

Chapter 4

Optical Coherence Tomography (OCT) for Examination of Artworks



Magdalena Iwanicka, Marcin Sylwestrzak and Piotr Targowski

1 Introduction and Apparatus

1.1 Fundamentals of OCT Technique

Optical coherence tomography (OCT) is an optical interferometric technique originating from diagnostic medicine at which it is a well-established method [1, 2]. Relatively early after its invention OCT was used for the examination of artworks: this application is reported in the literature since 2004 [3]. It uses light of very low temporal coherence (broad spectrum) in order to provide high in-depth resolution and simultaneously of high spatial coherence to ensure high sensitivity. There are many configurations in use: in the most common one a Michelson interferometer is utilised with a broadband infrared light split between an object beam and a reference beam. The narrow object beam penetrates the examined artwork and is reflected or scattered at its internal features. After returning to the instrument it is superimposed with the reference beam, and thus the interference signal is obtained. It may be detected spectrally (Fourier domain systems with the constant length of the reference arm of the interferometer) or temporarily at the single detector (time domain system with the variable length of the reference arm). A list of applications of optical coherence tomography to the investigation of various cultural heritage objects can be found elsewhere [3–5].

For examination of the objects presented in this study we have used the system designed and built especially for the examination of cultural heritage objects under 7FP Charisma project at N. Copernicus University in Torun, Poland. It is a Fourier

M. Iwanicka (✉)

Faculty of Fine Arts, Nicolaus Copernicus University, Torun, Poland

e-mail: magiwani@gmail.com

M. Sylwestrzak · P. Targowski

Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University,
Torun, Poland

© Springer Nature Switzerland AG 2018

D. M. Bastidas and E. Cano (eds.), *Advanced Characterization Techniques,*

Diagnostic Tools and Evaluation Methods in Heritage Science,

https://doi.org/10.1007/978-3-319-75316-4_4

domain OCT instrument with a spectrograph used as a detector. As a light source the instrument utilises superluminescent multi-diode emitting in band 770–970 nm providing the beam intensity up to 800 μW at object. This irradiation level is considered non-invasive even for light-sensitive materials. In practice, the ability to differentiate thin layers is denoted by the axial (in-depth) resolution, which equals ca 2.2 μm (in material of refractive index equal to about 1.5). Lateral resolution (the ability to differentiate between structures occurring close to each other in lateral plane) is about 13 μm . These features make our instrument especially well-suited for the examination of thin-layered structures, such as easel paintings. The axial imaging range is 1.7 mm and sensitivity 98 dB. The distance to the examined object from the most protruding element of the device is 43 mm and the structural information from the area up to $17 \times 17 \text{ mm}^2$ may be acquired in one measurement. Data collection time for one 2D cross-section (B-scan) is 0.15 s. Two standard video cameras enable the precise documentation of the position of examined area at the object.

Nowadays, the requirement for non-invasiveness of examination techniques (not interfering with the substance of the artwork in any way) is an important issue in conservation science. There have been no systematic studies on this matter regarding OCT, although it may be assumed that the intensity of the probing beam proclaimed safe for the human retina (according to the American National Standards Institute regulations [6]) may be considered safe for any kind of artwork.

Additionally, OCT provides better representativeness of results (in comparison to traditional, invasive sampling methods) due to the fast data collection and no need for any special object preparation (Fig. 1). Usually sampling is permitted only to spots where some damage has occurred previously or, in case of easel paintings, areas of lesser visual importance. OCT provides structural information from the spots which cannot be sampled, and, in cases when sampling is still required, helps to limit it to few representative spots.

Unfortunately, the diversity of objects being within a circle of interest is in case of OCT limited by the properties of the materials constituting the artwork. The major limitation of what may be examined with OCT lies in the transparency of subsurface structures of the object [7, 8] to infrared radiation. This drawback practically excludes some areas of objects or even whole groups of objects. For example, within the same painting one may find areas with paint layers permeable for OCT radiation and enabling deeper imaging, whereas in other spots only the transparent varnish layer is discernible in the tomogram. It has to be noted, however, that some objects that are in principle not permeable for infrared, had been to certain extend examined with success; such examples are stones [9, 10] and wall paintings [11].

