Non-invasive imaging of subsurface paint layers with optical coherence tomography

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Abstract Optical coherence tomography (OCT) systems are fast scanning infrared Michelson interferometers designed for the non-invasive examination of the interiors of the eye and subsurface structures of biological tissues. OCT has recently been applied to the non-invasive examinations of the stratigraphy of paintings and museum artefacts. So far this is the only technique capable of imaging non-invasively the subsurface structure of paintings and painted objects. Unlike the traditional method of paint cross-section examination where sampling is required, the non-invasive and non-contact nature of the technique enables the examination of the paint cross-section anywhere on a painting, as there is no longer an issue with conservation ethics regarding the taking of samples from historical artefacts. A range of applications of the technique including the imaging of stratigraphy of paintings and painted artefacts, the imaging of underdrawings to the analysis of the optical properties of paint and varnish layers is presented. Future projects on the application of OCT to art conservation are discussed.

Keywords: optical coherence tomography, Michelson interferometer, art conservation, paint, varnish, infrared imaging, infrared reflectography, 3D imaging, refractive index, confocal microscopy

Introduction

Conservation ethics place an increasing emphasis on non-destructive and non-invasive methods of analysis and preventive conservation. In the case of paintings, conservation ethics limit sampling to regions of damage and edges of paintings, which can be unrepresentative of the painting as a whole. In general, non-invasive techniques not only reduce the need to take samples from artefacts, but also enable examinations on any area of an object, hence providing a global and representative view.

Technology is often the driving force behind the direction taken by a discipline. For example, in the 1930s non-invasive optical methods were routine in the scientific examination of works of art, while microchemical analysis was a new emerging method viewed as giving limited information, though it was useful in providing supplementary information to those routine imaging techniques (Gettens 1933). Nowadays, as a consequence of technological developments since the 1930s, microchemical analysis is considered routine, and the new emerging non-invasive optical methods are considered desirable but ineffective at examining the interior beneath the surface. However, this perception may change with new developments in imaging technology. It is particularly beneficial to borrow imaging technologies used in other disciplines such as biomedical imaging where there is a similar need for non-invasive methods, or astronomy or remote sensing when there is no alternative to remote, therefore non-invasive, methods.

Most non-invasive techniques currently used for point (i.e. non-imaging) analysis of painting materials can only examine surface layers (e.g. fibre-optic Fourier transform infrared (FTIR), micro Raman), or analyse all the paint layers together (e.g. X-ray fluorescence), so that it is not possible to obtain the information on stratigraphy and the composition of the separate layers that can be achieved through analysis of cross-sections of paint samples. Current routine non-invasive imaging methods of examination of paintings include X-radiography, infrared reflectography (IRR), macrophotography, ultraviolet fluorescence imaging and raking light imaging. The last three methods give information mostly on the conditions of the surface of a painting. X-radiography is routinely employed to examine the structure of the support of a painting, as well as details of areas painted with pigments containing heavy elements. IRR is one of the most useful techniques for studying the underdrawings beneath the painted layers, which would otherwise be invisible to the eye. Both X-radiography and IRR reduce the 3D information of a painting into 2D, thus losing the detailed depth-resolved information on the subsurface stratigraphy. In this paper, we present the applications of a new emerging non-invasive imaging technology to the examination of subsurface structures of paintings and potentially other artefacts.

Ever since the invention of the Michelson interferometer for the detection of ether in 1881, it has been used in a wide range of applications from spectroscopy to metrology and from astronomy, through chemistry to biomedical research. In the early 1990s, optical coherence tomography (OCT) – a fast, high resolution, 3D scanning technique based on the Michelson interferometer – was first developed for *in vivo* scanning of the eye and other biological tissues (Huang *et al.* 1991). Since the pioneering work by our group and others, OCT has been applied to art conservation to produce cross-sectional images of paintings and archaeological objects non-invasively (Liang *et al.* 2004; Targowski *et al.* 2004; Yang *et al.* 2004; Liang *et al.* 2005a). OCT typically operates in the near infrared and probes the subsurface structure of an object by measuring the backscattered light at each depth position. Since OCT is based on interferometry, interference between the light reflected back from the reference mirror and the light backscattered from the object occur when the optical path length between the two are within the coherence length. The depth resolution given by the coherence length or the bandwidth of the light source is decoupled from the transverse X-Y resolution given by the numerical aperture of the objective. To achieve high depth resolution, short coherence length or wide-band sources are required, since the coherence length is given by

