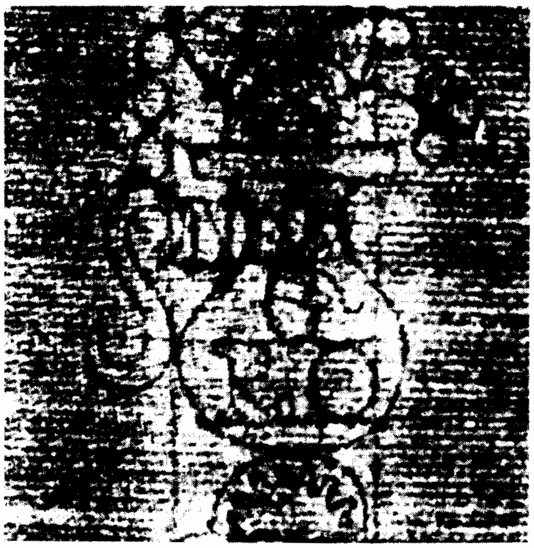
The processing of this image also serves to illustrate an important principle that applies to morphological processing. This principle, known as *deconstruction*, recognizes that the effects of some large filtering elements during erosion and dilation can be replicated by the successive application of smaller filtering elements. This has important implications for the amount of computation required. In the present example of the Rembrandt watermark, the single application of the 41 × 41 pixel filter involved 1681 calculations for each pixel; the same result could have been achieved by 10 successive applications of a 5 × 5 pixel filter, involving only 250 calculations for each pixel in the image.

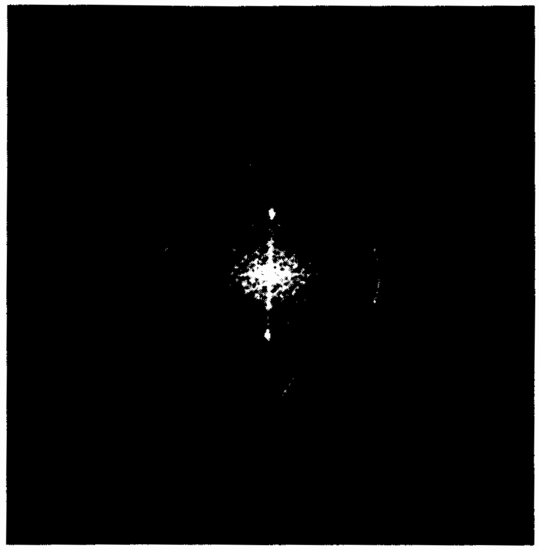
Fourier Transform

The *Fourier transform* (FT) is a mathematical operation which makes it possible to recognize and examine the periodicity of features within an image (see, e.g., Oppenheim and Schafer 1989, chapter 8; Castleman 1996, chapter 11). Calculating the FT is practical only for very small images because each pixel in the transformed image contains some element or fraction of each and every pixel from the original image. Thus, the number of calculations required rises rapidly as the square of the number of pixels and an image containing a million pixels would require a million calculations for each of the million pixels (i.e. a total of $10^6 \times 10^6$ calculations). Fortunately a variant known as the *Fast FT* (FFT) has been developed which drastically reduces the number of calculations required. One of the limitations to using the FFT is that the original image must be square and the length of each side of the image, in pixels, must be a power of 2 (256, 512, 1024, etc.).

Although the FFT image is very different in appearance from the original image, as can be seen in Figures 2.13(a) and (b), it is important to note that the transformed image contains exactly the same amount of information as the original image. The original image can be restored by applying an inverse procedure. Transforming the image into this new format using the FFT has several advantages as it can be filtered in very subtle ways. However, it is manipulation of the periodic features which is of particular interest here (Jain 1989, Chapter 5; Castleman 1996, Chapter 11).

Figure 2.13(a) shows part of the radiograph of a watermark in which horizontal features created from the imprint of the paper-making mesh can be seen. However, their presence interferes with the viewing of other features in the watermark. The removal of this mesh from the image using non-Fourier filters would be very difficult and might cause some degradation of the image of the watermark itself. The FFT image of the region (Figure 2.13(b)) shows, amongst other things, three bright spots. The central bright spot is related to the overall brightness of the image, but the two spots above and below the centre arise


(a)


(b)


(c)

Figure 2.13. *β-radiograph of a watermark showing (a) horizontal 'laid' lines, an imprint left by the mesh used to make the paper; (b) the FFT of the image. The bright spots above and below the centre of the image correspond to the laid lines and wispy artefacts correspond to the lines on the original etching, and (c) the restored radiograph after Fourier processing. Note that the laid lines have been removed.*

from the regular spacing of the mesh. The position and intensity of these spots relate to the periodicity and brightness of the mesh structure in the original radiograph, and it is possible to calculate the spacing of the mesh from the distance of the spots from the central spot (Dessipris and Saunders 1995). Furthermore, by 'editing' the FFT image and then restoring the image by an inverse transform, the appearance of the mesh structure in the radiograph can be modified. In particular, if the upper and lower spots are deliberately removed then the mesh structure will not appear in the restored image thus allowing the watermark itself to be seen more clearly (Figure 2.13(c)).

STEREORADIOGRAPHY

Radiographs contain a 'flattened' two-dimensional (2-D) view of the internal structure of a 3-D object. Although this type of image is valuable there is little information on the relative depths of features within the object. However, by using different views of the same object it is possible to regain depth information. The different methods are discussed by Spicer (1985).

The 3-D component of human vision is derived from the difference between the images received by the left and right eyes. Depth can be reintroduced or simulated using radiographs, provided two radiographs are used and that the images they contain were taken from slightly different positions. This can be done by moving the X-ray tube: the object is first positioned correctly under the X-ray tube and then the tube is moved about 3 cm to the left of the centre and the first exposure made. The tube is then moved an equal distance to the right of centre and a fresh film used to make the second exposure. The two films, viewed side by side, under a stereo viewer, give a 3-D image. Another method is to make both exposures on a single film, moving the tube from one side to the other between exposures. Each exposure time is half of what it would be for a single exposure. It can also be done by moving the object an amount equal to the distance between our eyes (see below, p. 42; also Figure 3.20 and Chapter 7). The perceived depth can be exaggerated by increasing the distance the object is moved or through a combination of rotating and moving the object (Kozlowski 1960), although Spicer (1985) has pointed out the disadvantages of the latter.

