**IOSUD - Polytechnic University of Timisoara**
**Doctoral School of Engineering Studies**

# "BIOMEDICAL IMAGING IN DENTISTRY AND NDT USING A RANGE OF INVESTIGATION TECHNIQUES, FOCUSING ON OPTICAL COHERENCE TOMOGRAPHY (OCT)"

**Doctoral Thesis - Abstract**

for obtaining the scientific title of doctor at
Polytechnic University of Timisoara
in the doctoral field of *MECHANICAL ENGINEERING*

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scientific supervisor Prof. Dr. *DUMA VIRGIL-FLORIN*

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## *Introduction*

This doctoral thesis has as its main theme *Optical Coherence Tomography* (OCT) [1], utilized as a medical imaging method in dentistry [2], but also the use of other traditional dental investigation techniques based on X-rays, the latter mainly for the validation of OCT results in the biomedical field. OCT was also approached in aspects related to *Non-Destructive Testing* (NDT) for the industrial field, but also for the study of biomedical materials. In this direction OCT was validated using other techniques, such as *Scanning Electron Microscopy* (SEM). Thus, the field of the thesis is that of Mechanical Engineering, area of specialization Fine Mechanics & Optics, with the focus on aspects of measurement (in this case, photonics and optomechatronics) systems.

To be able to address these research directions and to perform the proposed studies on certain applications of OCT in Dentistry and NDT (with the validation of the results with other imaging techniques, according to the above), the first part of the study reviewed the most utilized imaging techniques, primarily medical ones that are currently utilized [3-5]. Based on the practical experience of the doctoral student (as medical physicist), the most utilized imaging methods in Dentistry (i.e., 2D radiography and 3D Cone Beam Computed Tomography – CBCT) are addressed [6-8]. In the second, original part of the study, OCT investigations [1,9,10] were carried out with the existing system in the PhD Supervisor's laboratory, highlighting the benefits compared to the usual methods based on X-rays. The envisioned OCT investigations include evaluation of caries, adaptation of dental crowns to teeth, verification of implants, instruments, laboratory components and laboratory works or analyses of enamel and dentin of teeth that are considered healthy. In the third part of the Thesis, the investigations continued with aspects of NDT, for topics of current interest.

OCT is a medical imaging method that does not use ionizing radiation (such as X-rays), but laser radiation in the infrared (IR) range, so it is not harmful to body tissues (when utilizing appropriate wavelengths). This is a relatively new method (introduced in the '90s), in full development, although it was originally introduced (only) for ophthalmology. Different types of images are made (compared to those obtained using radiography); the images obtained with OCT include volumetric/3D reconstruction type - like those of computed tomography (CT). They can help in the diagnosis, as well as in other imaging methods. OCT, like all other similar medical techniques, has its advantages and drawbacks, but it certainly has applicability in Dentistry, both for *ex vivo* [2,11-13] and *in vivo investigations*, the latter directly on the patient [14,15].

The thesis has obtained results with a direct applicability in the medical field (as pointed out in the publications in Web of Science (WoS) journals) for the first time to our knowledge: the optimization of X-rays equipment used to perform dental radiographs with the help of OCT [16], as well as demonstrating the complementarity of these two imaging techniques for dentistry [17]. It was possible to calibrate the equipment in such a way that the radiographs are of the best possible quality with an as low as possible radiation dose. The possibility to find the best settings for the X-ray equipment was given by the fact that exact measurements could be made on the images obtained with the OCT system. In contrast, on the radiographs the dental conditions to be quantified were not even visible. After applying the protocol developed in this thesis, the quality of radiological images allowed for the detection of such conditions. However, it was concluded that some issues can be diagnosed only on OCT images. Knowing the shortcomings that OCT has over X-rays and discovering the disadvantages of X-rays compared to OCT, the conclusion is that the two medical imaging techniques are complementary. These results are presented in Chapters 3 and 4.

In addition to these two results in the medical field, we utilized in the thesis the OCT system for achieving metrological measurements and for analyzing various samples in the NDT field. These results are presented in Chapters 5 to 7. Thus, we also utilized OCT as an alternative method to SEM or micro-CT. The results obtained for each direction of research demonstrated that the images and measurements performed with OCT are consistent with the results obtained with other imaging methods.

### *Justification of the choice of the research topic*

I've had a passion for science since childhood, participating year after year in the school Olympiads in mathematics, physics, and chemistry. I also followed this passion in university, where I specialized in Medical Physics (at UVT), after three years of bachelor's degree and two years of master's degree. Since the last year of my master's degree, I had the opportunity to collaborate with Prof. Dr. Virgil-Florin Duma, who guided me towards this doctorate, being my scientific supervisor. I chose this theme for two reasons. The first reason was that of continuity. My master dissertation was also about OCT in dentistry - at UVT -, also under the guidance of Prof. Duma. The second reason why I chose this topic is the fact that I work as a medical physicist in a dental clinic in Timișoara, where I can apply all the things learned or achieved in research projects. The work started from studying the applicability of OCT for as many dental conditions as possible. The advantage is that I had at my disposal both the equipment from the clinic (dental radiology systems) and the OCT systems from Prof. Duma's laboratory at the Aurel Vlaicu University of Arad. In addition to the equipment, I also had access to medical cases and was well connected to the demands of the medical doctors and to their patients' needs. Thus, several research directions were opened.

Radiological systems are no longer technological novelties. Thus, we use radiology in the thesis only as a comparison method for the Swept Source (SS)-OCT system functional in the laboratory. Within the research group led by Prof. Duma, prototypes of handheld samples were also developed for a better applicability of the system, with the idea of using OCT *in vivo*, besides *ex vivo*. Thus, using micro-electro-mechanical systems (MEMS) or laser galvoscanners, 3D/volumetric reconstructions can be made.

In terms of the OCT technology, such systems have moved from the original Time-Domain (TD) OCT technique (where a broad spectrum of illumination was used and a photodetector obtained signal by scanning the length of the reference arm) to Spectral Domain (SD) OCT, where moving arms are no longer needed. Instead, a spectrometer detects the broad spectrum of interference. Finally, the technique has reached SS-OCT (as in the experimentally developed laboratory system I worked on), which does not require mobile arms, and where a narrow spectral line is passed through a range of wavelengths and the signal is obtained by using a dedicated photodetector.

The theoretical part, both for the radiology and the OCT parts offered me both knowledge and skills for the practical part of the doctoral thesis, as well as ideas for scientific papers. Delving deeper into these topics together with the coordinator, we noticed what are the possible research directions, where the current state is at the international level, and what niches have remained uncovered for research.

### *The structure of the doctoral thesis*

This doctoral thesis is structured in 8 chapters, the first two chapters being introductory to the subject of medical imaging; the usual techniques and the equipment used was described, with an emphasis on OCT. Chapters 3 to 7 are based on published or forthcoming journal papers. These chapters are an essential part of the research because they represent my personal contributions to the field. Chapter 8 is the chapter that concludes the thesis and is dedicated to its conclusions and the directions of work opened by the thesis.

