VANESSA DE OLIVEIRA CHAVES

Optical coherence tomography in the detection and diagnosis of dental enamel demineralisation areas

UNIVERSIDADE FERNANDO PESSOA

PORTO

2019

VANESSA DE OLIVEIRA CHAVES

Optical coherence tomography in the detection and diagnosis of dental enamel demineralisation areas

UNIVERSIDADE FERNANDO PESSOA

PORTO

2019

VANESSA DE OLIVEIRA CHAVES

Optical coherence tomography in the detection and diagnosis of dental enamel demineralisation areas

---

Vanessa de Oliveira Chaves

Trabalho apresentado à Universidade Fernando Pessoa como parte dos requisitos para obtenção do grau de Mestre em Medicina Dentária.

Orientador: Prof. Doutor António Lobo Ribeiro

RESUMO

A cárie dentária e a erosão dentária são os principais problemas em odontologia. O diagnóstico correto, especialmente em lesões precoces, é vital para o plano de tratamento adequado. O exame visual-tátil e a radiografia dentária são os métodos mais utilizados para esse fim. A tomografia de coerência óptica (OCT) é outro método imagiológico capaz de melhorar o exame visual-tátil no diagnóstico de lesões em esmalte. A sensibilidade do instrumento é muito alta, geralmente mais de 90% e a especificidade normalmente acima de 95%. Utiliza o princípio da interferometria óptica com uma fonte de luz a emitir no infravermelho próximo (comprimento de onda na região de 1300 nm). Um software de processamento de imagens adequado pode melhorar a produção de imagens, incluir zonas colorimétricas e produzir uma imagem-3D, reduzindo a subjetividade na interpretação. Por não utilizar radiação ionizante e obter uma imagem nítida em tempo real, pode ser um bom substituto para a radiografia dentária em caso de avaliação diagnóstica de esmalte e dentina dentários.

Palavras-chave: Cárie dentária, Erosão dentária, Métodos diagnósticos, Tomografia de Coerência Óptica.

ABSTRACT

The dental caries and dental erosion are the major dental problems in dentistry. The correct diagnosis, especially in early lesions, is vital for the proper treatment plan. Visual-tactile examination and dental radiography are the most used methods for this purpose. The optical coherence tomography (OCT) is another imaging tool with the capability to improve the visual-tactile examination in enamel diagnostic. The instrument sensitivity is very high, usually more than 90% as the specificity is usually higher than 95%. It uses the principle of optical interferometry with an optical source emitting in the near-infrared (wavelength close to 1300 nm). Proper processing image software can improve the imaging production and present a 3D-image as reduces subjectivity with a colorimetric presentation. As it not use ionising radiation and offers a clear image production in real time, can be a good substitute to dental radiography in case of enamel and outer dentin diagnostic assessment.

Keywords: Dental caries, Dental erosion, Diagnostic methods, Optical Coherence Tomography

DEDICATORY

To my beautiful family.

ACKNOWLEDGMENTS

I would like to thank Professor António Lobo for his great orientation and passion in collaborate with this work.

I would also like thank my husband Ricardo Noschang for the scientific help and support though all this process of change in our lives.

To my friend in the University and outside of the Dentistry field, thank you all for make our lives better and fun.

My final acknowledgment to my sweet daughter Olivia that was comprehensive in my absence and participative in several moments including going to the University with me.

INDEX

TABLE INDEX

I. INTRODUCTION

The pathologic alterations that cause demineralisation of dental tissues are among the most frequent diseases of the stomatognathic system (Salas *et al*., 2015, Frencken *et al*., 2017). Both dental caries and dental erosion affect individuals of all age groups (Costa *et al*., 2018) and, in contrast to a series of population preventive measures, their prevalence is still high (Frencken *et al*. 2017). Both alterations, if not adequately addressed, have a progressive evolution that lead to the loss of dental tissue, decrease in masticatory function and corresponding decrease in the quality of life of the affected individual (Haag *et al*., 2017). It is consensus that early diagnosis has an important role in limiting the damage of these alterations, since the implementation of preventive procedures and early treatments can reverse the initial disease process or avoid surgical intervention (Lee *et al*., 2016).

The diagnosis of dental caries is clinically centred in the visual-tactile evaluation (VTE), associated or not to a complementary examination with intra-oral radiography of the dental elements and bone support. However, due to its inherent subjectivity and individual ocular capability, the visual-tactile exam does not always allow a consistent detection, especially in early lesions (Novaes *et al*., 2012). The need for a caries lesions diagnostic standardisation in both clinical and populational studies, a novel system of classification was developed (Ismail *et al*., 2007) and called the *International Caries Detection and Assessment System* (ICDAS). This system is based on the visual-tactile evaluation of the dental lesion according to predefined criteria that are linked to the natural evolution of the caries disease. The ICDAS has been shown to be a relative sensitive and reproducible classification system to detect caries lesions (Erkstrand *et al*. 2011). Nevertheless, one of the major limitations of the visual examination as the only method of diagnosis is the low sensitivity for cases of incipient or non-cavitated caries, a clinical situation in which the carious process with tissue demineralisation is installed without the fragmentation of the external area of the dental enamel and loss of tissue continuity. Even in cases of small cavities the sensitivity of this instrument may still remain low (Elhennawy *et al*., 2018). The differentiation between active or non-active incipient lesions is also difficult through visual clinical examination, as well as in the approximal surface where direct visualisation is usually not possible. Another problem is that even using the ICDAS system, visual evaluation does not allow adequate quantification of the depth of the carious lesion (Gomez *et al*., 2013).

