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A NEW TOOL FOR PAINTING DIAGNOSTICS: OPTICAL COHERENCE TOMOGRAPHY

© 2006 г. T. Arecchi*, M. Bellini, C. Corsi***, R. Fontana**, M. Materazzi**, L. Pezzati **, and A. Tortora****

**University of Florence, Department of Physics, 50019 Florence, Italy*

***Istituto Nazionale di Ottica Applicata, 50125 Firenze, Italy*

****European Laboratory for Non-linear Spectroscopy, 50019 Sesto F.no, Firenze, Italy*

E-mail: lella@ino.it

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Abstract—Non-destructive techniques have seen a successful growth in last few years and among them optical ones are widely diffused and extremely well received in the field of painting diagnostics because of their effectiveness and safety. At present, many techniques for non-destructive investigations of paintings are available, nevertheless none of them is suitable for a quantitative characterization of varnish. However, varnish removal, either partial or complete, is a fundamental part of the cleaning process which is an essential step in painting conservation. This critical process has been carried out, up to now, without the possibility of any non-destructive measurement for assessing the actual varnish thickness, but microscope observation of micro-detachment. Optical Coherence Tomography (OCT) is a non-invasive technique which is well-established for biomedical applications. In this work we present a novel application of OCT to measure the varnish film thickness for painting diagnostics.

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INTRODUCTION

Working out a conservative project is always difficult due to the uniqueness of paintings. For application in cultural heritage diagnostics, non-destructive investigations are more appropriate than any other approach. Any painting is a case-study and has its own "history": starting from the original idea to its final appearance, passing through pentimenti and restoration interventions according to the style of the artistic movement. A variety of scientific investigation methods applied to paintings are, by now, an integral part of the repair process, both to plan the restoration intervention and to monitor its various phases. Among them, optical techniques are widely diffused and well received in the field of painting diagnostics because of their effectiveness and safety. During measurement, in fact, the painting is not even touched: the interaction occurs through low-power electromagnetic radiation. Many optical techniques are inherent either to the characterization of painting layers (IR reflectography [1], UV fluorescence [2], multispectral imaging [3], …) or to the surface shape and roughness (laser-line profilometry [4], micro-profilometry [5], …). Nevertheless none of them is suitable for a quantitative characterization of the top varnish layer.

A painting can be modelled as a multi-layer system: the support (either wood or canvas), the ground layer (generally made of gypsum and glue), one or more painted layers (depending on the presence of pentimenti or multiple paint brushes), and the protective varnish film (generally spread on the painting both to protect it or to make it brilliant). In every layer, whose typical thickness ranges from several tens to a few hundred microns, the original structure of the artwork is maintained, as well as further modifications and the presence of the deposit accumulated with the passing of time.

Due to aging, the upper layer is subjected to darkening and yellowing because of blanching and fading from ultraviolet exposure, dust deposition and overpainted layers due, for instance, to restoration interventions. This degradation can either alter the original appearance of painting polychromy or cause mechanical failure of the finishes. To address these adverse conditions, a process of examination and analysis is critical to the definition and interpretation of the varnish layer. Therefore, one of the most important and sometimes controversial stages of conservation process is the surface cleaning: decisions have to be made regarding partial or complete removal of varnish. Technical considerations include selection of a method that allows a great deal of control in the cleaning process, so that undesired layers can be removed without damage to the underlying ones. Traditional cleaning methods include mechanical or chemical removal, and restorers and conservators work would be considerably helped by the knowledge of the varnish thickness.

