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Advanced Methods in Caries Detection and Diagnosis

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Certification of supervisor

I certify that this project entitled –Advanced Methods in Caries Detection and Diagnosis – was prepared by (Mohamed Raad Ghani) under my supervision at the College of Dentistry / University of Baghdad in partial fulfilment of the graduation requirements for B.D.S degree.

Signature

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Supervisor

Dedication

To my family, I could never done this without your faith, support, and constant encouragement . thank you for teaching me to believe in myself, In God, and in my dreams.
To my supervisor Dr. Shatha Abdullah who believed in my abilities and was always there for me whenever
I needed
To all people who supported and encouraged me Family, Friends, Teachers and Colleagues. Many thanks to all of you.

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List of Contents

List of Figures

List of Tables

List of Abbreviation

Abbreviation	**The words**
AC	Alternating Current
ACIST	AC Impedance Spectroscopy Technique
CCD	Charge-Coupled Device
DEJ	Dentino-Enamel Junction
DSR	Digital Subtraction Radiography
et al.	And others
FACE	Fluorescence-Aided Caries Excavation
FD	Fourier-Domain
FOTI	Fibre-Optic Transillumination

ICDAS	International Caries Detection and Assessment System
LUM	Luminescence
MS	Mutans streptococci
NIR	Near Infrared Radiation
OCT	Optical Coherence Tomography
RI	Refractive Index
PTR	Photothermal Radiometry
QLF	Quantitative light-induced fluorescence
QOC	Questionable Occlusal Caries
TD	Traditional
UCD	Ultrasonic Caries Detector

Introduction

Dental caries is defined as an infectious disease of the teeth that leads to the destruction and dissolution of the calcified tissues of the tooth structure. The results of this infection is loss of tooth minerals that starts from the outer surface of the tooth and progress through the dentin toward the pulp, ultimately jeopardize the tooth vitality (**Cummins, 2013**). A unique interaction happens in the complex biofilm overlaying the tooth surface that includes the pellicle along with the oral microflora of the plaque (**Featherstone,2004**).

Dental caries still a common infection influencing a huge number of individuals around the world (**Frencken et al., 2017**). There has been a creating interest in dentistry that is moving away from the treatment of the disease to one based on the prevention of it. Concerning some other diseases, prevention is best when the detection of the disease is early. Broad carious lesions are typically simple to detect because of clear clinical or radiological signs. Then again, carious lesions in the early phases are challenging, Hence, The inability to detect early caries, leaving those detectable only at the deep enamel, or cavitated stage, has resulted in poor results and outcomes for remineralization (**al- Khateeb et al., 1997; Amaechi and Higham, 2001**).

Visual detection and Visual-tactile strategies utilizing the dental explorers and air drying with amplification and radiographs are the regular methods generally utilized for detection of caries (91%) (**Makhija et al., 2014).** However, it appears to have low sensitivity for early, non cavitated carious lesions detection and decent sensitivity in the detection of a cavitated dentinal carious lesion that cannot be treated by the chemical preventive or therapeutic treatments (**Zandona and Zero, 2006; Alomari et al., 2015).**

Several criteria have been developed based on visual examination, aiming to decrease subjectivity and improve the ability to monitor lesions. In 2005, the ICDAS (International Caries Detection and Assessment System) criteria was reviewed and issued as ICDAS II (**Ismail et al., 2007**). The diagnostic accuracy and the reproducibility for the occlusal caries detection was demonstrated by ICDAS-II at varying phases of the caries process comparable to those published in earlier studies by means of the same visual criteria. The ICDAS-II also has the ability to observe caries with time because of its moderate to strong relation with the histological extent (**Jablonski-Momeni et al., 2008).**

Recently, there is an increase in research activity surrounding diagnostic methods, particularly in the assessment of early caries lesions. Techniques based on visual, radiographic, and some novel technologies have emerged, each has its benefits. However, systems based on the auto- fluorescence (such as Quantitative Light-induced Fluorescence [QLF]) of teeth and electrical resistance (such as CariesScan Pro) seem to offer the most hope for achieving reliable, accurate detection of the earliest stages of enamel demineralization **(Limeback, 2012)**.

Aims of the study

The aims of discussing the novel caries diagnostic strategies are due to:

1. There has been a developing paradigm shift in dentistry—one moving away from a surgical model of treatment to one based on the prevention of disease.

2. As with many disease entities, prevention is at its most effectiveness when detection is early within the natural history of the disease. The ability to detect caries lesions at an early stage and correctly quantify the degree of mineral loss, ensuring that the correct intervention is implemented.

3. The failure to detect early caries, leaving those detectable only at the deep enamel, or cavitated stage, has resulted in poor outcomes for remineralization therapies.

Therefore, the ability to monitor early lesions and determine if they have indeed arrested or stabilized is also key to ensure effective prevention and preservation of tooth structure.

Review of Literature

1. Dental Caries:

Dental caries (tooth decay) is a bacterial infectious disease that can be characterized by a progressive demineralization process that affects the mineralized dental tissues. It is considered to be the most prevalent oral disease worldwide and it is the main cause of tooth loss among the population (**Selwitz et al., 2007**). The prevalence of dental caries among the general population is linked to their socio-economic and demographic conditions, including some behavioral aspects (**Veiga et al., 2015**). Hence, the prevalence of dental caries in the most developed countries show an obvious tendency to decline in the last three decades of the twentieth century and early twenty-first century (**Costa et al., 2012**).

Throughout the 20th century, the most etiological factor of dental caries that captured the most attention was the mutans streptococci (MS) group. Researchers succeeded to isolate *Streptococcus mutans* from human carious lesions. Even though the *S. mutans* is one of the most researched cariogenic microorganisms, it is only one of more than 500 species that are found in dental plaque (**Paster et al., 2001)**. Some previous studies had shown the role of yeast (*Candida albicans*) and some novel species of bacterial communities are strongly associated with dental caries (**Becker et al., 2002; Klinke et al., 2009**).

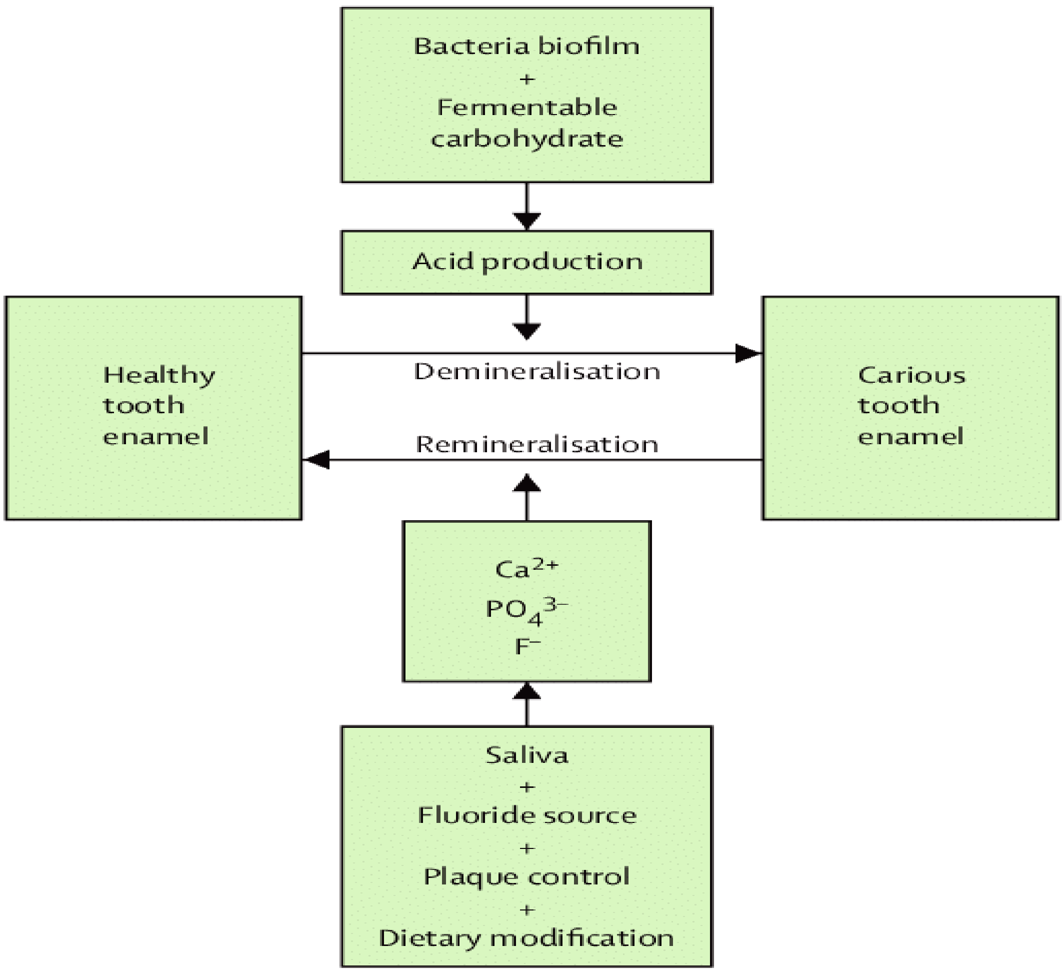
Dental caries cannot occur in the absence of dietary fermentable carbohydrates (like sugars and starch-containing food), it is intiated due to the interaction between the acid-producing bacteria and the fermentable carbohydrate and for that reason it has been characterized as a ―dietobacterial‖ disease (**Bowen and Birkhed, 1986**).