The radiographs can be combined optically using an optical instrument termed a stereoscope, although these tend to be expensive and the resulting image is limited in size. Another way to combine the images is to create red-green stereo pairs. Here, the radiographs are scanned and placed into different layers of colour image: one radiograph for the red layer, the other for the green. It is important to align the images where the overlap occurs. When the image is viewed using glasses fitted with one red and one green lens, the red image is seen by the eye which is covered by the red fitter and the green image is seen by the eye covered by the green filter. As long as the viewer has stereoscopic vision, the technique works even if the viewer is red-green colour blind.

An example of a red-green stereo pair is shown in Plate 2.1, which is an image of a part of the Essendon shield (although red-green glasses have not been provided with this book, they can be easily manufactured from the appropriate coloured gelatin sheets). The image shows the structure and placement of objects within the image and aids our understanding of the design on the shield.

COMPUTED TOMOGRAPHY

A further level of sophistication in the development of radiographic methods is provided by computed tomography (CT), also known as CAT (computer-aided/assisted/axial tomography) scanning, which is most familiar in medical applications and was developed mainly for that purpose. In conventional radiography the 3-D structure of the body or object is projected on to a 2-D film, where the optical density at a given point on the radiograph provides a measure of the overall attenuation of the X-ray beam as it traverses through the subject. Consequently, when a radiograph of a patient's anatomy or an object's structure is displayed in 2-D (height and width), information with respect to the third dimension (depth) is lost. This limitation has normally been overcome, where appropriate, by acquiring images from more than one angle. Techniques such as stereoradiography and conventional 'non-CAT' computer assisted tomography may provide some 3-D information. However, these techniques are laborious and the inability of conventional radiography to spatially resolve 3-D structures and to distinguish the soft tissues was a deficiency in the medical field not properly overcome until the advent of CT.

CT was developed in Britain by Sir Godfrey Hounsfield in the early 1970s. Essentially, CT scanners measure the relative transmission of X-rays through an object in different directions and then compute this information to construct a cross-sectional image (Herman 1980). Typically, a scanner consists of a large gantry with a hole in the middle, through which a patient (or Egyptian mummy!) passes, lying on a table (see Figure 7.6(a)). The gantry conceals the complex equipment, including the X-ray source and detectors. First-generation scanners employed a finely collimated pencil beam of X-rays, whilst fan beams have been used in subsequent generations. The beam passes through the patient and then into a detector, collimated to avoid scatter. Separate parallel projections are made at angular intervals around the patient. Having completed this set of projections (or slices) the table is moved slightly (typically a few millimetres), positioning the next axial slice of the patient in the path of the X-ray beam for the next series of projections. The number of slices taken and the linear spatial interval between them is determined by the requirements of the examination. The data from these projections are stored in a computer and this part of the whole process is known as the 'acquisition' (see Chapter 7).

CT scanner images are composed of 3-D information and each element of the image is called a voxel, the 3-D equivalent of the 2-D pixel. Associated with each voxel is a value related to the relative linear attenuation at the X-ray energy being used for the scan. This is known as the CT (or Hounsfield) number, and is calculated by reference to the attenuation of water, measured under the same conditions. Water is used as a reference because its attenuation can be measured conveniently and reproducibly, and because its attenuation is similar to that of human soft tissues. By convention the CT numbers of air and water are defined as -1000 and 0. Thus, the CT number for a tissue pixel is calculated as:

$$\text{CT number} = 1000\,\frac{(\mu_t - \mu_w)}{\mu_w} \tag{2.3}$$

where:

μ_t = measured linear attenuation coefficient of the tissue;
μ_w = measured attenuation coefficient of water.

A typical CT number for bone is given as $+1000$ by Farr and Allisy-Roberts (1997, p. 102), who provide a more detailed introduction to the use of medical CT scanners.

Once the set-up has been standardized, the transmission data can then be used either as digital information or, by analogue conversion, as a pictorial display on a monitor. Each set of projections, therefore, can provide a CT image which is a representation of an axial slice of the subject at the point where the X-rays were incident. Although the 3-D section is compressed into a 2-D CT image, the slice thickness dimension is very thin (1–10 mm). The resulting image is conventionally shown as a transverse section of the anatomy of the patient. A number of contiguous thin slices can be manipulated in the computer to create images in alternative planes; this is referred to as 'reformatting'. A further refinement of the software has been the introduction of the dimension of distance from the observer which facilitates the production of a 3-D image which can be rotated in any direction on the monitor. Further information on medical imaging can be obtained from Bushberg *et al.* (1994). CT scanners have been used to examine a variety of archaeological and cultural materials, perhaps most extensively in the study of mummies (see, e.g. Hughes 1996; Taylor 2004; also Chapter 7): useful discussions are provided by Bonadies (1994); Illerhaus *et al.* (1995); Ghysels (2003) and Jansen *et al.* have reported studies on ceramics, stone, wood, mummies and scarabs within mummy wrappings (2001, 2002a, b), using high-resolution CT scans (see also Mees *et al.* 2003 for applications to geological materials, including the conservation of stone). The literature is increasing rapidly, much of it is available through the WorldWideWeb. Additional references will also be found in Chapters 3 and 7.

Advances continue to be made, especially in the medical field. CT scanners with multiple arrays of detectors developed in the late 1990s dramatically reduce exposure times. The X-ray source and detectors move round the patient to complete the slice. By 2004, multislice scanners could capture up to 4 slices in 0.5 s and this capability is being increased. An entire body scan takes 1–2 min to show all internal injuries in trauma cases. Virtual postmortems can be carried out, and materials of different density, such as metals or stone, can be distinguished. This enabled the arrowhead which caused the death of the Iceman (see Chapter 7) to be located and identified. At the time of going to press, a CT investigation into the cause of Tutankhamun's death and a programme of examination of other Egyptian mummies has been reported (Booth 2005; see also Chapter 7).

