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COMBINING TIME DOMAIN WITH SPECTRAL DOMAIN OPTICAL COHERENCE TOMOGRAPHY FOR HIGH QUALITY NONINVASIVE INVESTIGATIONS IN DENTISTRY

BY

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Abstract. The purpose of this study is to evaluate the capability of optical coherence tomography (OCT) to characterize the dental prostheses interfaces. Using the Spectral Domain Optical Coherence Tomography (SD-OCT) the diagnosis method is faster in comparison with the Time Domain OCT. In this way a quick investigation with the SD-OCT permits to evaluate the prosthetic samples and focus in the areas with problems and materials defects. For a better characterization of these areas the Time Domain OCT obtain better results despite the scanning time.

Key words: optical coherence tomography; noninvasive investigations; dentistry.

1. Introduction

The longevity of dental restorations is an important health concern. Longitudinal studies are appropriate to give an exact insight into the longevity of restorations. A prosthetic restorative procedure is considered successful if the prosthesis demonstrates a survival rate of 95% after 5 years and 85% after 10

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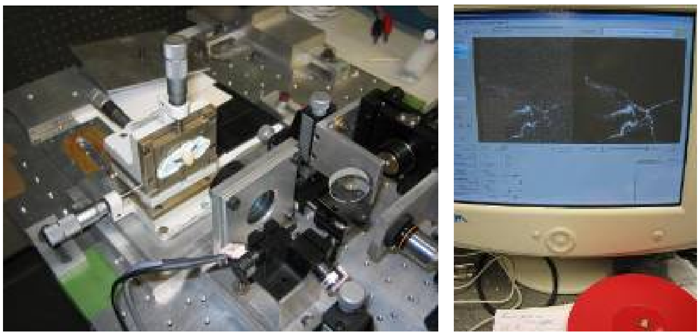
years. Dental interfaces represent one of the most significant aspects in the strength of the dental prostheses under the masticator load. For a conventional preparation with a reduction of tooth substance between 63% and 72%, a resin-bonded fixed partial denture (RBFPD) design may be prepared with a maximum tooth hard tissue loss of 3%…30% (Edelhoff & Sorensen, 2002). Debonding might be minimized by using a retentive preparation design with slots and boxes (Behr *et al*., 1998). The survival rates of these restorations, which were investigated up to 20 years now, vary between 60% (11 years – Probster & Henrich, 1997), 66% (20 years – De Backer *et al*., 2006), 83% (in 13 years – Ketabi *et al*., 2004) and 95% (10 years – Behr *et al*., 1998). A non-precious metal framework may show corrosion, and different thermal expansion coefficients of tooth and metal may lead to stress in the adhesive bond and ultimate adhesive failure. This may be associated with the development of recurrent caries if the patient does not notice the defect in time. A cantilever design with just one retainer was reported to improve the survival probability of RBFPDs (Wolfart & Kern, 2006; Kern & Glaser, 1997; Komine & Tomic, 2005; Ries *et al*., 2006; Rosentritt *et al*., 2008). Thus, cantilever RBFPD would be preferred since this treatment modality would preserve sounder tooth substance if it has higher probability of survival as stated. Koutayas *et al*. (2000) reported high fracture rates for two-retainer all-ceramic RBFPDs in contrast to comparable cantilever versions when cyclically loaded at 25 N. Clinical reports of a single-retainer RBFPDs showed promising results (Komine & Tomic, 2005; Ries *et al*., 2006; Koutayas *et al*., 2000; Botelho *et* al., 2002, 2006), and Kern (2005) stated a 5-year survival rate of two-retainer alumina ceramic RBFPDs of about 74% and for the single retainer bridges of 92%. K.J. Anusavice pointed out in several papers that the fractures in ceramics fixed partial prostheses could be initiated from the material defect trapped in the ceramic layers (Oh *et al*., 2002; Anusavice, 1996; Thompson *et al*., 1994). Making mental-ceramic or integral fixed partial dentures can lead to aeric inclusions in the ceramic layers that could initiate materials defects and lines of fracture in the aesthetic parts of the dentures. The common investigations methods of fixed partial dentures imply sectioning and metallographic microscopic analysis (Behr *et al*., 2000; Creugers *et al*., 1990). These methods could lead to damage of the small dimension material defects. Also these methods are limited to the dimensions of the cutting devices. Noninvasive research methods are very useful in characterizing the infrastructure of the fixed partial brides, due to the possibility of using the support after the evaluation in order to make a good and much more resistant dental bridge. One of these characterizing methods is the penetrating liquids method. This method allows discovering the materials defects of the infrastructure, but only the ones that are connected to the surface. The method is based on the flowing property of the liquids. The penetrating liquids method is a nondestructive method used for evaluating the continuity of the materials from which the dental works are made. By using this method, every defect zone that has any connection to the surface of the bridge can be revealed. The cost of this method is very low and the results are obtained rapidly and accurate. However, for the defects that are included in the core of the fixed partial dentures, this method has no applications. For the fixed partial dentures micro leakage investigations it is possible to use the method of laser micro spectral analysis (Koutayas *et al*., 2002). This method was first introduced in 1962, and was used specially to investigate the surface of metals. The method was reconsidered these years, when is also known as the method of spectroscopy by laser induced plasma. This method also requires low costs, compared with other point-like methods such as X-ray fluorescence spectroscopy or neutron activation method. This method is a quantitative but an invasive one and affect irreversible the investigated samples. Optical coherence tomography is a new noninvasive method that has many applications in dentistry (Sinescu *et al*., 2008). There are many possibilities to use this method in dentistry but it is hard to find the right parameters for each investigated sample. The purpose of this study is to evaluate the capability of optical coherence tomography (OCT) to characterize the dental prostheses interfaces.