### *Chapter 1 - Medical imaging techniques*

In **Chapter 1** of the doctoral thesis, a presentation of the various medical imaging techniques was made, including a description of each method, their classification and a discussion of advantages and limitations of each considered technique. It explains how X-rays, CT scans, ultrasonography, magnetic resonance imaging (MRI), positron emission tomography (PET), and OCT work. The classification of these techniques was made according to their source of image generation. This is essential for understanding how each method fits into a particular context. In terms of advantages and limitations, we pointed out that each medical imaging technique has its strengths and limitations. For example, X-ray radiography is widely used but involves exposure to ionizing radiation, while MRI provides detailed images of soft tissues with the drawback of being expensive. Some practical applications of each technique in the medical field are discussed, as well. This chapter also deals with the theoretical bases of OCT, with laser scanning systems and modalities – Fig.1, types of OCT, as well as applications of OCT in medicine and in NDT.

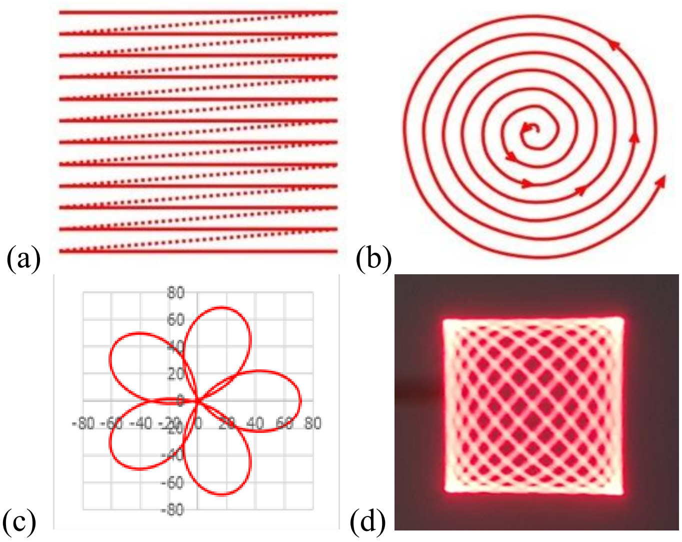



Figure 1. Modalities of optomechatronic laser scanning: (a) raster – used in the OCT system in this thesis, (b) spiral, (c) with Risley prisms, (d) Lissajous.

### *Chapter 2 – Imaging methods in dentistry*

In **Chapter 2** of the thesis, the equipment used in dental radiology was described, focusing on the one used in the research activity for the realization of this thesis. It is emphasized that new digital technologies are replacing the traditional method of using films in dentistry and that experience is essential for the effective use of this equipment. A specific example is considered, related to Planmeca ProMax 3D, which uses digital detectors to capture radiographic images. To obtain high-quality images, these digital detectors must be sensitive, and pixel size and background noise reduction are critical factors. The process of obtaining dental X-rays involves exposing the patient to X-rays, collecting the data and processing them to obtain images. The components and steps of this process are detailed.

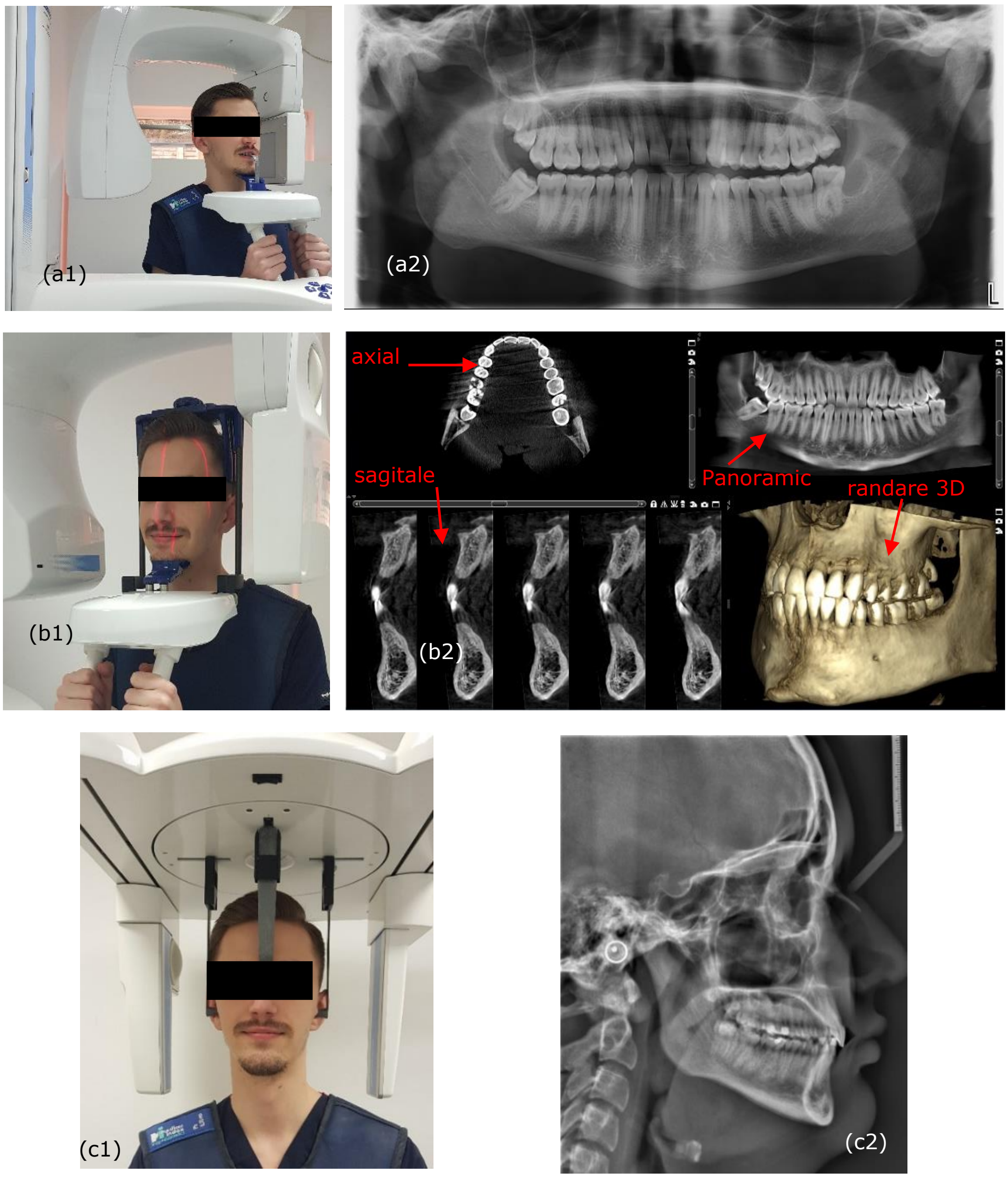



Figure 2. Example of the utilized Planmeca system from the dental clinic for (a1) panoramic, (b1) 3D CBCT and (c1) cephalometric investigations (of a healthy staff member). Images obtained: (a2) panoramic; (b2) 3D CBCT images, with axial, sagittal and panoramic views, as well as a 3D reconstruction; (c2) cephalometric.

