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Carious lesion detection technologies: factual clinical approaches

Amel Slimani,¹ Elodie Terror,² David J. Manton³ and Hervé Tassery^{*1,2}

Key points

Early detection and diagnosis of carious lesions allows timely intervention to minimise damage (minimal intervention).

The use of magnification when visualising teeth improves detection and characterisation of early lesions.

The appropriate use and interpretation of electronic devices/technologies can improve detection and monitoring of carious lesions.

Abstract

Minimal intervention dentistry is now accepted as the contemporary approach for caries management. The development of adjunctive technologies to assist early lesion detection has led to widespread marketing of various devices over the past two decades. A thorough understanding of the clinical relevance and limitations of such devices is required to make valid interpretation of their results. This paper will discuss the most common commercially available carious lesion detection technologies in order to give dental practitioners clear information about the devices' scientific principles, advantages and limitations within a clinical context.

Introduction

Contemporary caries management has evolved into using rational behavioural and therapeutic strategies involving minimally invasive treatments based on a more holistic understanding of the caries process.^{1,2} Everyday, clinicians face clinical challenges when it comes to early carious lesion detection and caries risk assessment. Clinical judgment remains the mainstay of the decision-making process regarding the threshold for restorative intervention. Intervention decision-making utilises a number of factors including lesion activity, surface cavitation and cleansability, among others. The clinician must assess these three main factors to determine the appropriate intervention in the context of that individual – personalised dentistry.³

It is now established that adjunct devices can make lesion detection more accurate, especially for early white spot lesions but also approximal lesions, where visual examination is least valid.^{3,4} These technologies may not only help lesion detection, but also inform appropriate carious tissue removal and ongoing lesion monitoring.^{4,5} It is important to have the capacity to monitor lesions and keep specific, appropriate and accurate records, especially when using minimally invasive strategies.⁶

Dental clinicians already use radiography as an adjunct method for lesion detection and quantification. However, it has been reported in a systematic review and meta-analysis that radiography is more appropriate for more advanced lesions.⁷ Moreover, radiography alone fails to indicate whether a carious lesion is active/inactive and/or cavitated.^{7,8,9}

Numerous studies have been conducted on different lesion detection devices, with the focus mainly on specificity and sensitivity of the device.¹⁰ Sensitivity relates to the proportion of individuals identified who have the disease, while specificity is the proportion of individuals identified who do not have the disease.^{11,12}

In the past decade, operative dentistry has shifted towards less invasive strategies which demand accurate detection and diagnosis, enabling appropriate strategies to be adopted, whether they be operative or non-operative in

nature. In some low-risk contexts, specificity is more relevant than sensitivity, to minimise overtreatment.^{7,13} It may be more appropriate to specify the positive predictive value of each device: the probability that a patient with a positive screening test truly has the disease; but these values are not usually available.^{14,15} As clinicians, we must ask ourselves: does this information have clinical relevance in everyday practice and how can this information help in the choice of lesion detection technology?

We will discuss the commercially available technologies for carious lesion detection, with an unconventional aspect, in order to determine how these devices can help us interpret the clinical situation: lesion cavitation, activity and cleansability.³ The presence of surface cavitation is the starting point for micro-invasive restoration, activity is a warning sign to reverse or to moderate the caries process/risk, and lesion/surface cleansability is a moderating factor.³

Visual examination

Naked eye carious lesion detection and visual acuity

Naked eye visual detection is the most commonly used method for lesion detection, currently.¹⁶ For human teeth, the average occlusal fissure depth ranges from 120–1,050 µm; the width in the middle part of the fissure

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varies between 40–156 μm ; the thickness of the enamel at the bottom of the fissure is between 270–1,008 μm ; and the occlusal angle is between 51.6–84.5°. ¹⁷ Normal visual acuity of the eye and retinal receptors have a spacing limit of 0.3 to 1 minute arc. ¹⁸ Therefore, in daily practice, at an average distance of 40 cm, the clinician is able to distinguish two points separated by approximately 130 μm , suggesting that most surfaces of the pits and fissures are not detectable visually (Fig. 1), even in the absence of biofilm and stain. The limit of the detectable distance between two planes located 40 cm apart is only 130 μm , reducing again the diagnostic capacity.