Additionally, raising sensitivity of modern Fourier domain instruments results in gradual increasing of the number of accessible objects.



Fig. 1 An in-situ examination of Raphael's *La Muta* in 2014 at Opificio delle Piere Dure in Florence, Italy with the portable OCT tomograph constructed at Nicolaus Copernicus University in Toruń

1.2 Interpretation of the Tomograms

The OCT results are usually presented as cross-sectional views, although some other post processing of the data enables revealing additional features of the object.

The structure of the examined object is shown in a false colour scale: warm colours correspond to high scatter/reflection of the probing light, whereas cold colours mark areas with low scatter. Transparent media (e.g. clear varnishes, glass or air above the surface of the examined object) or areas located beyond the range of penetration are shown dark. The ‘strongest’ line is usually the air-artwork interface with semi-transparent layers underneath.

It is important to note that the distances along the probing beam are seen in OCT as optical ones. Therefore, to measure true axial distances within the structures in the object (e.g. the layers’ thicknesses) one has to divide a distance obtained with the scale bar by the refractive index of the material (for most painting materials ca 1.5). Additionally, since the OCT scans tend to cover a relatively large area (up to 15 mm²), the axial (in-depth) scale is elongated comparing to the lateral one.

1.3 Additional Post-processing of OCT Data

If series of 150 adjacent scans is collected over an area, they comprise a 3-D cube of data points, which can be further processed with the technique called *gate imaging* described in detail elsewhere [12]. In brief: the slice of voxels of a given thickness (*gate width*) can be extracted from the data cube at a given depth (*gate depth*), always parallel to the surface of the painting and thus independently of its tilt. The ‘slice’ is averaged and presented in the false colour scale in a form of a 2-D *en face* image (map). This mode of data presentation is in many cases of a great help, e.g. for imaging of the retouchings and overpaintings [12], showing the pattern of internal cracks, delaminations or other structures located within a thick layer of varnish [13, 14]. In some cases, the parameters of canvas (thread count) may be recovered from its imprint in the paint layer [12], which can be especially useful for the paintings which had been lined or transferred in their past and therefore there is no direct access to the original canvas. The imaging of underpaintings is also possible with the quality of the image superior to the standard IR reflectography [15].

2 Exemplary Results of Examination of Artworks

2.1 Objects of Craftsmanship

In many decorative techniques semi-transparent paints or lacquers were used to obtain three dimensional visual effects. For instance, Japanese *nashiji* technique (imitated in 18th–19th c. Europe under the name of *aventurine lacquer*, or *mor-aqqash* in Islamic art) is based on embedding metal (usually gold) flakes in-between two layers of lacquers [16, 17]. OCT gives direct insight into the technology of making of such an object (Fig. 2).