Studies have also shown strong evidence that genetic influence the development of dental caries and that bacterial acid production was modulated by the environment (**Bretz et al., 2006**). Host-related factors are important factors that contribute in the formation, susceptibility and resistance of dental caries. Saliva plays an important role in the health of soft and hard tissues in the oral cavity. Therefore, the measurement of salivary flow is an important part of caries risk assessment and management (**Leone C W, 2001**).

Dental caries is a dynamic disease involving cycles of demineralization and remineralization (Figure1), the constituents of plaque and saliva dramatically influence the physicochemical process of demineralization and remineralization of tooth hydroxyapatite (the mineral element of teeth structure). Tooth demineralization under oral conditions is generally accepted to result from acid produced by the metabolism of cariogenic microorganisms in dental plaque leading to the formation of caries. However, it has been noted that superficial body and the surface zone of the carious lesion can form greater amount of fluoride when the lesion is compared with sound enamel in the nearby area. Here the role of remineralization comes. The remineralization process is the potential of saliva counteracts demineralization produced by cariogenic challenges and compensate for the demineralization process (**Hicks et al., 2004**).

In Iraq, many studies had been conducted to determine the caries experience among the children and adolescents.

In (**2000) Al-Azawi** examined 4695 students and found that only 30% is caries free.In (**2007) Ryadh** examined 1050 students and the caries prevalence was 72%, a study performed by **Ahmed in (2007)** found that the prevalence of dental caries in 12- year- old schoolchildren from Baghdad was 62%. Another study done **by Abdulla in (2009)** found that caries prevalence is 78.2%



. **Figure (1): Diagram of the caries process as regular flux of demineralization (destruction) and remineralization (repair) (Selwitz et al., 2007)**

1.1 Clinical and histological manifestations of dental caries:

The earliest evidence of caries lesion on the smooth enamel surface of a crown is the initial lesion or a –white spot lesion, these Initial lesions are chalky and white when the surface is dried out, and they are usually found on the facial and lingual surfaces of teeth. These early appeared dental caries are regarded as noncavitated and, with remineralization, are reversible (**Pitts et al., 2017**). Histologically, the initial lesion in the proximal surface has a triangular shape with its base directed to the outer surface and the apex facing the dentin-enamel junction DEJ ,while the occlusal caries the tip directed toward surface and the base facing the DEJ. (**Nyvad et al., 1999**). It has been shown experimentally and clinically that initial enamel caries lesions can remineralize (**Backer, 1966**). Calcium and phosphate ions from saliva can penetrate the enamel surface and precipitate on the highly reactive crystalline surfaces in the enamel lesion and this serves as the driving force for the remineralization process. The presence of trace amounts of fluoride ions during this remineralization process greatly enhances the precipitation of calcium and phosphate, resulting in the remineralized enamel becoming more resistant to subsequent caries activity because of the incorporation of more acid- resistant fluorapatite.

Remineralized (arrested) lesions may be observed clinically as either intact, smooth white lesions or discolored, usually brown or black spots (**Ritter et al., 2015**).

When a more advanced lesion develops, the surface becomes irregular and rougher than the normal enamel surface —due to micro cavitation— and it can be chipped away with an explorer, this can be considered as a sign of active caries (**Young et al., 2015**). When enamel demineralization advances to the DEJ, rapid lateral expansion of the caries lesion along the DEJ and dentin demineralization occur, it can be distinguished by the presence of a dark gray shadow or translucency noticeable through the enamel. In case of progressive carious lesion the enamel will have complete cavitation, and the dentin is clinically involved (**Young et al., 2015**).

Increasing the size of the lesion results in the weakening and eventual collapse of the enamel surface and the formation of infected dentin that is characterized by bacterial contamination ,Clinically, soft dentin (infected) lacks structure and can be easily excavated with hand and rotary instrumentation. Episodes of short-duration pain may be felt occasionally during earlier stages of dentin caries lesion progression (**Kidd et al., 2015**). In slowly advancing caries lesions, a vital pulp can repair demineralized dentin by remineralization of the intertubular dentin and by apposition of peritubular dentin (**ten Cate, 2001**).

Hypermineralized areas may be seen on radiographs as zones of increased radiopacity (often S shaped, following the course of the tubules) ahead of the advancing. These areas are usually shiny and darker in color but feels hard to the explorer tip, and are called ‒firm (afected) dentin, in contrast to sound dentin that is ‒hard dentin (Figure 2) (**Ogawa et al., 1983**).

The affected dentine is primarily characterized by demineralization of intertubular dentin and of initial formation of intratubular crystals at the advancing front of the caries lesion (Figure 2). Clinically, affected dentin does not deform upon pressure from an instrument, but it can be excavated with hand instruments such as spoons and curette without much pressure (**Kidd et al., 1996**). Another zone of dentin has been described in moderate and advanced caries lesions and it‘s called ―hard‖ (reparative) dentin. It represents the deepest zone of a caries lesion —assuming the lesion has not yet reached the pulp— and may include tertiary dentin, sclerotic dentin, and normal (or sound) dentin (Figure 2). Clinically, this dentin is hard, cannot be easily penetrated with a blunt explorer, and can only be removed by a bur or a sharp cutting instrument (**Farges et al, 2015**).

These caries zones (Table 1) are most clearly distinguished in slowly advancing lesions. In rapidly progressing caries lesions, the difference between the zones becomes less distinct (**Ritter et al., 2015**).

Table (1): Clinical Significance of Carious Lesion (**Ritter et al., 2015**).

	Biofilm	**Enamel Structure**	**Therapeutic Treatment**	**Restorative Treatment**
Normal tooth	Normal	Normal	Not indicated	Not indicated
Hypocalssified Enamel	Normal	Abnormal but not weakened	Not indicated	Only for esthetics
Noncavitated Caries	Cariogenic	Porous, weakened	Yes	Not indicated
Active Caries	Cariogenic	Cavitated, very weak	Yes	Yes
Inactive Caries	Normal	Remineralized, strong	Not indicated	Only for esthetics