Fewer than 3% of general dental practitioners combine visual inspection, radiography and optical-aided visualisation during the diagnostic steps, regardless of the dental surface. ¹⁹ In addition, the use of validated visual scoring systems tends to improve the accuracy of visual examination. ²⁰ The magnification of the images may be of concern as it may lead to overtreatment by less experienced practitioners; however, the problem may come rather from the synthesis of the diagnostic information, as this guides the type of intervention needed. ¹⁶ Being able to enlarge the image and retrieve and view stored images allows a review of one's own diagnostic processes – which is possible using most systems with image capture. ²¹ Fluorescence or other biophotonic signals provide even more complementary information. ^{22,23} The principle is: 'see better, understand better; therefore, do better'. Presbyopic deficiencies are inevitable for nearly every individual with increasing age;

Fig. 1 Magnified image of pit and fissure system. Soprolife images: focus macro mode (30X). Pits and fissures inside the major fissures with six different points of entry (red arrows)

however, loupes and operating microscopes enhance the visual performance of clinicians, independent of their age. ^{24,25,26}

Main clinical factors affecting intervention thresholds

A carious lesion detection device should, at the minimum, reveal the following clinical features of the lesion:

- Cavitation: enamel surface cavitated or not?
- Activity: active or arrested?
- Cleansability: is lesion cleansable? Including width of the cavitation (if present), depth, size location and shape.

Suitable additional clinical carious lesion detection criteria:

- Clinical relevance in daily practice: pre-/peri-operative aids
- Possibility to record images and videos
- Level of magnification variable according to clinical needs

- Caries adjacent to restorative surfaces (CARS) monitoring over time.

Preliminary professional prophylactic cleaning steps

The complexity, depth, width, cleansability and shape of the tooth surface or fissure – and, of course, caries activity – governs clinical decision-making. As the crystalline structure of demineralised enamel can be highly unstable, the use of a sharp probe is strictly forbidden and cleaning with a rotating brush in combination with prophylactic paste could alter the values given by the different diagnostic devices.

Moreover, the width of a rotary brush bristle is approximately 0.2 mm, too large to clean inside many pits and fissures. Diagnosis requires that the deeper parts of the fissure or the proximal area are cleaned well without damaging the demineralised enamel – often

Table 1 Prophylaxis powders available commercially²⁸

Powders (particle size)	Hardness (Mohs)	Non-destructive	Micro-destructive	Destructive	Adherent biofilm	Soft biofilm
Glycine (around 65 μm or less)	<2	+	+/- on active enamel lesion	-	+/-	+
Erythritol (around 14 μm)	<2.5	++	+/- on active enamel lesion	-	+/-	++
Sodium bicarbonate (around 74 μm)	2.5	-	+	+ on active enamel lesion	+	+
Calcium carbonate (Prophypearls; KaVo, Germany) (around 45 μm)	3	-	+	+ on active enamel lesion	+	+
Calcium sodium phosphosilicate (Sylc; OSSpray, London, UK) (around 50 μm)	>6	-	-	+++	+ (may cause cavitation)	+ (may cause cavitation)
Enamel/dentine	5/4					

Key:
+ = recommended
- = not recommended

not the case with traditional methods of cleaning. Therefore, our proposition is to clean with an air-polishing device using a combination of soft prophylaxis powders (Table 1).^{27,28} Of the listed products, Sylc powder (OSSpray Ltd., UK) should be used with caution as it can selectively remove the demineralised enamel. The use of disclosing or fluorescent plaque dyes can provide possible additional information/data for detection devices (Fig. 2).^{22,23}

Clinical recommendations

Occlusal surfaces

In the presence of adherent biofilm, it is safer to start with sodium bicarbonate or calcium carbonate powder and finish with erythritol powder. Erythritol can be used in the presence of soft biofilm (Fig. 3).