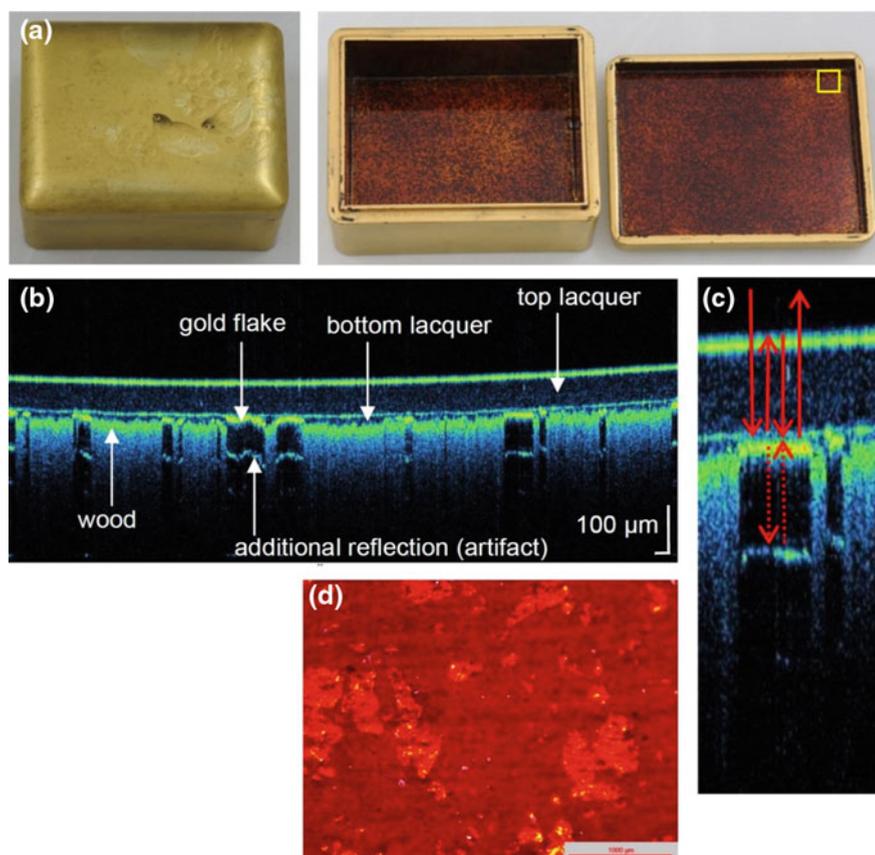


Fig. 2 **a** Gilded wooden box decorated with depictions of quails and herbs, Japan, 19th/20th c., District Museum in Torun, inv. MT/DW/392. Inside of the box and the lid is decorated in nashiji technique. **b** OCT tomogram and **c** tomogram fragment, from the lid (see text for explanation). **d** microscopic image of the inside of the lid

Top layer of lacquer is easily recognizable and its thickness (under $100\ \mu\text{m}$) and magnificent homogeneity may be assessed. Bottom lacquer layer (onto which the gold flakes had been sprinkled) despite of being relatively thin (ca $15\ \mu\text{m}$) makes a smooth surface over the roughness of wood. Wooden support is non-transparent to OCT imaging, however since it scatters the probing light, time of returning of the signal to the OCT instrument varies, which creates the effect of ‘fading’ of OCT signal in the tomogram. Gold flakes are basically also non-transparent to the infrared radiation, however since they reflect the probing beam strongly instead of scattering it, due to multiple reflection of light between the gold and the surface of the upper lacquer an artificial ‘interface’ is visible beneath the gold flake (Fig. 2c).

Apart from providing knowledge on the technology and layers’ build-up OCT can be a useful tool for fast assessing of the artwork’s state of preservation.

