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Garofalo, *Saint Augustine with the Holy Family and Saint Catherine of Alexandria* (NG 81), (detail of PLATE 4, p. 23).

TITLE PAGE
Garofalo, *The Virgin and Child with Saints William of Aquitaine, Clare (?), Anthony of Padua and Francis* (NG 671), (detail of PLATE 3, p. 22).

Improvements in the Acquisition and Processing of X-ray Images of Paintings

JOSEPH PADFIELD, DAVID SAUNDERS, JOHN CUPITT AND ROBERT ATKINSON

The technique of X-radiography was applied to the examination of paintings soon after the discovery of X-rays by Wilhelm Röntgen in 1895. Alan Burroughs, reviewing the early development of X-ray photography, credits Töpler in Dresden and König in Frankfurt with making the first shadowgraphs (as he termed them) of paintings in the late 1890s.[1] In 1915 a Dr Faber of Weimar was granted a patent for the examination of paintings by X-rays, which, according to Christian Wolters, apparently hindered the development of the technique, in Germany at least.[2] In other countries, however, the technique became more widely used after the First World War as the possible application of medical X-ray equipment to the examination of works of art became apparent.

Alan Burroughs became interested in X-rays in 1923 after a request from the Director of the Minneapolis Institute of Arts to examine a painted ornament on the outside of a mummy case.[3] After purchasing X-ray equipment, Burroughs made X-radiographs of paintings from the Fogg Museum of Art in Cambridge, Massachusetts, and the Metropolitan Museum of Art in New York,[4] and sent two 'expeditions' to Europe (in 1926 and 1927) to 'collect shadowgraphs of famous pictures'.[5] These expeditions coincided with renewed interest in the use of X-radiography in a number of European museums, particularly in Austria, Germany and the Netherlands.

Johannes Wilde began using the facilities of the Röntgenologisches Institut at Vienna University in 1928, before establishing an X-ray laboratory at the Kunsthistorisches Museum in 1930 and going on to make over 1000 X-radiographs of paintings by 1938.[6] At much the same time Martin de Wild gave several examples of paintings examined by X-radiography in his 1928 book, *Het natuurwetenschappelijk onderzoek van schilderijen*, including a portrait by Fran Hals from the National Gallery of Scotland, which revealed substantial changes in the composition.[7] In Germany, Walter Gräff in Munich and Kurt Wehlte in Berlin were both actively X-raying paintings. In 1932, Wehlte described his equipment and technique, publishing a photograph of the equipment, along with X-radiographs of three paintings from the Staatliche Kunstsammlungen in Kassel.[8]

It is clear that by the early 1930s the relatively small group of scientists and art historians using X-radiography were in contact with each other and exchanging information. For example, in 1933 Karl Steneberg from the Nationalmuseum in Stockholm, in publishing X-radiographs of Rembrandt's *The Conspiracy of the Batavians under Claudius Civilis,* also describes the studies being made in Vienna, Berlin and Boston, illustrating his article with X-radiographs made by Wehlte, Gräff and de Wild.[9] By 1938, Burroughs was able to draw on X-radiographs from over a dozen American and European museums,[10] including the National Gallery, London, which had set up an X-ray laboratory soon after the appointment of Ian Rawlins as Scientific Adviser in 1934.[11]

The apparatus used to make X-radiographs was relatively straightforward, comprising an X-ray source, an X-ray sensitive film or plate sealed in a light-proof envelope, and the object to be examined.[12] FIG. 1 shows the equipment at the

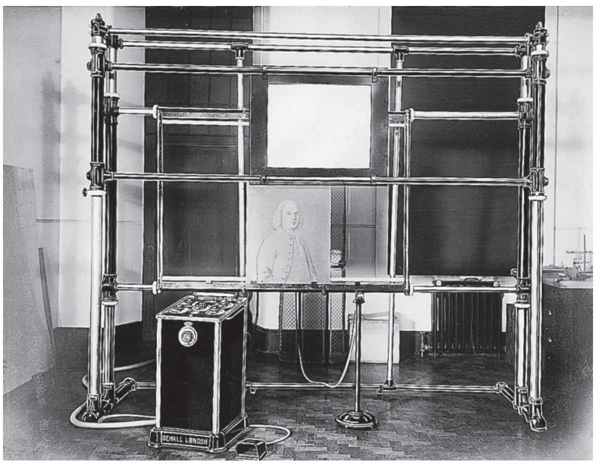


FIG. 1 The equipment used for X-radiography at the National Gallery during the 1930s.

National Gallery in the 1930s, which was used to produce a monograph, *From the National Gallery Laboratory*.[13] The painting was held vertically on an easel, allowing easy movement of the painting, without any danger of parts of the X-ray apparatus falling onto the object. The equipment also incorporated a fluorescent screen with which to view the image, something that would be impossible under current health and safety regulations.

The development of X-radiography gave conservators and art historians access to information related to the entire three-dimensional structure of an object, not just the surface.[14] The structure of wooden supports, canvas weave and areas of paint loss all feature in images published in the 1920s and 1930s. However, the most interesting information came from the paint layers, allowing different artists' hands to be distinguished in different stages of a painting, the discovery of previous compositions beneath the surface of the painting and, in a few cases, the detection of 'fakes'.[15]

In 1938, Rawlins discussed the question of reproducibility of results, commenting on the need for detailed recording of experimental conditions.[16] He also noted that completely different results could be achieved during the examination of an object if the experimental conditions, for example the exposure time, voltage and current, were altered. These adjustments allowed different features of the structure to be highlighted in the resultant images.

Current X-radiography procedures at the National Gallery

The methods used for X-radiography at the National Gallery have not changed greatly since Rawlins published his description in the late 1930s.[17] The main differences are dictated by health and safety practices. Paintings are now laid horizontally on a lead-lined table rather than held vertically on an easel. The X-ray source is mounted beneath this table, which has a rectangular aperture faced with Perspex through which the diverging X-rays pass.[18]

The National Gallery, like many other museums, uses pre-cut and packed 300 × 400 mm X-ray sensitive film (Kodak Industrex AA400) for routine X-radiography. This film is readily available and can be automatically processed in two and a half minutes in a Fuji Medical Film Processor type RG II. The main disadvantage of this method is that the size of each plate is fixed so that to examine the surface of paintings larger than 300 × 400 mm many separate X-radiographs must be made.

To ensure complete coverage, the film is first laid out on the surface of the painting allowing sufficient overlap between the individual plates, usually at least 50 mm. The overlaps are marked onto the outside of the envelopes containing the film, so that the grid of plates can be recreated during the sequential exposure of the films. An exposure test is made, but for a 50 second exposure typical settings might be 35 kV, 0.9 mA for canvas paintings; 35–40 kV, 1.1 mA for thin wood panels; and 45–50 kV, 1.2–1.5 mA for thicker wood panels. After the films have been developed they are examined on a light box to ensure that the overlap is sufficient and that the position of the films has not drifted away from the pattern determined earlier. 'Lead numbers' are placed under the top right-hand corner of each X-ray film prior to exposure, which appear on the developed X-ray films to indicate the position of each plate.