The systems are aimed specifically at medical applications, being designed to produce detailed images at safe dose rates. They are very expensive but suggest future directions in radiography, although speed and dose rate are not as paramount in materials examinations as in the medical field. Developments in the industrial field are often concerned with assembly line inspection and monitoring welds in pipes and constructions. The electronics industry, with increasing miniaturization, has led to the development of microfocus CT and nanofocus X-ray tubes, where the minimum spot size claimed is 900 nm (0.9 μm) with a tube current of 100 kV. This type of equipment is usually mounted in a cabinet and the size of the chamber is quite restricted.

PRACTICAL RADIOGRAPHY

Image Quality

There are a number of factors which determine the quality of the image, some of which have already been mentioned. All the detail required should be as clearly visible as possible, with sharpness or definition maximized and fogging minimized. In the first instance (even before any image processing is carried out), good quality images depend upon optimizing both the conditions of exposure (as discussed in Chapter 1) and the method of recording.

Radiographic contrast arises from variations in the intensity of the X-ray beam emerging from the subject. The overall contrast seen on the radiograph will depend also upon the characteristics of the film (or other recording medium). Films offering the benefit of higher contrast will suffer the disadvantage that they have less exposure latitude than less contrasty films. The level of contrast in the image can also be enhanced by using lower energy, softer radiation, but this will reduce the penetration of the beam. In addition, the range of density or thickness which can be shown on the radiograph is less than with harder, more energetic X-rays (Figure 2.14). Generally, the greater the contrast or density differences within the radiograph, the more clearly the main features stand out. However, if there is too much contrast, details in thicker and thinner parts of the object may be lost and the eye may be distracted by dramatic contrasts in the image, thus missing some of the detail. Image processing, including the use of false colour to represent the different grey shades in the image, can often enhance contrast to make features of interest more visible to the eye (see Image Manipulation, above), but it should be understood that the exposure conditions utilized are often a compromise.

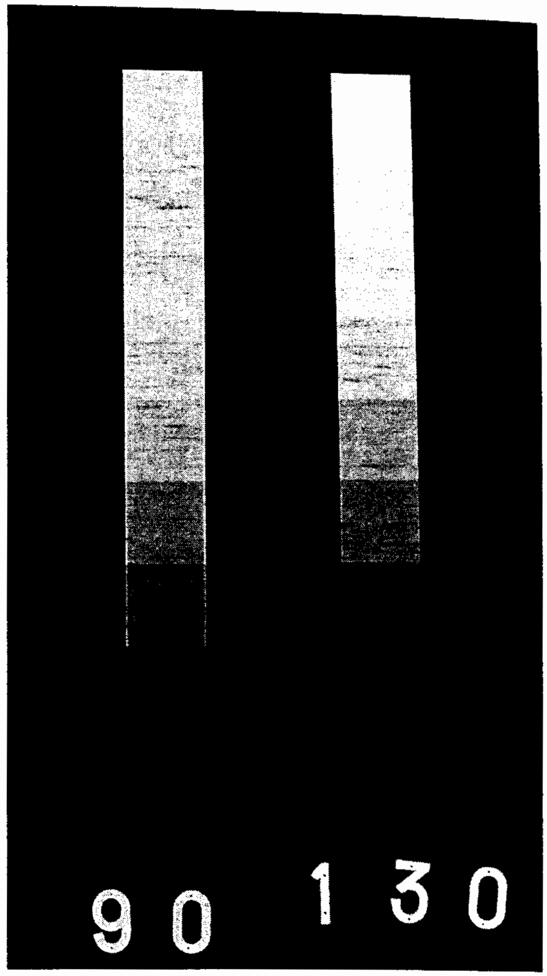


Figure 2.14. *Steel step wedge, radiographed at 90 and 130 kV, the lower energy gives an image with a smaller number of more distinct steps, while the higher-energy image shows a greater number of less distinct steps.*

Definition or sharpness may be described as the clarity with which details can be observed on a radiograph or screen. It is optimized by using a small spot size and a small object-to-film distance, as discussed earlier, in Chapter 1. Fine-grained film and an appropriate film processing regime also help to ensure good definition. The geometry of the object itself may restrict the definition which can be achieved: larger and more variable shapes tend to give less well-defined images. Sharp changes in profile provide abrupt changes in radiographic density, which are easier to discern than gentler changes. Larger objects, especially those which are heavily undercut, such as coin dies or solid statues, produce scatter which fogs the image and reduces definition. Scatter can be reduced by using filters, lead sheet, and packing as described in Chapter 1. The radiographs of the cast iron Chinese figure shown in Figure 2.3 illustrate how an image can be improved by using lead screens.

Sensitivity, in radiographic terms, is a measure of overall quality and in industry is often related to the need to distinguish particular features as a part of quality control. It can be measured by radiographing the object together with a penetrameter or image quality indicator (IQI) made of the same material as the object, and which may consist of plates of known thickness, or a series of elements such as wires or accurately drilled holes. Halmshaw (1995, p. 148) provides a general definition of sensitivity:

$$\text{Sensitivity (\%)} = \frac{\text{thickness of the smallest visible element}}{\text{thickness of the specimen}} \times 100 \qquad (2.4)$$

A step-wedge penetrameter, which consists of a wedge made from strips of suitable material (e.g. steel, if iron or steel is being radiographed), can be used to calculate exposure charts (Figure 2.14). Unfortunately for museum and archaeological radiography, the use of such charts is limited because of the irregular thickness, composition, corrosion and generally unpredictable nature of archaeological material. However, IQIs can be used to provide an objective guide to the sensitivity of the recording medium. Such usage is not restricted to film, and a wire indicator, attached with tape to the aluminium protective screen of an image intensifier, provides an indication of the sensitivity of the image intensifier's screen, cameras and display/recording system (see above, Sensitive screen fluoroscopy).

Problems

It is difficult to generalize about the problems which may arise in relation to archaeological and museum material, but a few examples of the difficulties encountered are discussed below.

Diversity

The sheer diversity of the requests is perhaps the largest single problem. Such requests may include making surveys of large numbers of excavated iron fragments, reporting on the state of a woodworm-ridden medieval statue, determining the construction of an Anglo-Saxon gold and garnet brooch, comparing watermarks in paper, discovering the construction and condition of a whalebone corset (see Box 1.3) or commenting on the construction of similarly styled ceramic vessels of different provenance.