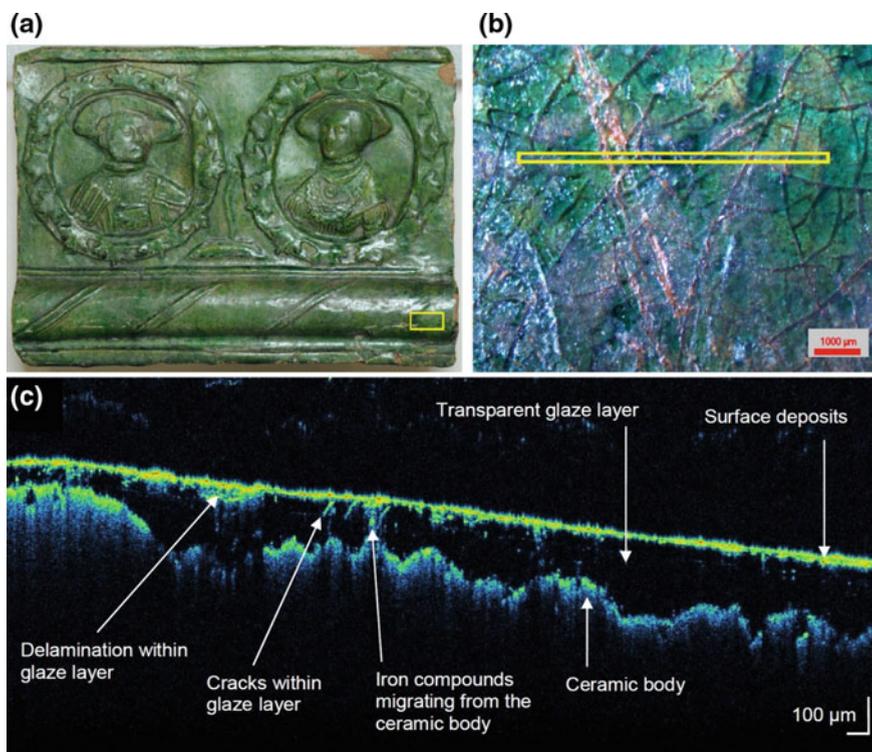


Fig. 3 **a** Ceramic tile, engobe, lead-based, copper-tinted glaze, Torun, 16th c.?, District Museum in Torun, inv. MT/ZK/1065, yellow rectangle marks the location of the microscopic image. **b** Microscopic image of the scanned area, yellow line marks location of the presented tomogram. **c** OCT tomogram

Revealing of many destruction phenomena within the subsurface layers is possible provided that the materials are semi-transparent to near infrared radiation. Transparent and semi-transparent glazes on ceramic objects (Fig. 3c) may be investigated in terms of its thickness and production faults (like air bubbles). Also time-related cracks and delaminations are easily recognised due to the large leap of refractive index between air and lead glass which constitutes the glaze. Semi-transparent dirt deposits on the surface (right-hand side of the tomogram in Fig. 3c) scatter and partially absorb the OCT beam, but, in this case, do not hinder the visibility of the ceramic body underneath the glaze. It is worth to note that OCT can be of use in planning conservation-restoration of such artefacts, through both identification of fragile spots and direct monitoring of the cleaning treatments [18].

More subtle phenomena like, for instance, migration of iron compounds from the ceramic body to the bulk of the glaze (through fine cracks) can be understood thanks to the precise localisation of the examined spot, direct comparison of the tomogram with a microscopic photograph, and, last, but not least, taking into

consideration the history of the object. In this case, the investigated tile was found among many other similar items on the archaeological site of the Teutonic Order Castle in Toruń during the excavation works in 1958–66. The castle ruins had been used as a wasteyard for the whole old city area since the middle 15th c., when the castle was demolished, up to late 19th century, the ceramic objects were therefore subjected to contact with water, earth and mineral depositions.

2.2 *Easel Paintings*

Since most pigments are non-transparent to infrared radiation when applied in thick layers, practical applicability of OCT to conservation of paintings lies in the imaging of superficial secondary layers rather than in resolving the painting technique of the artist. Information on the build-up of varnish layers (which are usually secondary and often multiple in number) and/or overpaint layers added during some past renovations is crucial for planning of modern restoration treatment.

In some cases optical coherence tomography may also help in authentication of the painting, usually as a complementary tool for some spectroscopic analyses. An interesting example of such an approach is resolving of the sequence of layers in the 17th c. Dutch still life painting, signed J. Walscapele (Fig. 4a). The painting had been in the past subjected to many renovation/restoration treatments. Their effects were obscured by the already aged, yellowed and deteriorated varnish of strong UV-induced fluorescence (Fig. 4b). However, macro-XRF scanning revealed the presence of pigments not used earlier than 19th c.: of zinc and barium white in all the highlights (Figs. 4c and 5e) as well as chromium green (in the area of the tablecloth). Apart from the abovementioned areas the other pigments identified were typical for the 17th c.: calcium based ground, lead white, vermilion, copper based green, ochres and umbers [19].

