Using Optical Coherence Tomography to Reveal the Hidden History of *The Landsdowne Virgin of the Yarnwinder* by Leonardo da Vinci and Studio

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Abstract:

Optical coherence tomography (OCT) was used for non-invasive examination of a well-known, yet complex, painting from the studio of Leonardo da Vinci in combination with routine imaging in various bands of electromagnetic radiation. In contrast with these techniques, OCT provides depth-resolved information. Three post-processing modalities were explored: cross-sectional views, maps of scattering from given depths, and their 3D models. Some hidden alterations of the painting owing to past restorations were traced: retouching and overpainting with their positioning within varnish layers as well as indications of a former transfer to canvas.

Keywords:

analytical methods, materials science, non-invasive structural imaging, reflectance imaging spectroscopy, stratigraphy

Understanding the internal structure of paintings is a critical issue for, among other things, planning future restoring interventions. Although invasive (sampling-based) analyses are still the most precise tools for the identification of the chemical compounds comprising painting materials in artworks, in

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many cases their use is not acceptable. Even in situations where sampling is allowed, the amount of material is obviously scarce and is limited to restricted spots on the painting.

The most popular non-invasive imaging modalities, namely UV-excited fluorescence, infrared (IR) reflectography, and X-radiography, yield detailed overall images which are relatively easy-to-interpret and which allow for the disclosure of many hidden details when compared with diffused-light photography. This makes imaging techniques a standard element in any scientific examination of paintings.[1] However, most of them even if providing area-wise information do not give any insight on the in-depth stratigraphy. The question is: "Are details invisible to these routine diagnostic tools accessible by other non-invasive optical imaging techniques?" Herein we show how optical coherence tomography (OCT), a white-light interferometric technique originally developed for medical diagnostics, can fulfill this need. Apart from OCT, other techniques are capable of providing spatially resolved and depth-resolved structural information (see the Supporting Information, pp.31-32, for further references).