Proximal surfaces

In the case of the proximal surfaces, cleaning remains more difficult due to poor access, but it is still mandatory for a non-invasive or micro-invasive approach. Characteristics of non-cavitated or cavitated lesions can only be assessed after cleaning. (Fig. 4). The use of orthodontic separators or plastic wedges to separate the teeth can help as well.

Complementary carious lesion detection aids

Loupes and microscopes

Loupes

The use of magnifiers cannot be questioned now.²¹ Magnification offers the dental practitioner unequalled perspectives in terms of lesion detection and diagnosis, even more so if the systems are accompanied by powerful LEDs. It is now possible to have magnification from 3.5X to 6.4X on the same lens frame (Fig. 5) and magnifiers emitting fluorescence excitation light are available (Fig. 6).

Microscopes

The clinical use of the microscope is now accepted as essential in endodontics. In addition, its daily use for other diagnostic and operative tasks is valuable, especially since fluorescence was added to it (Fig. 7). The European Society of Endodontology recommend the use of operating microscopes for deep caries management.²⁹ Microscope use can also improve the clinician's posture and prevent shoulder, neck and back pain and physical debility.²¹

Fig. 2 Plaque pre- and post-disclosing. a) Biofilm daylight image: cavitation surrounded by adherent biofilm (Soprolife camera). b) Same view with fluorescein dye (Soprocure perio mode)

Fig. 3 Cleaning of a fissure system before sealant placement. a) Occlusal view (Soprolife daylight mode). b) Occlusal view (Soprolife daylight mode + EMS dye plaque). c) After the cleaning step (sodium bicarbonate powder). d) Control of the biofilm activity and the remaining biofilm to be removed (red signal Soprolife mode II). e) Occlusal surface after cleaning (erythritol powder, Soprolife image Macro focus). f) High-viscosity glass-ionomer cement (Equia Forte HT, GC Corp., Japan) as sealant

Fig. 4 Plaque-disclosing dye application and subsequent resin infiltration of a white spot lesion. a) Application of dye plaque (TriPlaque ID gel, GC Corp., Japan). b) Visualisation of the young and mature biofilm. c) Non-cavitated lesion now visible in fluorescent mode (Soprolife view, pink arrows) after cleaning with erythritol powder. d) Treatment with resin infiltration procedures as no cavitation was observed (ICON, DMG, Germany)

Photonic carious lesion detection technologies

Fundamental principles

Naturally, light (photons) can propagate through the crystalline enamel and dentine tubules. Demineralisation causes changes

in the ultrastructure of enamel and dentine, and a consequence is the change in their optical signal due to the modified light-tissue interactions.

The optical properties reveal any changes in the sound structures – a modification of the crystalline and/or organic structure

will cause differential light transmission and absorption, increasing contrast and subsequently allowing the detection of carious lesions or defects.^{22,23,30} Therefore, a number of experimental optical carious lesion detection methods have emerged in addition to related clinical detection devices.

Lesion detection based on light transmission

Transillumination devices

Fibre-optic transillumination (FOTI) uses a white light to detect carious lesions clinically, but is limited by visual acuity (for example, Microlux Transilluminator, Addent, Inc., CT, USA; Phatelus Optic Transillumination Light, NSK, Japan). This technique has evolved into digital imaging fibre-optic transillumination (DIFOTI) using a charge-coupled device sensor (CCD) camera, so the lesion detection is performed on saved images and, therefore, the images can be reviewed (Table 2).^{4,22} DIFOTI, radiographic and visual examinations have been compared and contradictory findings reported.^{4,30,31}

Another DIFOTI technology uses near-infrared light transillumination (NILT) (780 nm wavelength; DIAGNOcam, KaVo Dental, Germany) instead of white light to illuminate the teeth and capture real-time images (Fig. 8). Longer wavelengths reduce light scattering and the beam penetrates further into the tooth.³² This device is designed for approximal and occlusal lesion detection. The reliability of this technique has been widely documented and found to be effective for early carious lesion detection, especially on approximal surfaces.^{30,31,33}