*Chapter 3 – Synergy between OCT and radiographs*

Chapter 3 demonstrates the synergy between Optical Coherence Tomography (OCT) and X-rays in dentistry. Dentistry has evolved significantly due to technological advances in diagnosis and treatment. Intraoral, panoramic radiographs, as well as Cone Beam Computed Tomography (CBCT) are the standard imaging techniques in dentistry but have the disadvantage of exposing patients to ionizing radiation. Thus, in order to reduce as much as possible, the exposure of patients to radiation, alternative imaging techniques such as OCT should be used. Also, X-ray techniques are limited in resolution: around 127 μm for panoramic radiography, 144 μm for intraoral radiographs and 75 μm for CBCT. SS-OCT, with an axial resolution of ~15 μm provides images on which a dental condition can be diagnosed at an early stage or one that is not visible at all on conventional radiographs. Thus, in this study different samples were used to be investigated with both methods, X-rays and OCT. Depending on the information that can be obtained from the images, we divided the dental conditions into 3 categories: those that can be investigated only using OCT, only with radiography, and for which both methods should be used in a complementary manner. The OCT investigations were mainly performed using an OCT system developed within the Laboratory of Optomechatronics and Biomedical Photonics of the "Aurel Vlaicu" University in Arad (the schematic diagram is presented in Figure 3). The radiographs were made in the Dental Experts clinic in Timişoara with the Planmeca ProMax 3D Classic machine presented above.

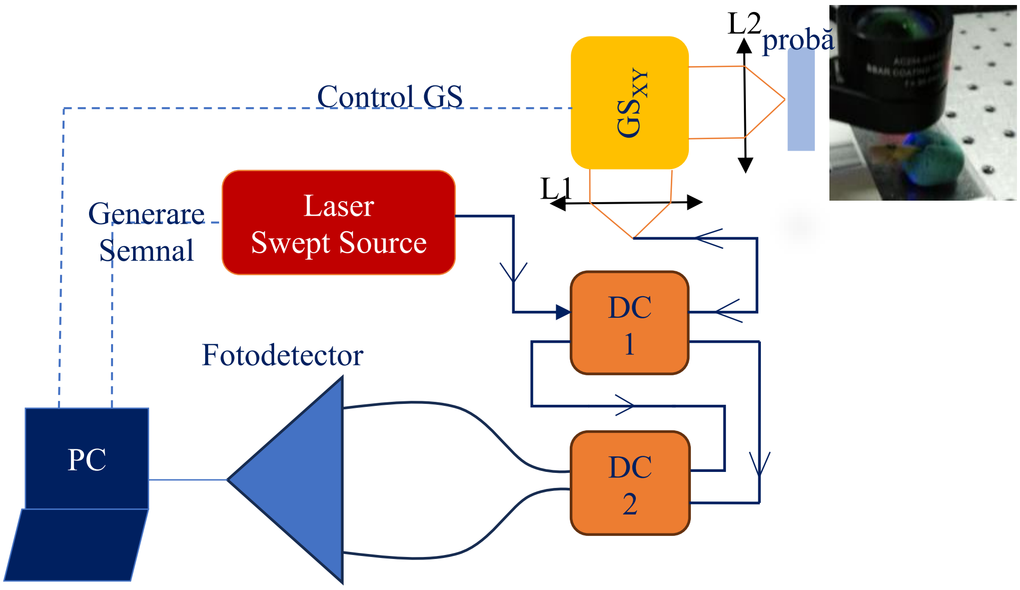



Figure 3. SS-OCT system developed in-house at 3OM Optomechatronics Group, using a laser interferometer . Components: Source with linear emission; DC1,2, single-mode fiber optic directional couplers (20/80 and 50/50, respectively); $GS_{XY}$, two-dimensional two-axis galvanometer scanner; L1,2, achromatic lenses; BPD, balanced photodetector; PC, personal computer.

The results presented in this chapter were disseminated in (and are reproduced after) the work [R.-A. Erdelyi, V.-F. Duma*, C. Sinescu, G. Dobre, A. Bradu, A. Podoleanu, Dental Diagnosis and Treatment Assessments: Between X-rays Radiography and Optical Coherence Tomography, Materials 13(21), 4825 (2020); https://doi.org/10.3390/ma13214825; **IF 3,623**; **Q1]**. The results showed that we can clearly delineate dental cases that can be diagnosed with OCT, with X-rays and cases where OCT and X-rays can be used in a complementary way **[**17] – Table 2.

Table 2. Appropriate medical imaging technique for certain dental problems.

| Dental problem | X-ray | October |
|---|---|---|
| Cavities | Cavities smaller than 0.5 × 0.5 mm are difficult to diagnose on any type of radiograph | Correct quantitative evaluation of (dimensions of) small cavities |
| Dental crowns (ceramic metal or all-ceramic) | Artefacts may appear, therefore the obtained images cannot be used | Accurate surface images for metal parts; high-resolution images below the sample surface for non-metallic (ceramic or polymer) crowns |
| Orthodontics | Suitable to measure/observe tooth movement | Accurate images for dental analyses (e.g. for enamel and dentin) |
| Evaluation of bone problems | Accurate investigations of bone density and assessment of bone quantity on 3D CBCT images | Low penetration power through bone - from 1 to max. 2 mm |
| Periodontitis | The disease can be monitored during treatment | Accurate measurements (only) of bone loss/gain are possible |
| Crown/seal adaptation | High quality images for materials that do not absorb excess X-ray radiation | High quality images for most types of materials used in dentistry |
| Enamel / dentine problems | They cannot be investigated on any type of X-ray | Qualitative images can be obtained, as well as quantitative assessments - even below the surface of the teeth |
| Soft tissue | It cannot be investigated on any type of X-ray | Quality images can be obtained. Limiting the depth of penetration to max. 2 mm |

### *Chapter 4 – Optimizing dental radiographs using OCT*

In **Chapter 4**, an innovative way to optimize (widely used in dentistry) X-ray units was developed. For this, the much higher resolution technology, OCT, was implemented. The results presented in this chapter were disseminated in (and are reproduced after) the paper [R.-A. Erdelyi, V.-F. Duma*, C. Sinescu, G. Dobre, A. Bradu, A. Podoleanu, Optimization of X-ray Investigations in Dentistry using Optical Coherence Tomography, Sensors 21(13), 4554 (2021); https://doi.org/10.3390/s21134554**; IF 3.874**; **Q2**].

The calibration of X-ray machines (especially their kV and mA parameters) is essential in order to obtain the highest quality images. The applied voltage (kV) influences the contrast of the radiograph, and the current (mA) regulates the intensity of the electric current to generate the X-ray beam. The data acquisition process is similar for all manufacturers of this type of equipment, and special algorithms are used for the reconstruction of 2D or 3D images. Panoramic, intraoral, and CBCT radiographs are common imaging techniques used in dentistry for diagnosing and evaluating dental and maxillofacial conditions. These techniques have distinctive characteristics in terms of resolution, contrast, artifacts, and color reproduction that may influence their interpretation and use in practice.

The research carried out in this chapter demonstrated that OCT can be used in the optimization of dental radiology systems. The optimization protocol involves the investigation of a dental condition with both techniques (OCT and radiography). Its principle is as following: an accurate diagnosis is made on OCT images (with an axial resolution of 15 μm, while panoramic X-ray and 3D CBCT images have a resolution of 150 to 200 μm) and then the optimal kV and mA settings for each type are sought of X-rays, until the dental condition investigated with OCT can be correctly diagnosed with X-rays as well.