Intra-buccal radiography (Rx) is a complementary diagnostic exam in which ionising electromagnetic radiation penetrates the tissues and generates, on a sensitive pellicle, an image of the object draw in grey gradation according to the relative permittivity of the biological tissue. Intra-oral inter-proximal radiographs (*bite-wing* type) allow the diagnosis of advanced occlusal and approximal caries with high sensitivity and specificity (Elhennawy *et al*., 2018) but do not have sufficient resolution for differential diagnosis of initial lesions because the overlap of the tissues structure image impairs the distinction of the caries process in the obtained image. Therefore, the diagnosis of occlusal carious lesions and their depth is still a clinical dilemma (Gomez *et al*., 2013) as well as the low accessibility of certain regions such as the approximal area or adjacent to the regions of the entrance of the occlusal fissures that also present visual limitations and radiography evaluation difficulties (Park *et al*., 2017). New approaches to evaluate the dental tissue health have arisen in order to reduce the use of ionising radiation as well as increase the sensitivity and specificity of the diagnosis of demineralised tissues, reducing the subjectivity in the analysis. To this end, instruments based on the use of photonics technology have emerged in the universe of diagnostics in Dentistry. These diagnostic instruments include fluorescence assessment devices such as DiagnoKavo® (Kavo Dental, Biberach, Germany), Near-infrared light transillumination (NILT) as the CariVu (Dexis, Biberach, Germany) and Optical Coherence Tomography (OCT).

Optical Coherence Tomography had its use consolidated in the medical field with wide use in clinical ophthalmology because the functionality that the technique offers, it is not invasive or destructive and can reach a high spatial resolution thus producing images of high quality that can be obtained in real time (Kishi, 2016). This equipment is based on the principle of low coherence interferometry (or white-light interferometry) through mainly the use of a Michelson's interferometer. In this technique, a visible or infrared laser light with low coherence length is emitted by the instrument and splitted, one to a reference mirror and one direct on the biological structures of study. The detection of the interference generated by the reflected radiation that emerge from the biological object and the reference mirror allow the obtainment of a two dimensional transverse image of the object. The image generated allows to differentiate the dental tissues with sufficient resolution (of the order of the tens micrometers) for the diagnosis of anatomical alterations or to calculate the level of demineralisation of the tissues. Infrared emission light sources are usually used, with central wavelengths ranging from 780 nm to 1550 nm (Maia *et al*., 2016). OCT also allows assessment of lesions on smooth surfaces and is able to expose structural defects in tooth enamel as micro-cracks (Park *et al*., 2017). Experimental studies have demonstrated the equivalence of OCT images with highly sensitive methods such as micro-computerised tomography (Park *et al*., 2017).

The main objective of this study is to present a bibliographic review of the recent clinical and laboratory applicability of OCT in Dentistry. Likewise, present studies that demonstrate its sensitivity and specificity to evaluate hard dental tissues with the presence of demineralisation (due to caries or dental erosion process), comparing the applications and limitations with traditional methods of diagnosis (visual-tactile exam and dental radiography). Our hypothesis is that OCT is a non-invasive diagnostic method with high potential for the evaluation of hard dental tissues alterations and its effectiveness in the diagnosis of enamel demineralisation is similar or better than radiographic examination and visual-tactile inspection.

Materials and methods

For the elaboration of this work, a web search was carried out in the databases available electronically: Pubmed Database, ScienceDirect and Scielo. This search was performed in April, 2019 using the keywords: dental, diagnostic methods, optical coherence tomography, dentin, enamel. The research protocols used were the following :

1. ((Optical coherence tomography) AND dental) AND diagnostic AND (dentin OR enamel) AND alive - Presented 27 results including 15 in the last 5 years.
2. ((Optical coherence tomography) AND dental) AND diagnostic AND (dentin OR enamel) AND *vitro* – Presented 72 results including 41 in the last 5 years.

The bibliographic survey with the keywords revealed a total number of 99 scientific publications, of which we mainly selected *in-vitro* and *in-vivo* studies and publications referring to the last five years. This choice was made based on that the OCT technology itself has evolved rapidly and the new equipment have more efficient imaging software and detection systems. An option was also made for articles exclusively in the English language, the predominant one in the journals of high scientific impact.