However, DITOFI does not differentiate between developmental defects of enamel and carious lesions, and fails to assess caries activity.³⁰ Practitioners should correlate the given DIAGNOcam caries levels with the percentage risk of cavitation and the treatment needs.^{10,34,35}

Detection based on fluorescence

Today, lesion detection methods based on fluorescence have become common in the dental industry. Laser-induced intrinsic fluorescence (auto-fluorescence) of human teeth was suggested in the early 1980s to discriminate carious from sound tissues.³⁶ Natural auto-fluorescence of dental hard tissues expresses different emission wavelengths, whether from sound or carious tissue.^{37,38,39} Sound structures emit a green fluorescence, while red fluorescence is emitted from carious tissues, dental plaque and calculus.^{40,41,42,43} A systematic review and meta-analysis on

Fig. 5 Loupes with magnification 3.6X to 6.4X (ExamVision ApS, Denmark; Orasoptic, USA 3.5X–5.5X) (image courtesy of Odontik, ExamVision)

Fig. 6 Loupes with fluorescent excitation (Designs for Vision, Inc., NY, USA) (image courtesy of Liviu Steier)

Fig. 7 Fluorescence microscope images (Zumax OMS 3200, China). a) Red fluorescence before excavation. b) Reduction of the red fluorescence after excavation on the enamel dentine margin

fluorescence-based carious lesion detection adjuncts revealed an improved performance in detecting advanced caries lesions.⁴⁴ This is clinically relevant as it can be useful during operative procedures such as carious dentinal tissue removal.

Fluorescence systems only

The DIAGNOdent Pen (KaVo, Germany) consists of a handpiece using a red laser diode (655 nm). Two interchangeable probes are available, one for proximal and one for occlusal surfaces. The emitted fluorescence is

Table 2 DIFOTI summary table based on the new clinical criteria

Tools/clinical criteria	DIFOTI (DIAGNOcam)	Comments
Cavitation	-	
Occlusal	No	Yes, if the cavitation is already visible to the naked eye
Proximal	No	
Activity	No	N/A
Cleansability	No	N/A
Image	Yes	N/A
Magnification	Yes	No data/not variable
Operative aid	No	Yes, in pre-operative steps to reduce the need for bitewings. See relationship between clinical extent and treatment need (Figure 8)
Sensitivity ³⁵	63%	For carious lesion detection adjacent to resin composite
Specificity ³⁵	95%	For carious lesion detection adjacent to resin composite

Score	Diagnosis& criteria for proximal surfaces	Probable diagnostic/ treatment needs
0	Sound surface No signs of less translucent enamel or dentin detectable	No active dental intervention - Patient-based prevention & self-management - Regular, risk-related diagnostic check-ups & professional prevention
1a	Enamel caries First detectable signs of less translucent enamel	Preventive intervention - Patient-based prevention & self-management - Regular, risk-related diagnostic check-ups & professional prevention
1b	Enamel caries Less translucent enamel is clearly detectable	Preventive or minimal invasive intervention - Patient-based prevention & self-management - Caries infiltration AND/ OR - Regular, risk-related diagnostic check-ups & professional prevention
1c	Enamel caries Less translucent enamel reaching the enamel-dentin junction	Minimal invasive intervention - Patient-based prevention & self-management - Caries infiltration AND/ OR - Regular, risk-related diagnostic check-ups & professional prevention
2a	Dentin caries Less translucent enamel involves the enamel-dentin junction	Minimal invasive or operative intervention - Patient-based prevention & self-management - Bitewing radiography to determine lesion progression into dentin - Caries infiltration OR restoration - Regular, risk-related diagnostic check-ups & professional prevention
2b	Dentin caries Enamel, enamel-dentin junction and dentin are affected by less translucent hard tissue	Operative intervention - Patient-based prevention & self-management - Bitewing radiography to determine lesion progression into dentin - Restoration - Regular, risk-related diagnostic check-ups & professional prevention
3	Cavitated dentin caries Enamel, enamel-dentin junction and, in addition, a cavity is detectable	Operative intervention - Patient-based prevention & self-management - Bitewing radiography to determine lesion progression into dentin - Restoration - Regular, risk-related diagnostic check-ups & professional prevention

