Optical Coherence Tomography for non-destructive investigations of structure of easel paintings

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ABSTRACT

In this contribution the application of Optical Coherence Tomography (OCT) for non-invasive structural imaging of easel paintings will be presented. Since the technique permits imaging semi-transparent layers accessible for infrared light, the varnish and glaze layers are usually under investigation. The major emphasis will be laid on application of OCT to resolving specific conservation problems, arising during the restoration process. The examples of imaging multi-layer varnishes and subsequent alterations will be given and the application of these images for authentication of inscriptions will be discussed. Since the thickness of imaged layers may be directly measured with OCT in completely non-destructive, quick and convenient way as many times as necessary, the application of the technique to generation of varnish thickness maps will be presented.

Keywords: structural imaging, Optical Coherence Tomography (OCT), artwork, easel painting

1. INTRODUCTION

Non-invasive methods for examination of objects of art have been in focus of interest of conservators and art historians since over a century – X-rays were used for inspection of underneath layers of paintings [1] by Toepler in 1895, shortly after being discovered. At present many other methods, also often originating from medicine, are used for non-invasive examination of objects of art. In addition to standard radiography, 3D imaging with an aid of computed tomography (CT) is used in examination of various art objects successfully. However the resolution offered is not sufficient for examination of paintings. Among other methods X-ray fluorescence [2], neutron-induced autoradiography [3], high-energy proton-induced X-ray emission (PIXE) [4] and most popular IR reflectography should be mentioned [5]. Unfortunately, these methods lack in-depth resolution: although they permit identification of certain components of the object, it is not possible to determine to which of thin layer of the painting they belong.

Optical Coherence Tomography (OCT) utilises infrared light for non-invasive structure examination of weakly absorbing objects and has been under consideration for the examining of objects of art since 2003 [6]. In this case the in-depth (axial) resolution is obtained by means of interference of light of high spatial (to ensure sensitivity) and very low temporal coherence (to ensure high axial resolution). In practice, IR sources of bandwidths from 25 to 150 nm are utilised. Resolutions obtained ranges from 15 down to 2 μm in the media of refracting index equal 1.5.

The obvious limitation of the method lays in the transparency of investigated medium to infrared light [7-8]. Therefore OCT is mostly used for the examination of transparent and semi-transparent structures like varnishes and glazes in easel paintings [9-11]. It is possible to measure thickness of these layers non-invasively in as many places as desired. If the axial resolution permits, the superimposed layers of different varnishes (e.g. retouching and original) can be discerned. The method may be also used for identification of position of certain pigmented layers, like signatures, within the varnish-glaze structure [12]. The penetrating power of the infrared light in combination with the high contrast of coherent imaging was also successfully used to imagine underdrawings [10]. Recently the high resolution OCT instrument was utilised for revealing the surface details of varnished punchwork [13]. Among other applications an increasing attention is given to imaging of the structure

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of both archaeological and stained glass [8,14]. In this case, when investigated objects are well preserved, taking samples is not possible. OCT permits non-invasive inspection of their internal structure, including the range of corrosion processes.

Another interesting application for imaging of internal structures of archaic jades was described in 2004 [15] but not developed further unfortunately. Other objects investigated with OCT were samples of parchment with iron gall ink [16] and porcelain and faience (glaze layer only) [17].

High speed variation of OCT technique permits real-time imaging of certain conservation process like varnish laser ablation [14,18] and tracking deformation of paintings caused by unstable environmental conditions [19].

2. METHODOLOGY

All tomograms to be presented have been obtained with a prototype Spectral OCT instrument based on an optical fibre Michelson interferometer set-up, constructed at the Nicolaus Copernicus University in Toruń (Poland). The instrument of axial and transverse resolutions of 9 µm and 15 µm respectively, utilises a broadband ($\Delta\lambda$ = 50 nm, central wavelength 845 nm) superluminescent diode as the light source. The infrared beam of high spatial but low temporal coherence is divided into two signals with equal amplitudes by the fibre coupler. This two beams propagate in two arms of the interferometer: a reference and an object ones. The reference arm comprises a polarization controller which provide optimal conditions for interference, a neutral density filter for adjustment of the power of light to achieve the shot-notice-limited detection, a block of glass acting as a dispersion compensator and the stationary reference mirror. The object arm comprises transversal scanners (X-Y) responsible for scanning across the sample and a lens focusing the probing beam on a sample. The light beams: back-reflected from the reference mirror and backscattered or/and reflected from the element of object's structure return to the coupler and interfere. To protect the light source from the back reflected light an optical isolator is inserted between the source and the coupler. To collect the interferometric signal a custom-design spectrometer is utilised. It comprises a volume phase holographic grating with 1200 lines/mm and an achromatic lens which focuses the spectrum on a 12 bit single line CCD camera (2048 pixels, 12 bit A/D conversion). The spectral fringe pattern registered by this detector is then transferred to the personal computer. This signal after the Fourier transformation yields one line of the cross-sectional image (A-scan). Scanning across the sample with transversal scanner (X-Y) enables collecting a 2-D cross-sectional image (B-scan). Additional scanning in the perpendicular direction gives 3-D information about the spatial structure of the sample.