2. Optoelectronic Noninvasive Investigations

For this study two systems were used, a time domain system (TDefOCT) working in *en-face* mode at 1,300 nm and one spectral domain system (SDOCT) that works at 840 nm. For the TDefOCT all prostheses were investigated with 100 slices per sample and 18 lateral degree. For details the scanning was performed at 8 lateral degree for a better visualization (Fig. 1). SDOCT system uses a wavelength band centred on 840 nm, has an axial resolution of less than 6 μ and an imaging speed of 20 frames per second (Figs. 2 and 3). For TDefOCT, *C*-scans are made from many *T*-scans along either of *X*, *Y*, repeated for different values of the other transverse coordinate, *Y*, *X* respectively in the transverse plane. The repetition of *T*-scans along the other transverse coordinate is performed at a slower rate than that of the *T*-scans, which determines the frame rate. In this way, a complete raster is generated. Different transversal slices are collected for different depths, *Z*, either by advancing the optical path difference in the OCT in steps after each complete transverse (*XY*) scan, or continuously at a much slower speed than the frame rate. The depth scanning is the slowest in this case. It is more difficult to generate *en-face* OCT images than longitudinal OCT images as the reference mirror is fixed and no carrier is produced. Therefore, in order to generate *T*-scans and *T*-scan based OCT images, a phase modulator is needed in order to create a carrier for the image bandwidth. This complicates the design and introduces dispersion. Research has shown that the *X*- or *Y*-scanning device itself introduces a path modulation which plays a similar role to the path modulation created by the longitudinal scanner employed to produce *A*-scans or *A*-scan based *B*-scans.



a *b*

Fig. 1 – RBFPD in front of the TDefOCT scanning head (*a*) and defects identified inside the ceramic layers by TDefOCT investigation (*b*).

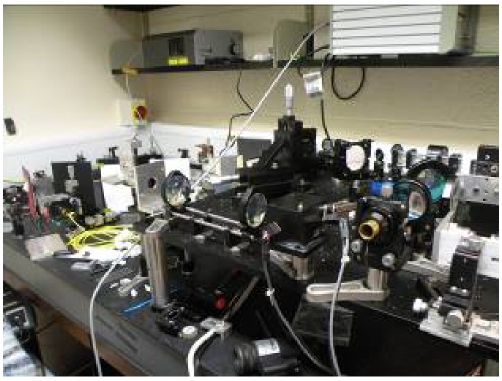
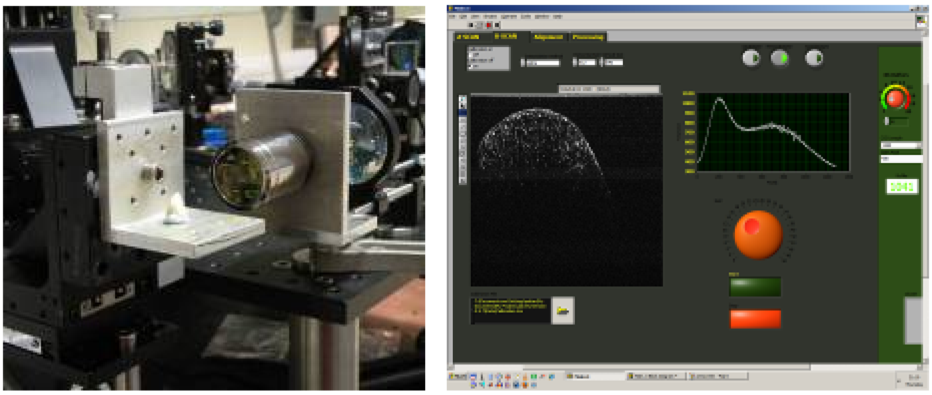