Fig. 8 DIAGNOcam classification of findings on approximal surfaces (image courtesy of Jan Kühnisch)

quantified as a score ranging from 0 to 99. For occlusal surfaces and pits: 0–12 = healthy tissue, 13–24 = demineralised enamel and >25 = dentine involved. For approximal surfaces: 0–7 = healthy tissue, 8–15 = demineralised enamel and >16 = dentine involved. This device provides a numerical reading only and does not record images and videos (Fig. 9).

Clinically, the DIAGNOdent Pen tends to overestimate carious lesion depth/extent. The probe size being larger than some pits and fissures, and remaining debris in the deepest parts of the fissures, may increase the fluorescence and subsequently the false-positive results.²² A recent multicentre study, including 628 occlusal fissures, revealed wide intra- and inter-investigator variability for the DIAGNOdent Pen.⁴⁵ Great variability of sensitivity and specificity exists for this system (sensitivity: 0.43–0.98 occlusal/0.16–0.82 approximal; specificity: 0.66–1 occlusal/0.25–0.96 approximal), which confuses diagnosis.¹⁴ For proximal surfaces, the system is inefficient. DIAGNOdent has been reported to be poorly correlated with carious lesion depth and not effective for monitoring lesions over time.^{46,47,48,49} The cut-off values do not consider confounding factors such as stain, which may inflate the values. Overall, clinical relevance is poor (Table 3).

Another technology uses fluorescence as an aid for carious tissue excavation, an example being SIROInspect (Sirona Dental Systems GmbH, Germany). It is known as fluorescence-aided caries excavation (FACE).⁵⁰

The SIROInspect device uses an excitation wavelength of around 405 nm.⁵¹ The practitioner needs to use bespoke glasses to see the fluorescence of dentine. The device appears suitable for identifying carious dentine exclusively during excavation to minimise tissue removal, although no cut-off value data is available for mineral density. The FACE system is also limited by visual acuity as no image/video can be recorded and no magnification is possible. Another device using a dual-wavelength curing light (D-Light Pro, GC, Japan) offers a dentine carious lesion detection mode with a near-UV light excitation. The clinical relevance remains low (Table 3).

Combination of camera and fluorescence systems

Quantitative Light-induced Fluorescence

The first generation device using the Quantitative Light-induced Fluorescence (QLF) system for lesion detection was the Inspektor Pro (Inspektor Research Systems

BV, Amsterdam, the Netherlands), released in 2003 and mainly used for research purposes. This intraoral camera uses a halogen lamp emitting blue light and captures images subsequently analysed using the Inspektor Pro Software. This technology is now utilised in Qraycam and Qraypen (Aiobio, Republic of Korea) devices for clinical use.

This technology aims to detect enamel mineral content based on fluorescence changes in carious and sound enamel, and bacterial activity from the porphyrin reaction of oral bacteria after excitation at 405 nm, inducing fluorescence within the tooth structure (Fig. 10). The emitted fluorescence is filtered by a single high-pass filter and the resulting images captured by a micro-CCD camera. The novelty of this system lies in the bespoke software (QA2 version 1.24, Inspektor Research Systems BV, Amsterdam, the Netherlands) that allows measurement of variation of the fluorescence on enamel surfaces reflecting mineral density changes.⁵² However, literature on the QLF technologies can be confusing as authors usually name the system solely as QLF, despite six different devices having been developed for research or clinical purposes.