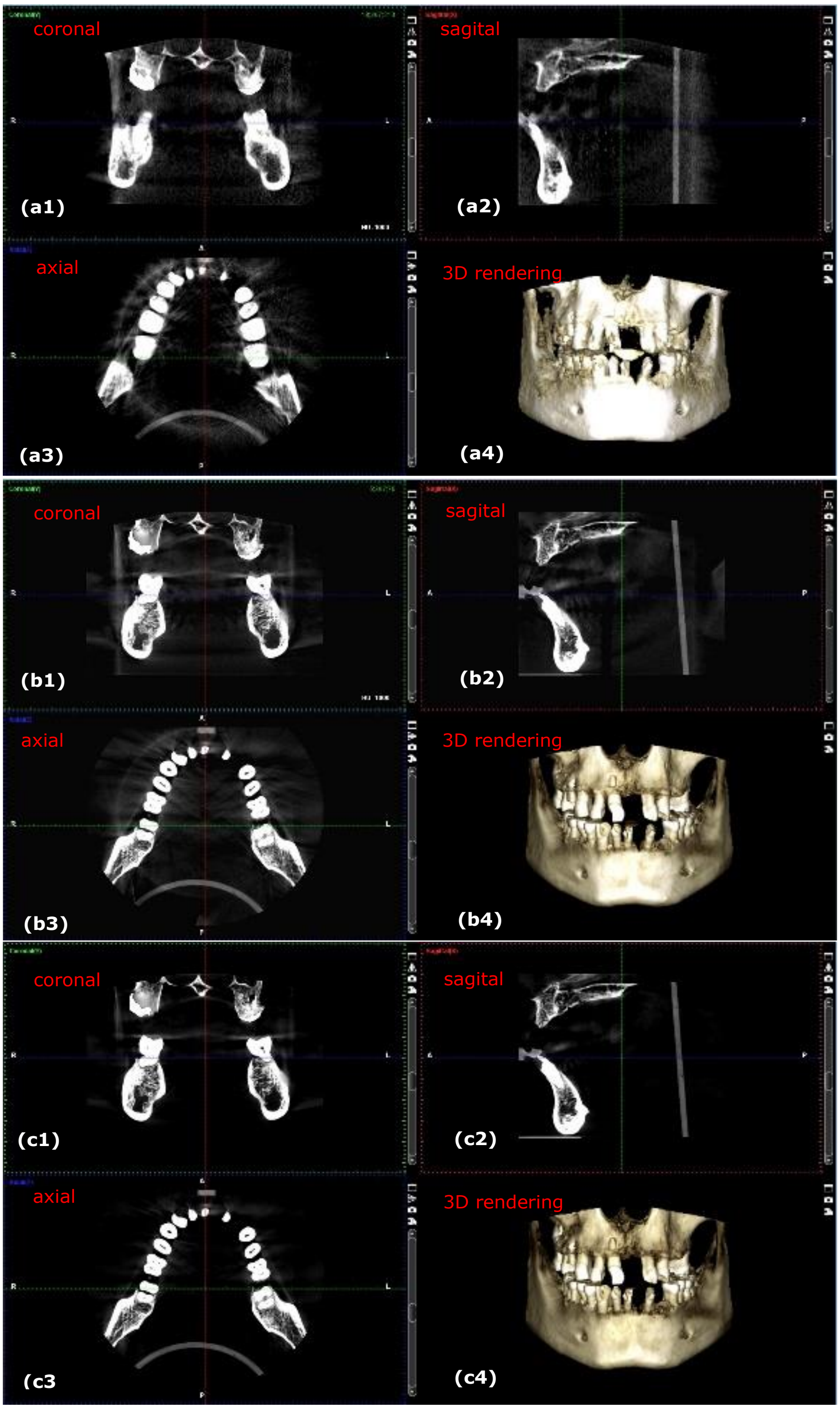



Figure 4. 3D CBCT images obtained by the optimization process. The steps of this process include: (a) the first 3D CBCT images with the lowest voltage and current values (b) an intermediate 3D CBCT; (c) Highest quality 3D CBCT obtained. The four corresponding images in each panel represent: (1) coronal view; (2) sagittal view; (3) axial view; (4) 3D rendering.

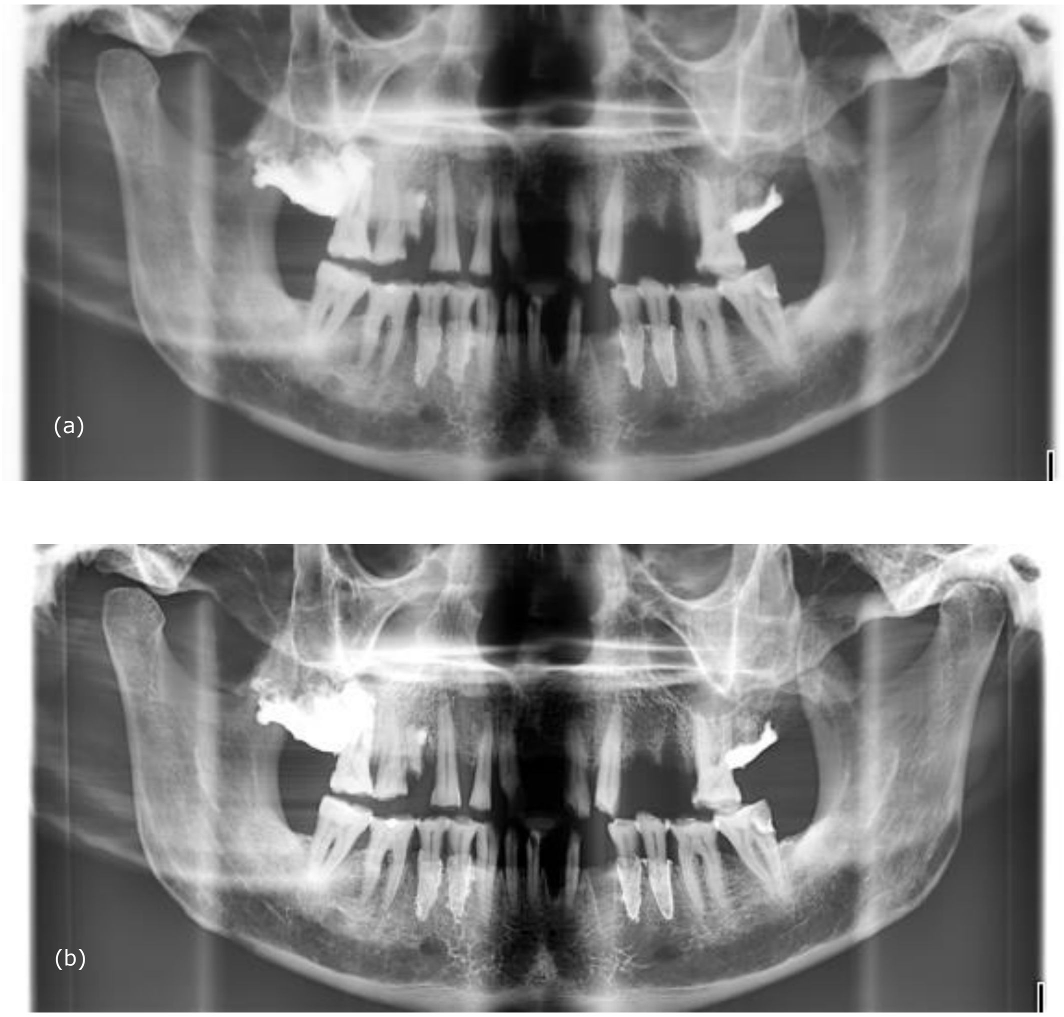



Figure 5. Panoramic radiographs obtained during the optimization process (a – non-optimized, b – optimized).

After the optimization of the X-ray equipment, the settings obtained for taking X-rays radiographs were applied on patients [16]. An improvement in the quality of the radiographs and a reduction in the radiation dose was observed.