$$l_c = \frac{4\ln 2}{\pi}\frac{\lambda_0^2}{\Delta\lambda}$$

where λ_0, $\Delta\lambda$ are the central wavelength and bandwidth of the light source. The depth resolution is half the coherence length. This is in contrast to a confocal microscope where both the depth resolution and the transverse resolution are given by the numerical aperture of the objective. Hence, for the same depth resolution, OCT can operate at a greater working distance than confocal microscopes. This may be one reason why confocal microscopy has not been used directly on paintings because of the close working distances required (a few millimetres), which render the technique potentially hazardous. In addition, OCT compared to confocal microscopy is able to probe up to three times the penetration depth in scattering media, since it takes advantage of the coherence properties of light and registers only coherent signals (Izatt *et al.* 1994). Since OCTs are designed for *in vivo* examinations of a highly sensitive organ – the eye – it has the added advantage of a comfortably remote working distance of typically ~1–2 cm.

Currently, there are two main types of OCT: time-domain OCT (TD-OCT) and Fourier-domain OCT (FD-OCT). Wide-band sources such as the superluminescent diode (SLD), Kerr lens mode-locked laser and supercontinuum sources have been used to achieve high depth resolution. Sub-micron resolutions are achievable using specialised ultra-wide band sources (Drexler 2004). However, these novel broad-band sources are currently very expensive. Figure 1 shows schematic diagrams of the two types of OCT. A recent review of OCT is given by Tomlins *et al.* (2005). TD-OCT scans the depth of an object through moving the position of the reference mirror. In contrast, the reference mirror position is fixed in a FD-OCT and a spectrometer is used to record the interference spectrum, which is later Fourier transformed back to obtain the depth-resolved structure of the object. Within TD-OCT technology, the most common type collects a series of 2D cross-section images which are then stacked to obtain a 3D image. An alternative to this kind of conventional TD-OCT is *en-face* TD-OCT (Podoleanu *et al.* 1996, 2000) which takes images in planes parallel to the painting surface one after another in depth, which is particularly convenient for the examination of paintings. The *en-face* scans provide an instant comparison to the familiar sight of a painting. Features seen with the naked eye can easily be compared with features hidden below the surface.

In biomedical applications, the speed of acquisition is crucial for *in vivo* examination of biological tissues. However, in the case of examination of paintings, speed is of less importance except for the examination of temporal effects such as tracking the deformation of canvas and laser cleaning (Targowski *et al.* 2006a; Gora *et al.* 2006). Currently, FD-OCT is the most promising in biomedical applications, as it is faster at achieving the same sensitivity, however, FD-OCT has a number of drawbacks compared to TD-OCT (for a detailed discussion see Leitgeb *et al.* 2003). For paintings, the main drawback of the FD-OCT is ghost images associated with highly reflective surfaces such as a freshly varnished painting or gilded areas. In addition, for wavelength longer than 1 μm, FD-OCTs are significantly more expensive than TD-OCTs. Paint is in general more