II. DEVELOPMENT

Dental caries is a multi-factor disease, caused by bacteria present in the dental plaque that alters the dental mineral content thought the acidic metabolism of sugars from the individual diet. The process of dental caries is continuous, starting with the demineralisation of the enamel crystals at the atomic level and if not interrupted, it evolves to cavitation of the dental element (Featherstone, 2008). The process is influenced by the equilibrium of the demineralisation-remineralisation process obtained by the regulatory agents of oral pH and plaque removal. Dental erosion is also a process of altering the minerals of dental tissues by acids, but these acids originate from the individual diet or from endogenous secretion (Lussi *et al*., 2012). The process of dental erosion is also continuous and can lead to severe structural changes and tooth sensitivity but is not associated with the presence of bacteria. Although there was a general reduction in the development of dental caries lesions on smooth surfaces of the teeth, on the occlusal and approximal surfaces its incidence is considered high (Frenken *et al*, 2017).

The diagnosis of both dental processes may seem simple when it is possible to visualise cavitated lesions in exposed areas to direct visualisation. However, in non-cavitated approximal and occlusal lesions, this evaluation has a more subjective tendency, and as such, the opportunity of early diagnosis may be lost.

In order to standardise the various diagnostic protocols for visual-tactile inspection and to promote coherent information on diagnosis, prognosis and dental caries treatment protocol, cariology specialists developed the *International Caries Detection and Assessment System* (ICDAS) (Ismail *et al.* , 2007). It was developed to be used in clinical practice, education, research and public health (Pitts and Erktrand, 2012). It is based on visual-tactile inspection with the use of a blunt tip probe to prevent injury to fragile areas. It is performed on cleaned surfaces of teeth and after removal of water with jets of compressed air. It consists of a six-stage classification of caries disease (1-6) in which each code refers to several progressive and predictable changes in dental caries (Table 1).

Table 1. ICDAS codes based in Ismail *et al*. (2007).

Code 0	Sound tooth (healthy)
Code 1	First clinical sign of demineralisation visualised with dry tooth (white spot)
Code 2	First clinical sign of demineralisation visualised in non-dried tooth
Code 3	Cavitated lesion located in dental enamel without affecting dentin tissue and without internal darkening
Code 4	Internal darkening related to dentin tissue, with or without enamel cavity
Code 5	Distinct cavity in dental enamel with visible dentin affection
Code 6	Extensive cavity in dental enamel with exposed dentin

The criteria of the ICDAS instrument that uses the visual alterations of demineralised enamel (which is more opaque and "chalky" than the healthy one) has the capacity to diagnose caries lesions *in vivo* with a moderate sensitivity, including initial lesions (Novaes *et al*., 2012). Some studies (Diniz *et al*. 2012, Lee *et al*. 2016)) have shown moderate to discrete results. In the study of Diniz and collaborators (2012), the visual evaluation with ICDAS system allowed the correct detection of 66% of the incipient caries lesions before the samples lesions were confirmed by histology. Lee *et al*. (2016) presented sensitivity results of the ICDAS instrument very close to the previous study shown, with agreement with the histology around 65% in cases of positive lesion in occlusal tooth surface diagnostic.

Another limitation that the visual-tactile evaluation with the ICDAS method may incur is to estimate the depth of the lesion. In a histological evaluation carried out by the team of Gomez *et al*. (2013), it was shown that half of the samples classified with ICDAS code 1 (the first sign of caries in dried tooth enamel) presented results in which the lesion is already revealed in more than half of the dental enamel of samples. Half of the samples classified clinically with ICDAS code 2 (distinct alteration in tooth enamel) had already affected dentin (Gomez *et al*., 2013). Therefore, the ICDAS can encompass a variety of dental lesions depths in each code and still fail to detect some incipient lesions that did not manifest as visually perceptible alteration of tooth enamel (Park *et al*., 2018).

The last important limitation refers to the need for intense training of the system by the professional before its clinical use, requiring another experienced professional as a supervisor. The lack of prior training incurs wide divergences in the definition of dentinal lesions (Lee *et al*., 2016).

The use of intraoral radiography as an auxiliary diagnostic tool for dental caries lesion detection has been date the last century, especially in suspicious of occlusal enamel or dentin lesion and to evaluate the approximal area, which in a normal dentition usually does not allow direct visualisation. As a tool for diagnosis, it allows the visualisation of lesions that affected the dentin but does not allow a concrete diagnostic in enamel lesions (Erkstrand *et al*., 2011, Park *et al*., 2018). It is also an exam that naturally presents a sub-dimension of the size of the lesion since it only presents changes in the radiological image when there is a large mineral loss. According to Diniz *et al*. (2012), the most indicated radiation incidence to generate a radiographic image for caries interpretation purposes is the inter-proximal intra-oral radiography (known as the *bite wing* technique), has high specificity for evaluating caries lesions but low sensitivity for all types of lesions (29% to 44%). He concluded that the accuracy of the inter-proximal radiograph for healthy teeth is low (32%) but is acceptable when there is the presence of caries in dentin (86%). In this study radiography aided in the diagnosis of only 15% of enamel caries lesions, which confirms that it is not suitable for the diagnosis of incipient lesions or enamel restricted lesions. Therefore, although it is the most used method to complement the clinical diagnosis, it presents little or no information on the status of incipient lesions of dental caries (Park *et al*., 2018).