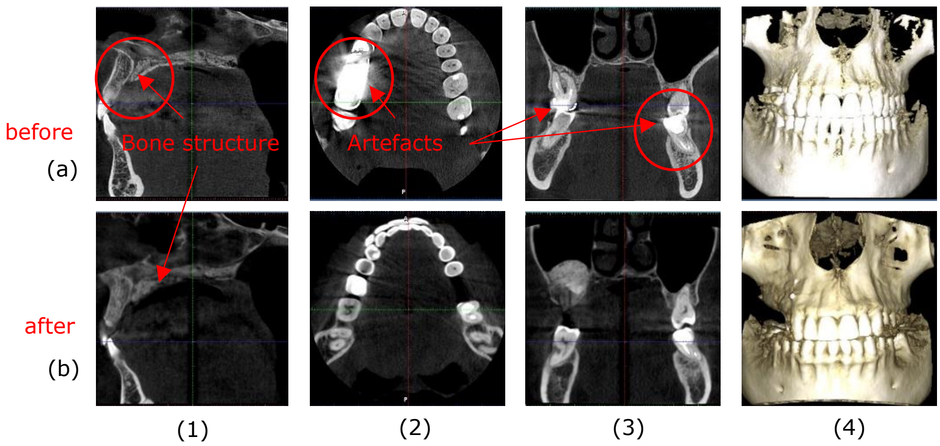



Figure 6. 3D CBCT performed on the same patient (FC, male, 29 years): images (a) before and (b) after optimization. Notations: (1) axial, (2) sagittal, (3) coronal, and (4) 3D rendering.

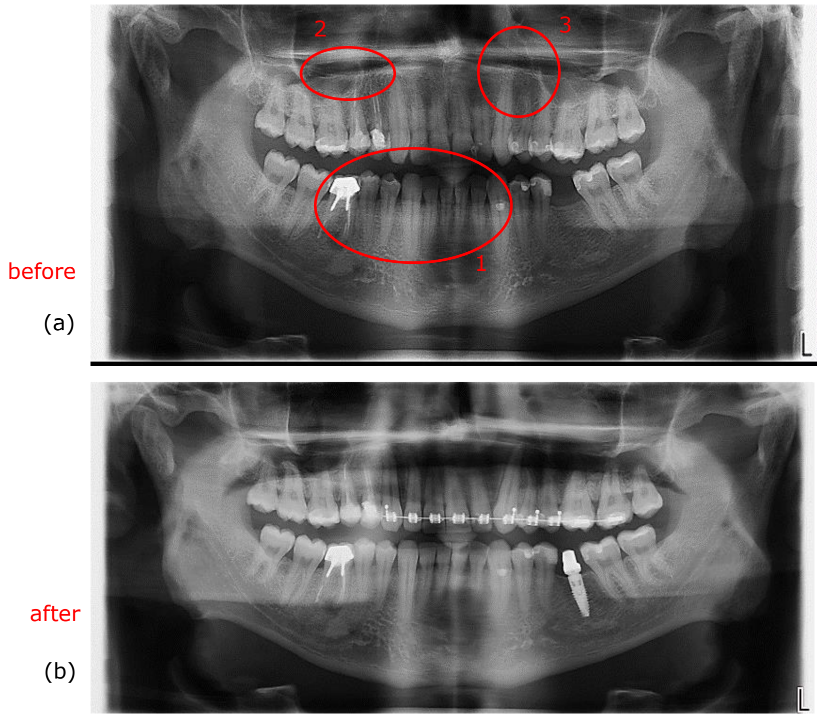



Figure 7. Panoramic radiographs taken on the same patient (FC, male, 29 years old) (a) before and (b) after optimization.

***Chapter 5 – The effect of an anaerobic fermentation process on 3D printed PLA materials of a biogas generating reactor***

Chapter 5, focused on OCT for NDT, deals with the testing of 3D printed polylactic acid (PLA) reactors for biogas production using anaerobic digestion. The impact of temperature, pH and aqueous phase on the tested reactor was investigated, together with the effect of gas phase / biogas produced. Two separate batches of materials used one after the other inside the reactor were considered in a realistic situation. Two essential parameters inside the reactor (pH and temperature) were continuously monitored over a period of 25–30 days for each of the two biogas generation processes. The results presented in this chapter were disseminated in (and are reproduced after) the work [A. Cioabla, V.-F. Duma*, C. Mnerie, R.-A. Erdelyi, GM Dobre, A. Bradu, A. Podoleanu, Effect of an Anaerobic Fermentation Process on 3D-printed PLA Materials of a Biogas-generating Reactor, Materials 15(23), 8571 (2022); https://doi.org/10.3390/ma15238571; **IF 3.4**; **Q2**].

OCT imaging was performed with the same system as in the previous studies. For the SEM analyses, an FEI Quanta 250 system was used. The investigation procedure involved mounting the samples on conductive copper supports with carbon wafers and exposing them to the scanning electron beam. To obtain high-quality images, all investigated PLA samples were coated with gold before SEM analysis [18] .

The study indicated that polymeric materials such as PLA are suitable for the development of components and small-scale bioreactors for anaerobic digestion process research for biogas production. The results of the experiments show that the test plates used in the study are partially affected by the chemical and biological reactions inside the reactor. However, the developed structure allows multiple tests to be performed and indicates that PLA-based 3D printed materials are a viable solution for manufacturing components in such applications.