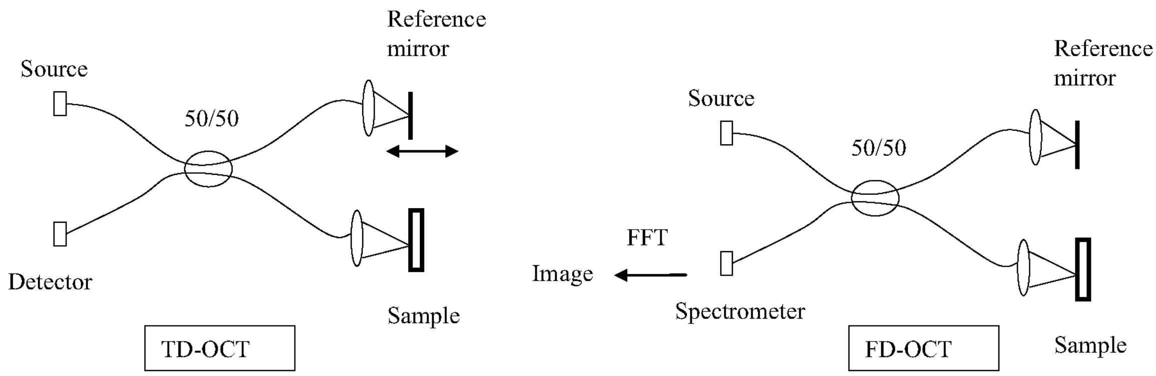

Figure 1 *Schematic diagram of fibre-based OCT systems. The backscattered light from the sample is combined with back-reflected light from the mirror, and the interference signal is detected either directly (TD-OCT) or through a spectrometer (FD-OCT). Left: TD-OCT where the depth information is probed by scanning the reference mirror. Right: FD-OCT where the reference mirror position is fixed, the detector is replaced with a spectrometer, and the depth-resolved structure is recovered through a fast Fourier transform.*

transparent to near infrared light at longer wavelength than 1 μm which makes longer wavelength OCTs more desirable for the examination of paintings (see Peric *et al*., in this volume, pp. **xx–xx**).

Table 1 Specifications of the OCT systems used in this paper.

OCT system	Type	Wavelength (nm)	Depth resolution (μm)	Transverse resolution (μm)
1	FD-OCT	930	6	9
2	*En-face* TD-OCT	1300	20	25

Application to technical examination of painting

In this paper, we will concentrate on the application of OCT to the examination of paintings. The OCT systems used range from *en-face* TD-OCT to FD-OCT with wavelengths of 930 nm, 1300 nm and depth resolutions of 6 μm and 20 μm. Table 1 gives the specifications of the two OCT systems used. The systems should not be considered as typical of their types: they were used simply because we had access to them. The typical speed of acquisition of a cross-section image is between 2–10 frames/second. System 1 is a commercial system from Thorlabs and system 2 is a prototype laboratory system (Liang *et al*. 2005a).

Non-invasive, non-contact imaging of paint cross-sections

A test panel was prepared with a traditional ground layer of chalk mixed with rabbit-skin glue, on top of which a layer of smalt in linseed oil was painted. An image of a cross-section taken with OCT system 1 is shown in Figure 2, where the bright dots are the smalt particles. The uneven chalk layer under the smalt layer can also be seen. OCT registers the backscattered light from the sample. The greater the backscattering, the brighter the image is, hence we can conclude that the chalk layer is much more scattering than the smalt layer. Backscattering is greatest at sharp boundaries between refractive indices. The bright edge at the top of the smalt layer is due to the strong reflection at the boundary between air and the smalt layer. Similarly, the smalt particles are seen as bright spots as a result of the scattering due to the difference in refractive index between the pigment particles and the oil medium.

Figure 3 shows an example of OCT images of paint stratigraphy on a seventeenth-century painting from the National Gallery, London. Multiple paint layers can be seen, and the cross-section images show the marked cupping of the paint surface particularly well. Further investigations are needed to interpret the layer structures fully. This example demonstrates the usefulness of combining non-invasive OCT imaging of subsurface structure with the examination of sample cross-sections, where microscope examinations of sample cross-sections can aid the interpretation of OCT images, and OCT images in turn can show how similar or different the layer structures are between regions on a painting.

