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Traces of former restorations of Raphael's *La Muta* as seen by Optical Coherence Tomography

Magdalena Iwanicka[a], Marcin Sylwestrzak[b], Piotr Targowski[b]

[a]Institute for the Study, Restoration and Conservation of Cultural Heritage, Faculty of Fine Arts, Nicolaus Copernicus University, Toruń, Poland

[b]Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Toruń, Poland

The application of optical coherence tomography (OCT) as a non-invasive method for the examination of internal structures was developed primarily for medical diagnostics and commonly used in ophthalmology for imaging of the retina. Over the last ten years it has also been employed in the imaging of objects of cultural heritage, such as easel paintings, historical glass, gemstones including jade and amber, and many others. The subject has recently been reviewed by Targowski & Iwanicka [1]. A complete bibliography can be found on the website www.oct4art.eu.

OCT is an optical technique which utilises interferometry of infrared light to obtain cross-sectional images of sub-surface structures of at least partially transparent objects. The major advantage of OCT over other non-invasive tomographic techniques, such as computed (X-ray) tomography, THz imaging or NMR tomography, is its higher axial resolution. The lateral resolution is usually significantly inferior but, importantly, the field of view is large: 1-5 cm2. An obvious drawback, though, lies in the limited transparency of many paint layers to penetration of the infrared beam. However, in the case of examination of easel paintings, OCT is well suited to the imaging of overlaid layered sub-surface structures such as varnishes and glazes, rendering any of their discontinuities and deterioration phenomena, as well as typical alterations, well visible.

The examination of *La Muta* was performed in March 2014 in Opificio delle Pietre Dure in Florence (Figure 1) with a portable ultra-high resolution spectral-domain OCT (SdOCT) tomograph [2]. The system was implemented at the N. Copernicus University in Toruń, Poland for the project CHARISMA within the Seventh Framework Programme of the European Union for the funding of research and technological development. The instrument was designed specifically for examination of objects of art, and equipped with an infra-red light source emitting in a band of 770-970 nm. The intensity of radiation at the painting was not more than 800 µW with the beam scanned over its surface at high speed. The lateral imaging resolution was about 13 µm, whereas the axial one was 3 µm with (an axial) imaging range of 1.4 mm. The distance to the object from the most advanced element of the device was 43 mm, and in a single measurement structural information from an area of (12 × 12) mm^2 was acquired. The instrument is capable of collecting both 2D cross-sections (B-scans) and 3D volume (cube) data. The collection of data for one B-scan takes 0.1 s, and for the cube about 15 s. The interferometric signal is analysed in a

Graphics Processing Unit with laboratory-designed software utilising Compute Unified Device Architecture (CUDA), which is a massive parallel computing platform and programming model, and then converted to images using software written in LabView [3].

Figure 1. Examination of Raphael's La Muta with Optical coherence tomography (OCT) in Opificio delle Pietre Dure in Florence

The OCT cross-sectional images are usually presented in a false-colour scale: cold colours (from dark blue to green) depict areas of low scattering efficiency, while warm colours (from yellow to red and white) represent highly scattering or reflecting structures. Non-scattering media: air above the surface of a painting and clear substances like some varnishes and adhesives, as well as areas not reachable by the probing beam (i.e., below the opaque paint layer), are shown in black. In all of the tomograms presented here, the probing light approaches from the top, and thus the first, strongly reflecting and/or scattering layer is the surface of the painting. It is pointed out that, for better readability and easier interpretation of the images, the depth scale is expanded with respect to the lateral one, as shown by the scale bars. Slices at different depths parallel to the painting's surface were extracted from the cube (3D) data and prepared for presentation in the same false-colour scale. As has been presented before[2] – for

Madonna dei Fusi (attributed to Leonardo da Vinci) – this modality is well suited to the imaging of past overpaintings, especially when they are covered by thick layer of secondary varnish.

The painting *La Muta* was examined at sixteen locations chosen after inspection of high resolution UV luminescence and VIS photographs (provided by OPD). The focus of the OCT examination was on alterations introduced into the painting during past restorations rather than on its primary technique of execution.