Soprolife and Soprocure cameras

The Soprolife camera (Fig. 11a; Acteon, La Ciotat, France) is an intraoral camera with two types of LED-emitting lights – visible and blue (450 nm). This allows the capture of daylight and fluorescence images (diagnostic and treatment modes). In addition to the three different image options, magnification up to 35X is possible. The image software enhances the fluorescence emission of the tooth, allowing the practitioner to improve their visual inspection and decision-making.²²

The camera is equipped with an image sensor (6.4 mm CCD) consisting of a mosaic of pixels covered with filters of complementary colours. The data collected, relating to the energy received by each pixel, allow retrieval of a tooth image. The camera operates in three modes: for daylight mode, four white LEDs are engaged; for the diagnostic and treatment modes, the light is provided by four blue LEDs (450 nm). A second camera, Soprocure (Fig. 11b; Acteon, La Ciotat, France), provides three clinical modes: daylight, caries and periodontal. The second mode focuses on enamel and dentine carious lesions, and the latter on gingival inflammation.²²

Fig. 9 DIAGNOdent Pen

Table 3 Fluorescence device properties summary based on the new clinical criteria

Tools/clinical criteria	DIAGNOdent Pen	SIROInspect (FACE)	Comments
Cavitation	-	-	Visual acuity is the limiting factor for FACE
Occlusal	No	No	
Proximal	No	No	
Activity	No	Yes*	*For dentine
Cleansability	No	No	N/A
Image	No	No	N/A
Magnification	No	No	N/A
Operative aid	No, false positive risk	Yes**	**Could help during dentine excavation (red signal variations)
Sensitivity ²³	87%	94%	N/A
Specificity ²³	50%	83%	N/A

Fig. 10 QLF images. a, b) Daylight images of white spot lesions. c, d) Fluorescence images of the same lesions

The tooth can be observed in daylight and fluorescence mode with a high level of magnification according to the preliminary steps. Any modification of the reflected light from dentine or enamel in comparison to a healthy area can be detected. Clinical decisions are not simplistically linked to numerical values (avoiding the pitfalls of cut-off values, although complicating interpretation of longitudinal records) and the system improves

visual inspection and informs clinical decision-making.

Soprolife/Soprocure putatively reveal advanced glycation end products (AGEs) produced from Maillard reactions and the clinical applications of the images are based on the light-induced fluorescence evaluator for diagnosis and treatment (LIFEDT) concept.²²

This clinical concept is built on five principles:

1. Depending on the diagnostic aids used, non-invasive, micro-invasive and invasive activities can be involved
2. Lesion activity and presence of surface cavitation are the main factors for intervention choice for carious lesions
3. Cleaning the deepest part of the pits and fissures without damaging the enamel is mandatory to allow visualisation
4. Fluorescence variations help to evaluate carious lesion activity and inform carious dentine tissue excavation (Fig. 12)
5. Burs have to be smaller than the width of the cavity – if not, sealing is preferable.

Occlusal carious lesion detection

A high level of magnification combined with a fluorescence signal gives a huge amount of information regarding potential cavitation and lesion activity, combined with the possibility to record images and videos – allowing peer review and reassessment of diagnostic decision-making. Fissures less than 0.1 mm wide, enamel cracks and translucency variation of the marginal crest are clearly visible (Fig. 13). A multi-centre study found that the Soprolife has good reproducibility for primary teeth, with better validity than the DIAGNOdent Pen.⁵³

Proximal carious lesion detection

The combination of magnification and fluorescence variation can help to recognise the presence and point of entry of carious lesions, and also help to detect enamel cracks (Figures 14 and 15). However, there is a lack of studies investigating proximal lesion detection using this device.

Clinical diagnosis of excavated dentinal tissue related to fluorescence signal

The end point of dentinal tissue excavation is now recommended to be at 'leathery dentine' (Fig. 16) on the pulpal floor and fluorescence can assist recognition of tissue to remove, limiting tissue damage and pulp exposure.^{2,54} Cleaning the margins of the cavity preparation continues to remain a challenge. Fluorescence helps to control dentinal tissue excavation due to the reduction of the red signal and increase of green fluorescence (Fig. 7).