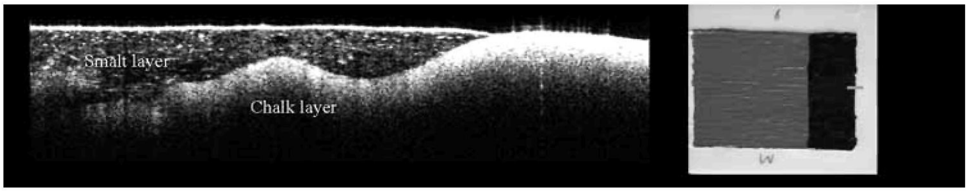

Figure 2 *Left: an OCT cross-section image of a painted panel of smalt in linseed oil over a chalk layer. Right: the test panel and the position of the scan (see Plate 29 in the colour plate section).*

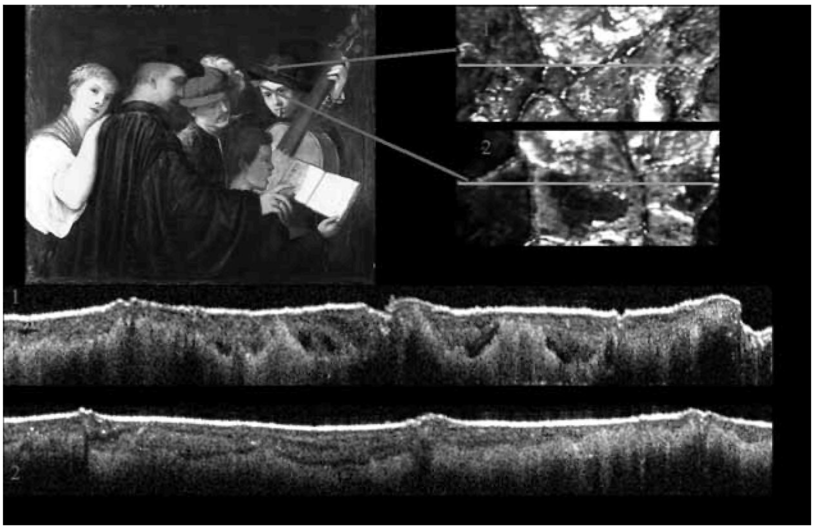

Figure 3 *Top left: A Concert (1600–50), after Titian (National Gallery, London N00003). op right: details of two regions on the painting examined by OCT system 1. Bottom: OCT cross-section images of the two regions at positions marked by the green line segment (see Plate 30 in the colour plate section).*

Imaging of underdrawings

Figure 4 shows that the dynamic range and resolution of the OCT images of underdrawings surpass any conventional infrared images. The separate droplets of the bone black drawings are clearly discernable in the OCT images. The high dynamic range is because interferometers register only coherent signals hence only backscattered light with a path length that matches (within the coherence length) the reference path length is registered. Stray light is automatically filtered out. For the imaging of underdrawings, it is most convenient to use an *en-face* scanning OCT where underdrawings can be seen as the 3D scan is progressing. For other types of OCT, it is necessary to wait until a full 3D scan has finished before *en-face* slices can be displayed. Figure 4e shows that the increased resolution of OCT system 1 compared with OCT system 2 (Fig. 4d) gives added information on the way the underdrawings are drawn making it possible to deduce not only the type of underdrawing (liquid) but also the direction in which it is drawn.

Figure 5 shows that unlike conventional infrared images such as infrared reflectography, OCT images can show the exact depth location of an underdrawing, e.g. whether the underdrawing was drawn above or below an *imprimatura*. The underdrawing absorbs the incident light, casting a shadow in the layers below.

An example of imaging underdrawings in a sixteenth-century painting is shown in Figure 6. In this painting, the underdrawing beneath drapery painted with red lake was easily visible to the naked eye. Such an area was imaged with the aim of determining whether the underdrawing was visible in the OCT cross-section image. The layers of red lake paint and varnish are clearly discernable. The dark lines/shadows lower down in the cross-section correspond to the underdrawing which seems to be directly below the red lake layer and above another layer that could be either the chalk ground or a priming layer.