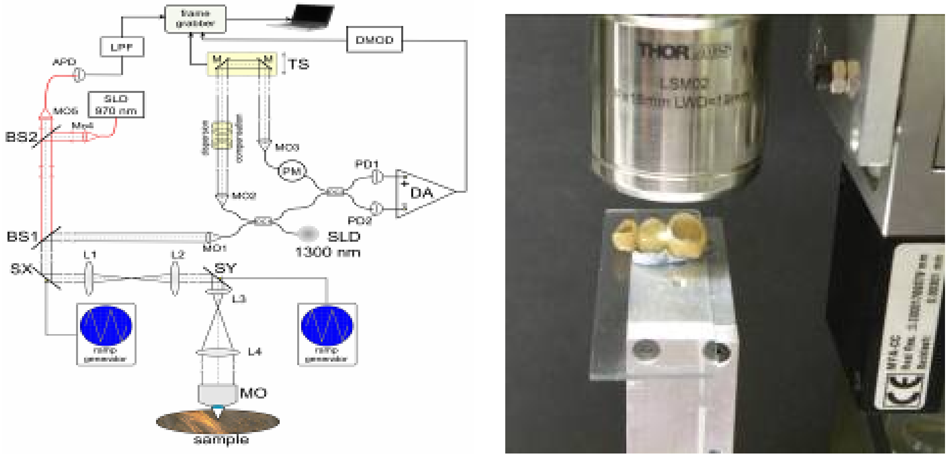
Fig. 2 – Aspects from the spectral domain system (SDOCT) investigations on RBFPD.



a *b*

Fig. 3 – The integral ceramic crown in the SDOCT (*a*) and the software used for the spectral OCT in the integral ceramic fixed partial dentures investigations (*b*).

All the samples were investigated by OCT combined with Confocal Microscopy in order to evaluate the surface of the interfaces. The confocal channel operates at a different wavelength than that of the OCT, to allow the utilization of a high gain silicon avalanche photodiode (APD). Light from a superluminscent diode at 970 nm is collimated by a microscope objective MO4 and reflected by a splitter BS2 (20% reflection) towards BS1. Light at 970 nm is transmitted *via* BS1 and BS2 towards the APD. The photo detected signal is amplified and low pass filtered in LPF (Fig.4). The samples were scanned using



a *b*

Fig. 4 – OCT combined with confocal investigation for samples investigations.

cone beam micro-CT. The cone-beam micro-CT scanner consists of a micro-focal spot X-ray tube (10...20 µm), *xyz*+rotary stage, and a micro-angiographic detector with a 45 µ pixel size. The X-ray exposure parameters were: 40 kVp, 1 mA and 300 ms exposure per frame. The samples were placed onto the rotary