Range of Materials

The wide range of materials encountered in archaeological radiography might include environmental remains such as fragile fish bones, wood, or fibres, textiles and paintings which require low-energy X-rays, often less than 60 kV (Gilardoni 1994) (see also Box 1.3). At the other end of the radiographic scale are large bronze statues (Born 1985) and artillery pieces such as cannon (Smith and Brown 1989). To radiograph such heavy objects as these, the radiographer probably has to consider approaching outside agencies, either industrial or academic research facilities, which may have equipment such as betatrons. As the work of Born and others has shown, this can be well worthwhile.

Most archaeological radiographers probably have access to generators capable of operating in the range 10–130 kV or 50–320 kV. Back-scattered electron radiography is effective for paper and paint images if a set capable of reaching 250 kV is available; alternatively, a ^{14}C source can be used for paper. Mention should also be made of a cabinet which can be attached to an X-ray diffraction set, allowing it to be used for radiographing paper, card and other light materials (Rendle *et al.* 1990). However, it is probably only in an industrial or government research facility (such as Bundesanstalt für Materialforschung und Prüfung in Berlin) that a range of equipment would be found capable of coping with the full range of archaeological materials.

Sometimes a wide range of materials is found on one object: the animal head from Mexico (McEwan *et al.* in press) (Figure 2.15) incorporates several different materials but nevertheless the radiograph was successful in distinguishing them and showing their distribution.

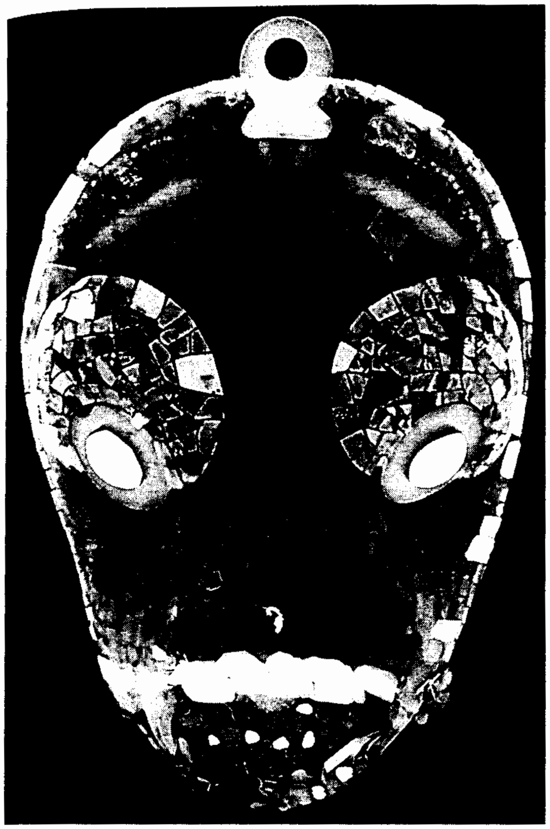


Figure 2.15. *Mosaic-decorated animal head from Mexico, made from wood,* AD *1400–1521 (ETH. St. 400a). The eyes are pyrite with rings of shell around them, the teeth are sharks' teeth, the head and eyebrows are decorated with seed pearls, and in the lower part of the mouth zircons, which are relatively radio-dense, show as the bright white stones. The roof of the mouth is covered with rectangular slabs of garnet, which because they are viewed edge-on also appear white, although they are not especially dense. The tesserae are mainly turquoise but some are malachite, which can easily be identified by its greater density on the radiograph. A small twist of wire in the mouth may have been an original attachment or part of a repair, probably made of gold. 3 mA, 5 min, 60 kV, 1 m distance, Kodak MX film.*

Awkwardly Shaped Objects

Awkwardly shaped objects test the radiographer's ingenuity: real-time radiography is ideally suited to examining large and bulky objects, as long as they can be fitted on to a turntable and moved safely (see also Chapter 8). A grid of lead letters and numbers laid over the surface of a large featureless item, such as an excavated block, is a great help in locating the position of finds (see Figure 8.9): distortion of the image, with some areas enlarged by geometric effects may make it difficult to identify the corresponding positions on the block and the screen. After an area of interest has been located, it can be radiographed using film.

Positioning the film close to the object, using packing and straps (as long as the integrity of the object is in no way compromised), helps to improve the quality when radiographing awkward features, such as the arms and legs of statues, which do not lie flat on a cassette. Using film in lead lined paper cassettes or light-tight plastic bags improves the film-to-subject distance and lead sheet or bags of lead shot as shielding help to prevent scatter in such circumstances. Several exposures at different settings are sometimes required for objects which vary considerably in thickness. The Anglo-Saxon single blade seax from Sittingbourne illustrated in Chapter 3 (Figure 3.24) required one exposure to show the iron blade and a second, longer one, with a lead front screen, to show details of the inlay.

Masking

Problems due to masking may arise when one part of an object is obscured or masked by another part. Masking difficulties were encountered while trying to discover the structure of a complex Anglo-Saxon brooch from Boss Hall (Figure 2.16). The upper surface is decorated with gold wire and cloisonné garnets and has a domed central panel. The pin is secured inside a small garnet-encrusted drum on the back surface. As the components masked each other, it was difficult to determine with certainty the internal construction of the brooch, even using conventional radiography, real-time viewing and image processing. Microfocus CT scanning would have been very helpful, had it been available.

The examination of the paint layer on a sheet of copper has already been mentioned in connection with back-scattered electron radiography (Bridgman *et al.* 1965); in this case, the paint layer would have been masked by the copper substrate in a conventional radiograph. Sometimes the problem appears insoluble: an attempt was made to radiograph the sheet copper interior of a glass table leg in the British Museum. The glass is a heavily leaded millefiore and it was not possible to image the copper interior of the leg; on the radiograph the thick layers of lead glass completely obscured any details of the thin, folded sheet copper within.