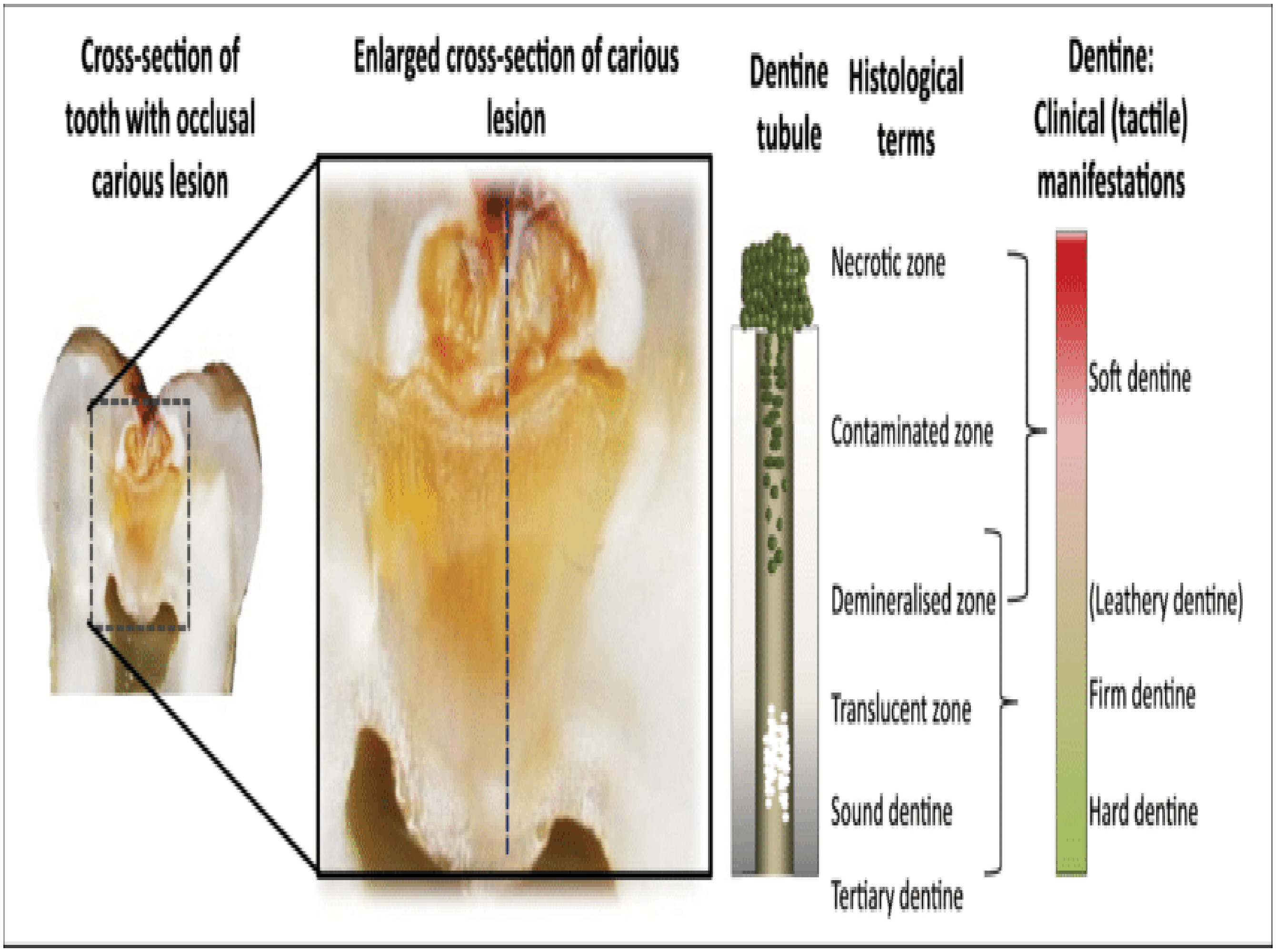


Figure (2): Cross section of occlusal caries (**Ritter et al., 2015**).

It is important to mention that not all dark discolorations are considered as carious lesions. It could be an indication of a lower mineral content in the enamel or are related to a number of various mechanisms throughout enamel development for example, stainning or hypomineralization (**He et al., 2010**).

2. Caries Detection Methods

Finding an accurate method for detecting and diagnosing any disease has been the goal of healing since the earlier centries. Today, there has been an increasing attention in dentistry toward the prevention of the disease rather than its treatment. As with other diseases, prevention is most effective when detection is early. Preventative methods encourage the remineralization of non-cavitated lesions resulting in inactive lesions, and here the role of fluoride comes to revers or stop caries if the thin surface layer covering the demineralized area was undamaged (**Hamilton and Stookey, 2005**). The ability to detect caries lesions at an early stage and correctly quantify the degree of mineral loss is as -if not more- important as its treatment (**al-Khateeb et al. 1997; Amaechi and Higham 2001**).

The need arose for caries detection methods that promote preventive therapies, these detection systems are aimed at enhancing the diagnostic process by facilitating either earlier detection of caries or enabling it to be quantified in an objective manner. Therefore, A range of new detection and monitoring systems have been developed and are either currently available or are still in the manufacturing stage. When assessing the effectiveness of such methods, the preferred reporting metrics are those of traditional diagnostic science; specificity, sensitivity, reliability and validity **(Limeback, 2012).** Specificity and sensitivity are both expressed as values between 0 and 1, values closer to 1 indicating a high-quality result. For an efficient caries detection method, values should be at least 0.75 for sensitivity and over 0.85 for specificity **(Karlsson, 2010**).

Relatively, these features are for qualifying of the diagnostic method itself, but are not assessments used for purposes of diagnosis or management **(Maupomé and Pretty, 2004).**

2.1 Visual Caries Detection Methods:

2.1.1 Conventional visual inspection:

Visual inspection is the most widely used caries detection system, it is daily used by dental practitioners with accompanying tactile examination using a blunt probe, ideally a periodontal probe, to detect differences in surface roughness. Assessment of features such as color and texture are qualitative in nature, and for this reason, it is considered subjective (**Bader et al., 2002**). These assessments provide some information on the severity of the disease but fail to quantify it, because they are limited in their detection threshold. Their ability to detect early, non-cavitated lesions is poor and only is restricted to enamel (**Maupomé and Pretty, 2004**).

The visual detection methods were found to have low level of reproducibility and sensitivity with high specificity. It is assumed that the low level of reproducibility are credited to the subjective nature of this method of carious lesion detection (rely on the examiner‘s interpretation) (**Ismail, 2004**).

In **1997, Ekstrand et al.** developed a new system related to the previous studies results to increase the sensitivity of the diagnosis of the carious lesion.

The sensitivity of examination tends to be improved by usage of Ekstrand criteria (Table 2) both in vitro (**Ekstrand et al., 1997; Tranæus et al., 2005**) and in vivo (**Angnes et al., 2005; Piovesan et al., 2013)**

Table (2): Visual clinical examination according to (Ekstrand et al., 1997)

Score	Interpretation	Visual Examination
0	Sound	No or slight change in enamel translucency after prolonged air drying (<5seconds).
1	Enamel Caries	Opacity or discoloration hardly visible without drying, but visible after air drying.
2	Enamel Caries	Opacity or discoloration visible even without air drying.
3	Caries in the outer half of the dentin	Localized enamel breakdown in opaque or discoloured enamel and/or grayish discoloration from underlying dentin.
4	Caries in the inner half of the dentin	Cavitation in opaque or discoloured enamel exposing the dentin.

Many researchers worked throughout the years to develop and improve the objectivity of the examiners. Systems like Nyvad Criteria, The American Dental Association Caries Classification System (ADA CCS), The Caries Assessment Spectrum and Treatment (CAST) and other scoring systems that were made to detect caries depending on visual and visual-tactile methods **(Ferreira and Longbottom, 2019).**

The International Caries Detection and Assessment System (**Pitts, 2004**) and the Universal Visual Scoring System for Caries Detection and Diagnosis (**Kuhnisch et al., 2009**) had been developed to improve the sensitivity of visual inspection.

2.1.2 International Caries Detection and Assessment System (ICDAS):

In the early 2000s, the need arose to develop a new visual index for caries that could be used in various applications, from epidemiology, research, dental education to clinical practice. From the development of the index, the proposal was to develop a caries management system where treatment pathway was linked to lesion status and patient risk factors. A number of consensus meetings were held, and the International Caries Detection and Assessment System I (ICDAS) was developed in 2002 (**Pitts 2004**). The ICDAS I was modified later to ICDAS II in 2005. The ICDAS I and II criteria include the theories from the researchers showed by (**Ekstrand et al., 1997)** and other caries detection systems described in the systematic review conducted by (**Ismail et al., 2004**).

Since tooth decay could be a dynamic process, categorization of them is difficult. The process is continuous and would be measured as stages representing minute loss of tooth structure that's currently not detectable using available technology for in vivo use. Therefore; there is a rely on visual signs that reflect caries process relatively (**Pitts et al., 2017**). The ICDAS is a 2-stage process; the first digit (Table 3) is to classify each tooth surface on its restoration status, followed by a second digit (Table 4) that records the caries severity of a tooth surface.