The original X-ray plates are stored in the temperature-controlled archive in the Photographic Department, and working copies are made for use in the Conservation Department. An internegative is first produced from each plate using Agfa Avitone P3p orthochromatic continuous tone duplicating film. The internegative is then used to make contact prints onto 300 × 400 mm sheets of Ilford Multigrade FB IV paper. Filtration of the light source in the contact printing equipment is often required to match the exposure in the prints for adjacent areas of the painting.

Finally, to make a mosaic image of the X-radiograph of the entire painting, the individual prints are trimmed and soaked in water to make them more supple before being attached to an appropriately sized piece of birch-faced plywood using heavy-duty wallpaper paste. The plates are aligned by matching features in the overlap areas. Once the paste is dry the image is retouched to hide the white cut edges and re-photographed using a standard 250 × 200 mm black and white film.

Current practice – problems and possible solutions

There are a number of problems associated with the current practice.

- The production of an internegative and contact print results in a loss of tonal information, as the density ranges of the Agfa duplicating film and Ilford paper are of the order of two,[19] compared to approximately six for the original X-ray film; getting the most information out of the film requires considerable skill during processing. Re-photography of the final mosaic image may also introduce further loss of information.

- Even when the photographer adjusts the contrast in the individual plates during processing there will be tonal differences in adjacent images that will become apparent when the mosaic is assembled.
- As they are life-size, the assembled mosaics can be very large and considerable space is required for their storage.
- Assembling a large mosaic is very time-consuming; we estimate that printing and assembling a mosaic of 50 X-ray plates takes one person-week.
- It is not always possible to align adjacent images perfectly.
- In the long term, when the prints deteriorate, the printing and pasting process will need to be repeated.

A number of museums circumvent many of these problems by using much larger format X-ray films to produce radiographs of whole paintings with a single exposure. For example, this type of film has been in use in Brussels from the mid-1970s, using a roll of film just over 1 m in width.[20] More recently, a group from the Opificio delle Pietre Dure in Florence have developed a method of sealing large-format X-ray film (up to 1.37 m wide) inside a black plastic envelope. After exposure, the developing, fixing and washing solutions are introduced into the envelope through a valve at one end, so that the film can be developed *in situ*, without a specially equipped darkroom.[21]

However, the new equipment required to make and develop such large-format X-radiographs is expensive, and it would, of course, be necessary to make a new X-ray exposure for every painting. Very large paintings (where the smaller dimension is greater than the width of the film) will still require more than one exposure to cover the entire area. We have sought, instead, to develop techniques that make better use of our existing equipment and the large collection of high-quality 300 × 400 mm X-radiograph plates stored in our photographic archive. This has had the added bonus that it might provide a solution for other museums and galleries that also use standard-format X-ray film, without the need to subject the painting to further X-radiography.[22]

Digitisation and mosaic assembly for X-radiographs

The approach adopted at the National Gallery has been to digitise the original X-ray plates and to assemble a mosaic image on a computer. This followed on from our existing programme of digitisation and assembly of infra-red reflectograms that began nearly a decade ago,[23] and has been refined over a number of years.[24]

Some preliminary experiments in which we digitised the X-ray film on a modified light box using a 12-bit monochrome camera indicated that it was possible to capture more of the density range by digitisation than could be preserved during the conventional production of the internegative and contact print. The digitised images offer a more convenient method of using the X-ray information, reducing the need to use, and perhaps damage, the original plate. The digital data can also be transferred around the Gallery for consultation by different departments on an Intranet and used directly in publications. It was clear, however, that although the individual plates were useful, an X-radiograph mosaic of the whole painting was usually required, to allow effective comparisons to be made between the areas covered by the separate plates.

Digitisation of X-ray plates

First an efficient means of digitising the X-ray plates was needed. The light box and camera method used in the preliminary study was adequate if only a few images needed digitising, but was too slow and cumbersome for routine use. Although, at 300 × 400 mm, the X-ray plates are approximately the same size as A3 documents (297 × 420 mm), the imaging area of some A3 scanners is too small to digitise an entire plate. In addition, many desktop scanners do not produce particularly high-quality images, either in terms of density range or resolution per millimetre. To ensure that as much information as necessary is captured from the original X-ray plates, a flatbed scanner with a large imaging area, high resolution, good density range and the capacity to scan the plates reasonably rapidly was selected.

The Fujifilm Lanovia C-550 scanner can image an area of 350 × 455 mm in transmittance mode (which is used for the X-ray plates) and is capable of producing images with a resolution of 5000 pixels per inch (ppi) and a density range of 3.9. However, this resolution is unnecessarily high for the amount of information on the X-ray plate. Enough information is captured from the original plate by scanning at a resolution of 300 ppi (12 pixels per millimetre). For larger paintings, where the mosaic may comprise over 50 individual plates, a scanning resolution of 150 ppi is sometimes used to give more manageable image files; if necessary, details from larger paintings can be scanned at 300 ppi. At 300 ppi each plate takes around three minutes to scan and produces a file of approximately 32 Mbytes; at 150 ppi the scan time is around 90 seconds and the file size is *c*.8 Mbytes. To ensure that the density range is preserved, the images are stored as standard 16-bit TIFF images, which can represent a density range of 4.8.

Mosaic assembly

The second step in producing X-radiograph mosaics was to develop new software to assemble the composite images from the digitised images of the individual plates.

Some years ago a system was developed at the National Gallery to create improved infra-red reflectogram mosaics.[25] This made use of the VIPS (VASARI Image Processing Software) package, which has been under continual development at the National Gallery since 1990.[26] The image processing tools in the VIPS package have been adapted to deal with the more difficult task of assembling X-ray mosaics. The difficulties arise from differences in the procedures for acquiring infra-red and X-ray images, and because the X-radiographs contain information about the three-dimensional structure of the painting.

When the individual images comprising an infra-red reflectogram mosaic are acquired, the painting is moved horizontally and vertically in a plane perpendicular to the focal axis of the camera, so that joining adjacent images requires only translation. However, even though the grid of X-ray film is laid out on the painting prior to exposing the individual plates, placing the film envelopes on the painting by hand inevitably results in some of the plates being rotated with respect to the others. In addition, because the surface of a painting is not perfectly flat, the distance between the X-ray source and the photographic film is not constant. Since the X-rays diverge from the source, the scale of each plate will differ slightly. Refinements have been made to the image assembly software to allow the sub-images to be rotated and scaled as the images are joined.