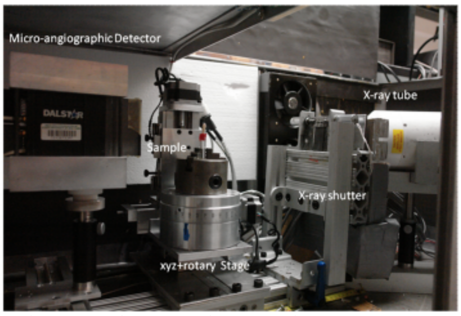
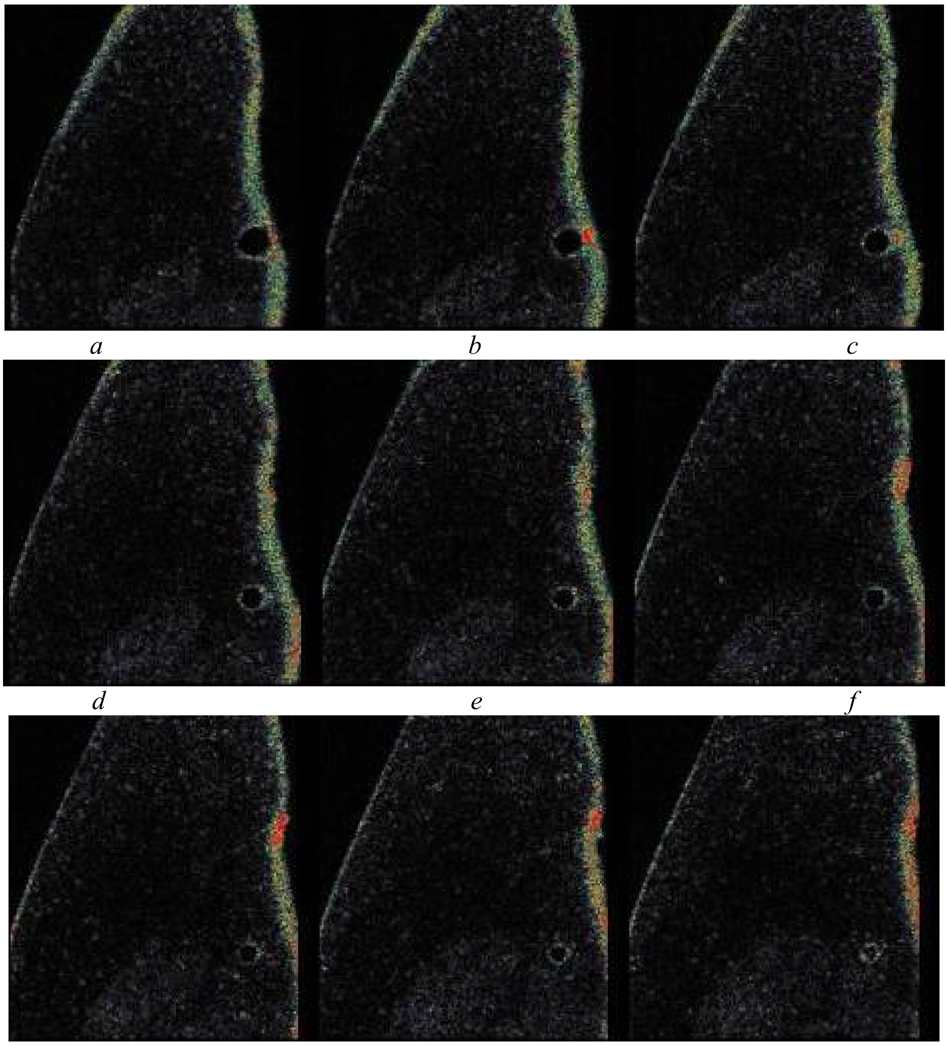


Fig. 5 – The cone beam micro-CT setup.

stage at a magnification between 2 and 1.1 depending on the sample size and scanned using one degree step increments. After projection acquisition they were reconstructed using a $(512)^3$ volume with a 45 μ^3 per voxel (Fig. 5).

3. Results

All samples were investigated using the above stated methods. Defects were found in all types of fixed partial dentures investigated: metal–ceramic and all ceramic systems. The most numbered defects were spotted in the ceramic layers applied by the dental technicians on the infrastructure (metal or non metal) (Fig. 6). The main advantage of the TDefOCT is the possibility to navigate through the integral ceramic crown in a non-invasive manner. The

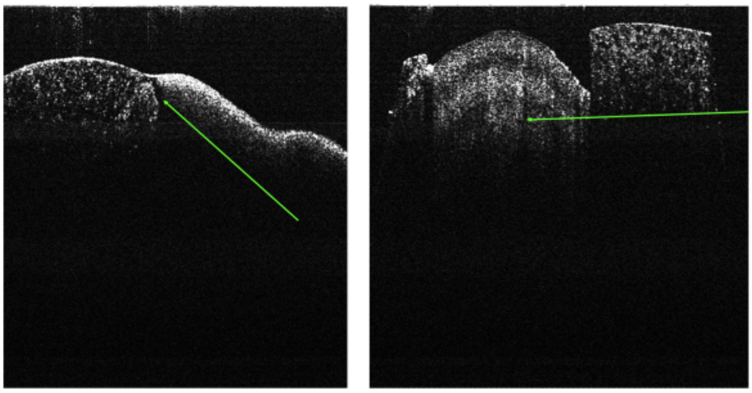


a *b* *c*
d *e* *f*
g *h* *i*

Fig. 6 – The evolution of the defect inside of the ceramic layers from an Empress ceramic crown.