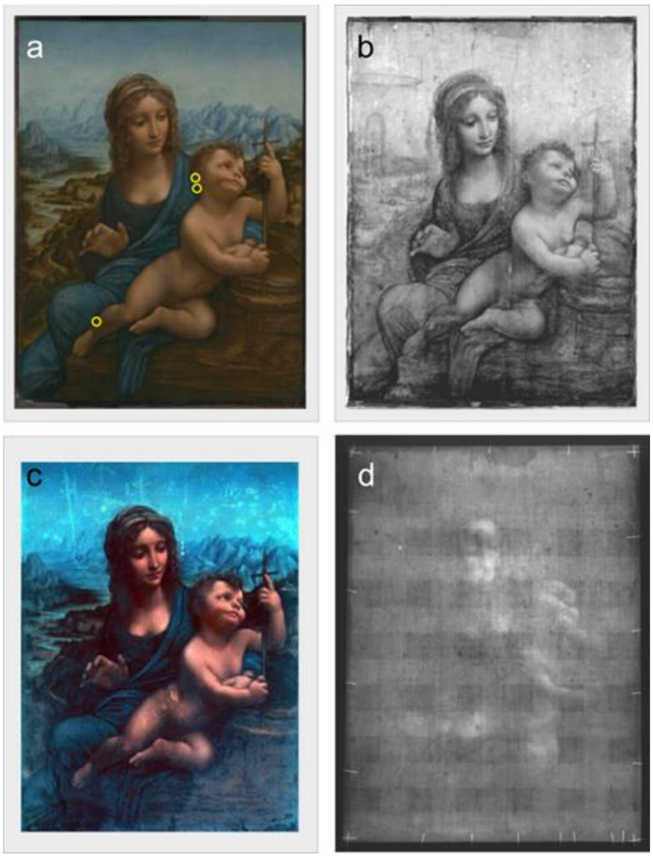

Figure 1. *The Landsdowne Virgin of the Yarnwinder*, Leonardo da Vinci and studio, 1501-1507 (?), originally oil on panel, transferred twice; 50.2 x 36.4 cm^2. a) visible light image obtained from multispectral acquisition with INO's scanner[2] in the 380-780 nm range with D65 illuminant and 1931 standard observer; yellow circles mark the location of the spots examined herein; b) Infrared reflectography acquired in the spectral band 1650-1750 nm with the same scanner, showing underdrawings (see the Supporting Information, pp. 8–28 for images in the other bands and PCA analysis).c) UV-excited fluorescence photography enhancing varnish inhomogeneities, acquired with a NIKON D750 camera (full-frame 4016 x 6016 pixel) using Wood lamps; d) X-radiograph acquired with an analogue X-Ray system (AGFA film, 50 kV, 5 mA, 1.5 m distance, 10 s exposure time). The two latter examinations took place in 2002-2003.

Leonardo’s original composition, "The Madonna of the Yarnwinder" had for many years exerted an influence on the work of the master’s pupils and assistants, as well as on that of close or distant followers, inspiring many imitations. Among the variety of ca. 40 surviving variants,[3] two have been recognized as the closest to Leonardo’s workshop. One has long been in the possession of the Dukes of Buccleuch. The other, examined herein, is known as The Lansdowne Madonna, from the name of its first confirmed owner. The painting has become publicly known in 1833[4] and since that time, the level of Leonardo’s autography both in The Lansdowne Madonna and in The Buccleuch Madonna has been a subject of the academic controversy. Scholars have been arguing about which of the two is the original composition by Leonardo and which the studio copy executed by one of his assistants, of which Il Sodoma (G.A. Bazzi) and A. Salaì were taken into consideration. However, at least partial attribution to Leonardo of the Lansdowne painting has recently been acknowledged. It had been extensively restored over the last century: transferred twice (in 1911 from panel to canvas and in 1976 to a composite support), as well as cleaned and retouched.[3b,4] At the end of 2002, the owner of The Lansdowne Madonna allowed its temporary importation into Italy and entrusted it to the Opificio delle Pietre Dure for non-invasive analyses.[4]

Since then, images of The Lansdowne Madonna of the Yarnwinder have been acquired, using radiation in different spectral ranges. A few examples are shown in Figure1 where images of the painting in visible light, infrared (IR), ultraviolet (UV), and X-ray radiation are reported

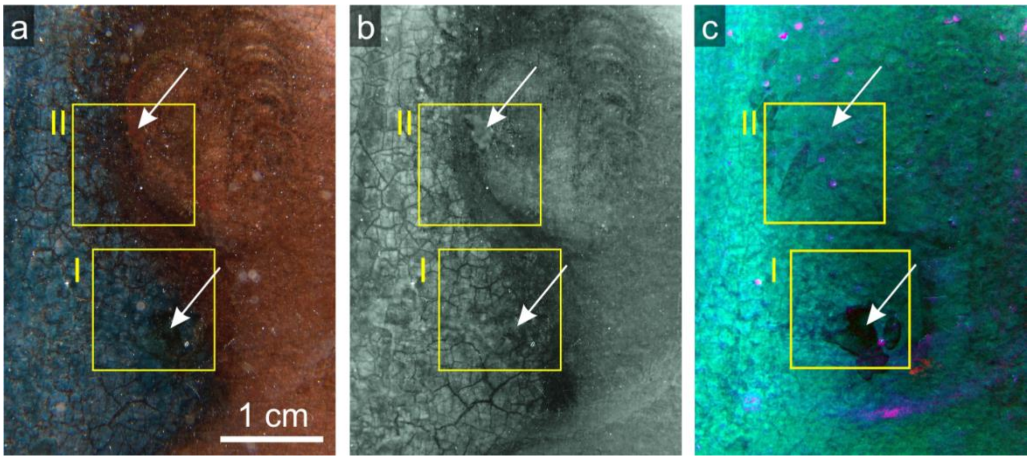

Figure 2. Detail of the Child’s ear as seen in a) visible light; b) NIR reflectogram at 950 nm; c) UV-excited fluorescence. Macro-images all taken with SONY DSC-F828 equipped with a 7 mm lens (f/2 F-stop, 1/30 s, 400 ISO). Images (a) and (c) were taken with IR noise removed using a hot filter. Yellow rectangles (12×12 mm^2) indicate the exact location of the OCT examinations after software registration (see Figures 3 and 4).