To perform a simple translation only one tie point in each image is required, so the software for the infra-red reflectogram assembly procedure relies on the user selecting a corresponding point in two

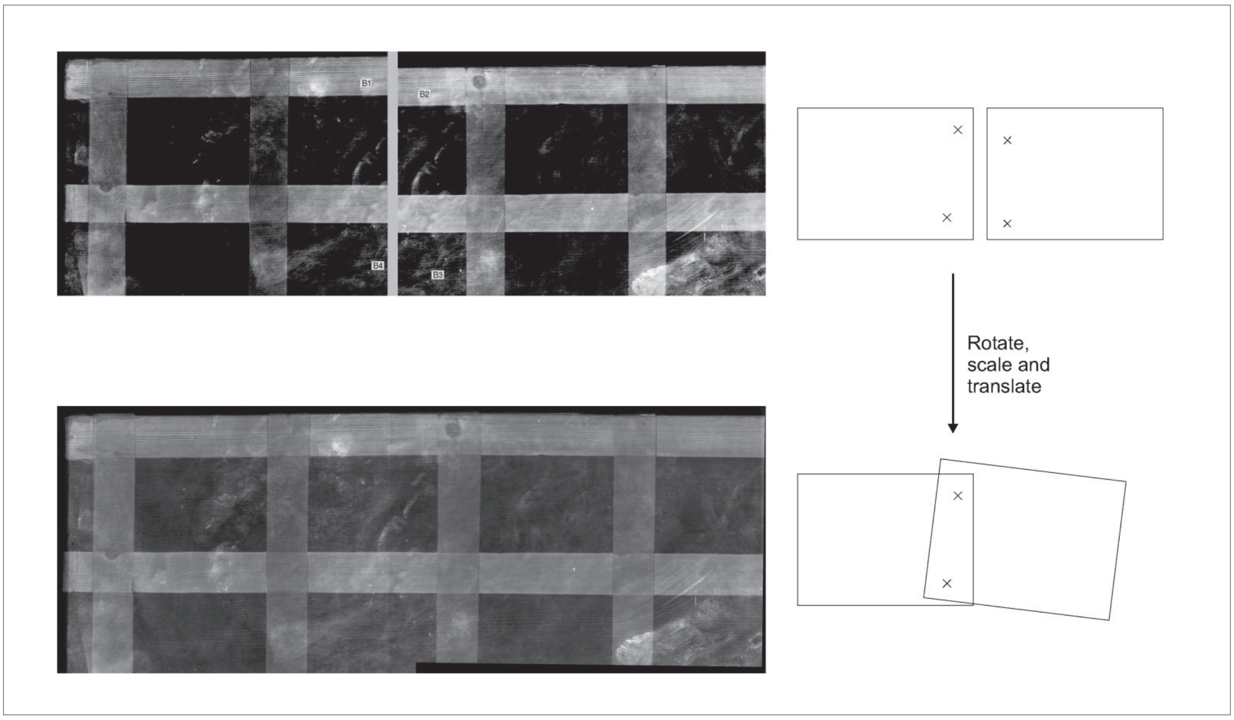


FIG. 2 Schematic showing the use of two tie points in each image to scale, rotate and translate an image during mosaic assembly; the line diagram to the right somewhat exaggerates the magnitude of the rotation and scaling required for the image pair to the left. Note that the slight difference in exposure between the two plates has not been corrected at this stage.

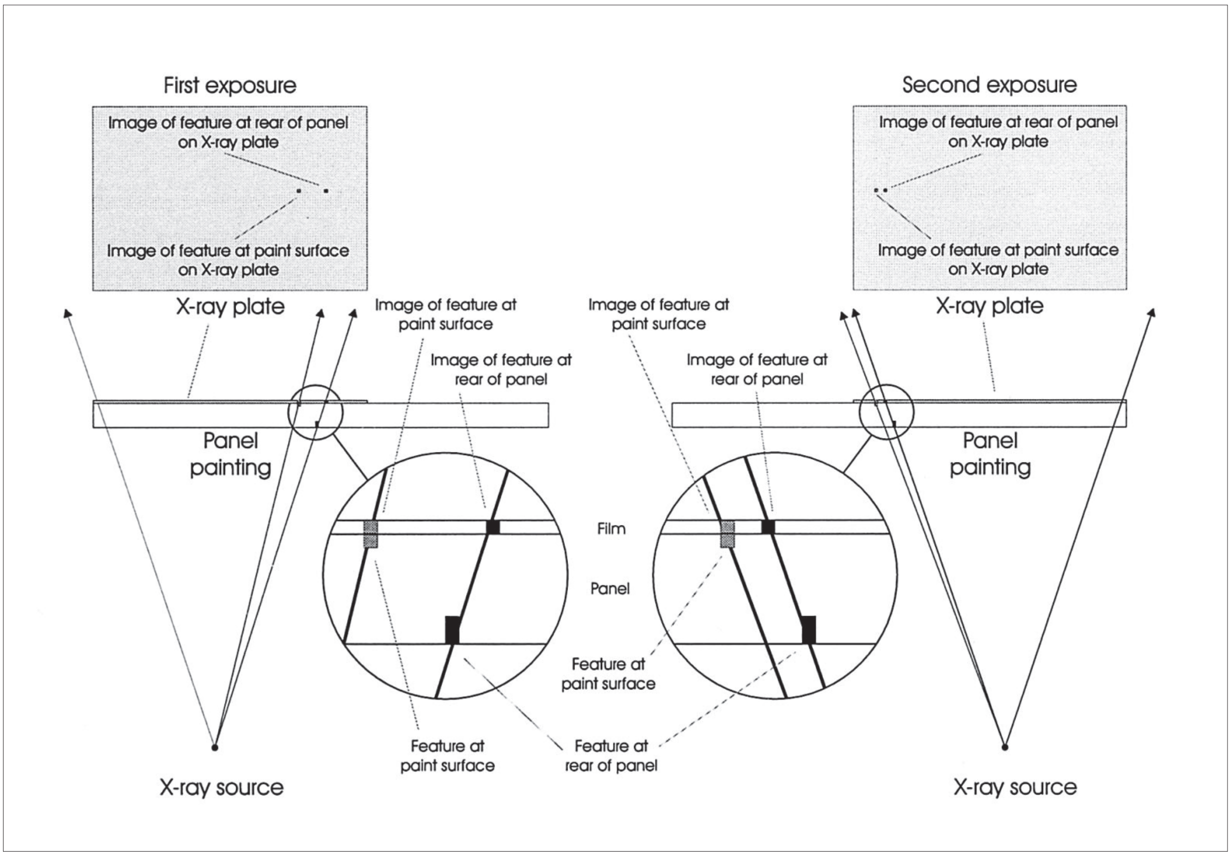


FIG. 3 The effect of diverging X-rays on the relative position in the images of features at different depths in the painting structure.

adjacent images. To rotate and scale the images more information is required; the user must select two tie points in each image (see FIG. 2). In the system developed to assemble infra-red images, the software improved the user's choice of tie points by searching the corresponding areas of the images to find a set of common points.[27] However, it has not been possible to use this procedure in the assembly of X-ray mosaics, as the X-radiograph contains information relating to features at different depths within the structure of the painting. Because of the divergence of the X-rays from the source, the relative positions on the images of features at different depths will change with the angle of incidence of the X-rays (see FIG. 3). As this effect will be at its greatest at the edges of the plates, where they overlap adjacent plates, the use of the automatic method for improving the selection of points would be inappropriate since, if points corresponding to features at different depths were used, an inaccurate join between the images would result. When assembling X-ray mosaics, the tie points are selected by the user and the join made without any computer assisted 'improvement' of the choice. It is important, therefore, that the tie points are selected carefully and accurately. As the surface (or near-surface) of the painting is generally of most interest, tie points are chosen that correspond to features in the paint layers; these might include craquelure, paint losses or brushstrokes. To ensure accurate matching of the tie points it is often necessary to zoom in on the individual pixels to make the final selection.[28]

The need to use more tie points and to make accurate selections makes X-ray assembly slightly slower than the equivalent operations for infra-red reflectograms. However, the number of joins to be made is generally lower, so the overall time required per painting does not differ greatly. As the individual infra-red images are quite small, the image of a complete painting is generally of the order of 20 Mbytes. Even when the original X-ray plates are scanned at the lower resolution used (150 ppi), the X-radiograph mosaics of larger paintings can produce large data files; one set of 42 plates produced a final image of about 200 Mbytes.