Table (3): ICDAS codes for restoration status (From the International Caries Detection and Assessment System (ICDAS) Coordinating Committee)

0	Surface not restored or sealed	
1	Sealant, partial	
2	Sealant, full	
3	Tooth colored restoration	
4	Amalgam restoration	
5	Stainless steel crown	
6	Porcelain or gold or PFM crown or veneer	
7	Lost or broken restoration	
8	Temporary restoration	
9	Used for the following conditions:	96:Tooth surface cannot be examined 97: Tooth missing because of caries 98: Tooth missing for reasons other than caries 99: Unerupted

Table (4): Description of the second digit that is used for coding the coronal primary caries (Jablonski-Momeni et al., 2008)

0	Sound
1	First visual change in enamel
2	Distinct visual change in enamel
3	Localized enamel breakdown (without clinical visual signs of dentinal involvement)
4	Underlying dark shadow from dentin
5	Distinct cavity with visible dentin
6	Extensive distinct cavity with visible dentin

As previously mentioned, the ICDAS criteria incorporate concepts from the research conducted by **Ekstrand et al. (1997),** which correlated between the severity of carious lesions and their histological depth. White spot lesions that can be seen after air drying are only limited to the outer half of enamel, while the depth of a white or brown lesion that can be seen without air-drying can be found between the inner half of the enamel and the outer third of the dentin. However, localized enamel breakdown without visible dentin indicates that the lesion extends to the middle third of dentin and a brownish or greyish shadow indicates that the lesion extends to the middle third of dentin; while cavities with visible dentin mean it extends to the inner third of the dentin (**Pitts and Ekstrand, 2013**).

Bakhshandeh et al. in **2011** stated that there is a strong relationship between the actual depth of the carious lesion that is identified histologically and the ICDAS value (Figure 3). Another study also found that there is a strong relationship between ICDAS criteria and histologic depth (**Neuhaus et al., 2010**). Because of the strong relationship between ICDAS scores and histologic depth that was supported by previous studies, ICDAS II criteria was used as gold standard in a study in which laser fluorescence was evaluated in occlusal caries detection (**Rechmann et al., 2012**).

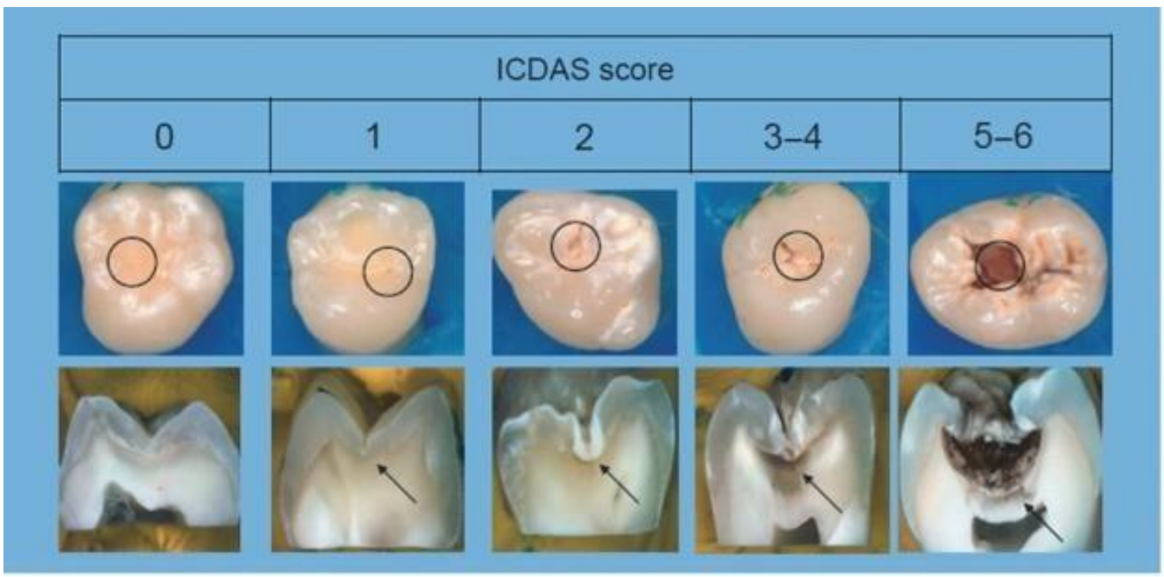


Figure (3): ICDAS clinical visual codes, based on evidence of the histological extent of lesions, stage the caries continuum (Pitts & Ekstrand., 2013).

There is developing evidence that ICDAS can prove to be a useful and reliable system in detecting early lesions (**Braga et al. 2009**). However, there is insufficient information to determine if the ICDAS codes are sensitive enough to support effective caries monitoring. For instance, is it possibly a potential for a lesion to double in size (or severity) and stay within the same code value? Research is being undertaken in this specific manner, and efforts are made to combine the ICDAS with other caries detection methods. Despite this limitation, the ICDAS system offers a good deal to dental practitioners in terms of developing an accurate approach to cavity examination as a part of the patient examinations (**Zandoná et al. 2010**).

2.1.3 Caries Detection Dyes:

The first caries disclosing dye was developed in the early 1970‘s and it consisted of a solution of 0.5% basic red fuchsin in propylene glycol. This dye selectively stain the superficial- and heavily degraded-collagen carious dentin layer (infected layer) with a red color (**Fusayama and Terachima, 1972**), it identified infected dentin. Yet, traces of viable bacteria were still detected at the deepest portion of carious lesions even after guided dentin carious removal .

A study by **Shimizu et al.(1983).** performed on extracted teeth with carious dentin (Figure 4) by the use of 1% acid red staining in propylene glycol base, the carious dentin was stained and both the depth of the staining and the depth of bacterial invasion were valued . Slight modifications were made over the years on commercial caries detection dyes **(Ferreira and Longbottom, 2019)**.

The application of the different types of dyes products is similar. Before application of dyes, carious cavity needs to be cleaned and air- dried. One drop of the dye solution is then applied to the lesion for 5 s (caries finder/ caries finder green) or 10 s (caries detector, seek/sable seek, snoop, caries marker) and rinsed away with water. The infected dentin is red-stained (caries detector, caries finder), green-stained (caries finder green/sable seek) or dark blue stained (Snoop) and removed by an excavator or a round steel bur of low speed without irrigation. According to manufacturer's instructions, solution needs to be re-applied on cavities to identify residual infected dentin until cavity floor is no longer stainable **(Harorli et al., 2014)**.

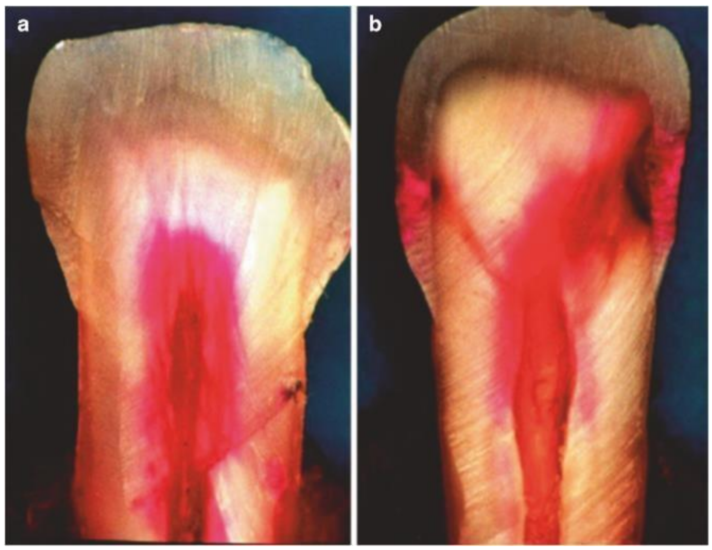


Figure (4): Longitudinal ground sections of sound teeth (a) and non-cavitated enamel lesion (b) after application of 1% acid red dye. Circumpulpal deep dentine as well as demineralized enamel and dentine are stained by the dye (Ferreira and Longbottom, 2019).

2.2 Radiology Based Caries Detection Methods:

The visual-tactile detection is able to detect caries lesions in accessible areas with high accuracy, however, such detection has a limited sensitivity for proximal, non-accessible lesions. For that reason, radiographs were introduced to complement these visual-tactile caries detection methods (**Gomez, 2015**).

2.2.1 Conventional radiographs (Film based radiology):

Conventional radiographs provide excellent images for most dental needs mostly used for caries detection purposes. Their primary use is to supplement the clinical examination by providing insight into the internal structure of teeth and supporting bone. The dental radiology is based on the fact that when the carious lesion develop, the mineral contents of the tooth in the dentin and enamel are reduced, which leads to reduction in the X-ray beam attenuation when passing throughout the tooth **(Gomez, 2015).**

Bitewing radiology has demonstrated the ability to identify caries in the approximal region earlier than by visual examination alone. Bitewing films are particularly valuable for detecting inter-proximal caries in the early stages of development before it manifest clinically, reveal secondary caries below the restorations and evaluating the inter-proximal bone condition (**Schwendicke et al., 2015**). The film has a flap on which the patient bites to keep the film in place against the crowns of upper and lower teeth simultaneously. Hence, the bitewing radiographic technique is most commonly used for detection of proximal surface dental caries (**Kamburoglu et al., 2012**).