The first *in-vitro* image (although from the eye) using Optical Coherence Tomography (OCT) was reported in the scientific literature for the first time in 1991 by Fujimoto's team (Huang *et al*., 1991). A few years after its introduction, the results of the first investigations of the use of OCT in Dental Medicine (Colston *et al*., 1998, Felschtein *et al*., 1998) were published, in which images of soft and hard tissues were obtained from the oral cavity. The OCT is an optical interferometric technique that uses electromagnetic radiation, usually in the near infrared spectra region. The system uses a light beam that is splitted in two optical path directions, one of which is directed to the object being studied and the other to a mirror that reflects the reference wave. The recombination of the two wave beams generates an interference pattern that contains spatial information about the object. This physical phenomenon follows the principle analogous to that used in ultrasound (sound waves), but with electromagnetic waves.

The first OCT devices were based on the time-domain (TD) detection of the wave time to reach the sensor, which calculates the temporal relationship while simultaneously scanning the optical path in an arm of reference. The radiation reflected by the object and the radiation reflected by the reference arm are interfered with an interferometer of the Michelson or Mach-Zehnder type. This interferometric signal is detected by a photodetector, which is different for the various OCT models (Katkar *et al*., 2018).

With the continuous development of this technique, a second line of OCT systems appeared, in which a diffraction grating was added to the initial model. This diffraction grating separates spatially the electromagnetic radiation reflected by the object and then is photo-detected and processed. This modification allows the mirror at the reference arm of the interferometer to be in a fixed position without loss of image definition. This type of OCT is known as Fourier-Domain (FD) OCT type, because after the diffraction of the waves from the optical grating, an inverse-Fourier transformation is calculated on the detected optical signals (Leitgeb, Hitzenberger and Fercher, 2003). This technique is also called Spectral-Domain (SD) OCT because analyses the signal in the optical spectral domain. The third important technological improvement in the OCT systems was to remove the diffraction grating and to use a tuneable emission optical source in conjunction with a simple and low-cost photodetector, unlike traditional optical detector used in the previous SD-OCT system. This new technique had the designation of Swept-Source (SS) OCT, and allows scanning frequencies much higher than the traditional TD-OCT.

The images generated by the OCT can be considered tomographic as the scan leads to the acquisition of several “slices” of the biological object. When the light source is statically incident on the object and its interference on the reference beam generates a single image, the image is called A-scan. By scanning the object, either by moving it or by sweeping the wavelength emission of the source, numerous cross sections of the object are generated and the sum of these images is called B-scan. The merging of B-scan information obtained from an object using suitable software can generate a three-dimensional image of the object, giving it the actual volumetric ratio. This image X-Y-Z is called C-scan and therefore a 3D-image can be generated almost in real time.

The OCT has its use in Dentistry mainly focused on the evaluation of demineralised tissue as in the case of dental caries lesions and dental erosion. This use rises in experimental *in-vitro* and *in-vivo* studies but already has clinical applicability with instruments that offer optical structures present in pen-type devices with size enough to allow intra-buccal use (Shimada *et al*. 2014). The OCT system is indicated to detect initial or incipient lesions in dental enamel (Nakagawa *et al*., 2013), to evaluate the progression of carious lesions on smooth and occlusal surfaces of dental enamel and dentin, both *in vitro* and *in vivo* (Shimada et al., 2010, Staninec, *et al*., 2011, Wijesinghe *et al*., 2016). It also has applicability in quantifying the remineralisation of incipient caries lesions and dental erosion (*in vitro*) (Kang, Darling and Fried, 2012) and to evaluate the quality of restorative treatments of carious lesions, especially tooth-composite adaptation, as well as to follow the restorative treatment in relation to caries recurrence or dental demineralisation. Cracks formation in the adhesive union can also be evaluated with OCT (Haak *et al*., 2018).

Studies with dental samples have shown that the potential of OCT in quantifying tooth enamel demineralisation is based on the increase in signal dispersion due to the reflection of the light emitted in contact with the demineralisation areas and porosities of the structure that suffered the mineral loss (Jones *et al*., 2006, Park *et al*., 2017). Because of the refractive index is superior to that of dental enamel in the image generated by the OCT, the demineralisation lesions represent a whiter coloration than the enamel (Park *et al*., 2017), while the dental cementum-enamel junction line is darker (Park *et al.* , 2018). This image modality even allows the perception of small mineral changes in volume, which qualifies it to evaluate incipient lesions of dental caries and the evaluation of the remineralisation of lesions (Lee *et al*., 2016). OCT imaging is very sensitive, and even lesions that are clinically superficial or not detectable can be diagnosed. It is possible to visualise the layers of demineralisation sites or clearly observe the formation of "inverted cone" image that is the common penetration form in occlusal tooth caries and depend on the depth of demineralisation (Ei *et al*., 2019). In the study of dental erosion, demineralisation by exposure to acid in low and high intensity protocols can also be perceived by the difference in reflectivity between healthy and eroded enamel. It is possible to observe alterations in dental enamel by exposure to citric acid even in small time intervals as 10 s range, making possible use the OCT in most of the traditional methodologies with this type of study (Mylonas *et al*., 2018).