3. RESULTS

The first example under consideration is an oil painting on canvas of unknown origin entitled Virgin and Child (Fig. 1). The picture is well preserved and thus the opportunity of sampling is strictly limited. The problem to be resolved was the authenticity of a thick and uneven brown glaze layer applied in some areas of shadows with characteristic beads-like structures on its surface. To investigate this, a series of OCT tomograms has been collected.

Fig. 1. ‘Virgin and Child’ – oil on canvas. Letters correspond to macrophotographs in Fig. 2

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In Fig. 2 exemplary tomograms are shown in an upper row, whereas corresponding macrophotographs in the bottom indicate the fragments of the painting where examination was carried out. In the tomogram in Fig. 2a the brightest line (first from the left) indicates picture's surface. In the highlight area of the painting (upper part of the tomogram) a low-scattering varnish layer is clearly visible as a darker band directly underneath the surface line. In the area of shadow (bottom of the tomogram) this structure is not recognizable. Instead, a thick moderately scattering layer of different optical properties is visible directly under the surface. Beneath this layer, a thin transparent layer (possibly original glaze or varnish) is discernible. Similar structure and sequence of layers can be seen in Fig. 2c, although the image was recorded in a different area of the picture. In both cases tomograms suggest that the uppermost thick layer present in shadows may be not original as it is not covered with varnish layer observed in the areas of highlights. On the contrary, the structure of painting registered at the Child's eye (Fig. 2e) that seems to be original, is clearly different: the thick semi-transparent layer in dark parts is not present. Both lights and shadows are homogeneously covered with a continuous varnish layer. Additionally, in shadows an extra glaze layer beneath the varnish is clearly visible.

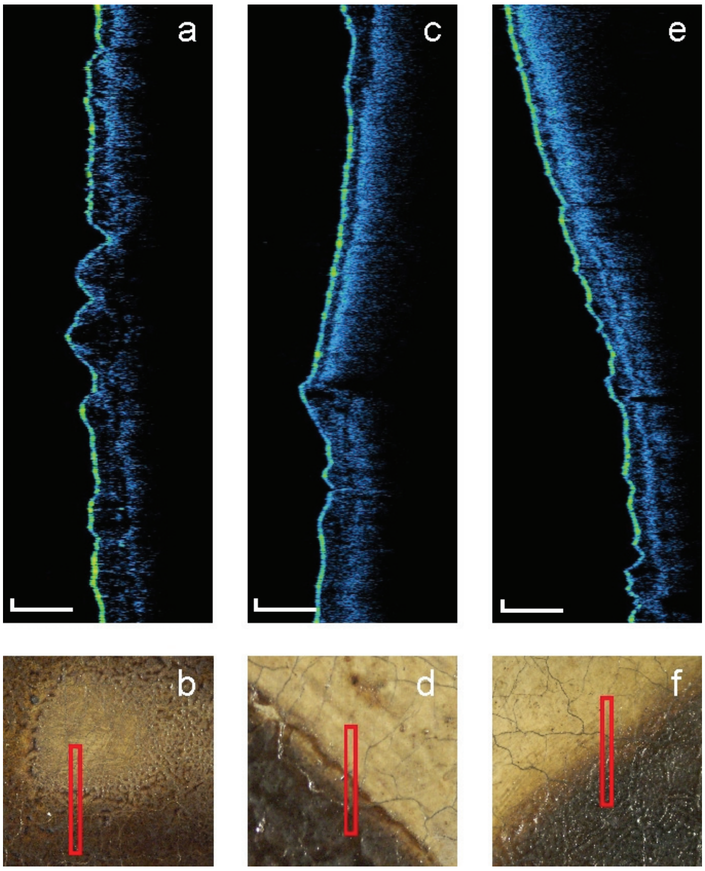

Fig. 2. (a) OCT tomogram from the Child's leg and its location (b); (c) OCT tomogram of the Child's hand and its location (d); (e) OCT tomogram of the Child's eyebrow and its location (f). Bars indicate 200 µm

The analysis of all tomograms leads to a conclusion that in the painting examined there are at least two different types of outward layer in shadows: one thick and pigmented – present at some areas of deep shadows at the Virgin and Child's figures, and another one, thin, transparent (like a varnish) covering a separate dark glaze layer together with highlights of the painting present at areas of models' complexions.