Monitoring cleaning processes

OCT cross-section images are particularly effective at showing translucent layers, including multiple varnish layers, and so can be used to monitor varnish removal. Given the fast acquisition speed, OCT can potentially be

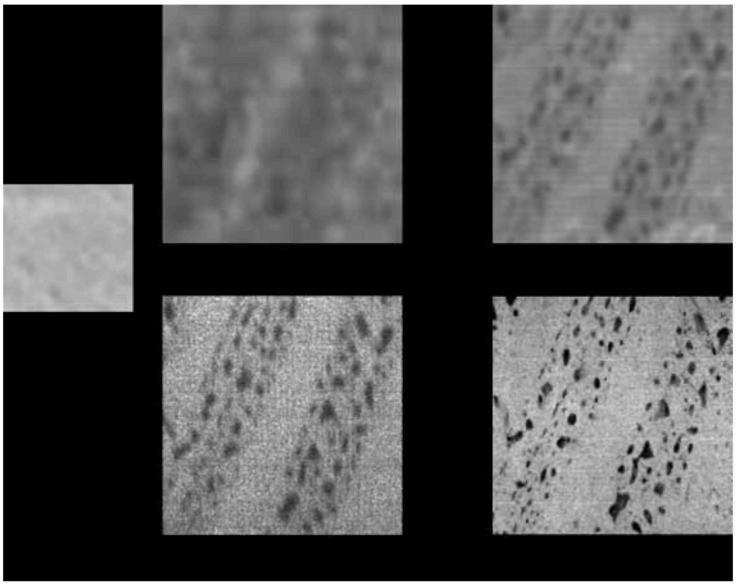

Figure 4 *(a) Colour images of a painted patch with two layers of lead-tin yellow paint over underdrawings drawn with a quill pen using an ink of bone black in gum; (b) near infrared Vidicon images; (c) near infrared images taken with a InGaAs camera; (d) the corresponding 1300 nm OCT image (system 2) of the average of layers containing underdrawings; (e) 930 nm OCT image (system 1) (see Plate 31 in the colour plate section).*

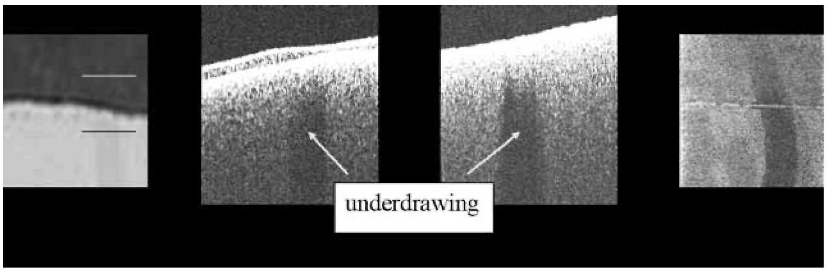

Figure 5 *(a) Colour image of a painted panel: the lower part is painted with an imprimatura on top of the underdrawing which is painted on a preparatory ground layer. The upper half has an additional paint layer above the imprimatura; (b) cross-section images collected with OCT system 2 of a scan in the top half of the image (line segment marked in yellow) showing the dark shadow of the underdrawing below two layers of paint; (c) OCT cross-section image of a scan in the lower half of the image (line segment marked in black) showing the dark shadow of the underdrawing below one layer of paint; d) en-face OCT image (system 2) of the underdrawing (see Plate 32 in the colour plate section).*