Experimentations had revealed that, when the dental caries on the occlusal surface was obviously noticeable on radiograph, the histological investigation showed that the demineralization was extended to or away from the middle third of the dentin (**Ricketts et al., 2002**). As a result, the extension of the dental caries would be under estimated by the radiographic examination (**Dove, 2001**).

2.2.2 Digital radiographs:

Digital radiography has offered the potential to extend the diagnostic capacity of conventional radiographs. A digital radiograph is comprised of a number of pixels, every pixel carries a value between zero and 255, with zero being black and 255 being white and the values in between represent shades of gray. However, with 256 gray levels, the digital radiographs have lower resolution than a conventional radiograph and research has confirmed this, with sensitivities and specificities of digital radiographs being significantly lower than those of regular radiographs when assessing small proximal lesions (**Verdonschot et al. 1999**). The digital radiograph offers the advantage of image enhancement by enhancing the white and black end (contrast). When these radiographs are enhanced, their diagnostic performance is as good as conventional radiographs, with reported values of 0.95 (sensitivity) and 0.83 (specificity) for approximal carious lesions. One must also mention the advantage of a decreased radiographic dose that the digital radiographs can offer. Digital images can also be archived and replicated with ease (**Pretty, 2006**).

2.2.3 Digital subtraction radiography:

Digital subtraction radiography (DSR) is a more developed image analysis tools. This method allows to distinguish small differences between successive radiographs that otherwise would have remained unobserved because the differences in density are too small to be recognized by the human eye. Digital subtraction radiography has been used in the assessment of the progression arrest, or regression of carious lesions. The basic technique of the subtraction radiology is that two radiographs of the same object compared by using their pixel values.

The value of the pixels from the first object is subtracted from the second image. If there is no change, the resultant pixel will be scored 0; any value that is not 0 must be related to either the beginning or progression of demineralization or the regression of the caries process **(Van der Veen, 2000).**

2.3 Light Based Caries Detection Methods:

2.3.1 Fluorescence-Aided Caries Excavation (FACE):

FACE is a tool that identifies the presence of bacteria in dentin with a hiegh degree of accuracy compared to the conventional way of using a dental probe to test hardness while assessing color visually at the same time. This allows precise differentiation between infected and non-infected dentin, allowing maximum preservation of tissue. Another useful feature that the tool can provide is that most resin based tooth- colored restorative materials which are sometimes challenging to differentiate from tooth substance can be readily differentiated using the fluorescence technique. This in turn can help to conserve healthy tooth structure when removing restorative materials **(Ferreira and Longbottom, 2019).** FACE works by exposing carious dentin to purple light of the wavelength of 405 nm and it presents as a red fluorenscence, this is due to the presence of fluorescent porphyrins (**Buchalla et al., 2004**). Non-carious areas show a green fluorescence (Figure 5).

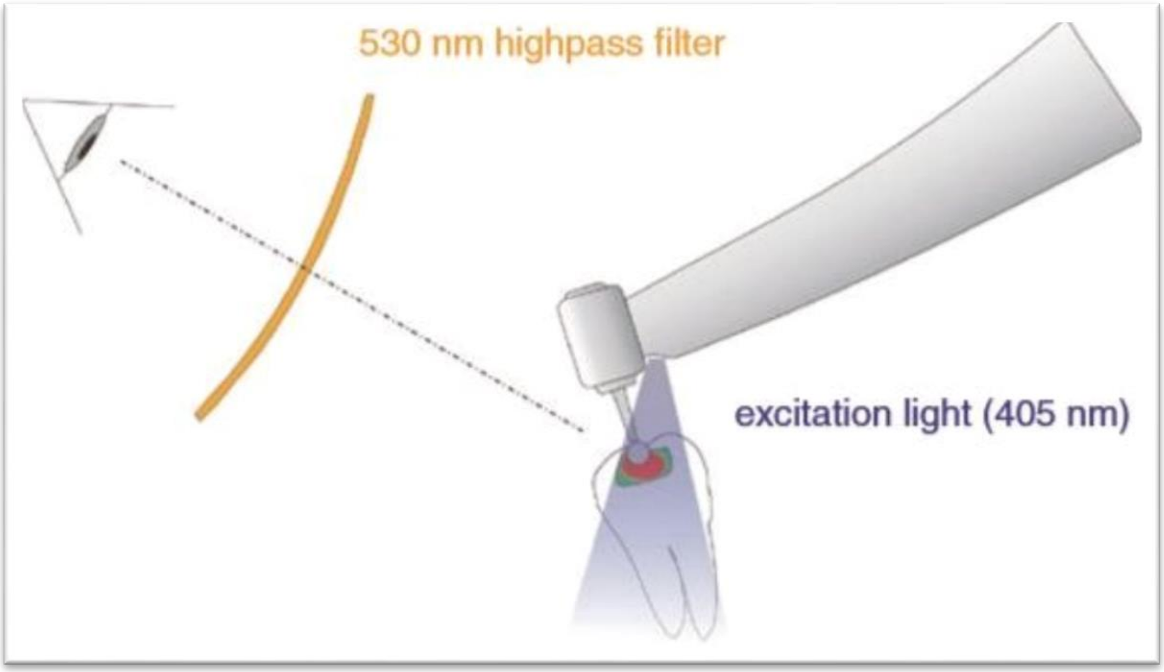


Figure (5): During FACE excavation the cavity is excited with violet light and observed through a high-pass filter (Ferreira and Longbottom, 2019).

2.3.2 Fibre-Optic Transillumination (FOTI):

The basis of using fiber optic transillumination to detect caries is based on the scattering of light phenomenon. Enamel is composed of densely packed hydroxyapatite crystals, producing an almost transparent structure (**Limeback, 2012**). The color of enamel is affected by the underlying color of dentin. When demineralization occur, the penetrating photons of light get scattered (change direction but do not lose energy), which results in an optical disruption. When visible light hits the normal tooth a whiter area appears which is so-called white spot ,This appearance is enhanced if the lesion is dried, therefore, it‘s advised to remove the water from the porous lesion.

Water has a similar refractive index (RI) to enamel, but when it is removed and replaced by air, which has a much lower RI than enamel, the lesion is shown more clearly. For this reason it must be ensured that the examinations are performed on clean and dry teeth (**Côrtes et al. 2003**).

Fibre optic transillumination makes use of these optical properties of enamel by using a white light with high intensity that is presented through a small aperture in the form of a dental handpiece. Light is shone through the tooth, and the scattering effect can be seen as shadows in enamel and dentine, which means dental caries appear as a dark shadow, so with this strength, the device has the ability to help in distinguishing between early enamel and early dentine lesions (Figure 6) **(Limeback, 2012).**

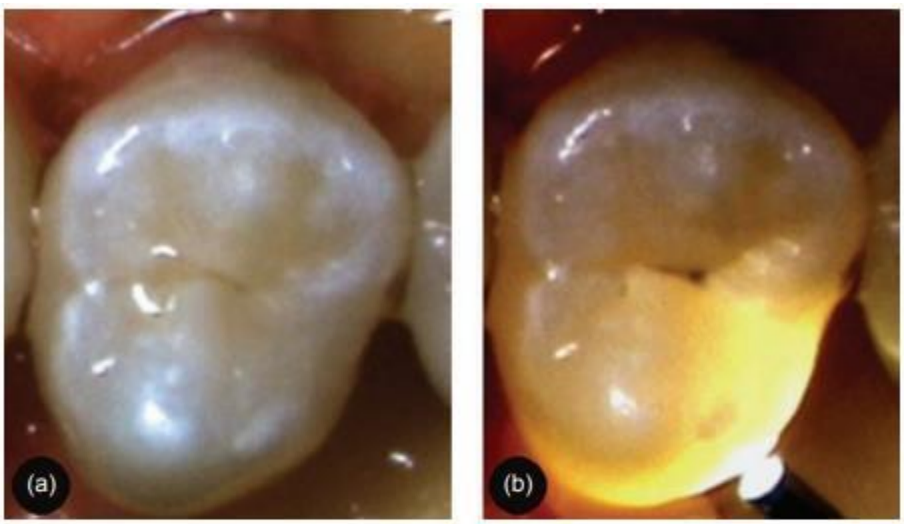


Figure (6): Example of FOTI on a tooth: (a) normal clinical vision; (b) with FOTI (Limeback, 2012).