Further two examples origin from the different picture. In this case the microscopic analysis of the cross-section of the sample taken from the painting (Fig. 3a) was suggested the presence of multi-layered varnish. With the OCT technique up to 4 varnish layers have been confirmed in many places, all over the painting (Fig. 3b). This information is important for planning of future conservation/restoration procedure and suggests that the picture underwent many treatments in the past.

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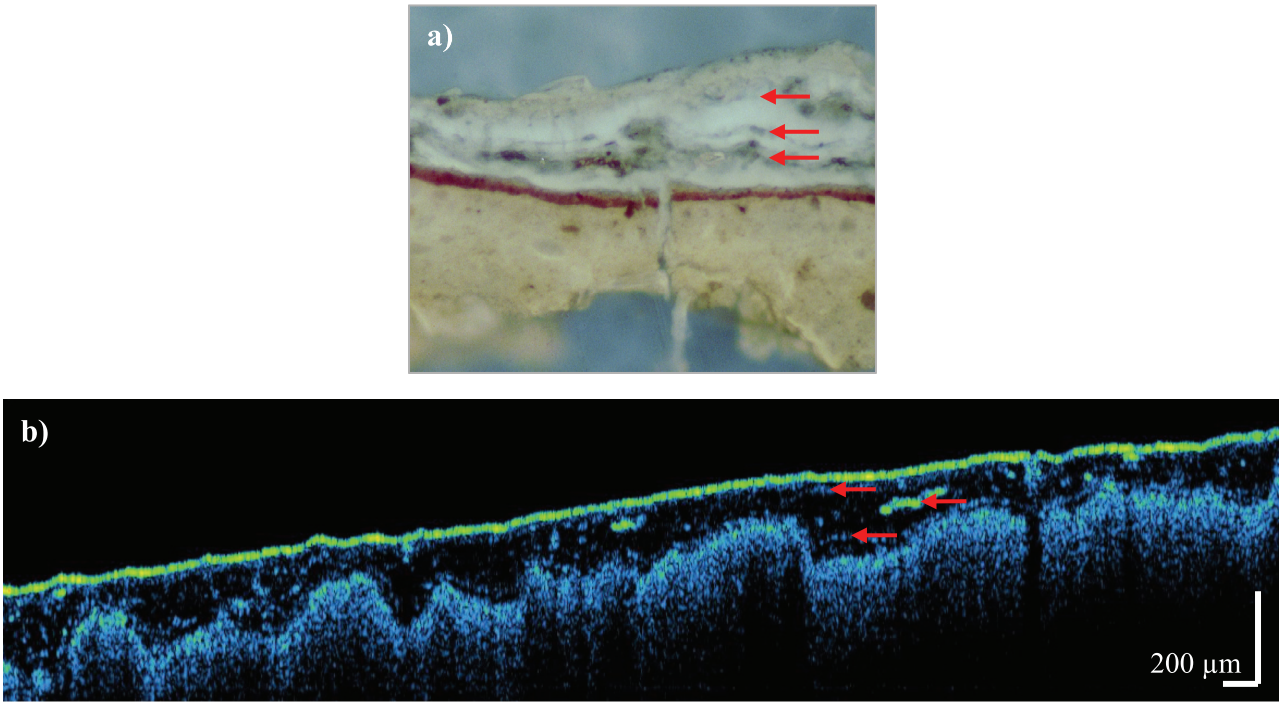

Fig. 3. Example of the multi-layered varnish over the paint layer: (a) microphotograph, UV excited fluorescence; (b) OCT tomogram. Arrows point to interfaces between consecutive varnish layers

Except multiple varnishing some areas of this painting were over-painted. In raises the question of the authenticity of inscriptions present in this picture. To dispel this doubts the stratigraphy of the object in the place of inscription must be identified. The routine method is to collect a sample and investigate its cross-section under microscope. However sampling in the area of any inscription (especially author's signature) is very undesirable and often impossible. In such a case the non-invasive OCT examination may be the method of choice. It can be used if the upper paint layer is transparent enough to IR to reveal the underneath structure. Such a case is presented in figure 4. As it is clearly seen from the OCT tomogram, in this case the inscription is located over the varnish covering the old paint layer, and thus it was added after the whole painting was finished.