OCT data were collected in 20 areas which were showing the presence of zinc/chromium. In most of the examined spots a highly scattering, yet infrared-permeable layer was found between the varnishes. It seemed highly probable that it was a 19th c. overpainting. To confirm this hypothesis the microsample (Fig. 4d, e) was collected from the lower edge of the composition (from a perimeter of a paint-loss) as a reference for interpretation of the OCT data. The observation of the cross-section in visible light and under ultraviolet illumination (Fig. 4d, e) confirmed that the secondary paint layer, in this case—dark green (marked 6 in Fig. 4d, e, f) is located between the varnishes.

Also it is a good example of how some layers differ in the photograph and OCT. Two varnish layers on top (7 in Fig. 4d, e, f) are well discernible in OCT (in all examined spots), whereas they are barely visible at the edge of the sample. Such problems may stem from various causes. First of all, OCT is sensitive to leap of refraction index between the layers as well as the presence of dirt, which acts as a light-scattering agent; in such cases the layers are well discernible in OCT tomograms. However, if they are too thin (under ca 3 microns) they will not be seen as

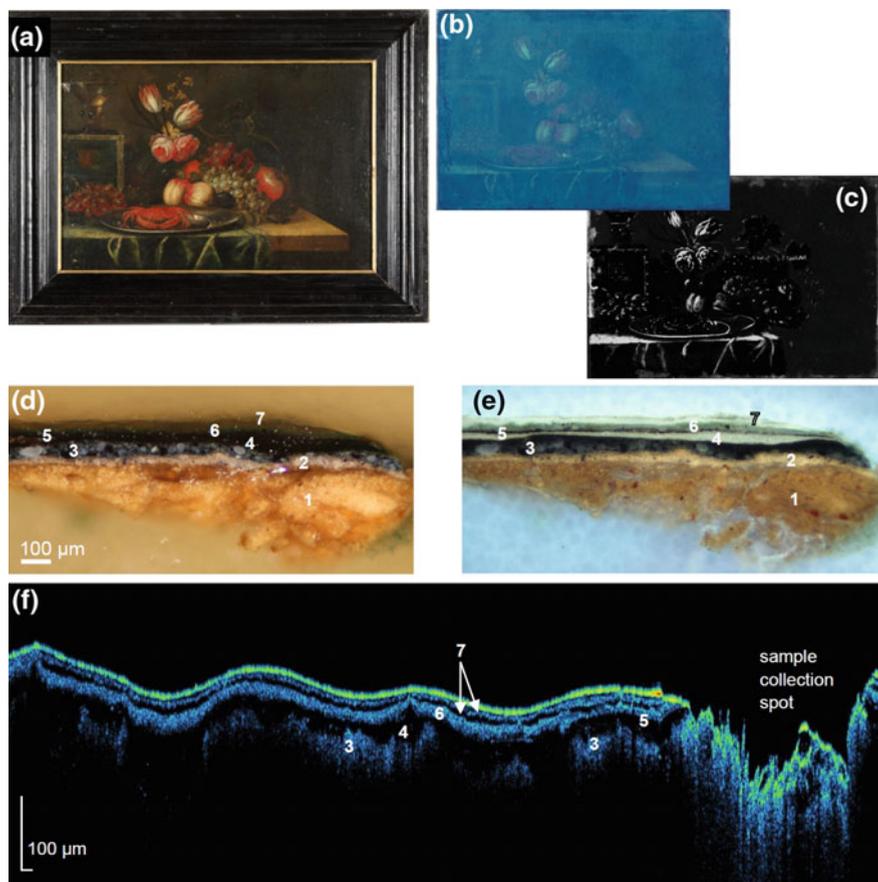


Fig. 4 *Still life with a crab*, Jacob van Walscapelle, 17th c., oil on canvas, 41 × 59 cm, Museum of Warmia and Mazury in Olsztyn. **a** Visible light; **b** UV-induced fluorescence; **c** macro-XRF scan (M6, Bruker Corporation) of the whole picture showing distribution of zinc; **d**, **e** microphotographs of a cross-section of a sample collected from