OCT is a broadband interferometric technique, utilizing infrared radiation in the 800—2000 nm range. Similarly to ultrasound imaging, it permits cross-sectional visualization of the internal structure of the object, but with an incomparably higher axial resolution (down to a few micrometers). The limited permeability to light of the structures examined restricts the imaging range to semi-transparent layers. In the case of easel paintings, these are varnishes, glazes, and the upper interface of opaque paint layers.

In most cases, the use of long-wavelength infrared radiation results in its higher penetration into the paint layer.[5] Nevertheless, in OCT there is a trade-off between the penetration and the axial resolution, the latter of which deteriorates with the square of the central wavelength. Herein, a near-infrared system [6] (770—970 nm) was used to provide an axial resolution of 2.5 µm in varnish and painting media. During examination, the painting was slightly tilted to avoid specular reflections from its surface. Cross-sections presented herein were stretched vertically to allow a convenient inspection of details. In OCT images, all in-depth distances are optical ones, and thus the structures embedded in media are additionally stretched by a factor equal to its refractive index (n_R). Therefore, all tomograms are equipped with two scale bars: one for the air above the structure and one for the media with n_R=1.5. Owing to the limited axial resolution, this number stands for all media constituting superficial layers of the painting. All the data were collected as 3D cubes over areas 12×12 mm^2. Each data set comprises 100 adjacent cross-sections (only single examples are shown; see the Supporting Information for full sets). Two diverse modalities of data analysis were applied to the data cubes: scattering maps and 3D surface models. The former provide area-wise distribution of scattering centers at given depths under the painting surface (see Ref. [7] or the Supporting Information p. 35 for details). These maps (for example, Figure 3b-e and the tomograms (Figure 3a and 4a) are shown in false colors: media that either do not scatter light or are not reached by it are shown as black. The layers of increasing, but still moderate, scattering properties are shown in colors from blue to green, respectively, and those of high scattering from light green to yellow. 3D surface models (Figure 5) were generated by automatic recognition of upper interfaces of the scattering structures layer-by-layer and converted into color-coded elevation maps. OCT scattering maps were precisely software-registered onto the relevant areas of high resolution visible, UV-induced fluorescence and NIR (950 nm) images (Figure 2).

The effects of former restoration interventions can be ascertained from optical examinations in various bandwidths: not surprisingly, different techniques provide complementary information. A good-resolution visible-light photograph (Figure 2a) is used as a fundamental reference for documentation purposes. In the case of areas I and II in Figure 2a, no traces of past treatments are seen at first glance. However, when compared with an infrared photograph (Figure 2b, some alterations (arrows) become recognizable also in visible light. Another routine examination is inspection of fluorescence emission in the visible region, excited by UV-A radiation (Figure 2c, as original materials generally emit a different fluorescence with respect to the added ones. The phenomenon is complex and many variables must be taken into account. The thickness and ageing of varnish layers and the properties of underlying layers owing to both pigment and binder are factors that influence the overall image, affecting the color and/or intensity of the fluorescence.[8] This explains why features interpreted as alterations in a UV-induced fluorescence image cannot be directly correlated with the IR reflectogram (areas I and II in Figure 2b and c. In area I, a large dark spot in the UV-induced fluorescence image (white arrow, Figure 2c does not correlate with any alteration visible in the IR macro-reflectogram (Figure 2b. On the contrary, in area II there is a clear indication of alteration in IR reflectography (Figure 2b but no trace of this intervention in Figure 2c, where only some other superficial retouchings are seen as dark brush strokes.