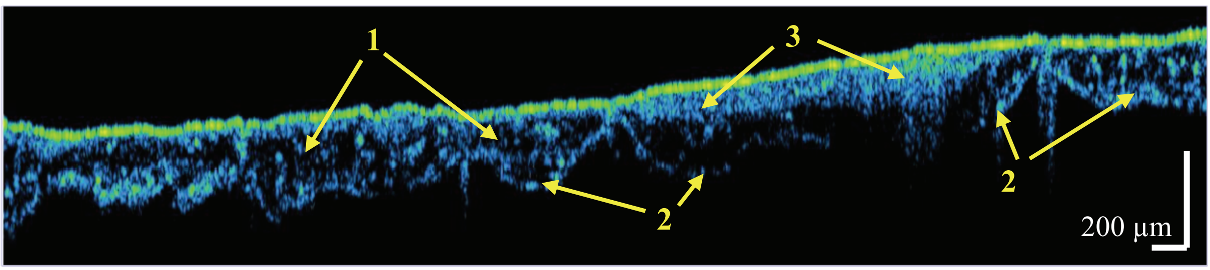

Fig. 4. Example of the inscription (arrow) located over the old paint layer: (1) varnish layer, (2) paint layer under varnish, (3) inscription painted over the original varnish-paint layer structure

In addition to collecting single 2D images (Fig. 2 to 4) the instrument used in this study is also capable of accumulating a series of parallel slices (B-scans). These slices may be then combined together to obtain 3D (volume) information of the examined sample. In the case of data presented in Fig. 5, 200 parallel B-scans were collected over 15 x 15 mm area of varnished paint layer. Then the automatic edge recognition procedure was used at every B-scan to localise the picture

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surface and subsequently the boundary between varnish and paint layer. From these data the varnish thickness may be easy calculated and combined into the false colour map (Fig. 5b). As one can see from the tomogram, the shape of both surfaces is distorted somehow by optical aberrations. However, the thickness data, as a differential result, are free from this artefact.

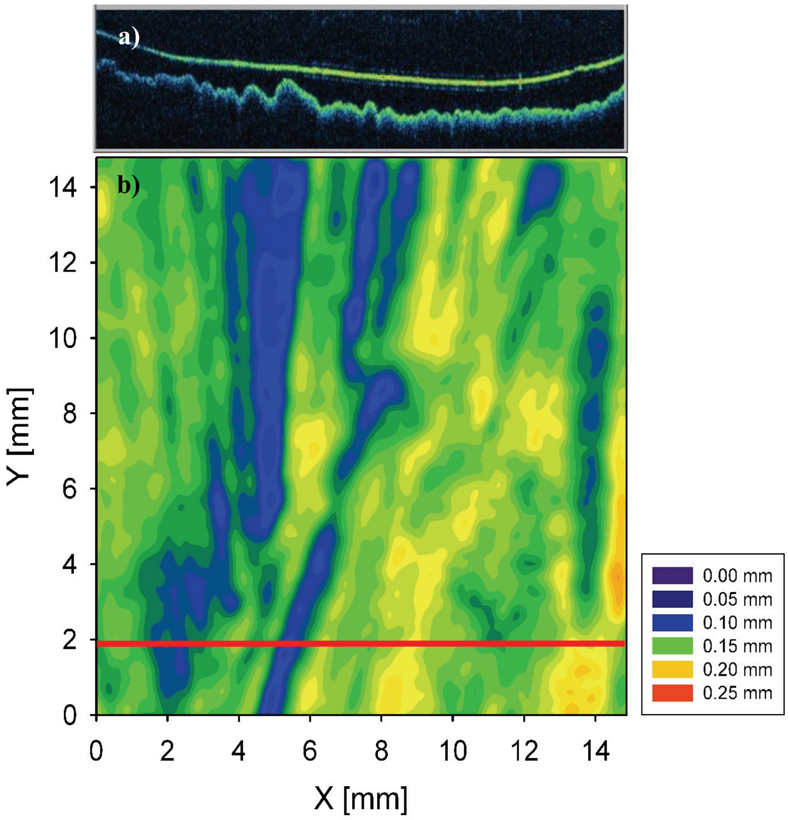

Fig. 5. (a) One of 200 OCT tomograms of the varnish layer over the fragment of oil paint; (b) a thickness map of the varnish layer obtained from a series of tomograms. The thickness is coded in false colours, red line indicates position of the tomogram shown in figure a

Data presented in Figure 5 illustrate significant heterogeneity of the varnish layer: within this small area thickness varies from 0.1 to 0.25 mm and the brush strokes of paint layer levelled by varnishing are clearly visible. The advantage of non-invasive OCT measurements over usual technique utilising a microscopic analysis of the cross-section of the sample collected from the picture is thus evident. It is never possible to take so many samples and thus the information obtained is not representative. The OCT examination is fast, relatively inexpensive and may be repeated as may times as necessary due to its non-invasive character. Therefore results obtained with this method are much more reliable.

4. CONCLUSIONS

Optical Coherence Tomography when used to examination of easel paintings may be helpful in determination of the structure of its outward, semi-transparent layers. Since the method may be applied many times and at many locations, the information gained is more representative than obtained from traditional sampling. However, for the univocal identification of structures imagined, it is recommended to compare tomograms with a microphotograph of a cross-section of the sample taken in painting's region allowed by conservation ethics. In certain cases, when the identification of clear varnish layer is obvious, the method may be used with strong confidence even without sampling, also for monitoring of restoration treatments concerning this layer.

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