the area of a green tablecloth near the lower edge of the painting: visible light (**d**) and UV-induced fluorescence (**e**), magnification 100×. Description of layers: (1) ground layer, (2) underpaint, (3) blue paint layer, (4) primary varnish, (5) superficial dirt, (6) green paint layer (secondary); (7) two varnish layers. **f** OCT tomogram from the perimeter of sample collection spot, the numbers correspond to the layers identified in the sample (Fig. 4d, e)

separate ones. On the other hand, also the technique of preparation of cross-samples has some drawbacks—e.g. some varnishes are easily dissolvable in embedding resin or, if they are brittle and therefore susceptible to delamination during sampling and embedding.

It is also important to note that although the information provided by the OCT data is restricted to superficial layers and doesn't show true colours, the single scan

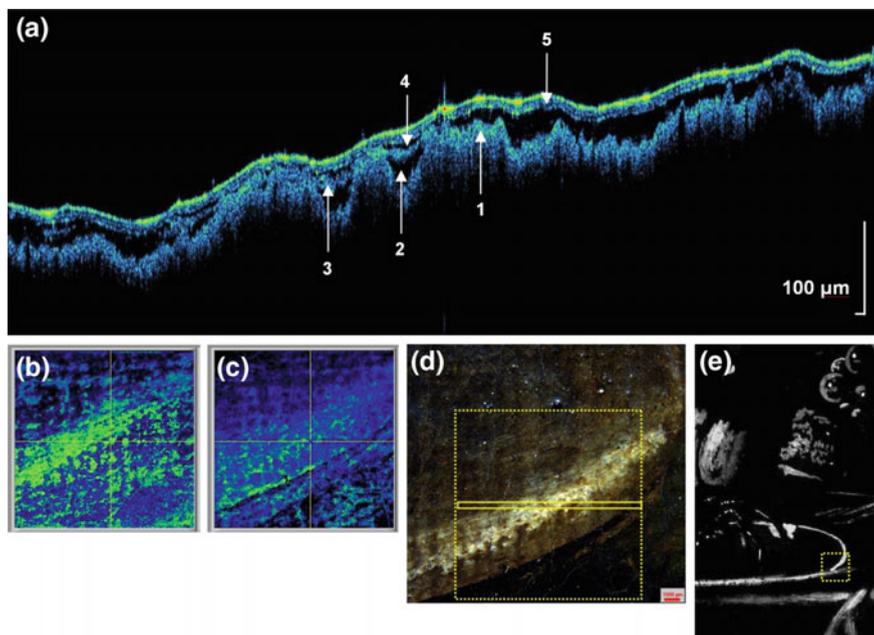


Fig. 5 *Still life with a crab*, Jacob van Walscapelle. **a** OCT tomogram from the area of the rim of the silver plate. Description of layers: (1) primary paint layer, (2) varnish, (3) zinc-rich (secondary) paint layer, (4) varnish, (5) two varnish layers; **b**, **c** coherence gate images—**b**: 19 μm gate depth, 7 μm gate width, **c**: 66 μm gate depth, 7 μm gate width; **d** macrophotography of the examined area, with dashed square marking the scanned area and yellow line marking the location of the tomogram; **e** macro-XRF scan (fragment) showing distribution of zinc, dashed square marks the scanned area

covers much larger area than the sample and therefore the OCT results are more representative.