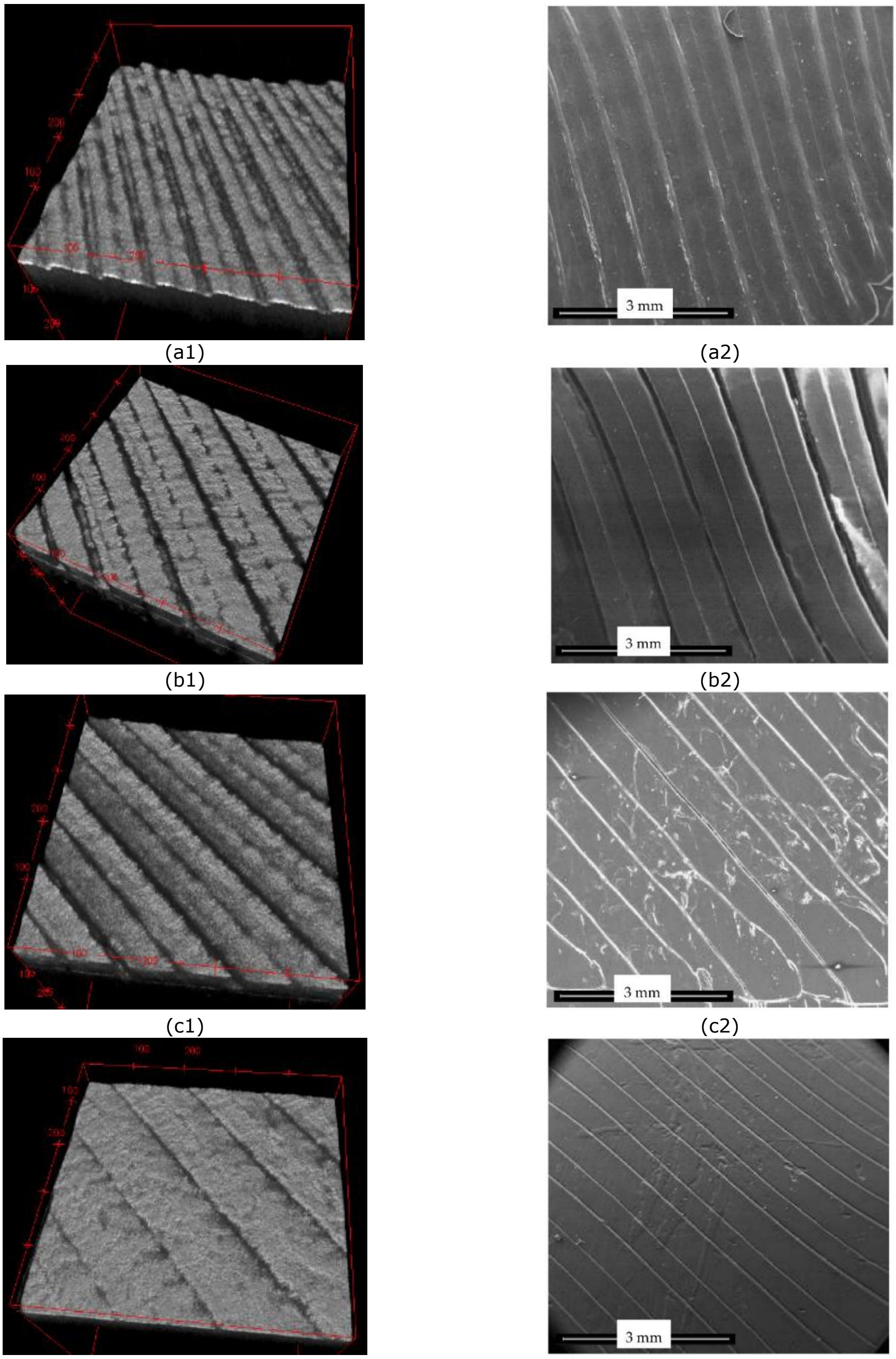



Figure 8. Image of test plates at different levels in the biogas reactor: (a1,a2) control plate; (b1,b2) upper plate (located in the upper part of the bioreactor); (c1,c2) middle plate (located in the central part of the bioreactor); (d1,d2) bottom plate (located in the densest part of the substrate in the bioreactor). The images in the left column (a1–d1) are 3D OCT reconstructions with an area of $3.5 \times 3.5$ mm $^2$, while the right column (a2–d2) are SEM images of the corresponding plate on the left (covered with gold).

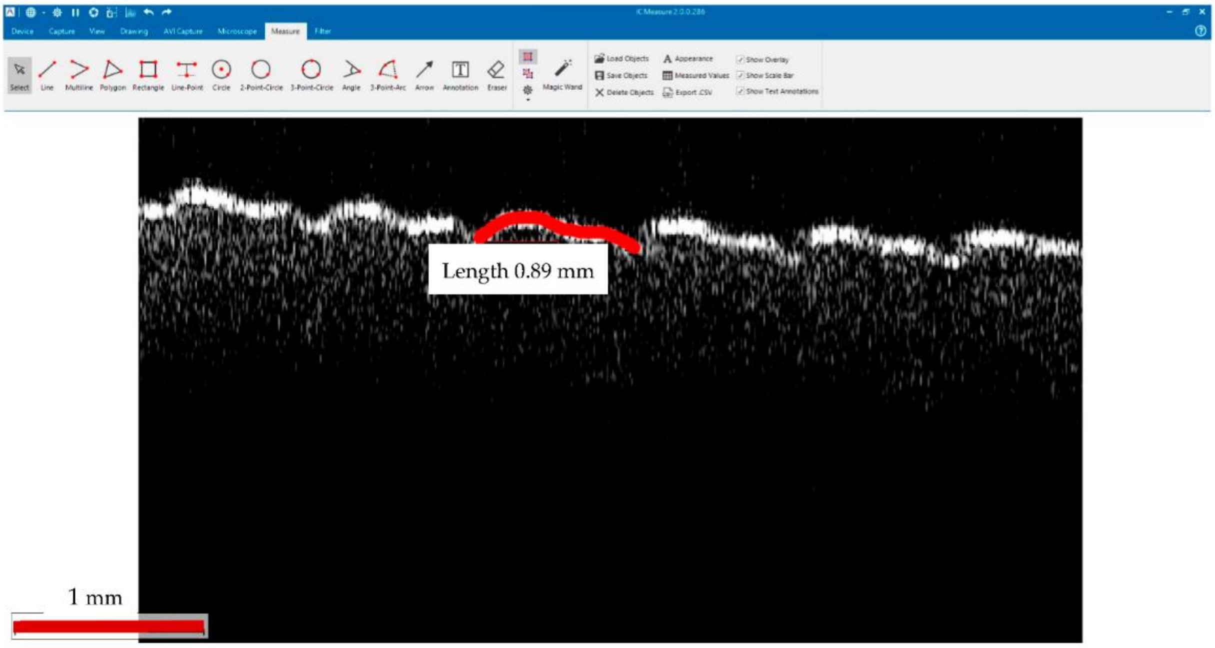



Figure 9. B-scan processed using the IC Measure program (The Imaging Source Europe GmbH, Bremen, Germany) to evaluate the lengths of the upper portions of each considered B-scan. Image dimensions are 3.5 (lateral) × 1.96 (vertical, along depth measured in air) $mm^2$.

Although further research is needed regarding the parameters, chemical composition and different types of substrates used in the tests, the conclusions of the study are promising for the use of these PLA materials in NDT researches in the field.

Figures 9 and 10 show the measured areas for each individual sample, for each individual group. The measurement results are presented in Table 3.

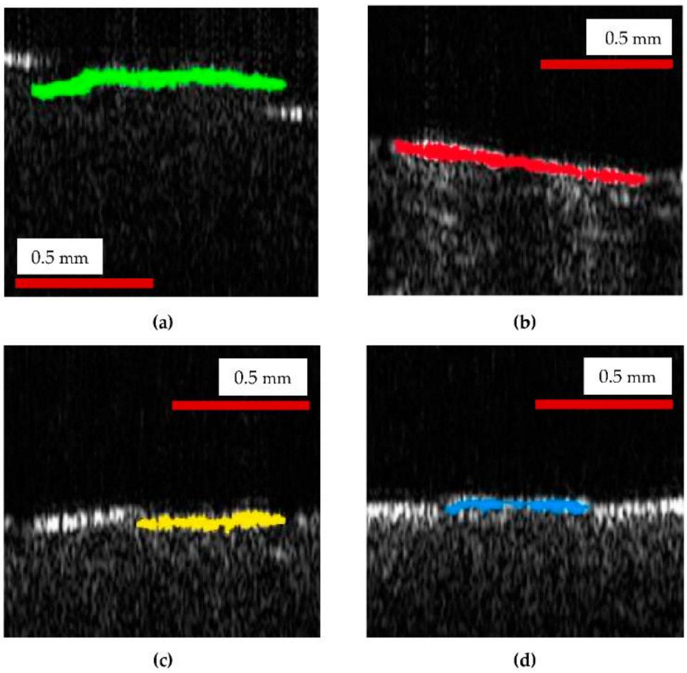
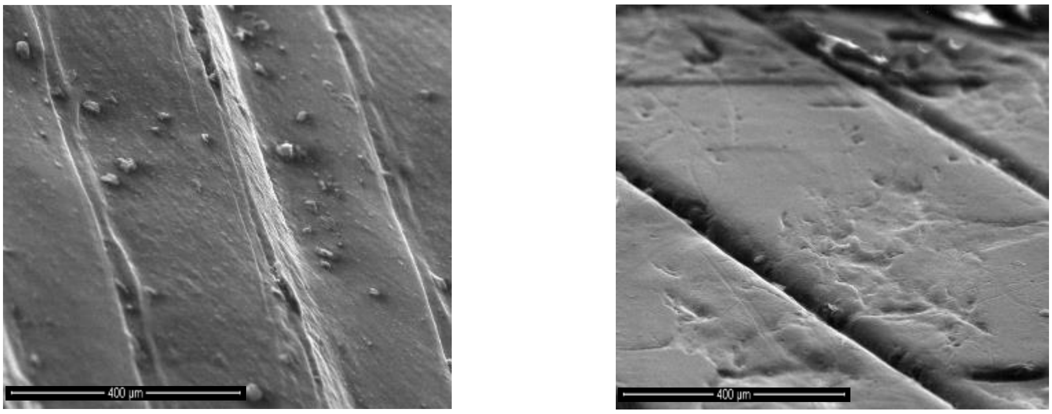