maximum depth for the TDefOCT is 3 mm in air, distance that could represent aproximativelly 2.5 mm in the ceramic layers. In this way each material defect could be very easily positioned. The investigation with TDefOCT could take till 2 min (depending on how many slides would be take from the sample). In the Fig. 6 the evaluation of the ceramic defect from an Empress integral pressed ceramic crown could be observed. The slides were 31 from 214 (Fig. 6 *a*), 33 from 214 (Fig. 6 *b*), 35 from 214 (Fig. 6 *c*), 37 from 214 (Fig. 6 *d*), 39 from 214 (Fig. 6 *e*), 41 from 214 (Fig. 6 *f*), 43 from 214 (Fig. 6 *g*), 45 from 214 (Fig. 6 *h*) and 47 from 214 (Fig. 6 *i*). Practically at the slide 47 the defect is starting to close.

The same sample was investigated with the SDOCT in order to evaluate the efficiency of this procedure in comparison with TDefOCT (Fig. 7). All the investigation was taken less than 2 s. In this interval of time 23,155 slides were obtained. The investigations could give only *B* scan slides. The defect observed in Fig. 6 was pointed out in the SDOPCT investigation starting with slide 1,745 (Fig. 7 *a*). Other defects could be detected too in various dimensions and in non stress areeas(Fig. 7 *b*).

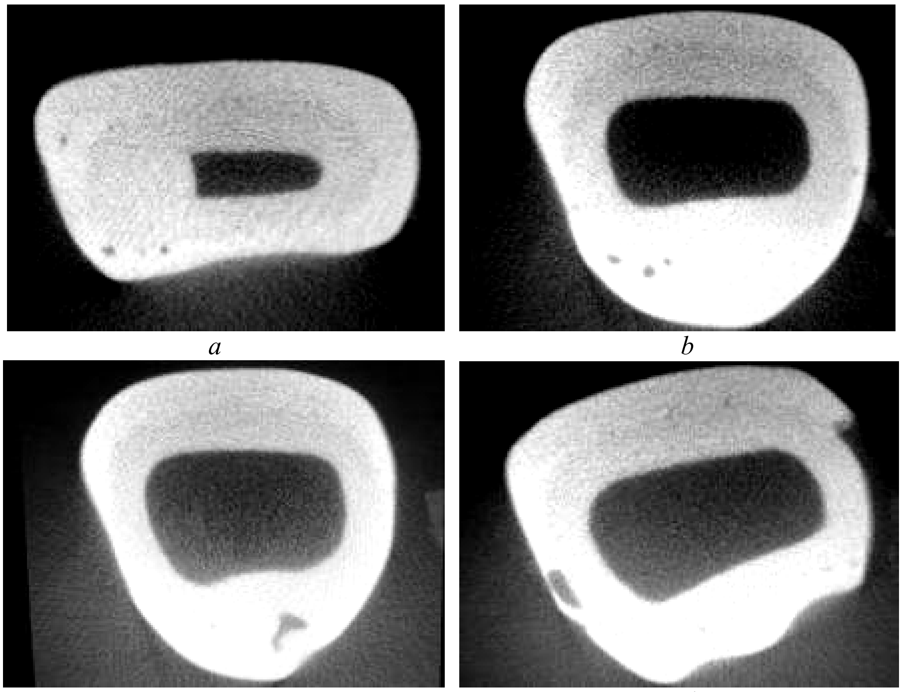


a *b*

Fig. 7 – SDOCT investigation of the sample investigated in Fig. 6.

All the results were validated by Cone Beam MicroCT investigations (Fig. 8). On the slides obtained by Micro CT investigations the defects inside the ceramic material could be spotted at the same distance as in OCT (Figs. 8 *c* and *d*). The MicroCT analysis revealed the other ceramic defects (Figs. 8 *a*, *b*) depicted with TDefOCT and SDOCT. Those defects are situated in area with no significant masticator load that could lead to intrinsic fracture in the ceramic layers.