A common approach is to use the information obtained through minimal sampling to interpret the results of multiple non-invasive analyses. In case of the Walscapelle painting it proved feasible since the good state of preservation of the painting in its central part had excluded further sampling. However, the OCT data collected in zinc-rich areas of highlights (Fig. 5) enabled to precisely locate the zinc-containing layer (3 in Fig. 5a, bright green colour in Fig. 5b) within the whole painting's structure: it is lying between the varnish layers. This conclusion was additionally confirmed by the gate imaging technique (Fig. 5b, c). The highlight on the rim of the silver plate (Fig. 5d) consists of a paint layer lying 19 μm beneath the surface of the painting (Fig. 5b), on top of varnish layer. At the depth of the primary paint layer, 66 μm under the surface (Fig. 5c) there is no paint layer in this shape. To conclude, in the case of *Still life with a crab* the synergistic use of structure analysis (by OCT) and surface-mapping (by means of macro-XRF) enabled resolving both the range, amount and time of renovations of the painting.

3 Conclusions

Optical coherence tomography (OCT) is a non-invasive technique of structural analysis of objects partially transparent to infrared radiation. In this chapter we have presented the results of its successful use for establishing sequence and thickness of transparent or semi-transparent layers as well as deterioration phenomena and secondary coatings in varnished wooden object of craftsmanship, glazed ceramic tile and an easel painting. In the latter case, thanks to the *gate imaging* data post-processing, visualisation of the pattern of overpaintings located within the object's structure was possible.

The other reported applications for cultural heritage objects involved examination of wall paintings [11], paintings on glass support [20], stained glass [21], semi-precious stones such as jade [22, 23] and amber.

Another important application of OCT lies in its potential to monitor the conservation process: removing of secondary layers [24] as well as the consolidation treatment [25] may be observed and evaluated in fast and convenient manner.

Acknowledgements The authors would like to thank Mrs. Alina Targowska and Mrs. Romualda Uziembło from the District Museum in Toruń as well as Mrs. Iwona Kluk from the Museum of Warmia and Mazury in Olsztyn for providing objects for examination.

This research has been co-financed by H2020 IPERION CH project (contract number: 654028) and conducted with use of the research infrastructure of Interdisciplinary Centre for Modern Technology of N. Copernicus University in Toruń, Poland, financed by Regional Operational Programme for Kujawsko-Pomorskie Voivodship (Project No.: RPKP.05.04.00-04-001/10).

References

1. Drexler W, Fujimoto JG (eds) (2015) Optical coherence tomography: technology and applications, 2nd edn. Springer, Berlin, Heidelberg, New York
2. Wojtkowski M (2010) High-speed optical coherence tomography: basics and applications. *Appl Opt* 49:D30–D61
3. Complete list of papers on application of OCT to examination of artwork may be found at <http://www.oct4art.eu>: Optical coherence tomography for examination of works of art, Accessed 15 Nov 2018
4. Targowski P, Iwanicka M (2012) Optical coherence tomography: its role in the non-invasive structural examination and conservation of cultural heritage objects - a review. *Appl Phys A* 106:265–277
5. Targowski P et al (2015) OCT for examination of artwork. In: Drexler W, Fujimoto G (eds) Optical coherence tomography. Technology and applications, Springer, Cham, Heidelberg, New York, Dordrecht, London, pp 2473–2495
6. American National Standard for Safe Use of Lasers: ANSI Z 136.1 - 2007, Orlando: Laser Institute of America, 2007
7. Liang H et al (2013) Optimum spectral window for imaging of art with optical coherence tomography. *Appl Phys B* 111:589–602