When investigating the ageing process of old paintings, it is of great importance to obtain insight into the painting technique as practised in the past, and the first

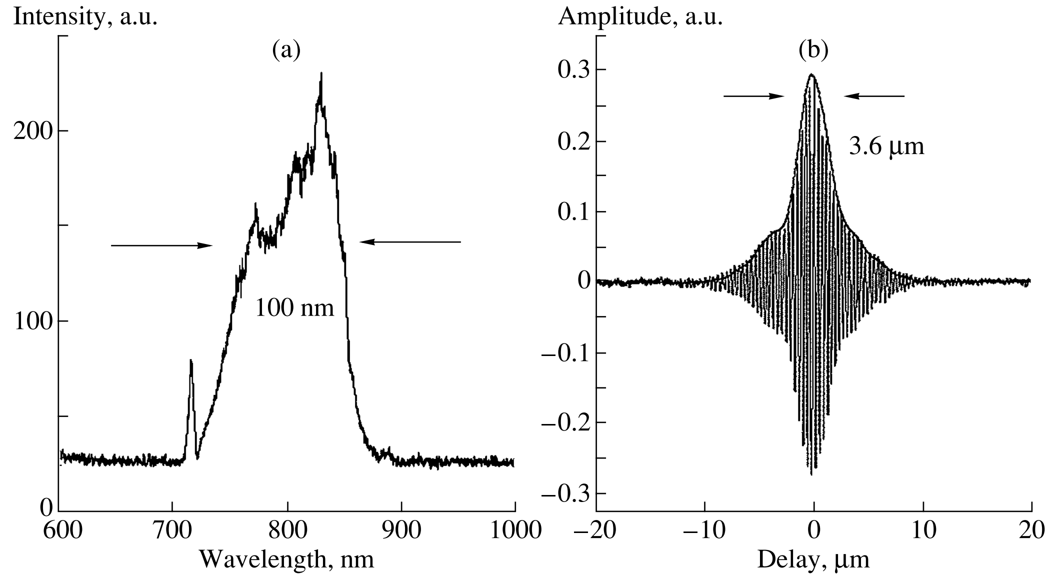

Fig. 1. (a) Spectrum of the Ti:Sa laser; (b) corresponding autocorrelation signal.

step of this knowledge is, to a large extent, based on the study of the varnish film. Up to now the only technique for measuring the varnish thickness is stratigraphy, a well known method since half a century for painting structure investigation. It consists in a painting micro-sampling usually taken from a detached fragment or from the border, which must be representative of the painting surface. The micro-sample is properly cut and embedded in a transparent liquid resin to form a small block that, after solidification, is polished so to highlight the cross-section of the fragment. Stratigraphic microscope examination is thus possible. This analysis is suitable for a quantitative characterization of the multi-layer structure of a painting, with the drawback of being invasive.

In this work we present a novel application of Optical Coherence Tomography (OCT) to painting diagnostics for non-destructive measurements of the varnish layer thickness. OCT is a relatively new high-resolution imaging technique that has been widely applied in medicine and biomedical field for probing biological tissues [6–8]. It uses visible or infrared light to provide non-invasive cross-sections of partially transparent or scattering media. The axial resolution is determined by the bandwidth of the source. Commercial sources, such as superluminescent diodes [9], generally provide resolution of a few tens of microns whereas laboratory-based solid state lasers have resolution better than 10 microns [10].

EXPERIMENTAL SETUP

OCT is a real-time imaging technology that generates tomographic images of partially transparent or scattering tissues. It performs coherence-domain reflectometry of tissue structure: radiation backscattered from different depth interfaces in the sample optically interfere whenever it overlaps, within the radiation coherence time, with a delayed reference field. The set-up is most commonly based on a Michelson interferometer with low coherence light sources. Depth resolution is limited by the source coherence length, whereas the focal spot size within the sample states the resolution transverse to the optical axis. A few tens of microns depth resolution can be performed with standard broadband sources such as superluminescent diodes [9], whereas laboratory-based solid-state lasers [10] provide sub-10 micron resolution, making possible subcellular imaging.