The scope of the structures of which the OCT allows to generate an image dependent of several physical factors, being the most important: the wavelength of the radiation used, the incidence and position of penetration of the light and the coefficient of absorption of the object structure. The most common wavelength used in dental SS-OCT is 1300 nm. At this wavelength the normal dental structure allows a light penetration depth with good definition of ~150μm, validated by the comparison of the images obtained with the OCT with those of the same sample analysed by polarised light microscope (Maia *et al*. 2016). Although its penetration is not enough to evaluate the relationship between the carious process and the pulp tissue in an intact tooth, it is possible to observe lesions involving the enamel-dentin junction (Park *et al*., 2017). This information that can lead to the conclusion of a dentine lesion. Other wavelengths may allow greater or lesser penetration into the dental structure. The study by Ei *et al*. (2019) using a wavelength of 1310 nm was able to penetrate and visualise up to 3 mm depth in the dental structure. The study by Trifanov *et al*. (2011) using laser radiation at 1060 nm achieved penetration in the dental surface of up to 10 mm. The quality of the image also depend of the wavelength and the optical signal processing of it is may be impacted in the most deep structure imaging formation.

For approximal area evaluation, the amount of light beam penetration may be a limiting factor for an adequate evaluation of this region (Golde *et al*., 2018), depending on the size and type of the optical radiation used. In dental cavities, where there is a deeper initial access, the OCT can be used to evaluate the relationship between dentinal tissues and pulp tissues and to assist in the diagnosis of the lesion depth or pulp lesion. This in close to real time capturing and processing even during in the trans-operative period, with the position of the OCT tip being 1 cm away from the reading area. This characteristics can allow a high-quality 3D and real-time image through a non-invasive, non-destructive and non-contact method (Park *et al*., 2017).

Another physical factor that interferes with the quality of the signal captured by the OCT refers to the angle of incidence of the radiation beam. Quality images obtained from the occlusal surface can be hampered by the incidence variation and optical reflectivity as well as the anatomy of the region of grooves and fissures. Park *et al*. (2017) found that the incidence perpendicular to the occlusal plane (0 degrees of occlusal inclination) is not very precise because there are many interferences (artefacts) caused by the superposition of the structures. They also noticed that the slight slope of the tooth (5 to 15 degrees of inclination) favoured obtaining more information in the images with less interference besides an accentuation of the contrast between healthy tissue and the affected by caries.

The third mentioned physical factor that interferes in obtaining the sharpest images with OCT is related to the high refractive index of external surface of dental enamel. Therefore, products were tested in an attempt to reduce the external refractive index to promote more contrast with the demineralised tissue. Park *et al*. (2017) used a glycerin gel at a thickness of 1.2 mm in the attempt of decrease the enamel refractive index and provide a higher contrast with the demineralised area. In this study they were able to obtained images with superior quality compared to the non-use of glycerin. Also, Polyvinyl siloxane (PVS) can be used to reduce dispersion in areas of high demineralisation, improving the image generated by the OCT (Kang, Darling and Fried, 2016) and with that, the demineralisation zones of dental enamel became more evident.

In order to improve the interpretation of the OCT images and thus reduce subjectivity, proper algorithms have been used to automatically calculate the lesion area in the dental enamel by delimiting the parameters of altered light reflectivity. The study of Maia and collaborators (2016) to evaluate the effect of the attenuation of the reflected light coefficient of the OCT, was able to obtain a final image quality superior to the conventional method, together with an algorithm of data analysis. With this, they obtained more precise results for the diagnosis of incipient caries in the dental enamel. From their study we can verify the good relation of the results of the OCT when compared with devices of quantification of induced fluorescence, Quantitative Light-induced Fluorescence (QLF) instruments, which are reference instruments in this type of studies. The C-Scans maps or “colorimetric maps” that were obtained through the processing algorithm, allowed a more accurate visual evaluation of the mineralization differences between healthy and affected tissue. The QLF evaluates the fluorescence change coefficient by the radiation dispersion while the OCT evaluates the dispersion directly (Maia *et al*., 2016). This is very important because the QLF has a good acceptance by the researchers for clinical evaluations of dental caries demineralisations (Karlsson, 2010).

III. DISCUSSION

The indications of OCT in dental medicine have grown as the instrument is improved and its effectiveness proven. In the investigation of dental enamel demineralisation lesions, both from dental caries and dental erosion this instrument has presented its greatest applicability until now. The comparison of the instrument with traditional methods has presented the OCT as an effective auxiliary diagnostic tool. Its greatest applicability however, until there is more development of the technology, is in the diagnosis of lesions in the outermost dental tissue, the dental enamel. It should be pointed out that the diagnosis of initial lesions on dental enamel, mainly the ones still not cavitated, is in agreement with the preventive-conservative focus of current dentistry. In this aspect, the OCT is at the forefront of traditional imaging tests such as inter-proximal radiography (Shimada *et al*., 2014).