At the National Gallery, the first stage after scanning all the plates is to remove the lead identification numbers from the images, so that they do not appear in the final mosaic. Fortunately, the numbers are usually placed in the overlap region, so that the area of a painting covered by a lead number also appears in the adjacent X-ray plate. The number is removed by copying the corresponding area in the overlapping image and inserting this into the first image.[29] The images are then cropped and rotated to minimise the difference in orientation between adjacent images; although the mosaic assembly step rotates and scales the images, it is easier to use if these differences in scale and orientation have already been minimised.

Pairs of images are then assembled by selecting two pairs of tie points as described earlier. To reduce positional errors across the final mosaic, the images are assembled in small blocks of 2 × 2, or 3 × 3, rather than in long rows or columns. These small blocks are then joined to form larger blocks in a similar manner, eventually yielding the mosaic of the whole image. Once the mosaic is complete, it can be automatically processed to reduce tonal differences in adjacent images caused by differences in exposure of the original X-ray plates.

A useful feature of VIPS is that a sequence of image processing operations can be saved periodically in a 'workspace'. It is not, therefore, necessary to save each joined image, as the compact workspace files are easily reloaded if changes need to be made to individual operations, for example adjusting the tie points used in one of the joins. Any changes are immediately reflected in the final image, which is only saved once the operator is satisfied with the result. The workspace can always be reloaded at a later date and further changes made. In comparison to the one person-week required to print and assemble a 50-plate mosaic by hand, a comparable image can be digitised and assembled using VIPS in under two days.

FIG. 4a shows an X-ray mosaic of Bosch's *Christ Mocked* (NG 4744) made by the traditional method of printing onto paper via an internegative; the joins between the individual plates can be seen. FIG. 4b shows the image assembled from the same six plates using the digital procedure described above. The joins are less visible and the geometric accuracy in the assembly is improved. The mosaic image can be written to a negative, from which a print can be made, or printed out life-size on a large-format inkjet printer.[30] Although these images are not necessarily permanent, they are easily reprinted from the original data without need for the lengthy reprocessing and pasting required to make a new hand-assembled X-radiograph.

Improving the readability of X-radiographs

The wealth of information about the three-dimensional structure of a painting that is presented by an X-radiograph has sometimes proved to be a mixed blessing. It is often difficult to interpret the information for one particular layer of interest in isolation from features that derive from other parts of the structure. A common example is the problem of interpreting information relating to the paint layers in X-radiographs of paintings with prominent cradles or stretchers. The search for a method to extract particular pieces of information from X-radiographs was an early research goal. This has sometimes been achieved by making several X-radiographs of the same area using different operating conditions for the X-ray source and varying the exposure time.[31]

Many of the techniques developed to make X-radiographs more readable have made use of moving X-ray sources or paintings. As can be seen from FIG. 3, if the position of the source is moved with respect to the painting and the X-ray plate, the image of features in the painting that are more distant from the photographic film shifts. If the X-ray source moves during the exposure, the effect is to blur those parts of the image, while the objects near the film, for example the surface paint layers, will remain in focus. This simple form of tomography, termed strato-radiography or strati-radiography, was used as far back as 1935, when Vermehren described a process to examine paintings using an X-ray source on a pendulum. This procedure captured only information relating to the surface of the object next to the X-ray film, in this case the paint layer, and was further refined either by a double movement of the pendulum or by rotating the painting.[32] In the 1940s Murray Pease used a source that traced an arc over the painting during exposure to obtain what he termed 'traversed-focus radiographs', and also proposed a system in which the painting and X-ray film were rotated during exposure from a stationary source.[33]

Methods have also been developed to minimise the tonal differences between the different regions in an X-ray plate during the printing process. Radiographs produced by this method are often termed logetronic radiographs, after one of the pieces of equipment used in their creation.[34] The technique relies on exposing different parts of the X-ray plate to different amounts of light during printing, either by using masks, or by using a cathode ray tube, whose output at a given point in its raster scan can be varied.

FIG. 4 Bosch, *Christ Mocked* (NG 4744). Panel, 73.5 × 59.1 cm

a. Traditional hand-assembled 'cut-and-paste' composite X-radiograph, re-photographed on black and white film.

b. Computer-assembled X-ray mosaic image.

c. X-radiograph made by filling the interstices in the cradle with sugar.

d. Histogram-matched radiograph derived from the computer-assembled X-ray mosaic image.

Another method of minimising the tonal differences created by structures such as cradles is to expose the X-ray plate with the interstices between cradle members filled with a material that has a similar X-ray absorbency to the surrounding wood.[35] At the National Gallery, sugar has sometimes been used for this purpose; the painting is placed face down on a prepared surface and the cradle is carefully packed with sugar. The painting is X-radiographed in the normal way, except that because the film is laid on top of the packing material it is not in contact with the paint film. Because of the diverging X-ray beam, X-radiographs produced in this manner are slightly larger than the painting, not exactly the same size. FIG. 4c shows the X-ray mosaic assembly for Bosch's *Christ Mocked,* with the cradle packed with sugar, printed at the same resolution as the 'normal' mosaic assembly in FIG. 4b described earlier.

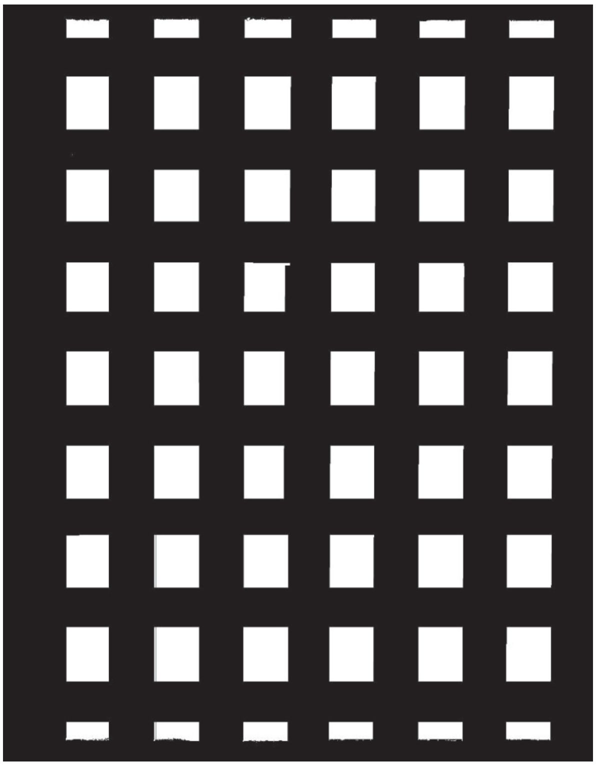
Quite apart from the problems of scale, there are other drawbacks associated with the above procedure when using the current equipment at the National Gallery. Packing the painting with a foreign material and moving it across a table while face down are not without hazard. After the painting has been X-rayed the sugar must be completely removed to avoid any residues being left on the wood, as these might encourage future infestation. Furthermore, it is not desirable to subject paintings to more X-ray exposure and we prefer to make use of the large number of X-ray plates that have already been made at the Gallery.