One drawback of this method is being subjective rather than objective**.**

However, this is common to many of the frequently used caries detection and assessment methods. With no continuous and recordable output, longitudinal monitoring using FOTI is complex and as with any visual scoring system, clinically significant changes are potentially required before they are identified by a scoring system **(Ferreira and Longbottom, 2019).**

In an effort to overcome this limitation, a step was made to digitalise the process, resulting in the development of a more advanced version of FOTI called DIFOTI (digital imaging FOIT). This system consists of a high intensity light with a CCD (Charge-coupled device) sensor that effectively replaces the human eye with a grey scale camera that can be fitted with either of two heads: one for occlusal surfaces and the other for smooth surfaces. Images are displayed on a computer monitor and can be archived for later use. DIFOTI has been shown to be as valid as radiographic investigation for all lesions, with suggestions of superior performance in the detection of early enamel lesions **(Schneiderman et al. 1997).**

2.3.3 Quantitative Light-Induced Fluorescence (QLF):

Quantitative Light-induced Fluorescence (QLF) is an optical visible light technology that offers the opportunity to detect early caries detection and then longitudinally monitor its progression or regression. It has been developed continuously over the past 30 years and is now available for clinical application in dental clinics (**Stookey, 2004**).

The QLF offers two forms of fluorescent detection (red and green), It can measure both the mineral content as a fluorescence loss and bacterial activity as a red fluorescence simultaneously (Figure 7).

The fluorescence changes detected by QLF can be visualized as an image, which quantify the physical characteristics of caries lesions and monitor its changes as numerical values. Based on these properties, this method gives evidence for detecting caries and preventive care (**Volgenant, 2016**).

The principles underlying the use of QLF to detect early caries lesions are as follows: visible blue light irradiating the teeth and reaching the dentinoenamel junction (DEJ) will induce fluorescence, Fluorescence is the phenomenon of which an object gets excited by a particular wavelength of light and the reflected fluorescent is of a larger wavelength. The fluorescence will be in a different color when the excitation light is in the visible spectrum. In the case of the QLF, the visible light has a wavelength (λ) of 370 nm, which is in the blue region of the spectrum and by using the band pass filter (λ >540 nm) to filter out the excitation light, we can readily detect the resultant auto-fluorescence of the tooth enamel by a small intra-oral camera. The image produced consists only of red and green color, predominately the latter (**van der Veen and de Josselin de Jong, 2000**).

When demineralization of enamel occurs, it reduces the autofluorescence and this can be quantified with a special software; $r = 0.73-0.86$ (**van der Veen and de Josselin de Jong, 2000**).

The source of the autofluorescence is thought to be the dentinal enamel junction (DEJ). When excitation light passes through the enamel it excites fluorophores contained within the DEJ.

Studies have shown that the presence of an area of demineralized enamel reduces the fluorescence for the fact that the scattering effect of the carious lesion results in less excitation light reaching the DEJ in this area, hence, any fluorescence from the EDJ is back scattered as it tries to pass through the lesion(**van der Veen and de Josselin de Jong, 2000**).

Figure (7): Example of QLF images of white-light and fluorescence images obtained at the same time (Ferreira and Longbottom, 2019).

The QLF device was first introduced in 2004 and later upgraded to three other generations. The device is standardly composed of a light box with a xenon bulb and a handpiece (Figure 8), light is passed to the handpiece via a liquid light guide, and the handpiece contains the bandpass filter (**Angmar-Månsson and ten Bosch 2001**). Live images can be displayed via a computer, and accompanying software enables patient‘s details to be entered and individual images of the teeth of interest to be captured and archived **(Stookey, 2004).**

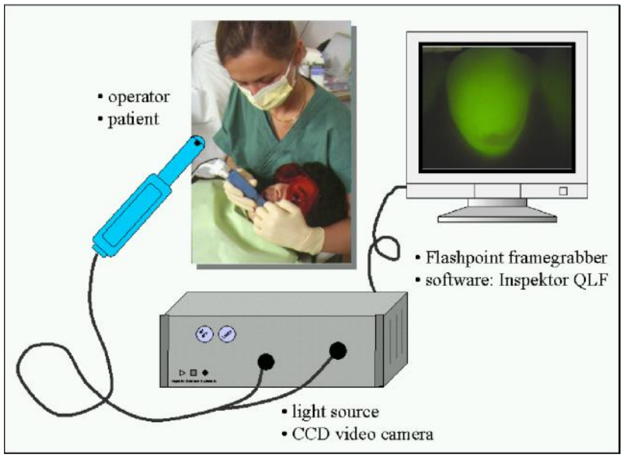


Figure (8): The QLF device (Limeback, 2012).

2.3.4 Laser fluorescence (DIAGNOdent):

The DIAGNOdent device was developed in late 1990‘s for assessment of occlusal sites after the discovering the ability of dental caries to emit fluorescence once activated with red light at the wavelength of about 650 nm. A pen-type DIAGNOdent device was later developed to expand its use on approximal sites by introducing two intra-oral tips: one designed for pits and fissures (occlusal sites), and the other for smooth surfaces. . Each device operate at a wavelength of 655 nm which produces a red light, the light is emitted from a particular laser diode that induces fluorescence of bacterial porphyrins. The intensity of the fluorescence emitted from carious lesion is directly related to the intensity of bacterial contamination, for instance, with lesion depth. DIAGNOdent was conceptualized as a hand-held device that's easy-to-use in dental clinics. Because DIAGNOdent is sensitive also for initial caries lesions it was also meant to be used as a tool for caries monitoring and it can be used for both primary and permanent teeth (**Lussi et al., 2006**).

DIAGNODent shows a numerical value on two LED displays (Figure 9), the first demonstrates the present reading while the second demonstrates the peak reading for that examination, the higher the number is, the larger the carious lesion present, and that‘s due to the fact that DIAGNODent can offer a reading on a zero to 99 scale (**Pretty, 2006; Khalife et al., 2009**).

Figure (9): The DIAGNOdent device (Limeback, 2012).

The device needs to be applied on teeth vigorously cleaned with a water spray. The prophylaxis paste or prophylaxis powder should be completely rinsed off to avoid wrong measurements. Remnants of several prophylaxis pastes, also calculus give a false positive fluorescence reading (**Lussi and Reich, 2005**).

The following states of caries are associated with the readings on the DIAGNOdent device: Values from 0 to 13: no caries; values from 14 to 20: enamel caries; values >20: dentinal caries, so the following guidelines for the clinical use of the DIAGNOdent are recommended: No active care is advised:

Values from 0 to 13; preventive care is advised: Values from 14 to 20; preventive or operative care is advised depending on the patient's caries risk, the recall interval, etc.: Values from 21 to 29; operative care is advised. (**Lussi et al., 2001; Iranzo-Cortés et al., 2017**).

DIAGNOdent Pen is a new device that was launched to market in 2008. The device is based on the same technology of the previous versions, few adaptations on the probe has been made to enable readings to be taken inter-proximally. Much of the research on this new device has been undertaken in vitro, and there is insufficient evidence available at present time to support its use as single tool for detection and monitoring although it does have utility as an adjunct (**Kuhnisch et al. 2009**). However, the sensitivity and the specificity of DIAGNOdent Pen was found to be superior to the visual inspection technique in a study by **Al-Qazzaz and Hassan** in (**2019)**. Also, DIAGNOdent demonstrated a stronger link to the ICDAS II than the visual inspection.

2.3.5 Photothermal Radiometry and Modulated Luminescence (The Canary System):

The Quantum Dental Technologies developed what is now known as the Canary System, which encompasses a completely different approach for caries detection. It is a nonionizing caries detection procedure to help detect, and monitor the tooth status as well as recording the changes found in the structure of tooth tissues. The Canary System uses Photothermal Radiometry and Luminescence (PTR-LUM) technology, It basically pulses low-energy laser light on the tooth surface, and when it interacts with the crystalline structure of tooth tissue, It converts to heat (Photothermal Radiometry or PTR) and light (luminescence or LUM), that can be emitted from the tooth surface once the laser is modulated and thus, the existence and the severity of the dental caries can be identified (**Abrams, 2009**).

The Canary System measures four signals:

1. The strength or amplitude of the converted heat or PTR signal.
2. The time delay or phase of the converted heat or PTR to reach the surface
3. The strength or amplitude of the emitted luminescence (LUM).
4. The time delay or phase of the emitted luminescence (LUM).