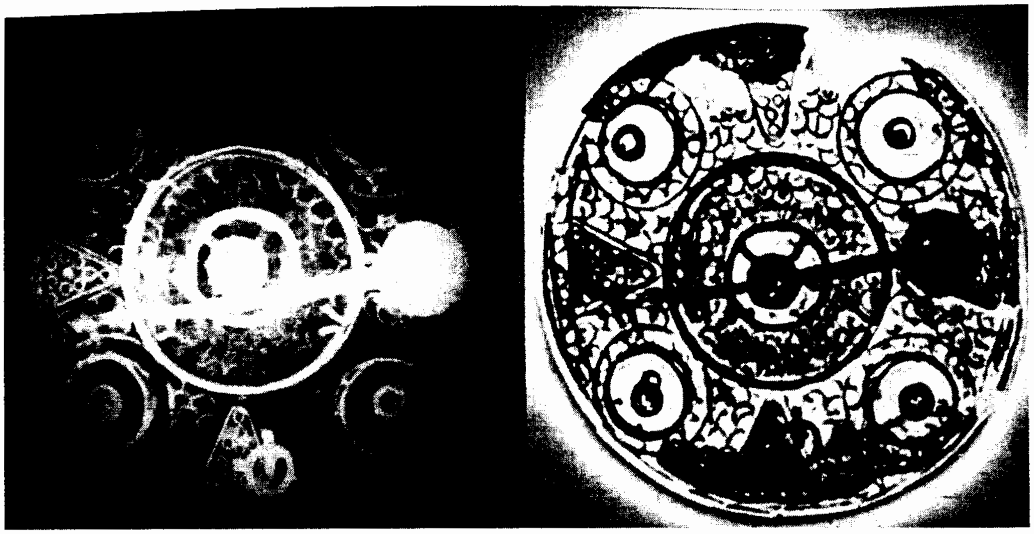


Figure 2.16. *Two views of an Anglo-Saxon gold and garnet brooch from Boss Hall, Ipswich. The brooch was made from several components and even with real-time viewing it was impossible to be certain of the construction.*

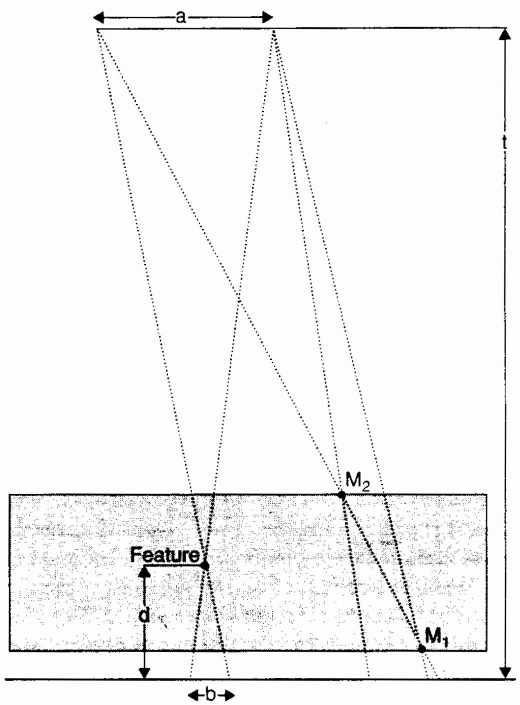


Figure 2.17. *Stereoradiography can be used to locate a feature within an object. The distance 'd' of the feature from the film can be calculated from the formula: $d = bt/a + b$, where 'a' is the tube shift, 'b' is the shift in position of the image of the flaw, and 't' is the source-to-film distance. Lead markers (M1 and M2) on the top and bottom assist in measurements (after Quinn and Sigl 1980).*

Superimposition

As the image of a 3-D object is displayed in 2-D when it is radiographed, designs or inscriptions from both sides of the object are superimposed which makes interpretation difficult. Real-time viewing can help to distinguish the images. Stereoradiography can also be used: this is a simple procedure, described in many textbooks (e.g. Quinn and Sigl 1980, pp. 114–16; Halmshaw 1995, p. 143). It has been of use in a number of applications, including the reconstruction of the metal thread design decorating a cushion found under the head of Archbishop de Grey (1216–55) in York Minster (Ramm 1971). Its use has been mentioned in this chapter (p. 37) and is also discussed in Chapter 7. The technique was used successfully for reading the pattern-welded inscriptions on both sides of an Anglo-Saxon sword (Figure 3.20). The surface of the sword was so corroded that it was difficult to see the inscriptions and reading them was impossible. Using stereoradiography, however, made it possible to separate the two inscriptions completely when viewed with a stereo viewer. Stereoradiography can also be used to calculate the position of features within an object, using lead markers attached to both surfaces to act as reference points (parallax method, Figure 2.17). Using very fine-grained film, microstructures and fine details such as cracks can be examined using stereopairs (Williams and Smith 1952).

Shallow Designs

If a design or inscription is only partly visible, the radiographer may be asked to try to reveal the missing section. This can prove to be difficult and is not always possible. The problems of geometry and unsharpness have already been mentioned: the edges of features such as chased or engraved designs or inscriptions, casting flaws or cracks tend to be small in relation to the source which leads to loss of contrast and blurring of the image. The difference in the absorption of the X-rays passing through the complete cross section (T in Figure 1.19) and the cross section reduced by the depth of a chased letter or an engraved outline (e in Figure 1.19) is very small. Generally the radiographer can try to ensure that the contrast range shows the maximum separation by using as low a tube voltage as possible. Sometimes it is helpful to record several radiographs of the same object under different exposure conditions, in order to optimize the visibility of different features. This is illustrated by the radiographs of the Roman spoon from Hoxne, shown as Figure 2.5 (see also Chapter 3 for further discussion of this and other inscribed spoons from Hoxne). Digital processing of a scanned radiograph may sometimes be useful in improving the visibility of cracks and other features. As in all types of imaging processes, radiographs are often a compromise, in which the radiographer seeks to optimize the conditions in order to show the features of interest clearly (Boxes 2.2 and 2.3).

Box 2.2 New radiographic facilities

Usually the type of objects and the materials to be radiographed in a new radiographic facility will dictate the choice of equipment, although this may be constrained by budgetary considerations and the space available. This section is intended to highlight some of the factors worth considering (see also Fell *et al.* forthcoming).