Several well-established techniques (e.g., UV-induced fluorescence, IR reflectography, X-radiography) enable imaging of the whole surface of the painting, but without in-depth resolution and with information from lower layers overlapping. The non-invasive acquisition of cross-sectional images of the artwork's structure over a relatively large area makes OCT the tool most especially suited to complementing such methods. Specifically, OCT enables disambiguation of interpretation of photographs of UV-induced fluorescence of the painting. Generally, the strongest fluorescence comes from the aged varnish. If some areas are dark (non-fluorescing), they are thus usually interpreted as due to the presence of an overpainting, since later-applied materials tend to have weaker UV-induced fluorescence than earlier-applied ones. Alternatively, if the shapes of low-fluorescing areas correspond with details of the composition, it is possible that the artist himself used some pigments which influence the UV-induced fluorescence of the binders [4]. However, the OCT examination revealed that this was not the case in the painting *La Muta*. The OCT cross-sections presented in Figure 2 reveal that the varnish layer in questionable locations has an uneven thickness. In areas of weak UV-induced fluorescence such as on the left-hand side of tomogram A and on the right-hand side of tomogram D, there is only one thin layer of varnish, with thicknesses estimated to be 9–11 µm and 10–20 µm, respectively.

The areas of strong UV fluorescence (which is typical for the majority of the surface) correspond to two layers of varnish (well visible in tomogram D), an upper one having a thickness of 20–30 µm, the lower one being only about 10 µm thick. In the case of the location shown in tomogram A, the maximum overall thickness of the varnish is 46 µm, and it corresponds to the strong UV-induced fluorescence visualized in Figure 2C.

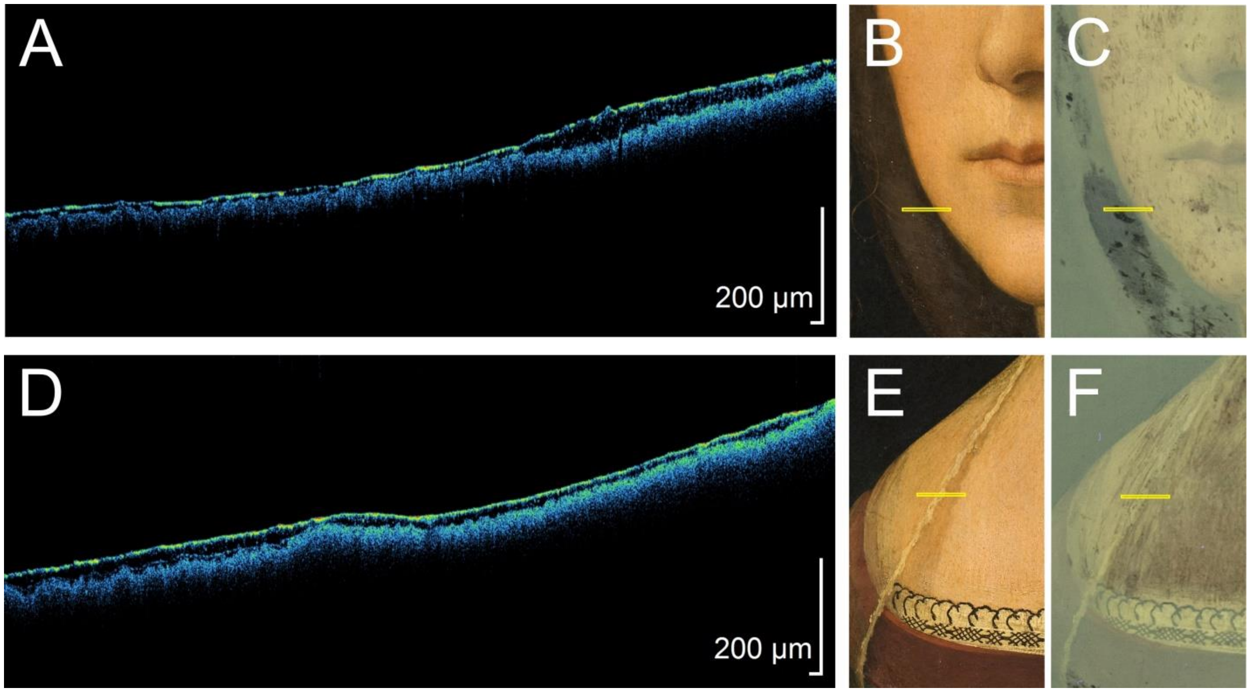

Figure 2. A, D: OCT tomograms of Raphael's La Muta showing local thinning of the varnish layer, visible as dark areas in the UV-induced fluorescence (C, F – respectively). The high resolution photographs (B, E) and UV-induced fluorescence images (C, F) were provided by Opificio delle Pietre Dure.