The Soprolife camera reveals dental tissue auto-fluorescence as an acid green image for healthy tissues, dark grey to bright red for active carious dentine, grey/green with red shadows for leathery dentine and dark red for arrested carious dentine.²²

Fig. 11 a) Soprolife camera. b) Soprocure camera

Fig. 12 a) Active dentinal lesion (Soprolife daylight mode). b) Similar image with fluorescence (red fluorescent active dentinal lesion, Soprolife mode II). c) Similar view with fluorescence after active tissue excavation (clean margins and red leathery dentine remaining, Soprolife mode II)

Fig. 13 a) Occlusal view of carious lesion with ICDAS score 5 (25X, Soprolife daylight mode). b) Similar view (Soprolife mode II): active lesion (red fluorescence) and identification of ICDAS score 5

VistaCam (iX)

VistaCam (iX) is an intraoral fluorescence camera (Dürr Dental, Bietigheim-Bissingen, Germany), using similar technology to QLF, which illuminates teeth with a violet light (405 nm) and captures the reflected light as a digital image. The reflected light is filtered for

light below 495 nm and contains the green-yellow fluorescence of normal teeth with a peak at 510 nm, as well as the red fluorescence of bacterial metabolites with a peak at 680 nm. The bespoke software (DBSWIN) quantifies the green and red components of the reflected light on a scale from 0 to 3 as a ratio of red to

green, showing the areas with a higher ratio, indicating carious tissue. A wireless version, the VistaCam CL iX with removable head camera and a light cure function, has been launched recently.

The camera is placed onto the tooth; images are recorded and analysed with the software, which then reveals the scores: 0–1 for healthy enamel; 1–1.5 for initial enamel demineralisation; 1.5–2 for deep enamel lesions; 2–2.5 for dentine lesions; and 2.5–3 for deep dentine lesions.

Previous studies assessed that the performance of VistaProof was in the range of the DIAGNOdent.^{55,56,57,58} In another study, two examiners with different levels of cariology experience examined the occlusal surfaces of teeth (one experienced dentist, one final year dental student) using the VistaProof.⁵⁹ The intra-class correlation coefficients for inter- and intra-examiner reproducibility for the fluorescence-based examinations were 0.76–0.95, and there was significant correlation between the fluorescence results and histological characteristics for both examiners ($r_s = 0.47$ and 0.55 ; $p < 0.01$). The VistaProof has the ability to demonstrate high reproducibility and good diagnostic performance for the detection of occlusal carious lesions at various stages of lesion development. However, the resolution of the images is poor and effective cleaning of the tooth is mandatory to avoid false positive readings (Figures 17a and 17b). The Proxi head of the VistaCam iX has been reported to provide comparable findings to radiographs for non-cavitated lesions; however, further evidence is required.⁶⁰ Summarised clinical relevance of fluorescent devices is presented in Table 4.

Clinical relevance of the fluorescent cameras remains high in contrast to the systems which do not record images or give cut-off values.

Other

The Canary system

The Canary system (Quantum Dental Technologies Inc., Ontario, Canada) is a pulse laser-based system that uses a camera and a combination of heat and light detection and quantification (frequency-domain photothermal radiometry [FD-PTR] and modulated luminescence [LUM]), putatively examining the crystal structure of teeth and mapping carious lesions (Fig. 18). The system measures four signals:

Fig. 14 Enamel crack (black arrow). a) Active carious dentine (red auto-fluorescence highlighted – red rectangle, Soprolife mode II). b) Lesion entry point (red rectangle, Soprolife mode II)

Fig. 15 a) Modification of the fluorescent translucency of the marginal crest (Soprolife mode I). b) Identification of the carious tissue below (red fluorescence of an active lesion, Soprolife mode II)

Fig. 16 Leathery dentine (Soprolife mode II)

Fig. 17 a) VistaCam image with red signal and numeric values before cleaning (>2 dentine caries). b) Reduction of the cut-off values after cleaning (1.3, initial enamel demineralisation)

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 generated from an algorithm combining these four signals, giving information regarding the probable status of the lesion structure: 0–20 for healthy/sound tooth structure; 21–70 for carious lesions; and 71–100 for advanced lesions. PTR provides a depth profile of lesion properties by varying the frequency of the laser beam. The detected