In our experiment [11], commercial Ti:Al_2O_3 Kerr-lens mode-locked solid-state laser (Femtolasers – Femtosource Scientific PRO) is used. Ultra-short laser pulses (FWHM ~ 12 fs) of great quality and stability are obtained by the compensation of high-order terms of intra-cavity dispersion by means of dispersive multilayer dielectric mirrors. The laser pulse is centered at 800 nm with ~100 nm bandwidth (Fig. 1a). The interference pattern FWHM determines the depth resolution, whose value is 3.6 μm in air (Fig. 1b).

Laser pulses are directed toward a Michelson interferometer and filtered to a mean power of 10–15 mW. The focal spot size and the confocal parameter are set by means of an iris at the Michelson entrance. Due to the varnish typical thickness, ranging from some tens of microns to a few hundreds microns, we operate with maximum transverse resolution without adjusting the focus position within the specimen. A 25 mm focal length lens is used to focus the probe field on the sample whereas dispersion compensation on the reference arm is achieved by means of an identical lens and a neutral filter. All the components are selected to optimally

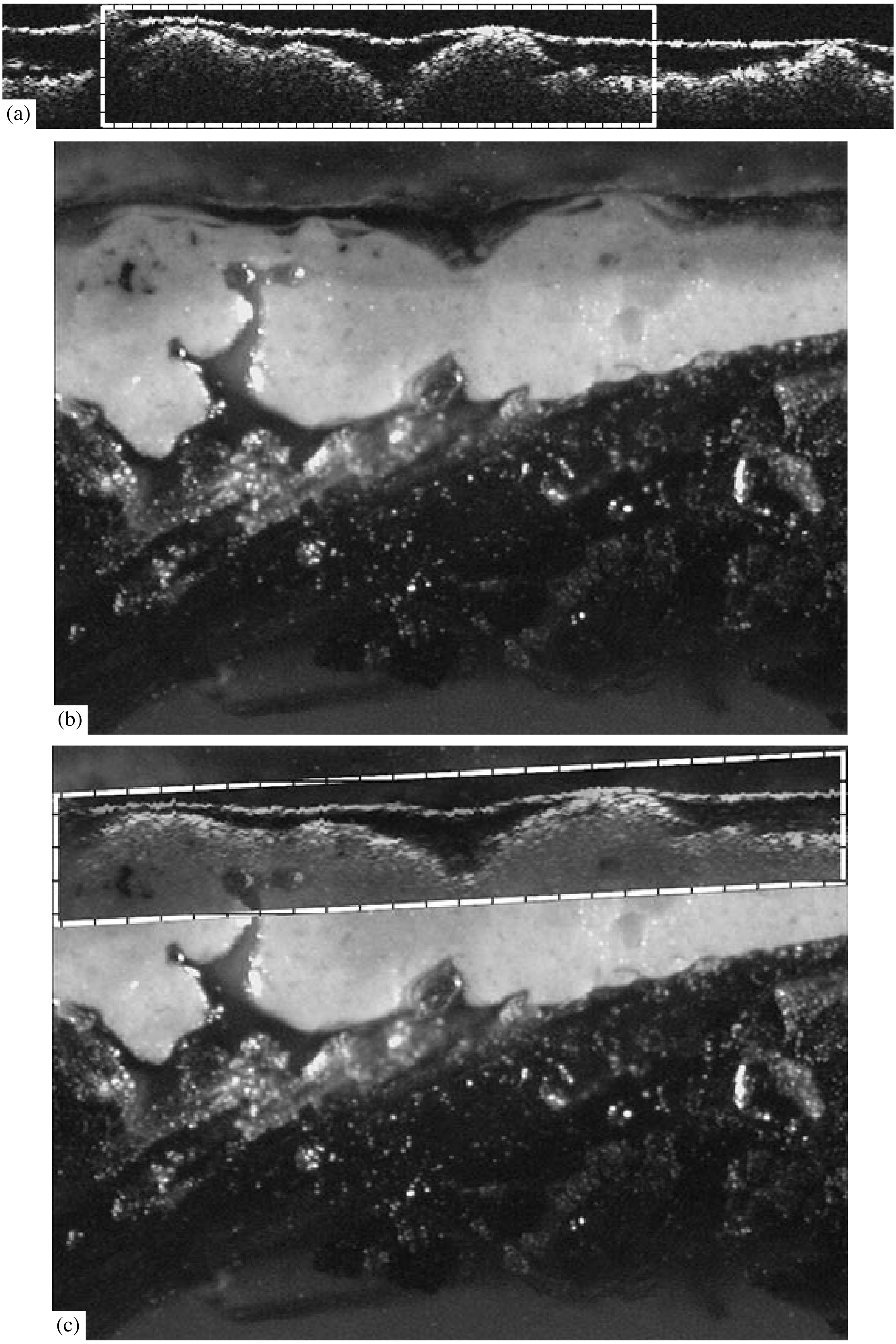

Fig. 2. (a) OCT image of a cross-section of the investigated area (dimensions: 2 mm length ×280 μm depth). The varnish film surface (first from the top) and the paint layer surface are clearly visible. The dashed line selects the region that is common to the microscope image; (b) cross-section image acquired with a microscope after detaching the investigated volume; (c) superposition of the two images. OCT image has been tilted for proper alignment.

perform at 800 nm. Scanning the sample in the axial (depth) and transverse direction is performed by moving the reference arm mirror and the sample, respectively, by means of two high-precision motorized translation stage. The Michelson output signal is detected by means of two balanced photodiodes, while scanning the motors. The resultant difference signal, properly amplified and filtered, is displayed in a standard 8-bit image format.

Two-dimensional data sets are generated by detecting the interference pattern at different transverse positions of the specimen. They represent the backscattering through a cross-sectional plane of the specimen, acquired for every sweep of the optical delay line in the reference arm. Images are generated by assembling adjacent axial scans to form a two-dimensional cross-sectional image of the optical backscatter from within the specimen.