It is essential that a Radiation Protection Advisor (or outside the UK, a similar advisor) (see Chapter 1) is involved at the design stage of any new or refurbished facility. This will help to ensure that all the safety factors required by the Ionising Radiation Regulations and the Code of Practice (or equivalent legislation), such as shielding, interlocks and controls appropriate for the intended equipment, are included at the design stage. This point is worth emphasizing, because the regulations and their requirements are not always understood by non-specialist architects, which can result in costly problems and budgetary difficulties at a later stage.

The decision to use a self contained radiographic cabinet or free standing equipment is an important one. The main points to be considered are listed in the following table: much depends upon the types of objects being examined and the space and funding available:

	Cabinet	*Free standing set*
Shielding integral to system	Yes	No
Self contained	Yes	No
Power limitation	Yes (usually 150 kVp)	No (up to 450 kVp)
Object size limitation	Yes (size of chamber)	No
Film to source distance	Usually 1 or 2 fixed distances	Continuously variable
Space requirement	Operator can be in same room	Needs separate shielded room
Upgrading	Depends on manufacturer	Easy to add equipment (e.g. image intensifier)
Variable exposure time[a]	May be limited	Flexible
X-ray source position	Fixed	Flexible[b]
Variable milliampere	Fixed	Flexible (some limitations)

[a] It is useful if the exposure time is controlled digitally as this means that accurate repeat exposures can be made.
[b] The X-ray tube may be mounted on a trolley or a gantry and the tube head may be rotatable, but suitable shielding must be provided.

When examining large objects, such as statues or pictures, it is convenient to have the X-ray tube mounted on a gantry, so that it can be moved to different positions to radiograph various parts of an object or the angle at which the beam passes through the object can be changed. Tube manoeuvrability is desirable when radiographing large or fragile objects because it minimizes the disturbance to the objects. It is also useful for stereoradiography (see pp. 36, 42; Ch. 7). The addition of a light (or laser) guide to the system which shows the position of the centre of the beam, is extremely useful and time saving. Pictures or textiles are often radiographed in specialized set-ups where the object rests on a table of variable height with the X-ray tube positioned underneath. If low-energy work is to be carried out, with the recording medium (e.g. film) directly exposed to the radiation, it is necessary to operate under darkroom conditions; this means that both the cabinet itself and the room where it is housed need to be blacked out and a suitable safelight installed. The same would apply to a radiography room and its antechamber.

The selection of the radiographic equipment will include the image recording system as well as the X-ray generator. Increasingly, digital recording is being used and it is likely that this trend will continue. If an all-digital system is selected, archive deterioration and disc reading problems should be borne in mind, as discussed above (pp. 29–31). At present the vast majority of archaeological material is recorded on film, at least in the first instance. Film does have the advantage that it provides a reasonably permanent record and can be examined anywhere with a light box (or even held up to the light!!). However, film requires a dark room for processing, with running water and proper ventilation. Suitable space is also needed for the storage of film, chemicals, various sizes of cassettes and intensifying screens, etc. and for the temporary storage of chemical waste.

When the throughput of film is relatively small, manual tanks of developer, stop bath and fixing solution can be used. Drying cupboards speed drying and the film is protected from atmospheric dust. If the number of films is large, a small film processor can be very useful (the types used by vets or some dental models are suitable). Typically, a finished film, ready for examination and storage, is delivered in about 5 min, but all the processing times can be set to different values if desired. It is very important to make sure that the equipment is clean and well maintained and that film is thoroughly washed to conservation standards in order to prevent deterioration and ensure long-term preservation.

It is also important to provide a bench or table in a secure, clean, dry area, preferably with wipe-clean laminated worktops, where objects can be prepared for radiography. Ideally the preparation area should be situated adjacent to the X-ray facility, to minimize the possibility of displacement of objects and identifiers or damage during transportation. The provision of a light box, fitted with an intense light source in this area enables radiographs to be checked against objects for identification and investigation of features of interest. It should be possible to provide a low ambient light which is best for viewing. Some lightboxes have shutters that can be moved to fit the size of the film to cut out unwanted light which distracts the eye and makes it difficult to see the radiograph properly. The same effect can be achieved with strips of any non-translucent material. It should also be possible to secure the area where the specimens are laid out to prevent damage, disturbance or theft.

Box 2.3 Running a radiographic facility

The basic aims of a radiographic facility (see also Fell *et al.* forthcoming) are to produce images which provide some form of long-term (ideally permanent) record of an object and answer questions for archaeologists, art historians, conservators, curators and archaeo-technologists:

- In a way which is sensitive to the objects themselves and also efficient and cost effective in terms of time, equipment use and materials.
- The unit must also operate so as to follow the appropriate Safety rules in relation to the use of ionizing radiation (see Box 1.2 on p. 6):
  - keep a record of use, operators and of any problems and outcomes;
  - provide assessments of risk and establish safe working practices in relation to local health and safety legislation. Hazards may be exacerbated by the need to carry out some procedures using safelights or completely in the dark;
  - make provision for the proper storage and disposal of any radioactive sources and chemical waste, including spent developer and fix.
- Ensure the integrity of images. A film radiograph provides a record of an object. It can also be scanned and recorded digitally which increases its usefulness. While it would be possible to alter important features in a digital radiographic image, it would not be easy to do this in a conventional radiograph. Industrial systems safeguard the original image and this would seem to be appropriate for cultural material as well.

The organization responsible for the facility will determine to some extent the nature of the work and what is a realistic throughput. Where material from excavations is radiographed there is often a huge number of objects to be recorded and much depends on the grouping – it is easier to produce a satisfactory radiographic exposure with maximum information when the objects are of a similar radiographic density. If film is used, film costs can be reduced if several exposures are made on the same film. This is done by laying out the objects on part of the cassette and 'masking off' the rest of the surface with lead sheet. After the exposure, the objects are removed and the lead is moved to cover the exposed area. The unexposed film is then covered with the new or re-orientated objects, and a second exposure made. This may be at a different kilovoltage or for a different milliamperes value. The use of lead screens also increases exposure latitude, enabling satisfactory exposures to be obtained for a greater variety of objects.

To ensure quality control, a standard step wedge made with different thicknesses of a material with a similar radiographic density to the objects should be included (see pp. 39–40). A lead letter can be attached to the back of the cassette to monitor backscatter and measures should be taken to reduce scatter from all sources (see pp. 13–14). Unless a high-quality radiograph is assured with step wedge or penetrameter to show the dynamic range, there is always the possibility that unexpected information could be missed. Scratches on the lead screens in the cassette can be reproduced on the radiographs, so the lead surfaces should be checked for damage.