According to Gomez and collaborators (2013) that used an SS-OCT, the instrument presented excellent specificity (98% of the teeth without lesion of dental caries received the correct diagnosis) for diagnosis of dental caries when confirmed by the histology of dental elements previously evaluated. Differences may occur on the various surfaces in which the images are produced with the OCT. This is due to the variation in tissue thickness and anatomy, which interferes with both the penetration of the light beam and the presence of more artefacts in the image. In dental enamel samples, Lee and coworkers (2016) obtained different sensitivity indices for the different zones evaluated. For the smooth surfaces they obtained 75% sensitivity and 94% specificity. Specificity refers to the amount of "false negatives" and the higher their value, the less chance of the negative result being presented as positive. For other areas, the sensitivity was higher, and for occlusal surface of grooves and fissures, an area of greater diagnostic challenge, the sensitivity was 80% and the specificity was 90%. In the approximal zone, normally difficult to access visually, Shimada *et al*. (2014) obtained favourable OCT results *in vivo* when compared to digital radiography. The OCT showed sensitivity of 92% for initial lesions in dental enamel and 84% for cavitary lesions. In deciduous molar teeth, Nakajima *et al.* (2014) found that the OCT was more sensitive to the detection of enamel caries than the average reported in the literature for permanent teeth. In their study, the OCT presented 93% sensitivity for incipient lesions in dental enamel, 89% for cavitated lesions in dental enamel. Because of the smaller thickness of the tooth, it could penetrate more in the dentin and with this it presented sensitivity of 91% for dentin lesions. Their results for dental caries lesions confirmed by confocal microscopy were statistically superior to those presented by the visual-tactile examination using the ICDAS system.

According to Gomez and collaborators (2013) the SS-OCT type used in their study, did not obtain good sensitivity for dentin tissue (only 32% of dental caries lesions were diagnosed positively). This contributes to the observations that light penetration into the dental structure can be limited with the use of some commercially available optical sources in the 1300 nm wavelength range. It can also be inferred that visualisation of the enamel-dentin junction line is probably the optical limit of OCT in healthy teeth with 1300 nm wavelength (Nakajima *et al*., 2012).

In dental erosion research, the OCT has presented favourable results for the reading of both demineralisation and remineralisation, with no difference to the results presented with topographic reading by optical profilometry, which is considered the reference standard for this type of study (Chan *et al*., 2014, Alguilan *et al*., 2019). In the case of dental erosion, some studies indicate that the reading quality of the OCT can be affected by the roughness that the erosive process generates in the dental enamel. This roughness could increase the dispersion of the light radiation and decrease the penetration of the beam in the enamel. However, the results of Alguilan *et al*. (2019) did not confirm this statement.

Although there are not yet many companies that offer OCT devices for clinical use in dentistry, the use of OCT in research is more evident. In research the OCT has the advantage of faster sweeping, which reduces the dehydration of samples when exposed to the external environment for long periods as in *in-vitro* studies performed with slower scanning instruments (Park *et al*., 2017). In *in-vivo* studies where there are fewer options of measuring instruments, OCT has the advantage of having greater sensitivity to tooth enamel than digital inter-proximal radiography and does not expose the patient to ionising radiation. However, radiography is still superior to evaluate the relationship between carious tissue and pulp tissue since OCT penetration still has its limitations (Shimada *et al*., 2014).

Although the OCT offers a great ability to scan the teeth and produce good images, there is a learning curve in the use of OCT equipment since the phenomena inherent to the technique, as artefacts or shadows, are not intuitively distinguished and may hinder the use of diagnostic images (Park *at al*., 2017). In order to increase the efficiency in the interpretation of OCT images, it is appropriate to use systems in which data are transformed into images based in colour maps according to the degree of mineralization of the dental zone evaluated (Zain, Zakian and Chew, 2018). There are also mathematical processing algorithms that can aid in artefacts reduction and image enhancement. Among them we can mention the Kernel transformation (Li *et al*., 2009). The use of appropriate algorithms for the evaluation of OCT data is one of the fundamental factors for the generation of high quality images to detect demineralised tissues (Maia *et al*., 2016). According to Golde *et al*. (2018), the DOPU (*Degree of Polarisation Uniformity*) algorithm, used in ophthalmology to visualise pigments in the human retinal epithelium, seems to be the one that presented the best results in dental surface imaging to date. By mathematical calculation of the interference pattern generated, the image becomes clearer and allows even an untrained dentist to differentiate the carious tissue from the healthy one (Golde *et al*., 2018).