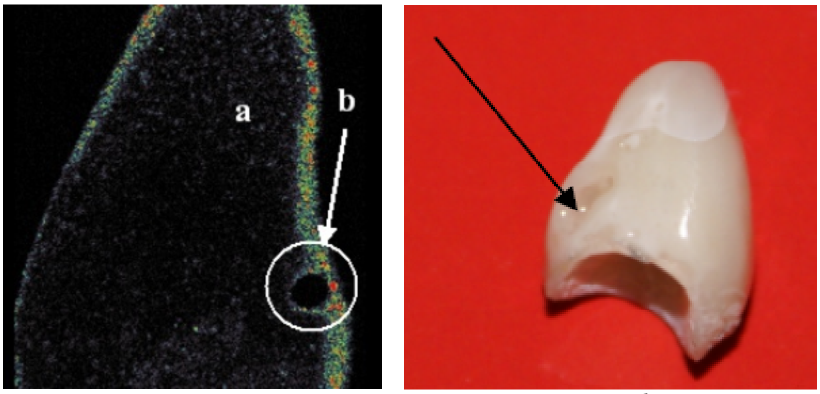
The last evaluation for the sample investigated by non-invasive methods was the metallographic one. Using a diamond bur, the ceramic layers were drilled till the defect was reached (Fig. 9 *b*)



a *b*

c *d*

Fig. 8 – MicroCT investigations of the sample investigate in Figs. 6 and 7.

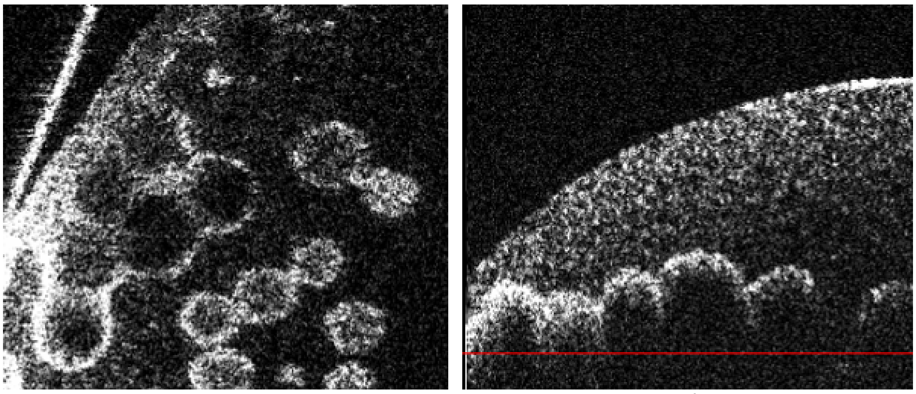


a *b*

Fig. 9 – The defect in sample evaluated in Figs. 6, 7 and 8 observed with OCT (*a*) was validated by the metallographic investigation (*b*).

Combined analysis of *C*-scan and *B*-scan images permits identification of the positive structures, such as retentions from metallic infrastructure in metal polymeric fixed partial prostheses. These retentions are very important to retain the polymer within the metallic infrastructure (Fig. 10). Because of many dental technology centers that are working today all over the world and because we can order fixed partial prostheses from such a center from an other country, the prostheses could come at the final stage, with no possibility of evaluation for the dentists. In this point the technological problems could appear in losing the aesthetic materials because of the absence of the retentions (Fig. 10).

Fig. 10 – The problems with the micro retentions in metal polymeric fixed partial prostheses.



a *b*

Fig. 11 – The imagistic result of a good metal polymer interface with metallic retention that increases the maintenance of the polymer on the infrastructure.

In this case a 2…3 min evaluation by TDefOCT system could solve the problems without damaging the prostheses (Fig. 11). *C* Scan OCT image of the fixed partial denture (Fig. 11 *a*), shows the retention bubbles which can easily be mistaken as material defects in the polymer. *B* Scan OCT image (Fig. 11 *b*) of the same investigated area shows the metallic retentions tending out from the infrastructure. For all OCT imagistic investigations 3-D reconstructions could be made (Fig. 12).