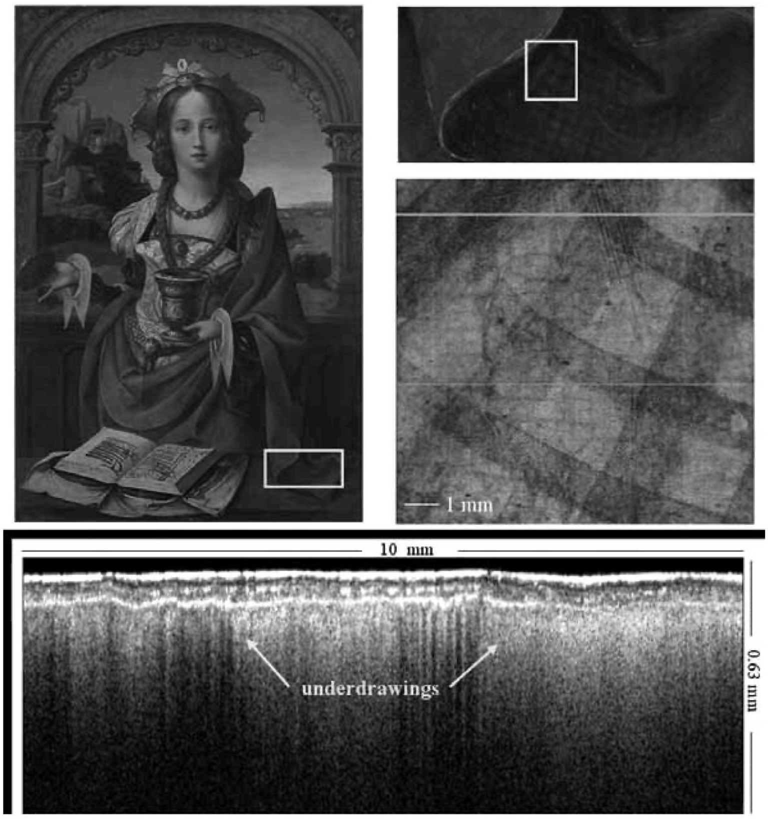

Figure 6 Top: a region on the red drapery in The Magdalen by an anonymous Netherlandish artist (National Gallery, London N00719). Right middle: OCT (system 1) en-face image at the depth of the underdrawing corresponding to the region marked by a yellow box. Bottom: OCT (system 1) cross-section of the region marked by a green line segment (see Plate 33 in the colour plate section).

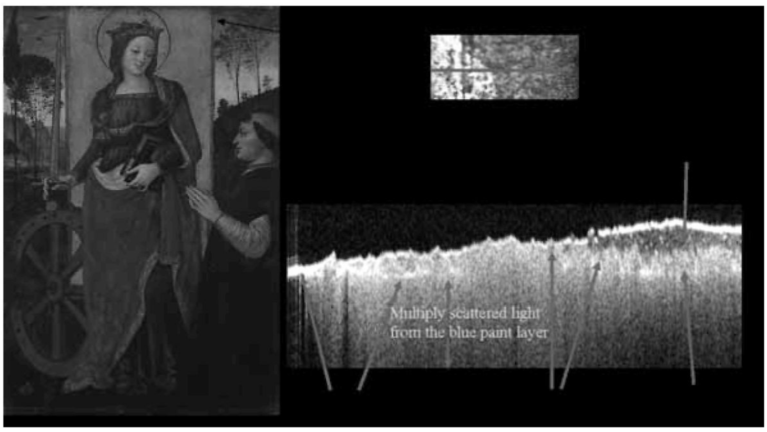

Figure 7 Left: Saint Catherine of Alexandria with a Donor (1480–1500) by Pintoricchio (National Gallery, London N00693). Top right: detail where the right-hand side is covered with an old yellowed varnish, partly cleaned on the left. Bottom right: an OCT (system 1) scan through the centre showing the old varnish region on the right and the cleaned area on the left (see Plate 34 in the colour plate section).

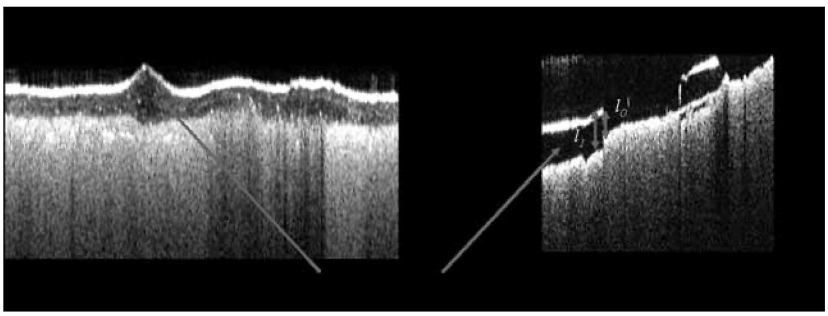

Figure 8 Left: an OCT (system 1) image of an old degraded varnish (>120 years old) from Figure 7. Right: a relatively new varnish (<50 years old) (see Plate 35 in the colour plate section).