8. Szkulmowska A et al (2007) Applicability of optical coherence tomography at 1.55 μm to the examination of oil paintings. In: Nimmrichter J, Kautek W, Schreiner M (eds) *Lasers in the conservation of artworks*. LACONA VI proceedings, Vienna, Austria, 21–25 Sept 2005, Springer, Berlin, Heidelberg, New York, pp 487–492
9. Bemand E et al (2011) OCT and NMR for non-invasive in-situ monitoring of the vulnerability of rock art monuments. *Proc SPIE*, 8084, 80840H-1-40H-8
10. Bemand E, Liang H (2013) Optical coherence tomography for vulnerability assessment of sandstone. *Appl Opt* 52:3387–3393
11. Striova J et al (2016) Optical devices provide unprecedented insights into the laser cleaning of calcium oxalate layers. *Microchem J* 124:331–337
12. Targowski P et al (2013) OCT structural examination of Madonna dei Fusi by Leonardo da Vinci. *Proc SPIE* 8790:87900N
13. Adler DC et al (2007) Comparison of three-dimensional optical coherence tomography and high resolution photography for art conservation studies. *Opt Express* 15:15972–15986
14. Iwanicka M et al (2016) On the application of optical coherence tomography as a complimentary tool in an analysis of the 13th century Byzantine Bessarion Reliquary. *Microchem J* 125:75–84
15. Liang H et al (2005) En-face optical coherence tomography—a novel application of non-invasive imaging to art conservation. *Opt Express* 13:6133–6144
16. Japanese art and design: a glossary, <http://www.vam.ac.uk/content/articles/j/japanese-art-and-design-a-glossary/>. Accessed 15 Nov 2018
17. Muzeum für Lackkunst - The ABC of Lacquer, http://www.museum-fuer-lackkunst.de/en/abc_of_lacquer. Accessed 15 Nov 2018
18. Iwanicka M et al (2017) The potential of OCT for assessing laser assisted removal of deposits from ceramic tiles. In: Targowski P, Walczak M, Pauli P (eds) *Lasers in the conservation of artworks XI*. Proceedings of the international conference LACONA XI, 20–23 Sept 2016. NCU Press, Torun, PL, pp 105–114
19. Iwanicka M et al (2016) Combined use of optical coherence tomography and macro-XRF imaging for non-invasive evaluation of past alterations in 17th c. Dutch painting. In: Proceedings of 2nd international conference on art & archaeology 2016: art and archaeology strengthened by measurement techniques, 11–14 Dec 2016, Jerusalem, Israel. <https://art2016.isas.co.il/wp-content/uploads/sites/10/2017/03/Session-I-Minerals-Pigments-Dyes-3-Iwanicka.pdf>. Accessed 15 Nov 2018
20. Iwanicka M et al (2011) Through-glass structural examination of Hinterglasmalerei by optical coherence tomography. In: Radvan R, Asmus JF, Castillejo M, Pouli P, Nevin A (eds) *Lasers in the conservation of artworks VIII*. Proceedings of the international conference on lasers in the conservation of artworks (Lacona VIII), 21–25 Sept 2009. CRC Press, Taylor & Francis Group, Sibiu, Romania, London, pp 209–214
21. Kunicki-Goldfinger J et al (2009) Characterization of glass surface morphology by optical coherence tomography. *Stud Conserv* 54:117–128
22. Liang H et al (2008) Optical coherence tomography in archaeological and conservation science - a new emerging field. *Proc SPIE*, 7139, 713915-1-15-9
23. Yang M-L et al (2012) Using optical coherence tomography to characterize the crack morphology of Ceramic Glaze and Jade. In: Liu G (ed) *InTech: Selected topics in optical coherence tomography*, Rjeka, Shanghai
24. Iwanicka M et al (2013) Application of optical coherence tomography (OCT) for monitoring of some conservation treatments. In: Saunders D, Strlič M, Korenberg C, Luxford N, Birkhölzer K (eds) *Lasers in the conservation of artworks IX*. Proceedings of the international conference on lasers in the conservation of artworks (Lacona IX), 7–10 Sept 2011. Archetype Publications Ltd., London, UK, pp 11–25
25. Iwanicka M et al (2011) Application of optical coherence tomography (OCT) for real time monitoring of consolidation of the paint layer in Hinterglasmalerei objects. *Proc SPIE*, 8084, 80840G