Table 4 Fluorescence cameras summary based on the new clinical criteria

Tools	QLF/Qraycam	Soprolife/SoproCare	VistaCam	Comments
Cavitation	-	-	-	Quality of the images is better with Soprolife/SoproCare With Qraycam, quantification of the mineral loss is possible via bespoke software
Occlusal	Yes	Yes	No	
Proximal	No	No, except if teeth separated	No	
Activity	Yes	Yes	Yes (cut-off values)	N/A
Lesion cleansability	Yes*	Yes + video	No	*No data
Image	Yes*	Yes + video	Yes*	*No data
Magnification	Yes (no data)	Yes (up to 25X)	Yes*	*No data
Operative aid	No*	Yes**	No*	*Could help in pre-operative step **All restorative steps
Sensitivity ²³	68%	93%	92%	N/A
Specificity ²³	70%	87%	37%	N/A

Fig. 18 The Canary system (image courtesy of Stephen Abrams)

LUM and PTR signals combined reflect the tooth surface's condition. The handpiece is applied to the tooth surface and dental arches, and Canary values are calculated by the system.

By varying the pulse of the laser beam, a depth profile of the lesion to detect a carious lesion up to 5 mm deep from the tooth surface and as small as 50 µm in size is claimed. This allows the device to monitor lesions over time.^{61,62,63} A recent multi-centre clinical study concluded that the Canary system is able to discriminate between sound and carious enamel on smooth and occlusal surfaces.⁶⁴ Canary software allows the creation of graphs and reports on status and changes in lesions, and patients can access their reports via the 'Canary Cloud' web-based site (Table 5).

A complete summary of the different systems is given in Table 6.

Conclusions

Early carious lesion detection can be clinically challenging; however, despite this, monitoring early lesions is an important part of minimal intervention caries management. The use of adjunctive lesion detection technologies has produced much research over the past two decades and contradictory findings are published for all devices. Understanding the biological concepts related to the device may help the clinician to use the devices properly, but also to recognise the advantages and the limitations of each device as the results of any imaging technology are limited by the practitioner's interpretation. These caries detection devices can also be beneficial when radiography is not possible (for example,

Table 5 Canary system summary based on the new clinical criteria

Tools	Canary	Comments
Cavitation	-	*Related to the intraoral camera
Occlusal	Yes*	**Probable lesion related to the photothermal radiometry and luminescence signals through the marginal crest
Proximal	Yes**	
Activity	No	No data
Lesion cleansability	-	No data
Image	Yes	N/A
Magnification	Yes	No data
Peri-operative aid	No	N/A
Sensitivity*	93% ⁶⁵	*Proximal lesion
Specificity*	82% ⁶⁵	*Proximal lesion

Table 6 Summary of the devices

Device		Physical principle	Cavitation	Caries activity	Cleansability	Proximal caries	Limiting factors
Without image	DIAGNOdent	Laser (655 nm)	-	-	-	-	Visual resolution power, false positive signal, no pictures, no videos, no recording
	FACE, GC light	Fluorescence (405 nm)	-	+/- red signal	-	+/- transillumination	
With image	Canary	Laser (655 nm) + photothermal radiometry	+/- (daylight video)	-	-	+/- laser signal through the marginal crest	Systems with no magnification
	Soprolife	Fluorescence + magnification (450 nm)	+	++ red signal	+	+/- transillumination effect	N/A
	VistaCam	Fluorescence (405 nm)	-	+	-	-	Systems with no magnification
	DIAGNOcam	Infrared (780 nm)	-	-	-	++ (transillumination effect)	Systems with no magnification
	QLF	Fluorescence (290–405 nm)	-	++ red signal	+/-	+/- (transillumination effect)	Systems with no magnification

pregnant, geriatric or non-compliant paediatric patients). Currently, research attention is on computer-assisted image analysis to support dental procedures, and future findings may benefit caries detection technologies as well.^{66,67} Clinicians have to keep in mind that appropriate and thorough training on the use of any detection device is necessary to ensure good data collection and appropriate interpretation.

Author contributions

A. Slimani and E. Terrer are joint first co-authors and contributed equally to this manuscript.

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