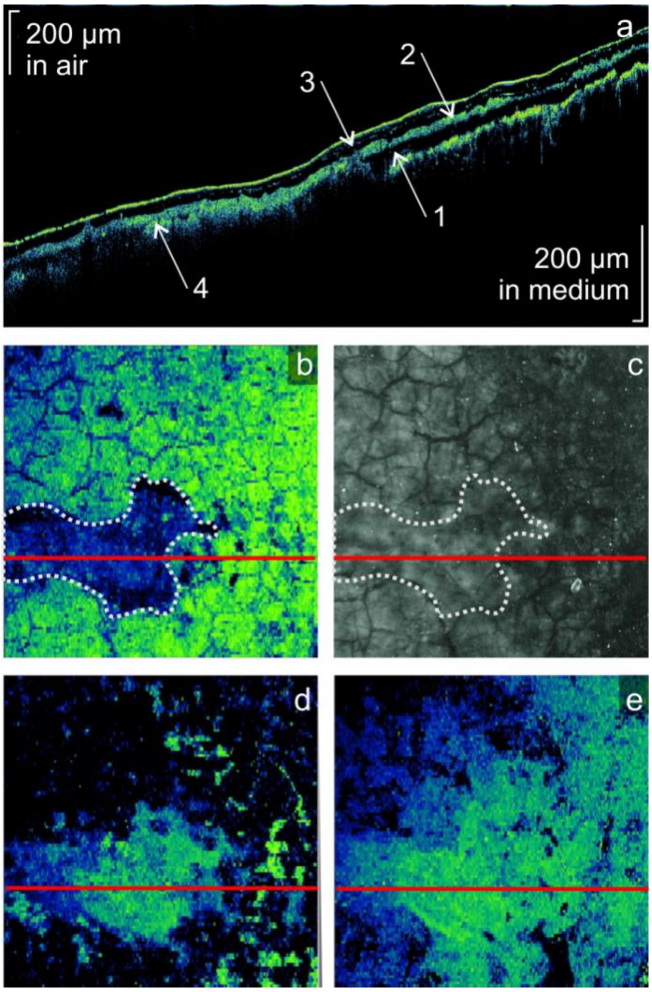

Figure 3. Details of area I in Figure 2. a) OCT cross-sectional view of subsurface layers: 1=varnish layer, 2=semi-transparent retouching, 3=varnish layer, opaque putty (see text for detailed descriptions). b) OCT scattering map showing structures present at 74 µm depth under the surface and c) the same area as seen in high-res IR reflectography. d),e) OCT scattering map showing structures present at 52 µm and 35 µm depth under the surface, respectively. The red line in (b)-(e) indicates the location of the cross-section shown in (a).

This ambiguity can be overcome with OCT. A cross-section over the area I is shown in Figure 3a, corresponding to the red line in Figure 3b-e. In the right-hand part of the image Figure 3a, the structure of the superficial layers of the painting may be described as following: over an opaque paint layer a non-scattering, about 27 µm thick varnish layer (1) is present. Above this, a semi-transparent layer of retouching (2) is covered with two more varnish layers (3) of overall thickness of about 32 µm (Supporting Information, p. 285). In the left part of the image, the bottom layer of varnish is not present, replaced by the opaque structure (4) built up to the level of the retouching, namely a putty (material used in painting restoration for filling ground and paint losses). The discrepancy between NIR and UV images (Figure 2) can be explained with the depth-resolved scattering maps obtained from OCT data. The map collected from a depth of 74 µm (Figure 3b) shows the original opaque paint layer. In this case, the dark blue area indicates the lack of signal from the structures located deep below the surface of the putty. The shape of this dark area (dotted line in Figure 3b,c) correlates well with the shape of the structure recognizable in the macro-reflectogram (Figure 3c). A lack of craquelure can be observed within the perimeter of the putty, whereas around it correlates well with the pattern seen in macro-reflectogram. The map collected at 52 µm (Figure 3d) shows the bottom varnish as dark blue (the lack of signal is due to its very low scattering ability) surrounding the strongly scattering area of the putty (light blue and green). Finally, the map at 35 µm (Figure 3e) shows retouching exceeding the area of the putty and covering the original paint layer, thus not in line with modern conservation approach.