The OCT cross-section presented in Figure 3 was collected in the area of the red bosom of the dress. The varnish (1) is thin (8–10 µm) and the glaze layer (2) well visible. However, in the centre of the scanned region, a non-transparent overpainting (3) covered by a 15 µm layer of varnish was revealed, both in the cross-sectional view (A) and in the slice image (B). The latter is obtained from the same OCT data cube as the former, and provides additional information on the size and shape of the intervention. It is worthwhile noting that this overpainting/retouching is not easily recognizable in the UV-induced fluorescence photograph (D).

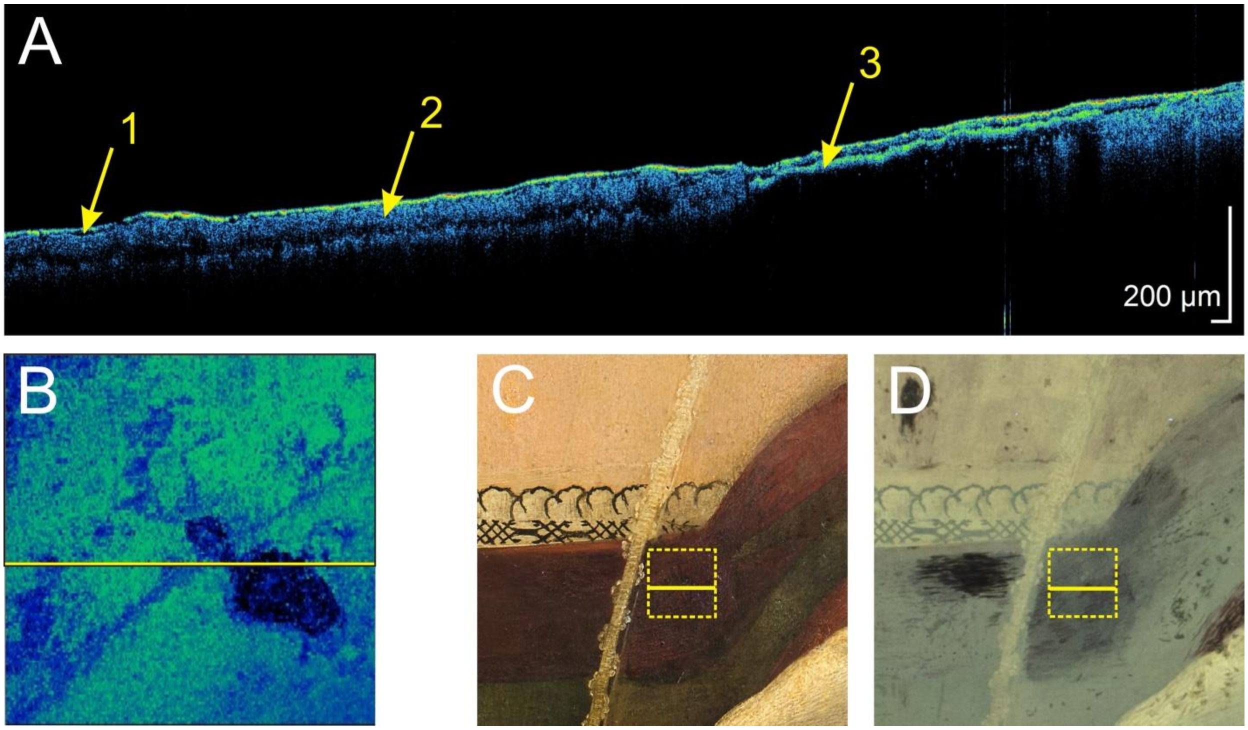

Figure 3. OCT tomogram of Raphael's La Muta showing thin varnish layer (1), glaze layer (2) and overpainting (3) under two (?) layers of varnish. The image (B) was extracted from OCT cube (3D) data and shows the signal from a 5 µm thick slice located 39 µm below the surface of the painting. The high resolution photograph (C) and UV-induced fluorescence image (D) were provided by Opificio delle Pietre Dure.

In conclusion, the OCT examination allowed a more precise description of the state of preservation of the painting, including determination of the thickness and number of layers of varnish as well as revealing the cause of unevenness in the UV-induced fluorescence of some areas. Specifically, as performed in the case of *La Muta*, scanning across the boundaries of areas of different appearance helps in attribution of the feature to a particular layer of the object. With the OCT technique it is also possible precisely to determine the localisation of overpaintings, even if they are not particularly visible in UV-induced fluorescence images due either to being masked by other sources of low fluorescence or to lying under highly fluorescent varnishes. All of these point to the potential of OCT in helping to solve conservation issues more precisely in particular cases where the need arises.

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