RESULTS

A fragment of a nineteen-century oil painting, kindly supplied by the Opificio delle Pietre Dure, Florence, was measured to demonstrate the capabilities of OCT for non-destructive analysis of ancient painting varnish. A set of OCT images were acquired on a 2×2 mm area of the painting. In the axial direction, depths ranging from some tens to a few hundreds microns were investigated by scanning the reference arm, whereas lengths up to 3 mm were covered in the transverse direction by moving the sample with a micrometric step. Acquisitions were repeated every 250 μm in the other transverse direction, for mapping the whole investigated area. One of the acquired images is shown in Fig. 2a: the probed depth is 280 μm and the transversal scanned distance along the sample is 2 mm with sampling step of 5 μm.

A micro-sampling was then performed on the painting fragment under investigation, keeping memory, by means of a marker, of the scanning direction. The detached volume was imbedded in a liquid epossidic resin and, after solidification, was polished across a plane containing the axial direction. Microscope cross-section images were acquired at different polishing depths, corresponding to our acquisitions every 250 μm. In Fig. 2b, the microscope cross-sectional image corresponding to the analyzed area of Fig. 2a is shown. The superposition of the two images, after proper alignment, highlights the perfect agreement of the two results obtained by means of the two different and independent measurements described above (Fig. 2c).

CONCLUSIONS

In this work, we have presented the first application, to our knowledge, of Optical Coherence Tomography (OCT) to painting diagnostics. The experimental set-up based on a Michelson interferometer is composed of a mode-locked Ti:Sa laser source with central wavelength at 800 nm and bandwidth of about 100 nm, for good axial resolution.

At the interferometer exit port, the difference signal from two balanced photodiodes was acquired and processed while sweeping the optical delay line in the interferometer reference arm, for different positions on the sample. Two-dimensional reflectivity maps of the specimen were then generated, which represents the backscattering through a cross-sectional plane.

Comparison between OCT data acquired on selected areas for different positions every 250 μm and microscope images obtained after micro-sampling were carried out. The results show a very good agreement between the two data sets.

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