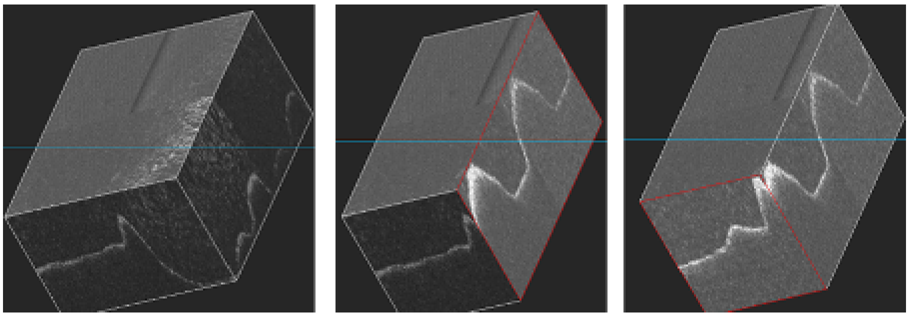
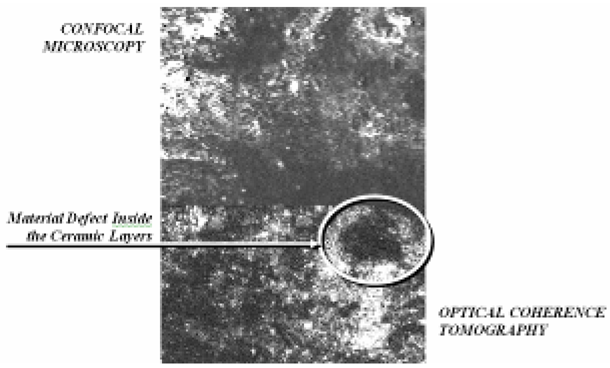


Fig. 12 – Three dimensional reconstruction of the metal polymeric interface with the metal positive retention identified inside the polymer material.

a *b*



c

Fig. 13 – Optical Coherence Tomography Investigation of Metal Ceramic Fixed Partial Dentures (*a*); Combining the Optical Coherence Tomography and Confocal Microscopy in Detection of Material Defects in Ceramic Fixed Partial Dentures (*b*) and Details from the metal ceramic fixed partial denture: a big aeric inclusion inside the ceramic layers (top). The Confocal microscopy investigation; (bottom) The Optical Coherence Tomography Investigation. Defects inside the ceramic layers can be seen in the interface zone at 0.3 mm (measured in air) from the ceramic top (*c*).

For ceramic prosthesis, the defects identified using the OCT system could lead to fracture of the aesthetic ceramic materials. Ceramic materials are sintered at high temperature, which excludes the possibility of repair once the prosthetic constructs, permanently fixed in the oral cavity. Sometimes the evaluation of the materials defects is very difficult to achieve and in this moment the confocal microscopy could offer important information about the investigated positions on the sample (Fig. 13).

4. Conclusions

In conclusion, Optical Coherence Tomography could act as a valuable noninvasive method in analysing the integrity of dental prostheses. This will save time and resources by eliminating prostheses with defects before they are mounted in the patient's oral cavity. The detection of ceramic defects before oral inserting the prostheses allows all the corrections in order to avoid the fracture of the ceramic component. The fractures that occur within the structure of these prostheses were motivated by the elasticity module of the ceramics and by the defects within the ceramic layers. Early detection of substance defects within these layers allows for optimal corrections before inserting them and applying masticator stress together with reduction of fractures. For the big material defects a good evaluation can be done by a fluorescent agent. For the imbedded ceramic defects the *en-face* OCT noninvasive method of evaluation remains the only method capable to evaluate the prognostic of a prosthetic construct. Using the Spectral Domain Optical Coherence Tomography (SD-OCT) method the diagnosis method is faster in comparison with the Time Domain OCT. In this way a quick investigation with the SD-OCT permits to evaluate the ceramic samples and to focus in the areas with problems and material defects. For a better characterization of these areas the Time Domain OCT obtains better results despite the scanning time.

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COMBINAȚIA TOMOGRAFIE OPTICĂ COERENTĂ ÎN TIME DOMAIN CU SPECTRAL DOMAIN UTILIZATĂ PENTRU INVESTIGAȚII DE MARE ACURATEȚE ÎN MEDICINA DENTARĂ

(Rezumat)

Scopul acestui studiu este acela de a evalua capacitatea tomografiei optice coerente (OCT) pentru caracterizarea interfețelor protezelor dentare. Utilizarea Tomografiei Optice Coerente lucrând în Spectral Domain (SD-OCT) conduce la un diagnostic mai rapid în comparație cu Time Domain (TD-OCT). Astfel, o evaluare rapidă realizată cu SD-OCT permite selectarea zonelor de interes a căror aprofundare se poate completă cu TD-OCT, în ciuda unui interval de scnare mai lung.