A Canary Number is created from an algorithm combining these four signals and is directly linked to the status of the tooth crystal structure (**Silvertown et al., 2016**).

A particular benefit of this technology is that the manufacturers claim that the use of pulsed lasers will enable a depth profile of a lesion to be determined (**Jeon et al., 2004; Jeon et al., 2008).**

The Canary System scale is a graduated scale where lower values point to sound enamel and higher values point to more advanced dental caries. It ranges from 0 to100, where 0 to 20 value refers to a healthy sound tooth, a 21to70 value indicates an initial carious lesion, and 71to100 value indicates an advanced decay (Figure 10) **(Silvertown et al., 2016).**

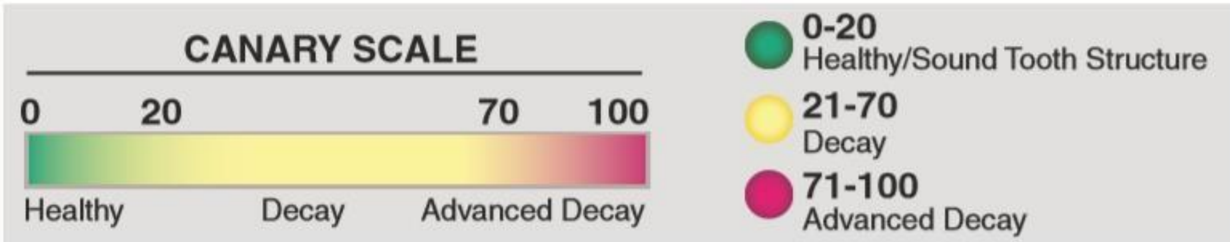


Figure (10): The Canary Scale (Silvertown et al., 2016).

One of the advantages of the Canary System is that having the tooth to be completely dried is not quite necessary and any stain does not have an effect on the reading. The device consists of a handheld wand and console that are linked to a computer and The Canary System software can be installed on dental practice workstations throughout the dental office (**Amaechi, 2009**).

2.4 Electricity Based Caries Detection Methods:

The concept of using electrical signals for the detection of caries is not new, reports in the literature found evidence from the 1950s in the United Kigdom , In 1970s, the –Vanguard was the first device that used fixed frequency electricity to monitor caries (**White et al., 1978**) and this showed very promising diagnostic performance when was evaluated in the later decade**.** Different attempts were made over time to create the most reliable use of electrical signals for caries detection until a major technological advance came in the late 1990‘s when Nature Medicine used the first multiple electrical frequencies and reported a method known as the AC Impedance Spectroscopy Technique (ACIST) **(Ferreira and Longbottom , 2019**).

2.4.1 CarieScan Pro Device:

The CarieScan Pro device was developed to offer ease of use with high accuracy and low price. The most significant advantage of using this device is the absence of any risks associated with ionizing radiation. This safety consideration is especially important in preventive treatments (**Pitts, 2010**).

The principle used for CarieScan PRO hand held dental device is the ACIST which proved to detect early caries, so that the preventive treatment can begin at an early stage (**Rochlen and Wolff, 2011**).

The ACIST technique take advantage of the fact that the hydroxyapatite of enamel of the tooth has a high electrical resistant and when demineralization occur, there will be a reduction in electrical resistivity due to the increased size of pores by demineralization, which are occupied with fluids that rise the electrical conductivity (**Huysmans et al., 2000**).

The CarieScan Pro device uses a small electrical current that determine the mineral density of the dental substrate and produce an accurate and reliable picture of the remineralization/demineralization of the tooth structure **(Agustsdottir et al., 2010).**

The CarieScan PRO comes with a built-in system test for automatic calibration and installed software to perfom the measurements and it presents it both numerically: on a scale from 0 to 100 as well as by a way of color coding: (from green to red). The greater the numerical value, the more serious the spread of the caries.

Lesion extent and depth are evaluated using the CS cut-offs acclaimed by the manufacturer: 0 = likelihood of being sound; 1–50 = initial stage of enamel caries; 51–90 = deep enamel caries; 91–99 = likelihood of established caries spreading through the enamel and into superficial dentine; 100 = likelihood of established dentine lesion (**Jablonski-Momeni and klein, 2015**).

A comparison made by **Akgul et al. in 2018** between CarieScan pro, bitewing radiography and tactile examination in the detection of occlusal caries in primary teeth. The highest sensitivity was seen with CarieScan PRO (92.65%) radiography (79.41%) and tactile examination (76.47%). In bitewing radiograph, the specificity was 95.24%, with CarieScan pro being 92.86% and the tactile examination was the least specific with 71.43%.

Fig. (11) cariescan pro device.

2.5 Caries Detection Methods On Probation:

There are some developing techniques that may have apromising future in caries detection**.**

2.5.1 Near-Infrared Reflectance Imaging (NIR):

Several studies in vitro and vivo carried out over the past 20 years to demonstrate the advantages of near-IR (NIR) imaging devices for caries detection. With increasing wavelength, the light scattering in the enamel of the tooth decreases, enamel is most transparent near λ = 1300 nm (**Jones and fried, 2002**). At this wavelength, NIR light can penetrate a factor of 30 times further through the tooth enamel than is possible in the visible range without scattering for markedly better performance. Light scattering increases by 2–3 orders of magnitude with demineralization at λ = 1300 nm, indicating that high contrast in transillumination between sound and carious tissues is found near λ = 1300 nm as well (**Darling et al., 2006**).

One of the advantages of the NIR systems is that they promise the ability to penetrate through stain and hence offer the potential to mitigate this confounding factor that is such an issue in occlusal caries diagnosis. When using NIR, stains can be easily differentiated from actual demineralization of the carious lesion (**Ferreira and Longbottom, 2019**). In a study done by **Almaz et al**. **in (2016)** found that it is necessary to use wavelengths greater than 1150 nm with NIR to avoid interference from stains when measuring lesion contrast in reflectance and transillumination modalities, as the chromophores that are responsible for stains on teeth cannot absorb light at longer wavelengths since there is not sufficient energy for electronic excitation.

The NIR allows approximal and occlusal lesions to be viewed with high contrast due to the minimal scattering of sound enamel (Figure 12), and this can be exploited for reflectance imaging of early demineralization **(Darling et al., 2006).** NIR transillumination is at least as sensitive as radiography for detection of occlusal and proximal caries. Significant work is involved in developing this system into clinically and commercially acceptable applications **(Ferreira and Longbottom, 2019**).

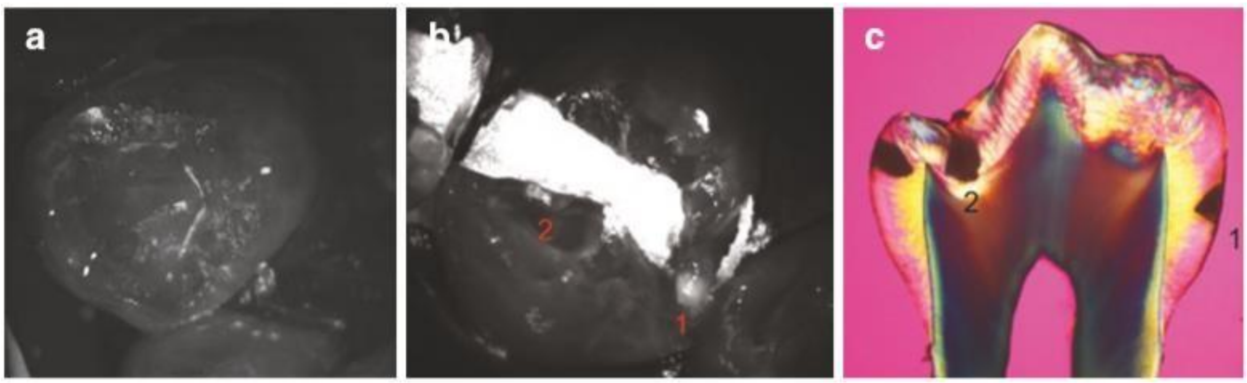


Figure (12): NIR in vivo reflectance images of two teeth at 1500–1700 nm (a and b) along with a polarized light micrograph (c) of a section cut from the tooth shown in (b) from the first clinical study utilizing NIR reflectance (Ferreira and Longbottom, 2019).