Histogram-matched radiography

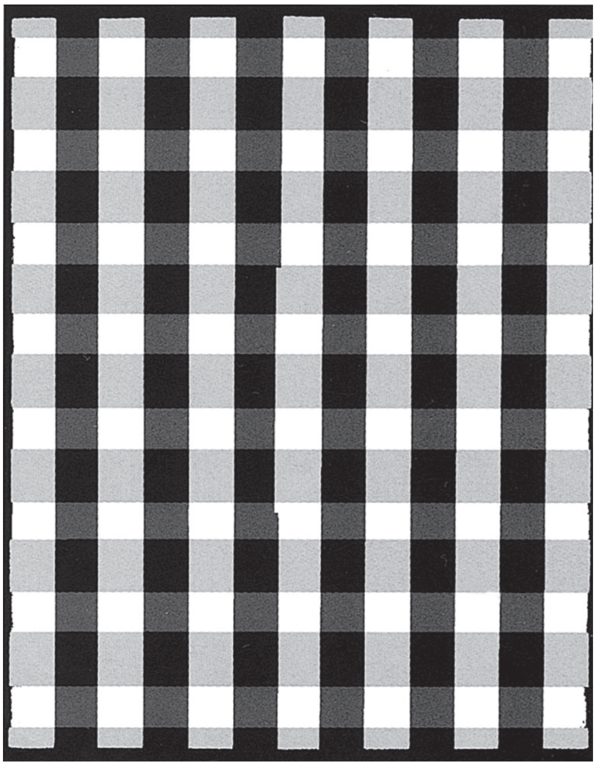
With these considerations in mind, we have attempted to develop a simple image processing method to reduce the tonal imbalance caused by the secondary structure of the painting (typically cradles and stretchers) in the X-radiograph, so that the features associated with the surface paint layer are more easily read. This method takes as its starting point the 16-bit digital X-ray mosaic assembled using the procedures described earlier.

The image is first divided into a number of regions, according to the thickness of the secondary

FIG. 5 Masks generated during the production of the histogram-matched radiograph of Bosch's *Christ Mocked*.



a. The 'control' mask defining those areas of the painting not affected by the secondary support (cradle).



b. The set of four masks, including the control mask (black), the areas covered by the horizontal cradle members (dark grey), the areas covered by the vertical cradle members (light grey), and the regions of overlap between the horizontal and vertical elements (white).

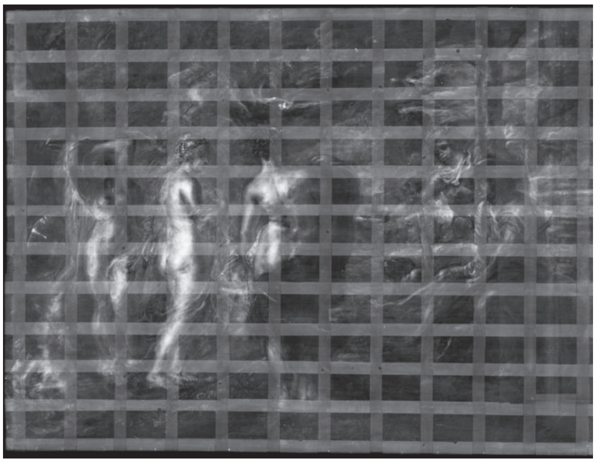


FIG. 6 Rubens, *The Judgement of Paris* (NG 194). Panel, 144.8 × 193.7 cm.
a. Computer-assembled X-ray mosaic image.

b. Histogram-matched radiograph derived from the computer-assembled X-ray mosaic image.

FIG. 7 Constable, *The Hay-Wain* (NG 1207). Canvas, 130.2 × 185.4 cm.
a. Computer-assembled X-ray mosaic image.

b. Histogram-matched radiograph derived from the computer-assembled X-ray mosaic image.

support in these areas. The X-radiograph of *Christ Mocked*, seen in FIG. 4b, provides a typical example. A set of masks has been created which separates the image into four types of area. In the first there is no secondary support, while the second and third masks correspond to areas where either the vertical or horizontal cradle members affect the X-ray image. Finally a fourth mask covers the region where both horizontal and vertical cradle members absorb part of the X-radiation; FIG. 5a shows the first of these masks and FIG. 5b the set of masks defined for *Christ Mocked*. This method assumes that each of the cradle members is of similar thickness and absorptivity, an assumption that has produced good results to date. It is possible to treat each of the members separately and create a larger set of masks, but this will increase the time taken for the subsequent processing steps. At present the masks are defined manually, which although potentially time consuming, has not proved to be any slower than using automatic processes such as edge detection.[36]

The mask defining the area with no secondary support is then used as a control area, against which the tonal ranges of the remaining areas are matched. VIPS takes the original image plus the set of masks and uses 'histogram matching' to remove tonal differences between the areas.[37] The tonally matched areas are then recombined; the edges are automatically blended at this stage to avoid discontinuities at the interface between adjacent areas. We have termed the X-ray images produced in this manner 'histogram-matched radiographs'. Although automatic, this process can take some time, depending on the size of the original image, the number of masks and the speed of the computer.[38] Because the sequence of image processing steps, from the definition of the masks to the histogram matching, can be stored as a workspace, small changes can be made (to the outline of one of the masks for example) and the result of these actions viewed in the final image before the latter is stored to disk. If necessary, extra masks can also be defined and the effect of their application assessed before the processed radiograph is stored. The histogram-matched X-radiograph mosaic of *Christ Mocked* is shown in FIG. 4d below the mosaic before processing (FIG. 4b) for comparison.

The procedure works equally well for larger paintings. For example, the X-ray mosaic of Rubens's *The Judgement of Paris* (NG 194), which was produced from 42 individual plates, is shown in FIG. 6a. The histogram-matched radiograph (FIG. 6b) provides greater readability of the features in the paint film, without the disruption caused by the complex cradle structure. We have also applied the same technique to X-radiographs of paintings on canvas, greatly reducing the effect of the stretcher members and keys. FIGS 7a and 7b show the X-radiograph mosaic (30 plates) and histogram-matched radiograph for Constable's *The Hay-Wain* (NG 1207). The image is again made more readable by the reduced tonal contrast, something which could not easily be achieved by using sugar or a similar substance, as it is not usual to pack material into the back of paintings on canvas.

Strati-radiography and stereo radiography

We have also experimented with two other simple methods of reducing the effect of the secondary support. First, we constructed a trolley that is pulled by a small electric motor along a pair of tracks mounted on the table used for X-radiography. The painting is placed on the trolley and moved slowly across the aperture in the table (FIG. 8); this is roughly equivalent to the strati-radiographic methods described by Pease, Vermehren and Loose.[39] FIG. 9a shows the digitised X-ray image for Gossaert's *The Virgin and Child* (NG 1888) made under normal circumstances; as the painting is small (305 × 235 mm) only a single X-ray plate is needed. FIG. 9b shows the equivalent X-radiograph made while the painting and plate were slowly traversing the X-ray source. The parts of the image corresponding to the structural elements of the painting are rather blurred, while the information about the paint layers remains in focus. In particular, the marked wood grain in the cradle, which made the surface details difficult to read, is suppressed by the general blurring of the cradle members.