Frequently objects are radiographed in plan and profile views. If very specific questions are being asked of an object, especially in regard to construction or decoration, a number of different exposures at several angles may be required which is much more time consuming. Lead-lined paper cassettes, such as Readypack, can be shaped to fit closely around an object to improve contact, or small cut pieces of film, sealed in light-tight bags, with or without lead foil, can be used. Dental film has already been mentioned. It is also useful to have a supply of pieces of lead sheet available to place under and around an object to reduce scattered radiation. Variously shaped pieces of expanded polystyrene or similar material can be used to support the objects and retain them at the correct angles during radiography. Ideally, the person who requested the radiography should be present to explain what they want (and why), and to assess the information before the objects are removed, as it is very irritating (cost ineffective too) to have to reconvene when better communications would have allowed the work to be completed more efficiently. If this is not possible, written explanatory notes should be supplied. It helps to involve the radiographer as part of the investigative team.

It is important to maintain the temperature of film processing at the correct level and ensure that the solutions have not become exhausted in order to maintain radiographic standards. Film processors are designed to run at appropriate temperatures so this is not usually a problem, but needs to be checked periodically. Tanks used for manual processing can be surrounded with running water in large sinks (if a temperature of 20°C can be maintained) or a thermostatically controlled water jacket to keep the temperature even, otherwise the development and fixing times can be adjusted to take account of the ambient room temperature, according to the manufacturer's instructions. The chemicals are kept fresh by excluding air as far as possible when not in use. It is helpful to note the date when they came into use and if there are any doubts, a step wedge can radiographed, and the film processed and compared (using a densitometer) with a standard film of the same wedge, prepared for the purpose under ideal conditions. In industry, processing monitor control (PMC) strips are used to maintain film processing standards. Fully exposed areas which appear grey rather than black or a slightly brownish hue in the radiograph are warning signs. If a processor has not been used for a week or so it is advisable to pass a test strip through the machine make sure it is functioning correctly. Solutions are replenished automatically during use, but a processor should be drained and cleaned if it is to be idle for any length of time. Some radiographers feel that manual tank development is more satisfactory because of the possible buildup of chemicals on the rollers and also that the washing sequence may not fulfill conservation standards, but these pitfalls can be avoided with care. The main disadvantage of a processor is that it is relatively expensive to buy in the first place. Film radiographs should be stored at a low relative humidity, in the dark, held upright in clear inert sleeves to protect them from scratches and finger marks during examination.

Each facility will have its own recording system but it is safer to have a paper record as well as an electronic one. A radiograph needs a unique number and lead numbers or letters can be used for this. They can also be used to identify individual objects when several are included on the same radiograph (see Figure 8.9), and to indicate the orientation or distance (e.g. on the front and back of a large object, such as an excavated block) during exposure. Usually the operator's name, date and exposure conditions are noted (film-to-source distance, kilovoltage, milliampere, time, screens, filter, film) at the time of exposure, together with any comments by the radiographer and the details of the object or objects, including the archaeological date, find site, etc. Where several objects are included on the same radiograph, it is helpful to number each artefact on the radiograph itself, either using lead letters or numbers (see Figure 8.9) or by writing on the film directly with a fine permanent overhead marker pen or a pencil or a suitable ink, so that everything can be identified. However, it should be mentioned that writing with thick white ink is not suitable for use with some scanners as it can adhere to the rollers. Written or electronically recorded reports should contain the recorded information together with any appropriate comments, deductions or recommendations made by the radiographer. That radiographers are successful in much of their endeavour is suggested by the increasing number of investigations which make use of radiography, often as an adjunct to other microscopical and analytical techniques, in the technical and scientific examination of antiquities. In radiography, technological development, fuelled by the demands of the medical and industrial fields, has provided archaeological scientists and conservators alike with a powerful, non-destructive, investigative tool to answer many of their questions.

REFERENCES

Alexander, R.E. and Johnston, R.H. (1982) Xeroradiography of ancient objects: a new imaging modality. In *Archaeological Ceramics* (eds J.S. Olin and A.D. Franklin), Smithsonian Institution Press, Washington DC, pp. 145–54

Barkalow, R.H. (1971) Solidification Structures and Phase Relations in M2 High Speed Steel, p. 76

Boag, J.W. (1973) Xeroradiography. *Physics in Medicine and Biology*, **118**, 3–37

Bonadies, S.D. (1994) Tomography of ancient objects. In *Ancient and Historic Metals* (eds D.A. Scott, J. Podany and B.B. Considine), Getty Conservation Institute, Marina del Rey, California, pp. 75–83

Booth, J. (2005) CT scan may solve Tutankhamun riddle. *Times* 6th January, 2005.

Born, H. (ed.) (1985) *Archäologische Bronzen. Antike Kunst – Moderne Tecknik*, Staatliche Museen Preussischer Kulturbesitz Museum für Vor- und Frühgeschichte, Berlin, pp. 126–38

Bridgman, C.F., Keck, S. and Sherwood, H.F. (1958) The radiography of panel paintings by electron emission. *Studies in Conservation*, **3**, 175–81

Bridgman, C.F., Michaels, P. and Sherwood, H.F. (1965) Radiography of a painting on copper by electron emission. *Studies in Conservation*, **34**, 1–7

Bushberg, G.T., Seibert, J.A. and Leidholdt Jr., E.M. (1994) *The Essential Physics of Medical Imaging*, Williams and Wilkins

Castleman, K.R. (1996) *Digital Image Processing*, Prentice-Hall

Clark, G.R. (1955) *Applied X-rays*, McGraw-Hill, New York, pp. 238–62

Clogg, P. and Caple, C. (1996) Conservation image enhancement at Durham University. In *Imaging the Past* (eds T. Higgins, P. Main and J. Lang), British Museum Occasional Paper 114, British Museum, London, pp. 13–22

Darlington, M.W. and McGinley, P.L. (1975) Fibre orientation distribution in short fibre reinforced plastics. *Journal of Materials Science*, **10**, 906–10

Dessipris, N.G. and Saunders, D. (1995) Analysing the paper texture in Van Dyck's Antwerp sketchbook. *Computers and the History of Art*, **5**(1), 65–77

Farr, R.F. and Allisy-Roberts, P.J. (1997) *Physics for Medical Imaging*, Saunders, New York

Fell, V., Mould, Q. and White, R. (forthcoming) Guidelines on the X-radiography of archaeological metalwork. *English Heritage Guidelines Series*.