It should be taken into consideration that the images generated by the OCT, although reliable in proportionality, are affected by the refractive index of the objects and cannot be accurately interpreted without prior knowledge of the respective indices. In the literature, studies indicate that refractive indexes for enamel, dentin and pulp tissue are 1.63; 1.55 and 1.54 (Hariri *et al*., 2012, Majtuk *et al*., 2015), respectively. Another important measure that must be taken into account in OCT images is the optical attenuation coefficient of the target object to be analyse, which relates to the penetration depth of light into the object's volume. An example of this is the difference in the coefficient for enamel and dentin, due to the greater presence of water and organic tissues (> 50% by volume) in the later, increases the energy absorption and reflects differently from the enamel that has only 10% of organic structure. This coefficient is also important in the early diagnosis of dental caries because it was verified that the demineralised tissue presents a marked difference with the healthy enamel, and the carious tissue presents an increase of the optical attenuation coefficient (Ueno *et al*., 2016).

IV. CONCLUSION

With all the information above, we can conclude that the OCT is an important tool to complement the visual-tactile clinical diagnosis, increasing the characterisation of incipient lesions while providing information of areas with mineral alterations that are not directly visible to the human eye but are already present. Its use is not limited to examination of carious lesions but can be used in dental erosion study, mapping the success of dental restorations and monitoring remineralising treatments in dental enamel.

The OCT has in the research its greatest use in dentistry so far. It is possible to obtain high sensitivity in both *in-vitro* or *in-vivo* study and OCT has the capability to replace traditional exams such as profilometry and histology, optimising the time of data collection.

Optical Coherence tomography also presents technical limitations such as penetration depth of the radiation beam in zones of high optical diffraction and the need for initial training by the operator. On the other hand, there are algorithms and data transformations that tend to facilitate image manipulation and increase the quality of the images produced by the OCT. It is a path that ophthalmology has followed and today ophthalmologic OCTs offer a wide range of features to improve equipment performance. In dentistry, although it began its studies with OCT later than ophthalmology, is going in the same direction thanks to the attractive advantages of the OCT that are the capture of images in real time with the possibility of obtaining three-dimensional images of the objects without the use of ionising radiation.

V. BIBLIOGRAPHY

Alguilan, M. A. *et al*. (2019) Impact of surface micromorphology and demineralization severity on enamel loss measurements by cross-polarization optical coherence tomography. *Journal of Dentistry*, 81, pp. 52-58.

Chan, K. H. e*t al*. (2014) A Method for Monitoring Enamel Erosion Using Laser Irradiated Surfaces and Optical Coherence Tomography. *Lasers in Surgery and Medicine*, 46(9), pp. 672-678.

Diniz, M. B. *et al*. (2012) The performance of conventional and fluorescence-based methods for occlusal caries detection An in vivo study with histologic validation. *Journal of the American Dental Association*, 143(4), pp. 339-350.

Ei, T. Z. *et al*. (2019) Three-dimensional assessment of proximal contact enamel using optical coherence tomography. *Dental Materials*, 35(4), pp. e74-e82.

Enhennawy, K. *et al*. (2018) In vitro performance of the DIAGNOcam for detecting proximal carious lesions adjacent to composite restorations. *Journal of Dentistry*, 72, pp. 39-43.

Erkstrand, K. R. *et al*. (2011) The Reliability and Accuracy of Two Methods for Proximal Caries Detection and Depth on Directly Visible Proximal Surfaces: An in vitro Study. *Caries Research*, 45(2), pp. 93-99.

Featherstone, J. D. B. (2008) Dental caries: a dynamic disease process. *Australian Dental Journal*, 53, pp. 286-291.

Frenken, J. E. (2017) Global epidemiology of dental caries and severe periodontitis - a comprehensive review. *Journal of clinical periodontology*, 44(18), pp. S94-S105.

Golde, J. *et al*. (2018) Detection of carious lesions utilizing depolarization imaging by polarization sensitive optical coherence tomography. *Journal of Biomedical Optics*, 23(7), pp.071203-1 - 071203-8.

Gomez, J. *et al*. (2013) In vitro performance of different methods in detecting occlusal caries lesions. *Journal of Dentistry*, 41, pp. 189-186.

Haag, D. G. *et al*. (2017) Oral Conditions and Health-Related Quality of Life: A Systematic Review. *Journal of Dental research*, 96(8), pp. 864-874.

Haak, R. *et al*. (2018) OCT for early quality evaluation of tooth–composite bond in clinical trials. *Journal of Dentistry*, 76, pp. 46-51.

Hariri, I. *et al*. (2012) Effects of structural orientation of enamel and dentine on light attenuation and local refractive index: An optical coherence tomography study. *Journal of Dentistry*, 40(5), pp. 387-396.

Huang, D. *et al*. (1991) Micron-resolution ranging of cornea anterior chamber by optical reflectometry. *Lasers in Surgery and Medicine*, 11(5), pp. 419-425.

Ismail, A. I. *et al.* (2007) The International Caries Detection and Assessment System (ICDAS): an integrated system for measuring dental caries. *Community Dentistry and Oral Epidemiology*, 35(3), pp. 170-178.

Jones, R. S. *et al*. (2006) Imaging artificial caries on the occlusal surfaces with polarization- sensitive optical coherence tomography. *Caries Research*, 40(2) , pp. 81-89.