In the second method, two X-radiographs are made with the painting and X-ray film in different positions with respect to the source, rather as shown in FIG. 3. The result is that features from the structure appear in a different position on the X-radiograph when compared with features at or near the surface, producing a 'stereo pair' of images, which are digitised and aligned using the craquelure or other surface features.[40] These can be viewed either by 'flipping' between one image and the other (on a computer monitor) or by presenting the two images as a red/green stereo pair that can be viewed with stereo glasses.

Neither of these methods has as yet been applied to larger paintings, that is, those that require more than a single X-ray plate. Provided a safe method of moving the painting can be found, the first method could be applied to larger paintings, since the resulting images can then be joined using the mosaic assembly software described earlier. Indeed it may

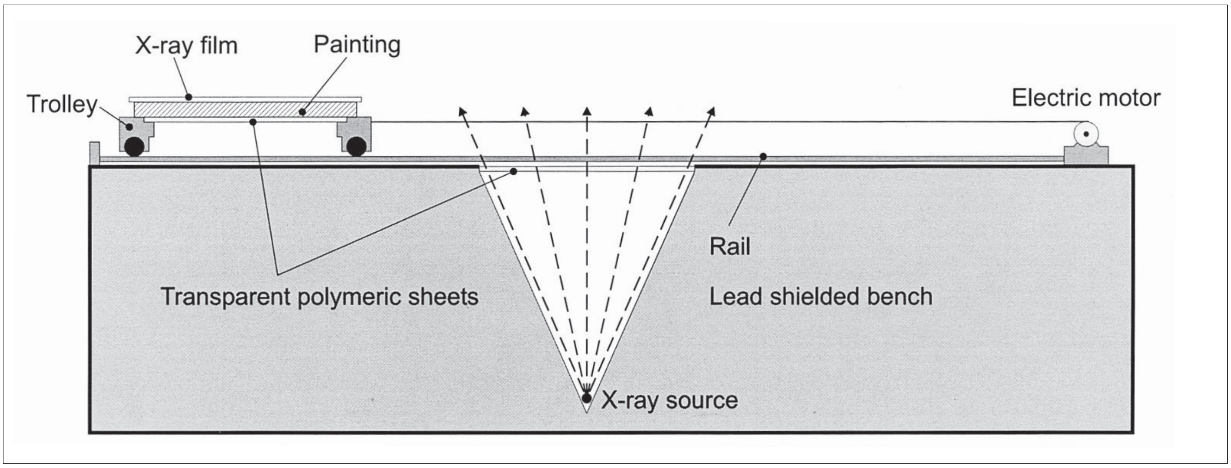
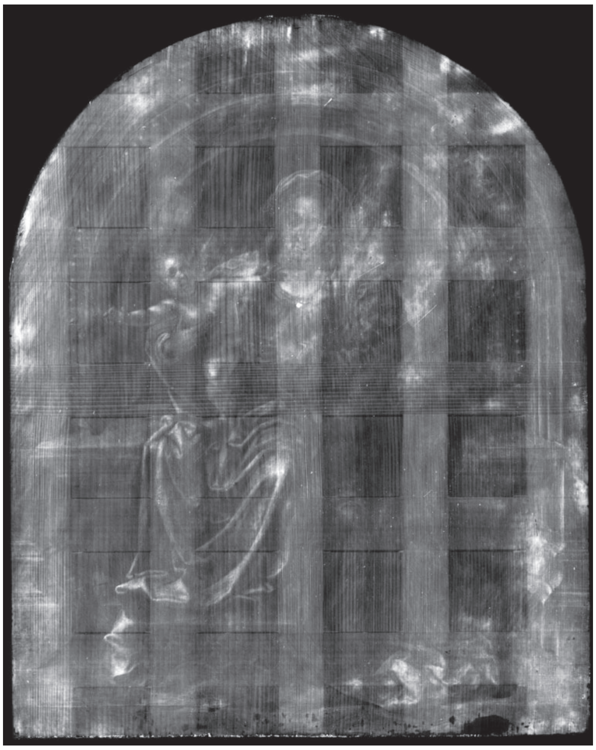


FIG. 8 The simple experimental set up used to acquire strati-radiographs at the National Gallery



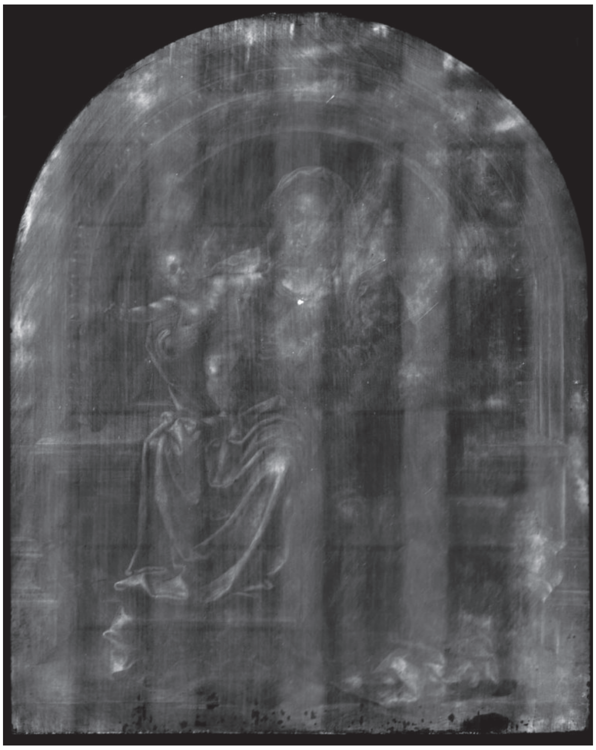


FIG. 9 Gossaert, *The Virgin and Child* (NG 1888). Panel, 30.5 × 23.5 cm.
a. Digitised X-ray plate made while the painting was stationary.

b. Equivalent radiograph made while the painting was moving with respect to the X-ray source.

be easier to select appropriate tie points, as the image of the secondary structure is no longer so prominent. While it would be possible to apply the second method to larger paintings, making two X-ray exposures for each region of the painting and creating two mosaics, the position of the paintings during each exposure would need to be more closely controlled than our present equipment allows. Otherwise, the shift in position of the structural elements will vary from plate to plate and switching from one mosaic image to the other may well make the image harder, rather than easier, to interpret.

Conclusions

Using a high-quality flat-bed scanner, the digitisation of X-radiographs is a straightforward process. The resultant images can then be assembled into mosaics using the VIPS package, producing images that are usually free from visible joins and geometric distortion (caused by positioning errors during traditional manual mosaic assembly). Because the density range of the original plate is preserved during digitisation and mosaic assembly, these images can be used to produce high-quality printed X-radiographs in reports and publications without the need to handle the valuable original X-ray plates. The digitised images are presently stored on CD-ROM, but will also be transferred to a server to allow access across the Intranet using the Gallery's information management system, VERMEER.