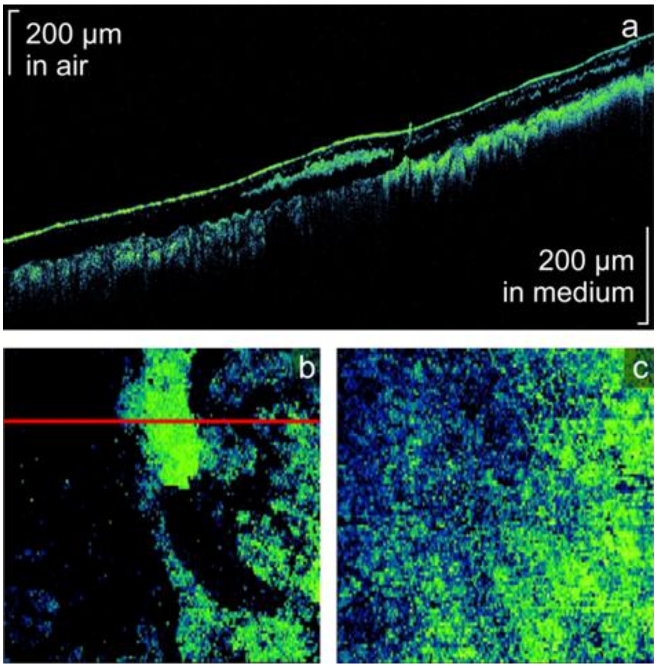

Figure 4. Details of area II in Figure 2. a) OCT cross-sectional view of subsurface layers; b),c) OCT scattering maps showing structures present at 36 µm and 108 µm depths under the surface, respectively. The red line in (b) indicates the position of the cross-section shown in (a).

The OCT cross-section of area II (Figure 4a) reveals an alteration (marked by a white arrow in Figure 2) as a clearly visible thick green spot. It is only partially transparent to the OCT probing light, casting a shadow on layers below. However, the dark strip beneath this structure suggests that it is rather a thick overpaint lying on varnish than an overpainted putty as in the case shown in Figure 3. The depth-resolved map (Figure 4b) extracted at 36 µm shows not only this strong overpainting but also the much more extensive one, widely spread and following the shape of the ear of the Child (green in the OCT scattering map; Figure 4b) It is not visible in the Vis inspection and not detected by either NIR reflectography or UV-excited fluorescence. The map collected at 108 µm (Figure 4c) shows a rather homogenous original paint layer. It therefore remains an open question as to just why this intervention was performed. Unfortunately, OCT does not permit evaluation of the state of preservation of the paint layer regarding its fine abrasions or discolorations. A definitive answer would be available during a future restoration, if this overpainting were to be removed.