2.5.2 Optical Coherence Tomography (OCT):

Optical coherence tomography (OCT) is a noninvasive imaging technique that uses low-coherence light for creating cross- sectional images to capture micrometer-resolution, two- and three-dimensional images from within internal biological structure **(Bouma and Tearney, 2002).** The first images of the soft and hard tissue structures of the oral cavity by using OCT that measured the reflectivity within dental hard tissues to a depth of up to 3–5 mm in enamel and 1–2 mm in dentin with an axial (depth) resolution exceeding 10 μm.

The early OCT system was based on time-domain (TD) detection in which echo time delays of light were identified by measuring the interference signal as a function of time, while scanning the optical path length of the reference arm **(Fujimoto and Drexler, 2008).**

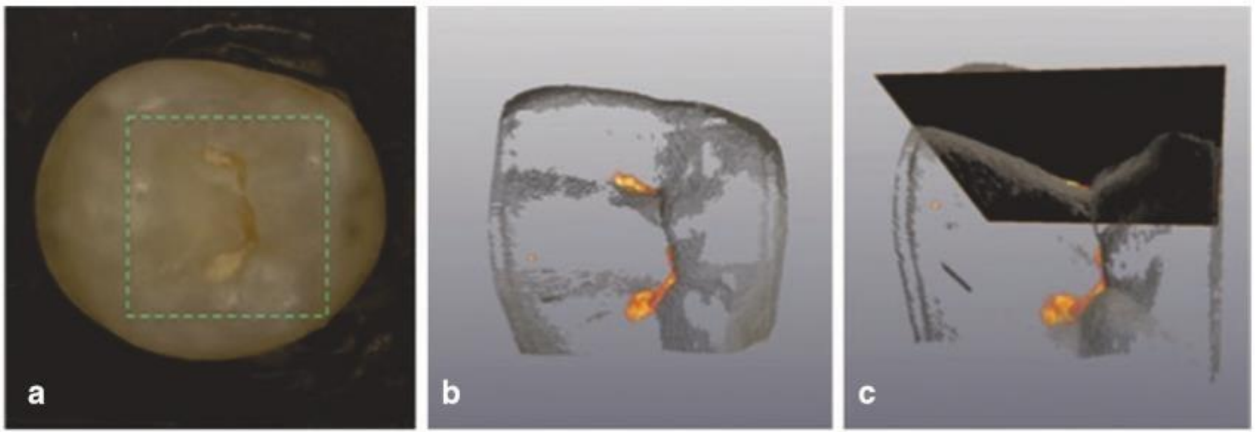


Figure (13): (a) visible image of an extracted tooth with demineralization in the fissure (b and c) Show the acquired OCT scans segmented to show areas of demineralization (red/yellow) (Ferreira and Longbottom, 2019).

The OCT can be used in different manners regarding caries detection:

1-Quantitative measurements of lesion severity.

2-Diagnosis of Questionable Occlusal Caries (QOC) lesions.

3-Diagnosis of root caries.

4-Diagnosis of secondary and residual caries.

OCT has been revolutionized in recent years by the development of Fourier-domain (FD) techniques that provide a distinct increase in sensitivity compared with traditional (TD)-OCT (**Leitgeb et al., 2006**).

2.5.3 Ultrasound techniques:

As a general definition, Ultrasound means high-frequency sound waves in the range of 2–16 million cycles per second, Human ear cannot perceive these sounds, as it can only hear sounds in the range of 50–18,000 cycles per second (**Cheeke and David, 2012**). The principle behind the technique is that sound waves can pass through gases, liquids, and solids and through the boundaries between them and therefore images of tissues can be collected through the reflected sound waves. In order for sound waves to reach the tooth, they must pass first through a medium like water and glycerine (**Hall and Girkin 2004**). Abrupt change in medium starts a series of vibrations that produce the sound waves transmitted into the tooth being examined and thus create a characteristic sound (echo) that differentiate between intact and demineralized enamel surface (**Cheeke and David, 2012**).

A study made by **Matalon et al. in (2007)** reported that an ultrasound device can discriminate between cavitated and non-cavitated inter-proximal lesions. Another study by **Ziv et al. in (1998)** found that ultrasonic measurements at 70 approximal sites in vitro resulted in a sensitivity of 1.0 and a specificity of

0.92 when compared to a histological gold standard (microscopy and QLF) with high sensitivity and specificity. Further histological validation was also undertaken by using transverse microradiography and ultrasound A final in vivo study was undertaken using a device described as the Ultrasonic Caries Detector (UCD), which examined 253 approximal sites and claimed a diagnostic improvement over bitewing radiography (**Bab et al. 1998**).

Despite these encouraging findings, few research has been undertaken using the ultrasound device, and the research has only been published as abstracts.

2.5.4 Bioluminescence Technology:

The commercially available device that uses the bioluminescence technology is CALCIVIS. The CALCIVIS has developed a completely novel imaging technology that was designed to enhance the assessment and management of demineralization due to dental caries and erosion. It helps dental practitioners to visualise early carious lesions, when it can be stopped and potentially reversed. The device works by indicating the presence of calcium ions, the major advantage of the system is that it allows live visualization of active enamel demineralization **(Ferreira and Longbottom, 2019**).

In a research done by **Fejerskov and Kidd in (2008)**, it had been shown that active caries lesions demonstrated ongoing demineralization of the enamel structure, leading to a loss of calcium ions from the hydroxyapatite of dental enamel,The system detects free calcium ions via a calcium-sensitive photoprotein. When enamel undergoes active demineralization, the levels of free calcium ions found in the fluid-filled pores of dental enamel gets elevated **(Fabregas and Rubinstein, 2014),** and in response to this interaction between the calcium ions and the protein solution, a bioluminescent signal is emitted and the device‘s camera detects this luminescence **(Deng et al., 2004).**

The intensity of the luminescence from each digital image can be quantified and plotted against calcium concentration by using special imaging software, as shown in (Figure 14).

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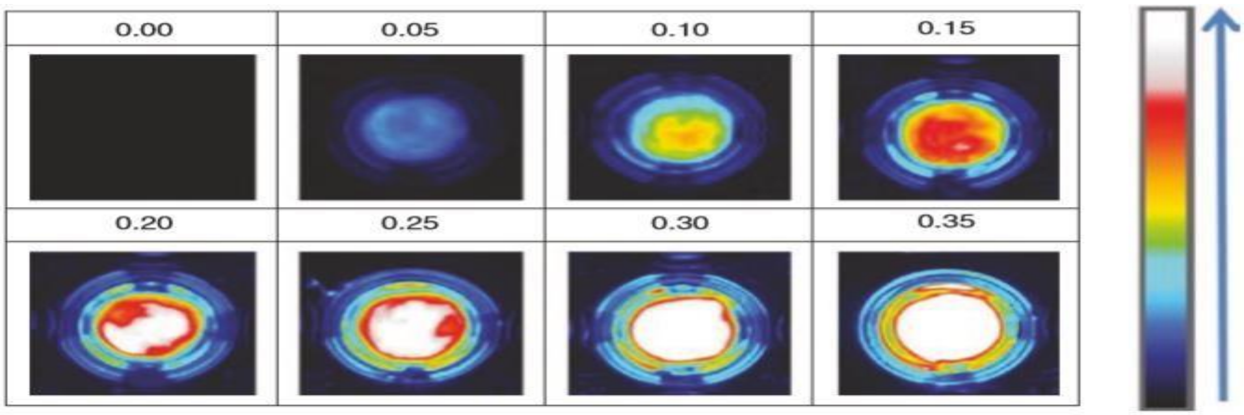

Figure (14): Detection of calcium ions in solution (Calcivis Ltd., Edinburgh, UK)

Time course studies in vitro have showed the system's capability to monitor both demineralization and remineralization of the enamel surface.

A technique to identify active demineralizing lesions (compared to techniques and technologies to detect caries lesions from being active or inactive) is of critical importance in helping dental practitioners in their diagnostic and treatment decision-making process concerning preventive dental care (Further research into the novel CALCIVIS Imaging System is hoped to determine the degree of the potential role in helping dental clinicians, especially in the field of preventive dentistry **(Ferreira and Longbottom, 2019**).

Conclusion

The purpose of caries detection tools is to detect dental caries at the early stage of caries and prevent its progression from demineralization to cavitation. Non of the mentioned techniques alone are sufficient for diagnosis of dental caries. In the future with the development of diagnostic tools, small changes in the tooth structure will be detected and the dental structures will be protected be implementing preventive treatment.

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