The histogram-matched radiographs produced using VIPS provide images that are more easily interpreted than those dominated by features caused by the secondary structure of the paintings, such as the cradle or stretcher bars. Histogram matching can be applied to large mosaic assemblies and tuned to provide good readability of the image of the surface paint layers. The wood grain and the position of the cradle members, stretcher and keys are still visible in the processed image, which can be useful if surface features are being related to the underlying structure. Strati-radiographic radiographs, made by moving the painting across the X-ray source, are useful for suppressing the wood grain in the cradle members of small panels, and may prove valuable for examining double-sided paintings. The method of making strati-radiographs described in this paper has the advantage that it does not require expensive new X-radiography equipment. However, this technique requires the painting to be subjected to another X-ray exposure, whereas the mosaic images and the histogram-matched radiographs can be made without subjecting the painting to further X-radiography, thus reducing handling of the painting and the need to remove it from its frame.

The image processing software used to assemble the mosaics, define masks and produce histogram-matched radiographs is available for free download along with instruction manuals for its use in the procedures described in this paper.[41]

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We would also like to thank Nicholas Penny for pointing out the early use of X-radiography at the Kunsthistorisches Museum in Vienna.

Notes and references

1 A. Burroughs, *Art Criticism from a Laboratory*, Boston 1938, pp. vii–viii. A more comprehensive early history of the X-ray examination of paintings in Germany is given in K. Wehlte, 'Aus der Praxis der maltechnischen Röntgenographie', *Technische Mitteilungen für Malerei*, 48, 1932, pp. 71–2

2 A patent was granted to Dr Alexander Faber of Weimar in 1915: *Verfahren zur Feststellung von Übermalungen bei Ölgemälden o. dgl.,* 15 Marz 1914 (Patent 289 935, 1915) [Procedure for the determination of overpaintings in oil paintings or similar]. According to Wolters, writing in 1938, this patent strongly hindered the development of the procedure in Germany: 'Allerdings wurde die Wichtigkeit und Ausbaufähigkeit des Verfahrens erst 1913 [sic] von einem Arzt, Dr. Faber in Weimar, erkannt. Ihm wurde ein Patent auf die Gemäldedurchleuchtung mit Röntgenstrahlen gegeben, das in Deutschland die Entwicklung des Verfahrens stark behinderte.' ('Certainly, the importance and expandability of the procedure was first recognised by a physician, Dr Faber in Weimar, in 1913 [sic]. A patent was awarded to him for X-raying paintings, which in Germany very much hindered the development of the process'): C. Wolters, *Die Bedeutung der Gemäldedurchleuchtung mit Röntgenstrahlen für die Kunstgeschichte*, Frankfurt am Main 1938, p. 12.

3 Burroughs 1938, cited in note 1, p. viii, note 3.

4 A. Burroughs, 'Notes on the Principles and Process of X-ray Examination of Paintings', *The Smithsonian Report for 1927*, Washington 1928, pp. 529–33.

5 Burroughs 1938, cited in note 1, p. viii.

6 *Dictionary of National Biography 1961-1970*, eds E.T. Williams and C.S. Nicholls, Oxford 1981, pp. 1074–5.

7 A.M. de Wild, *The Scientific Examination of Pictures*, trans. by L.C. Jackson, London 1929, pp. 92–104.

8 Wehlte 1932, cited in note 1, pp. 70–80. Wehlte presented X-ray images of portraits by Rubens and Rembrandt from the Staatliche Kunstsammlungen, Kassel. Much the same material was published in another article in the same year: K. Wehlte, 'Gemäldeuntersuchungen mit Röntgenstrahlen', *Verhandlungen der Deutschen Röntgen-Gesellschaft*, 25, 1932, pp. 12–18.

9 K.E. Steneberg, 'Röntgenografien i tavelforskningens tjänst', *Tidskrift för konstvetenskap*, 17, 1933, pp. 1–15. Steneberg also refers to a meeting of experts in Rome in 1930, at which progress in X-radiography was reviewed.

10 Burroughs 1938, cited in note 1.

11 Ian Rawlins was appointed Scientific Adviser in 1934. In October 1935, he published the first report of the X-ray equipment used at the National Gallery. F.I.G. Rawlins, 'The Physical Laboratory at the National Gallery', *Science Progress*, 30, 1935, pp. 236–42.

12 An X-radiograph is created when X-rays pass through an object and strike a sensitive film or plate. The contrast in the image is produced by the differential absorption of the X-rays as they pass through the object; the degree of absorption is a function of the thickness of the material through which the radiation passes, and the X-ray absorptivity of that material. Broadly speaking, elements with higher atomic mass absorb X-rays more strongly than the lighter elements, so metal nails attaching a canvas, or metal dowels used in panel construction, will contrast well with wood or canvas. Pigments that contain one or more of the heavier elements will also absorb X-rays more strongly; common examples are mercury-containing vermilion and lead white.

13 I. Rawlins, *From the National Gallery Laboratory,* London 1940.

14 A general discussion of the information available about the history and condition of paintings from their X-radiographs is given in C. Hassall, 'Paintings', in *Radiography of Cultural Materials*, eds J. Lang and A. Middleton, Oxford 1997, pp. 98–116.

15 Among the first examples of art historians making use of X-ray information is Johannes Wilde's study of Giorgione's *Three Philosophers* and Titian's *Gypsy Madonna*, from the Kunsthistorisches Museum,

Vienna: J. Wilde, 'Röntgenaufnahmen der "Drei Philosophen" Giorgiones und der "Zigeunermadonna" Tizians', *Jahrbuch der Kunsthistorischen Sammlungen in Wien*, 6, 1932, pp. 141–54. At the National Gallery, Philip Pouncey published X-radiographs made by Ian Rawlins in his analysis of the authorship of a work then attributed to Ercole Grandi: P. Pouncey, 'Ercole Grandi's masterpiece', *Burlington Magazine*, 70, 1937, pp. 161–8. An early example of the use of X-radiography to detect fake paintings was in the case of the considerable number of paintings attributed to Vincent van Gogh that came onto the art market through the dealer OttoWacker between 1925 and 1928. When these paintings were exhibited alongside fully authenticated works by Van Gogh in Berlin in 1928, X-radiographs made by Kurt Wehlte helped to confirm the difference in technique between the real and forged paintings. K. Wehlte, 'Röntgenuntersuchungen im Wacker-Prozeß', *Kunst und Künstler*, 31, 1932, pp. 75–178.

16 F.I.G. Rawlins, 'Physical Factors in X-ray Photography', *Technical Studies in the Field of the Fine Arts*, VII, No. 2, October 1938, pp. 73–9.

17 F.I.G. Rawlins, 'X-rays in the Study of Pictures', *The British Journal of Radiology* Vol. XII, No. 136, April 1939, pp. 239–45.

18 The X-ray equipment at the National Gallery is an Andrex BW85 source, controlled from a BW434 control panel in an adjoining room. The source will not operate unless all doors into the examination room are closed and the warning lights at each entrance illuminated.

19 Density range indicates the difference in optical density between the darkest and lightest parts of an image. The scale is logarithmic, so that a density range of 3 represents a ratio between the darkest and lightest areas of 1000. At 3.9 the density range of the scanner is much greater than that of internegative production (2.2) or producing contact prints (2.1) indicating that the scanner captures more tonal information than is present in the hand-assembled mosaic.