Kang, H., Darling, C.L. and Fried, D. (2012) Nondestructive monitoring of the repair of enamel artificial lesions by an acidic remineralization model using polarization-sensitive optical coherence tomography. *Dental Materials*, 28(5), pp. 488-494.

Kang, H., Darling, C.L. and Fried, D. (2016) Use of an optical clearing agent to enhance the visibility of subsurface structures and lesions from tooth occlusal surfaces. J*ournal of Biomedical Optics*, 21(8), pp. 081206-1 - 081206-7.

Kishi, S. (2016) Impact of swept source optical coherence tomography on ophthalmology. *Taiwan Journal of Ophthalmology*, 6, pp. 58-68.

Lee, R. C., *et al*. (2016) Infrared Methods for Assessment of the Activity of Natural Enamel Caries Lesions. *IEEE Journal of Selected Topics in Quantum Eletronics*, 22(3), 9p. <*pii*: 6803609>.

Leitgebt, R., Hitzenberger, C. K. and Fercher, A. F. (2003) Performance of fourier domain vs. time domain optical coherence tomography. *Optics Express*, 11(8), pp. 889-894.

Li, J. *et al*. (2009) Speckle Reduction and Lesion Segmentation of OCT Tooth Images for Early Caries Detection. *Conference proceedings : 31Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 2009, pp. 1449-1452.

Lussi, A. *et al*. (2012) Analysis of the erosive effect of different dietary substances and medications. *British Journal of Nutrition*, 107(2), pp. 252-262.

Nakajima, Y. *et al*. (2014) Detection of occlusal caries in primary teeth using swept source optical coherence tomography. *Journal of Biomedical Optics,* 19(01), pp. 016020-1 - 016020-9.

Novaes, T. F. *et al*. (2012) Performance of fluorescence-based and conventional methods of occlusal caries detection in primary molars – an in vitro study. *International Journal of Paediatric Dentistry*, 22(6), pp. 459–466.

Maia, A. M. A. *et al*. (2016) Evaluation of dental enamel caries assessment using Quantitative Light Induced Fluorescence and Optical Coherence Tomography. *Journal of Biophotonics*, 9(6), pp. 596-602.

Majkut, P. *et al*. (2015) Validation of Optical Coherence Tomography against Micro–computed Tomography for Evaluation of Remaining Coronal Dentin Thickness. *Journal of Endodontics*, 4(8) , pp. 1349-1352.

Mylonas, P. *et al*. (2018) *In vitro* evaluation of the early erosive lesion in polished and natural human enamel. *Dental Materials*, 34(9), pp. 1391-1400.

Nakagawa, H. *et al*. (2013) Validation of swept source optical coherence tomography (SS-OCT) for the diagnosis of smooth surface caries in vitro. *Journal of Dentistry*, 41(1), pp. 80-89.

Novaes, T. F. *et al*. (2012) Performance of fluorescence-based and conventional methods of occlusal caries detection in primary molars – an in vitro study. *International Journal of Paediatric Dentistry*, 22(6), pp. 459-66.

Parker, K-J. *et al*. (2007) OCT assessment of non-cavitated occlusal carious lesions by variation of incidence angle of probe light and refractive index matching. *Journal of Dentistry*, 62 , pp. 31-35.

Parker, K-J *et al*. (2018) Optical coherence tomography to evaluate variance in the extent of carious lesions in depth. *Lasers in Medical Science*, 33 (7), pp. 1573–1579.

Pitts, N. B., Erkstrand, K. R. (2013) International Caries Detection and Assessment System (ICDAS) and its International Caries Classification and Management System (ICCMS) – methods for staging of the caries process and enabling dentists to manage caries. *Community Dentistry and Oral Epidemiology*, 41(1), pp. e41-e52.

Shimada, Y. *et al*. (2010) Validation of swept-source optical coherence tomography (SS-OCT) for the diagnosis of occlusal caries. *Journal of Dentistry*, 38(8), pp. 655-665.

Shimada, Y. *et al*. (2014) Noninvasive cross-sectional imaging of proximal caries using swept-source optical coherence tomography (SS-OCT) in vivo. *Journal of Biophotonics*, 7 (7), pp. 506-513.

Trifanov, I. *et al*. (2011) Characterisation of a fibre optic swept laser source at 1 !m for optical coherence tomography imaging systems. *Proceedings of the Society of Photo-optical Instrumentation Engineers*, vol. 7889, paper 7889-100, pp 1-7.

Ueno, T. *et al*. (2016) Optical analysis of enamel and dentin caries in relation to mineral density using swept-source optical coherence tomography. *Journal of Medical Imaging*, 3(3), pp. 035507-1 - 035507-9.

Wijesinghe, R. E. *et al*. (2016) Bio-Photonic Detection and Quantitative Evaluation Method for the Progression of Dental Caries Using Optical Frequency-Domain Imaging Method. *Sensors*, 16(12), pp. 1-12.

Zain, E., Zakian, Z. M. and Chew, H. P. (2018) Influence of the loci of non-cavitated fissure caries on its detection with optical coherence tomography. *Journal of Dentistry*, 71, pp. 31-37.