used for dynamic monitoring of the cleaning process. Figure 7 shows an example where part of an old degraded yellow varnish has been removed. The painting has an interesting layer structure where paint has been applied over a gold layer. The varnish, paint and gold layers can be seen in the OCT image. On the extreme left is the area where the bare gold layer is exposed, in the middle is the blue paint layer (probably ultramarine) over gold and on the right is the area where there is still old varnish on top of the paint. Effects of multiple scattering in the paint layer give the impression of a thick layer below the gold layer. If the paint layer is strongly scattering, light can bounce off a few times within the paint layer before being collected by the OCT. A photon collected by the OCT that was scattered more than once would have a longer path length than if it was scattered once. Since OCT registers optical depth rather than physical depth, these multiply scattered photons would appear to the OCT as coming from a deeper layer. This is why some of the multiply scattered light from the blue paint layer above the gold layer appears to be coming from below the gold layer. This highlights the importance of combining knowledge about the instrument and the painting in interpreting the images (which is what microscopists had to learn in the past to interpret cross-section images). Similarly, caution has to be employed in interpreting cross-section images in biomedical applications. However, paintings are perhaps more varied than the human eye or skin.

Measurement of optical properties of paint and varnish layers

The visual qualities of a painting are determined by optical parameters such as refractive index, thickness, absorption and scattering coefficients in each layer, and surface roughness of the varnish and paint. Measurement of these parameters can be useful for conservation treatment and in studies of deterioration processes. OCT makes it possible to study ageing processes using naturally aged 'real' paintings as statistical samples, rather than relying on artificially aged samples. The OCT images at 930 nm in Figure 8 show a clear difference in scattering properties of an old degraded varnish compared to a relatively new varnish. The chemical changes that occurred in an old varnish made it change colour and become less homogeneous, giving a hazy and yellowed appearance. This can be seen in the OCT image as increased scattering in the old varnish layer.

The traditional method of measuring refractive index (RI) of paint and varnish layers of a painting requires taking tiny samples and observing under a microscope the changes in their transparency when immersed in a series of liquids with calibrated refractive indices (RIs) (Townsend 1993). When the RI of the sample matches that of the liquid, the sample 'disappears'. We have demonstrated that OCT is capable of measuring RI non-invasively for varnish layers (Liang *et al.* 2005b). In Figure 8b, the top of the paint layer below the varnish layer appears to be lower than the top of the adjacent paint layer where the varnish had fallen off. This is because OCT measures the optical depth rather than physical depth, as varnish has a higher RI than air. The ratio between the optical thickness of the varnish (*l1*) compared to its physical thickness (*l0*) gives the RI of the varnish. Non-invasive measurements of RI of paint layers will be reported in a forthcoming publication.

Another application of OCT is in the dynamic monitoring of the drying and wetting processes of varnish layers. Preliminary studies (Liang *et al.* 2005b) on the monitoring of the drying processes of different varnishes confirmed that the varnish surface generally follows the roughness of the substrate as it dries, and that the degree of roughness depends on the type of varnish, as suggested by Berns and de la Rie (2003). Further work on the topic using OCT has also been reported by Targowski *et al.* (2006b).

Conclusion and future developments

OCT, a low coherence 3D scanning Michelson's interferometer, has potential as a powerful non-invasive technique for probing into the depth of paintings, providing 3D infrared image cubes that can show not only the structure of the paint and varnish layers, reveal underdrawings and their depth positions, but also provide some quantitative measurements of the optical properties of varnish and paint layers.

We have started a three-year project on OCT for art conservation, with the following objectives:

- To find the best method of obtaining quantitative measurements of optical parameters, such as refractive index, thickness, absorption and scattering coefficients, of the paint and varnish layers using OCT.
- To conduct a study of how the paint and varnish material of historic paintings or painted objects age in terms of their optical properties.
- To use OCT to assist practical conservation and address various issues in conservation and art-historical studies.
- To find the optimum wavelength bands in the visible to near infrared spectrum (400–2500 nm) for a dedicated OCT system for the conservation of painted objects. This has been found to be around 2.2 μm (see Peric *et al.*, in this volume, pp. **xx–xx**).
- To add extra wavelength channels to an existing OCT system to explore the potentials of spectral measurements for the identification of different materials in the paint layers.
- To specify a design for an ideal OCT system tailored for museum use.

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