20 G. Van de Voorde 'Het gebruik van de Cronaflex-film voor de radiografie van schilderen', *Institut Royal du Patrimoine Artistique Bulletin*, XIV, 1973/4, pp. 34–8.

21 A. Aldrovandi and O. Ciappi, 'La radiografia di grande formato: problemi e soluzioni tecniche', *Rivista dell'Opificio delle Pietre Dure e Laboratori di Restauro di Firenze*, 7, 1995, pp. 163–8.

22 For example, the Centre de Recherche et de Restauration des Musées de France (C2RMF) has digitised and stored around ten thousand 300 × 400 mm X-ray plates over the last decade.

23 R. Billinge, J. Cupitt, N. Dessipris and D. Saunders, 'A Note on an Improved procedure for the rapid assembly of Infrared Reflectogram Mosaics', *Studies in Conservation*, 38, 1993, pp. 92–8.

24 D. Saunders, A. Burmester, J. Cupitt and L. Raffelt, 'Recent applications of digital imaging in painting conservation: transportation, colour change and infrared reflectographic studies', *Tradition and Innovation: Advances in Conservation,* eds A. Roy and P. Smith, London 2000, pp. 170–6.

25 Billinge et al., cited in note 23.

26 The mosaic assembly and subsequent digital manipulation of the X-ray images was carried out using the VASARI Image Processing Software (VIPS) on a Hewlett Packard Kayak XU800 (866 Mhz, 256 MB) running under the Linux operating system (SuSE 7.1). See J. Cupitt and K. Martinez, 'Image processing for Museums', in *Interacting with Images*, eds L. MacDonald and J. Vince, Chichester 1994, pp. 133–47; J. Cupitt and K. Martinez, 'VIPS: An Image Processing System for Large Images', *Proceedings of the IS&T/SPIE Symposium on Electronic Imaging: Science and Technology, Very High Resolution and Quality Imaging*, 2663, 1996, pp. 19–28.

27 D. Saunders and J. Cupitt, 'Image processing at the National Gallery: The VASARI project', *National Gallery Technical Bulletin*, 14, 1993, p. 80.

28 A method is being developed to allow the tie points to be chosen automatically by detecting those features in the images due to the surface paint layers, particularly craquelure.

29 Although this step will not be required in institutions that do not use the lead numbering system, VIPS includes a procedure that automates their removal.

30 At the National Gallery we have used a Hewlett Packard DesignJet 5000ps printer to produce large-format images, up to 1.52 m wide and of more-or-less unlimited length (91 m). For very large paintings two (or more) 'strips' are printed and joined by hand.

31 An example is provided in A. Gilardoni, M.T. Gilardoni, A.A. Orsini, L.A. Orsini and S. Taccani, *X-rays in Art*, 2nd edn, Mandello Lario 1994, p. 79. Three exposures were made of a cradled panel painting by Giulio Romano. The high (17 kV, 5 mA, 300 seconds), standard (25 kV, 5 mA, 60 seconds) and low (47 kV, 5 mA, 12 seconds) contrast images show different degrees of detail in the regions obscured by the cradle members.

32 The early development of strato-radiography is described in detail in A. Vermehren, 'Sulle possibilità stereo-strato-radiografiche di un nuovo tipo di apparecchio a raggi X in dotazione presso l'Istituto Centrale del Restauro in Roma', *Bollettino dell'Istituto Centrale del Restauro*, 11–12, 1952, pp. 121–33. The 'new type of apparatus in use at the Istituto Centrale del Restauro' comprised a high table on which the painting and film rested. The X-ray source was moved by a motor along an arc-shaped rail beneath the back of the painting. The same method, there termed stratiradiography, was later described by Loose: L. Loose, 'La stratiradiographie et la tirage cathodique', *Institut Royal du Patrimoine Artistique Bulletin*, VII, 1964, pp.172–86.

33 M. Pease, 'A Note on the Radiography of Paintings', *The Metropolitan Museum Bulletin*, IV, 1946, pp. 136–9.

34 Loose 1964 (cited in note 32) describes this technique. 'Tirage cathodique' was a method of decreasing the contrast between regions of the X-radiograph by using a cathode ray tube, rather than a conventional light

source, to produce the contact print from the X-ray plate. The output of the cathode ray tube can be varied across the image plane of the X-ray plate to adjust the degree of exposure in the printed image, thus decreasing the tonal imbalance caused by the secondary structure. The technique is also called logetronic radiography after one of the pieces of equipment used, the LogEtronic printer (which in turn derives from 'Logarithmic Exposure'). See also R. Van Schoute and H. Verougstraete-Marcq, 'Radiography', in *Scientific Examination of Easel Paintings, PACT 13*, ed. R. Van Schoute and H. Verougstraete-Marcq, Chapter VII, 1986, p. 137. Confusingly, Van Schoute and Verougstraete-Marcq also use the term logetronic X-radiography to refer to the procedure in which a granular material is packed into the cradle interstices.

35 Materials that have been used for this purpose include sawdust, sugar and a powdered resin such as Lucite: C.F. Bridgman and S. Keck, 'The Radiography of Paintings', *Medical Radiography and Photography*, 37, 3, 1961, pp. 62–70.

36 The edge detection process usually needs to be tailored to individual paintings, or indeed to individual elements within the structure, particularly since there can be double 'shadows' at the overlap between plates. In addition, the boundaries in masks produced by edge detection usually contain some isolated pixels that need to be edited manually. In the future we plan to make use of a semi-automatic boundary selection procedure that is presently under development.

37 The simplest method of adjusting one area with respect to another would be to scale the values by a constant. This technique can only be applied if there is a linear relationship between pixel value and X-ray absorption. In practice, the film transfer function cannot be determined for X-ray films in the archive, as it varies between film types and batches. Histogram matching does not require information about the characteristics of the film in order to produce acceptable results as it operates on the pixel values in the overlapping regions. See, for example, A.K. Jain, *Fundamentals of Digital Image Processing*, New Jersey 1989, pp. 243–4. Histogram matching should not be confused with histogram equalisation, a technique that has sometimes been used to enhance the contrast of digitised X-radiographs, particularly those of three-dimensional objects. See T. Higgins, 'An introduction to digital image processing' in *Radiography of Cultural Materials*, eds J. Lang and A. Middleton, Oxford 1997, pp. 167–82; E. Lange and D. Watkinson, 'Image processing and its application to x-radiography', *Conservation News*, 47, March 1992, pp. 37–9.

38 Processing a 10 Mbyte image using 11 masks took 35 seconds on a computer with an 866MHz Pentium III processor and 256 Mbytes of RAM. Processing a 200 Mbyte image using the same number of masks took around five minutes.

39 Pease 1946 (cited in note 33), Vermehren 1952 (cited in note 32) and Loose 1964 (cited in note 32).

40 The use of stereo pairs to visualise the three-dimensional relationship between different features in the X-radiograph is not new, having been presented at least as long ago as 1952 by Vermehren, cited in note 32.

41 The VIPS software is available for free download from the VIPS web-site at: http://www.vips.ecs.soton.ac.uk Documentation is also available describing the software and its installation, as well as manuals giving a step-by-step guide to its current use in conservation applications (for example the work with X-radiographs described in this paper).