Gilardoni, A. (1994) *X-rays in Art*, Gilardoni SpA, Mandello Lario, Lecco

Ghysels, M. (2003) CT scans in art work appraisal. *Art Tribal*, 04, pp. 116–31

Gonzalez, R.C. and Woods, R.E. (1992) *Digital Image Processing*, Addison-Wesley, Reading, Massachusetts

Graham, D. and Thompson, J. (1980) *Grenz Rays*, Pergamon, Oxford

Halmshaw, R. (1971) The influence of film granularity on image detail on radiographs. *Journal of Photographic Science*, **19**, 167–77

Halmshaw, R. (1986) *Industrial Radiography*, Agfa-Gevaert

Halmshaw, R. (1995) *Industrial Radiology*, 2nd edition, Chapman & Hall, London

Herman, G.T. (1980) *Image Reconstructions from Projections*, Academic Press, London

Hughes, S. (1996) Three-dimensional reconstruction of an ancient Egyptian mummy. In *Imaging the Past* (eds T. Higgins, P. Main and J. Lang), British Museum Occasional Paper, 114, pp. 211–28

Illerhaus, B., Goebbels, J., Reimer, P. and Reisemeier, H. (1995) The principle of computerized tomography and its application in the reconstruction of hidden surfaces in objects of art. In *4th International Conference on Non-destructive Testing of Works of Art, Berlin* 1994, **45**, pp. 41–9, Deutsche Gesellschaft für Zerstörungsfrei Prüfung e. V., Berlin

Irving, A. and Ambers, J. (2002) Hidden treasure from the Royal Cemetery at Ur. *Near Eastern Archaeology*, **65**, 206–13

Jain, A.J. (1989) *Fundamentals of Digital Image Processing*, Prentice-Hall, New Jersey

Jansen, R.J., Koens, H.F.W., Neeft, C.W. and Stoker, J. (2001) Scenes from the past. CT in the archaeological study of ancient ceramics. *RadioGraphics*, **21**, pp. 315–321

Jansen, R.J., Poulus, M., Taconis, W. and Stoker, J. (2002a) High resolution spiral computed tomography with multiplanar reformatting, 3D surface- and volume rendering: a non-destructive method to visualise ancient Egyptian mummification techniques. *Computer Medical Imaging Graphics* **26**(4), pp. 211–16

Jansen, R.J., Poulus, M., Venema, H. and Stoker, J. (2002b) High resolution spiral CT of Egyptian scarabs. *RadioGraphics*, **22**, pp. 63–6

Jones, J., Caple, C. and Clogg, P. (1998) Digital image processing of X-radiographs. In *Look After the Pennies: Numismatics & Conservation in the 1990s* (eds D. Goodburn-Brown and J. Jones), Archetype Publications Ltd, London

Keene, S. (1987) The Winchester reliquary. In *Recent Advances in Conservation and the Analysis of Artifacts* (ed. J. Black), Institute of Archaeology, University of London, pp. 25–31

Kozlowski, R. (1960) La stereoradiographie. *Studies in Conservation*, **5**, 89–101

McEwan, C., Middleton, A., Cartwright, C. and Stacey, R. (in press) *Turquoise Mosaics from Mexico*, British Museum Press, London

Mees, F., Swennen, R., Van Geet, M. and Jacobs, P. (2003) *Applications of X-ray Computed Tomography in the Geosciences*, Geological Society (London) Special Publication 215

Niskanen, E. (1959) Microradiographic techniques as applied to the study of metals and ores. *Norelco Reporter*, **6**, No. 3

O'Connor, S. and Maher, J.C. (2001) The digitisation of X-radiographs for dissemination, archiving and improved image interpretation. *The Conservator*, **25**, 3–15.

O'Connor, S., Maher, J.C. and Janaway, R.C. (2002) Towards a replacement for xeroradiography. *The Conservator*, **26**, 100–14

Oppenheim, A.V. and Schafer, R.W. (1989) *Discrete-Time Signal Processing*, Prentice-Hall International, New Jersey

Quinn, R.A. and Sigl, C.C. (eds) (1980) *Radiography in Modern Industry*, Eastman Kodak Company, Rochester, New York

Ramm, H.G. (1971) The tombs of Archbishop Walter de Gray (1216–50) and Godfrey de Ludham (1258–65) in York Minster, and their contents. *Archaeologia*, **103**, 39

Rendle, D.F. (1993) The use of soft X-rays in forensic science. *British Journal NDT*, **35**, 381–3

Rendle, D.F., Cain, P.M. and Smale, S.J.R. (1990) An inexpensive device for the examination of light objects using soft X-rays. *Measuring Science Technology*, **1**, 986–8

Röntgen, W.C. (1896) On a new kind of rays. *Nature*, **53**, 274–6.

Serra, J. (1982) *Image Analysis and Mathematical Morphology*, Academic Press, New York

Smith, R.D. and Brown, R.R. (1989) Bombards: Mons Meg and her sisters, *Royal Armouries Monograph I*, Trustees of the Royal Armouries, London, 674–8

Spicer, D. (1985) Stereoscopic representation of archaeological data – a case for drawing conclusions in depth, *Science and Archaeology*, **27**, 13–24

Sternberg, S.R. (1986) Greyscale morphology. *Computer Vision. Graphics and Image Processing*, **35**, 333–55

Taylor, J.H. (2004) *Mummy: The Inside Story*, The British Museum Press, London

Watts, S. (1994) The application of xeroradiography to the analysis of archaeological artefacts. *Ancient Monuments Laboratory Report 22/94*, London

Williams, W.M. and Smith, C.S. (1952) A study of grain shape in an aluminium alloy and other applications of stereoscopic microradiography. *Transaction AIME/Journal of Metals*, p. 755