Figure 10. Details of OCT B scans from each of the sample plates from: (a) control group; (b) top plate; (c) middle plate; (d) bottom plate. The dimensions of each image are 0.92 (lateral) × 0.95 (vertical, along the depth measured in air) $mm^2$.

Table 3. Values of the lengths of the upper portions of the surface profiles of twenty B-scans, shown as examples marked with different colors in Figure 10. Evaluations using the program are shown on an example in Figure 9.

| **Sample** | **Reference (mm)** | **High (mm)** | **Center (mm)** | **Lower (mm)** |
|---|---|---|---|---|
| important contour measurements _ COLOR marked in the Figure 10 | 0.91 | 0.82 | 0.59 | 0.56 |
| | 1 | 0.7 | 0.64 | 0.6 |
| | 0.81 | 0.65 | 0.56 | 0.61 |
| | 0.84 | 0.69 | 0.53 | 0.49 |
| | 0.88 | 0.86 | 0.61 | 0.62 |
| | 0.98 | 0.84 | 0.63 | 0.59 |
| | 0.91 | 0.8 | 0.57 | 0.52 |
| | 0.83 | 0.84 | 0.63 | 0.54 |
| | 0.9 | 0.83 | 0.68 | 0.58 |
| | 0.89 | 0.78 | 0.59 | 0.57 |
| | 0.86 | 0.81 | 0.55 | 0.61 |
| | 0.92 | 0.69 | 0.59 | 0.5 |
| | 0.84 | 0.85 | 0.65 | 0.62 |
| | 0.81 | 0.76 | 0.61 | 0.58 |
| | 0.95 | 0.74 | 0.57 | 0.61 |
| | 0.87 | 0.81 | 0.6 | 0.53 |
| | 0.98 | 0.73 | 0.59 | 0.57 |
| | 1 | 0.8 | 0.62 | 0.55 |
| | 0.93 | 0.79 | 0.58 | 0.59 |
| | 0.89 | 0.76 | 0.61 | 0.6 |
| **Average (mm)** $\bar{\varepsilon} = \frac{\sum_1^N \varepsilon_j}{N}$ | **0.9** | **0.78** | **0.6** | **0.57** |
| deviation average absolute (mm) $MAD = \frac{\sum \lvert x_i - \bar{x} \rvert}{N}$ | 0.048 | 0.05 | 0.028 | 0.031 |
| **deviation (mm)** $\sigma = \sqrt{\frac{\sum_1^N (\varepsilon_j - \bar{\varepsilon})^2}{N-1}}$ | 0.059 | 0.059 | 0.036 | 0.038 |
| Standard error of the mean (mm) $SEM = \sigma/\sqrt{n}$ | 0.0130 | 0.0131 | 0.0078 | 0.0085 |



(a) (b)

Figure 11. SEM image of (a) a control sample (which was not in contact with biogas) versus (b) a middle sample - to highlight the level of degradation due to exposure to biogas.

The study also highlights the ability of OCT technology to assess the materials used for bioreactor walls, especially for batches used for biogas production. SEM can be useful for validating OCT results but is not absolutely. Therefore, this study highlights that only OCT can provide both qualitative and quantitative assessments, while SEM can provide additional information on the details of bioreactor wall degradation (Figure 11). Also, the differences between the impact of the vapor (in the upper part of the reactor) and the substrate (in the middle and lower part) on the walls of the bioreactor were highlighted.

### *Chapter 6 – Comparative Study of Decontamination of Titanium and Zirconium Surfaces: Imaging Assessments of Surface Damage*

This chapter of the study (on-going research) focuses on evaluating the effectiveness of laser therapy in decontaminating the surfaces of titanium and zirconium samples (Figure 12) that were contaminated with S. Aureus ATCC 25923 bacteria.

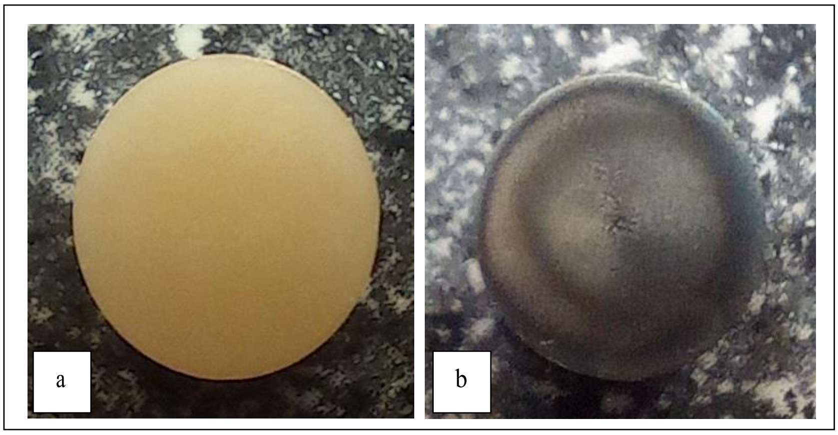



Figure 12. Zirconia (a) and titanium (b) samples prepared for SEM and OCT investigations.

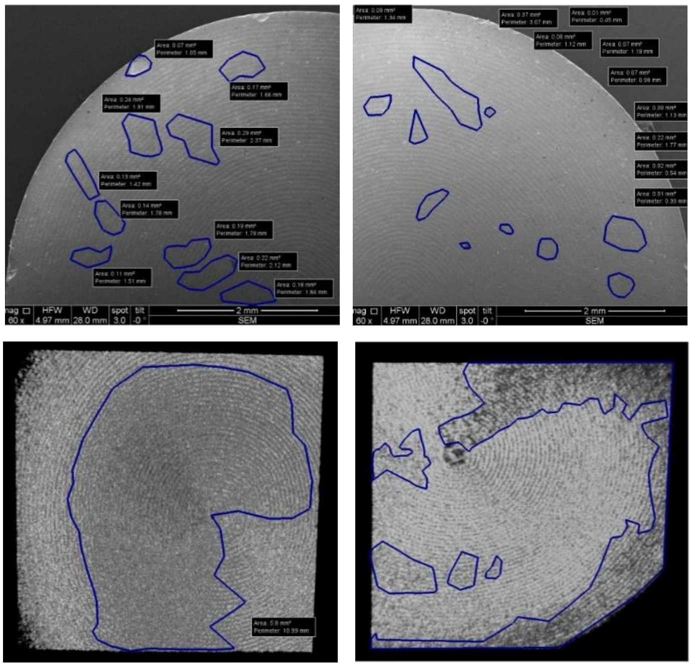


Figure 13. Measurements made on one of the samples.