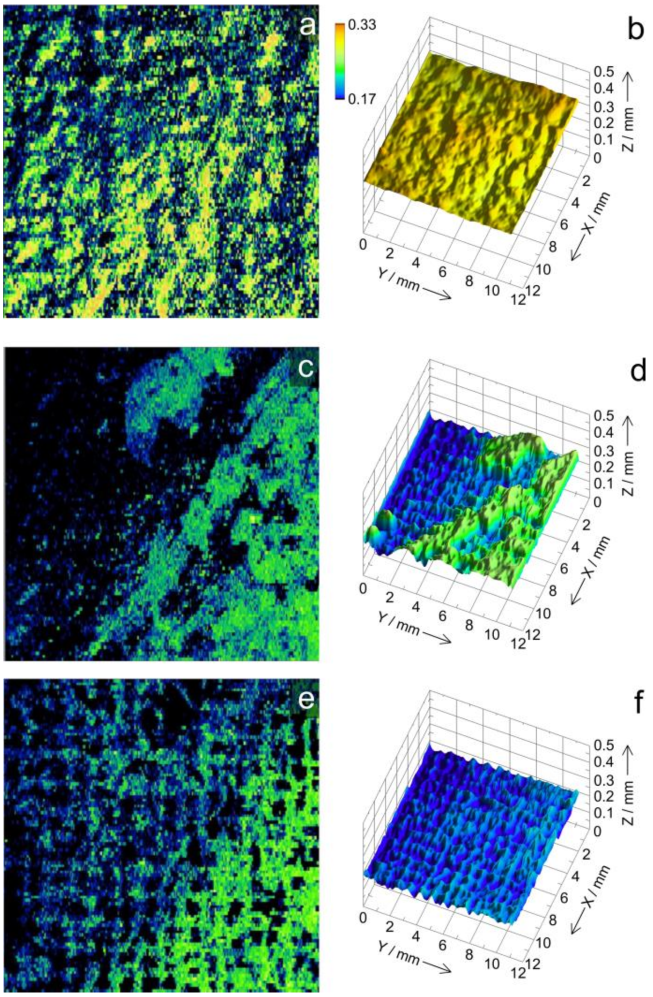

Figure 5. OCT scattering maps showing structures present at: a) the painting surface; c) 27 µm and e) 62 µm depth under the surface of the painting; b), d), f) 3D representations of structures at the same depths.

An interesting feature of The Landsdowne Virgin of the Yarnwinder is shown in Figure 5. Depth-resolved scattering maps (Figure 5a,c,e) are supplemented with topographic visualizations of the respective surfaces, also obtained from OCT data. In Figure 5a,b the outer surface of the painting is shown. Further down (Figure 5c,d), the surface of an overpainting is recovered and, where the overpainting is not present, the surface of the paint layer is already visible. Since the overpaint layer is semi-transparent, as seen in Figures 3 and 4, it is also possible to fully visualize the surface of the paint layer (Figure 5f). In this case, a criss-crossed pattern is well evident, which is also visualized in scattering map modality (Figure 5e), where the cutting surface is just touching the protrusions of the paint. This pattern is visible only locally (for example, not in areas shown in Figures 3 and 4) and was not created intentionally by the artist. It is most probably evidence of a past renovation of the painting, when pictorial layers were transferred from a wooden to canvas support. This treatment, not uncommon in the past, was performed with the use of a wax-resinous or similar thermo-plastic adhesive under significant temperature and pressure conditions, making it possible for the threads of canvas to have been incised into the paint layer. A few layers of varnish applied later filled up and leveled the surface, making this effect not easily noticeable on the surface of the Madonna. By means of Fourier analysis, it was possible to measure the spatial frequencies of these imprints. They are 11.7 cm^{-1} horizontally and 10.4 cm^{-1} vertically (see the Supporting Information, p. 163 for analysis). This result is consistent with conoscopic measurements performed in areas where the canvas imprint was not hidden under the overpaint.[9] Interestingly, inspection of the X-radiograph

(Figure 1d) reveals the presence of canvas as well, but with different thread frequencies: 8.0 cm^{-1} horizontally and 7.5 cm^{-1} vertically (in the area of Figure 5 as well as averaged over the whole picture), see the Supporting Information, p. 30 for details. This difference is far beyond experimental error and may be explained only by a double transfer: first to a more dense canvas, which is probably not present now, and then to the second, less dense one, which is still present within the composite-wooden panel.

In conclusion, we have demonstrated the usefulness of high resolution optical coherence tomography (OCT) in adding a 3rd dimension to the imaging techniques routinely used in art examination. In the case of The Lansdowne Virgin of the Yarnwinder, a panel painting attributed to Leonardo da Vinci and studio, OCT gave us additional insight into the painting. Some alterations, otherwise difficult to document, were discovered and visualized.

OCT's ability to provide stratigraphic information non-invasively in the form of both cross-sections and *en face* images makes it an effective tool complementing routine scientific artwork analyses. It opens new horizons in the diagnostics of paintings, allowing for the survey of any area on the painting surface and making it possible thoroughly to study both the painter's technique and the artwork's conservation history.

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