Twenty samples were analyzed, divided into 5 groups of 4 samples each. Images were obtained using SEM and OCT. SEM was used for assessing damage to sample surfaces following the sterilization procedure, while OCT demonstrated its ability to investigate these samples. The images were used for measurements, and the IC Measure software was used to calculate the total surface area of the probes (Figure 13).

The following conclusions emerged from the statistic results: (i) there is no significant difference between SEM or OCT measurements; (ii) Titanium is slightly more affected than Zirconium, but the differences are not large, from 9.3 for Titanium to 6.5 for Zirconium; (iii) the surface area affected by any of the chosen methods is small, but there is a difference between them (Conventional 3.55; Er:YAG 4.25 and Er:YAG + PDT 5.31).

The study of which this research is a part is still ongoing, in collaboration with UMF Timișoara, and is to be published after the completion of the biomedical aspects.

### *Chapter 7 – Comparison of micro-CT and OCT results for verification of fit of conventional versus crenellated veneers*

Chapter 7 focuses on the comparison between the results obtained with the help of micro-CT and OCT imaging techniques to verify the adaptation of conventional dental veneers (CO) versus crenellated ones (CR), which constitutes a patent of UMF Timisoara [19] – Figure 14.

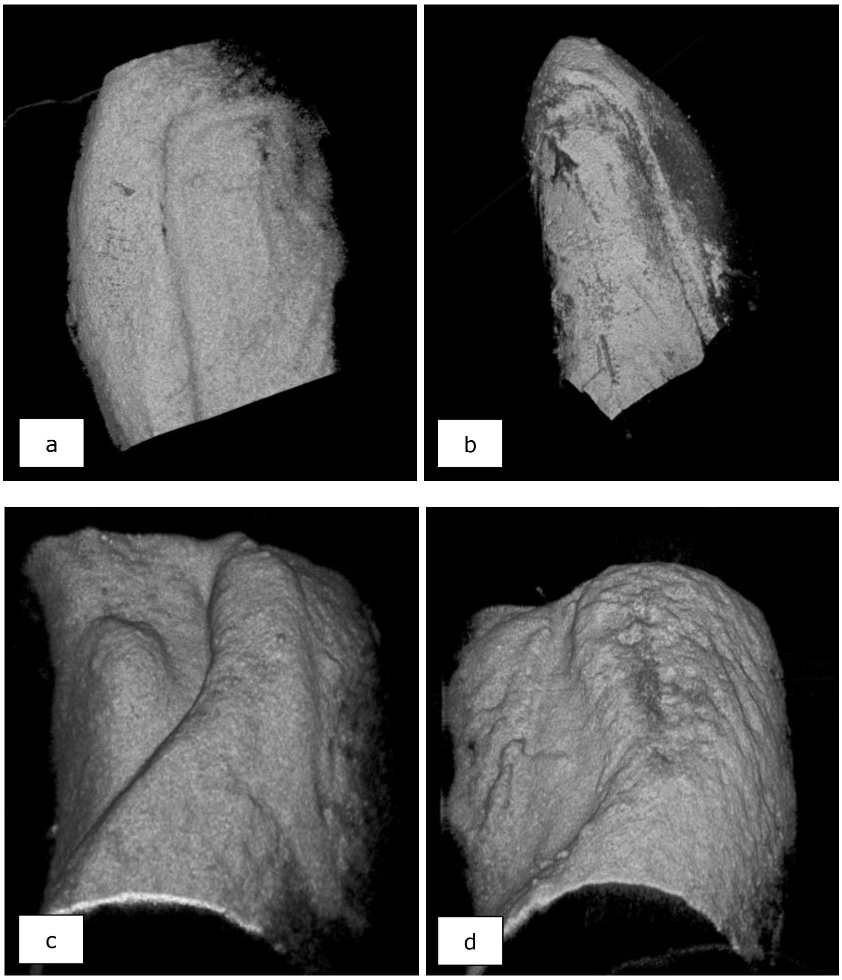



Figure 14. Images (a) and (b) are 3D reconstructions for the case of conventional veneers, and images (c) and (d) are 3D reconstructions for the case of crenellated veneers. The regions found in the images were taken into account for the evaluation.

The purpose of the study was to evaluate the influence of the sinusoidal marginal design of crenellated dental veneers on marginal and internal adaptation compared to conventional veneers. The working method involved the use of 10 teeth with dental veneers, divided into two groups: one with conventional veneers and another with crenellated veneers. OCT images were taken on each side of the teeth in the junction area between the veneers and the teeth. The analysis showed that crenellated veneers showed better results compared to conventional veneers, especially in terms of internal fit. These findings support the initial hypothesis that crenellated veneers may provide better fit and superior cementum homogeneity compared to conventional veneers. An important conclusion of this chapter is the fact that OCT can replace micro-CT in such analyses, due to the fact that the results of the study are confirmed by the study performed with the micro-CT method. This (in progress) study continues the one in [19].

## *Chapter 8 – CONCLUSIONS*

The research presented in this PhD thesis focused on the applicability of OCT as a biomedical imaging method in both dentistry and NDT. Thus, for each of the two research directions, the following results were achieved:

### I. OCT in dentistry

- OCT in Dentistry: This research has highlighted the importance of OCT in dentistry due to its ability to provide high-resolution images of oral tissues. The combined use of OCT and radiography has proven the synergy between these two technologies, contributing to proposing a more effective diagnosis and treatment of dental conditions [17] .
- Optimizing X-ray equipment using OCT: This research developed a procedure for optimizing X-ray imaging units in order to obtain the highest resolution images of dental issues (with the lowest possible radiation dose). This process improved the evaluation of dental details and parameters of X-ray units, facilitating the patients' diagnosis and treatment [16].

### II. OCT in NDT

- Use of polymeric materials in bioreactors: This research explored the use of PLA-based materials in the development of bioreactors for the production of biogas through anaerobic digestion. OCT has been used to evaluate the degradation of materials [18].
- Comparison of OCT with SEM in the study of titanium and zirconia materials: This study has compared the capabilities of OCT with those of SEM for imaging and measuring such materials processed with lasers for disinfection. The data showed that there was a good agreement between the results obtained with the two techniques.
- Validation of results with Micro-CT: This research has shown that OCT can validate results obtained with micro-CT, specifically regarding the study of the edges of dental veneers, crenelated (patented by UMF Timisoara) versus conventional.

Overall, the PhD thesis demonstrated the potential of OCT in various fields, including dentistry and non-destructive investigations [20] and tried to contribute to the development and optimization of relevant methods and technologies in these fields.

## *Future research directions*

1. Carrying out an extensive review work based on Chapter 1 of this thesis and classifying imaging methods according to the parameters of the images they provide.
2. Realization of (new) handheld probes (for dentistry) with laser scanners (i.e., 2D galvoscanner / polygon mirror scanner / MEMS) for OCT systems.
3. The development of new OCT systems for the analyses of samples from different fields,

(e.g., in collaboration with the University of Medicine and Pharmacy "Victor Babeş" Timișoara for biological samples).

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