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Abstract. The aim of this study was to assess the performance of two light-emitting diode (LED)- and two laser fluorescence-based devices in detecting occlusal caries *in vitro*. Ninety-seven permanent molars were assessed twice by two examiners using two LED- (Midwest Caries – MID and VistaProof – VP) and two laser fluorescence-based (DIAGNOdent 2095 – LF and DIAGNOdent pen 2190 – LFpen) devices. After measuring, the teeth were histologically prepared and classified according to lesion extension. At D₁ the specificities were 0.76 (LF and LFpen), 0.94 (MID), and 0.70 (VP); the sensitivities were 0.70 (LF), 0.62 (LFpen), 0.31 (MID), and 0.75 (VP). At D₃ threshold the specificities were 0.88 (LF), 0.87 (LFpen), 0.90 (MID), and 0.70 (VP); the sensitivities were 0.63 (LF and LFpen), 0.70 (MID), and 0.96 (VP). Spearman's rank correlations with histology were 0.56 (LF), 0.51 (LFpen), 0.55 (MID), and 0.58 (VP). Inter- and intraexaminer ICC values were high and varied from 0.83 to 0.90. Both LF devices seemed to be useful auxiliary tools to the conventional methods, presenting good reproducibility and better accuracy at D₃ threshold. MID was not able to differentiate sound surfaces from enamel caries and VP still needs improvement on the cut-off limits for its use. © 2011 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: 10.1117/1.3631796]

Keywords: occlusal caries; caries detection; laser fluorescence; light-emitting diode.

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1 Introduction

Occlusal incipient lesions have become difficult to be detected due to the wide-spread use of fluorides and their superficial remineralization potential that seems to delay the cavitation. Additionally, the changes in lesion morphology could lead to the presence of occlusal dentin caries under a fissure, which seems intact to the naked eye.¹ Visual inspection and radiographic examination have been commonly used in the clinical practice but they are able to detect caries lesions only at an advanced stage.²

Methods for the detection and the quantification of occlusal caries lesions have been extensively studied in the last years concerning their performance in detecting caries on smooth and occlusal surfaces. In addition to the visual-tactile method, these include radiography and light-induced fluorescence methods.³⁻⁶ These methods are based on the phenomenon of fluorescence, because caries tissues emit fluorescence with different intensities from healthy tissues when excited by lights at specific wavelengths.^{3,7,8}

Both devices, DIAGNOdent 2095 and DIAGNOdent 2190 (LF and LFpen, Kavo, Biberach, Germany), have been developed aiming the detection and quantification of occlusal as well as approximal caries lesions. These devices have shown controversial results depending on the methodology used in the studies. What is doubtless is that these devices are able to detect

better dentin than superficial enamel lesions.⁹⁻¹¹ Besides, some studies have also shown a better performance of these devices than the radiographic examination, suggesting that they could be indicated as auxiliary methods for caries detection.^{6,12,13}

More recently, other fluorescence-based devices were introduced in the market and few data have been published concerning their performance. These devices are comprised of a light emitting diode (LED) and have been developed also aiming at caries detection. The fluorescence camera VistaProof (VP, Dürr Dental, Bietigheim-Bissingen, Germany) is a device able to emit blue light, at 405 nm wavelength, to capture and digitalize images from the teeth while they are emitting fluorescence. The DBSWIN software that belongs to the product is supposed to analyze the digital images, correlate the green and red amount of pixels observed on the screen, and translate this ratio into numerical values. These values would be related, then, to the lesion severity. Few studies have been carried out on this device^{3,4,14} and it seems that the device is better in detecting dentin than enamel caries. Besides, the cut-off limits suggested are still useless in clinical practice.

Another LED-based device (MIDWEST Caries ID, MID, Dentsply Professional, York, Pennsylvania), which has not yet been tested but is already available on the market, has recently been developed and has been suggested as a caries detection tool. MID is a handheld device based on the reflection and reflectance of the emitted light. According to the manufacturer, when there is a change in the optical translucency and opacity of the dental tissues, the emitted green light changes to red

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and an audible signal could be heard. The faster the signal, the deeper the lesion. Results concerning this technology are scientifically supported by abstracts presented at conferences. No study in a major dental journal has been published to date and its performance on occlusal caries detection has yet to be tested as well.

Therefore, the aim of this *in vitro* study was to assess the performance of two newly developed LED (VP and MID) based devices and compare to both established LF and LFpen in detecting occlusal caries.

2 Material and Methods

2.1 Sample Selection

Ninety-seven permanent human molars were selected from a pool of extracted teeth, which were kept stored frozen at -20°C until use. Earlier studies showed that this method of storage does not significantly change the red fluorescence.¹⁵ All teeth had been extracted by dental practitioners in Switzerland (no water fluoridation, 250 ppm F^{-} in table salt). Prior to the extraction, patients were informed about the use of their teeth for research purposes and their consent was obtained. The teeth were defrosted for 3 h and the calculus and debris were removed using a scaler (Cavitron, Dentsply, York, Pennsylvania). They were cleaned for 15 s with water and toothbrush (Trisa ultra super-sensitive, BrushAbo, Switzerland) and for 10 s with a water-powder jet cleaner (PROPHYflex II, KaVo, Biberach, Germany) and sodium hydrogen carbonate powder. In order to not have powder remnants in the fissure,⁵ the teeth were then rinsed off with the three-in-one syringe for 10 s.¹⁶ During the measurements, they were stored in 100% humidity. Photographs of the occlusal surfaces were taken (at $6.25\times$ magnification) and one spot from each tooth was selected in the fissure surface (test site).

Assessments on each test site were carried out twice by two examiners observing a one-week interval between the measurements. No calibration training was performed and the examiners were informed about the function of the devices. Two LED-(MID and VP) and two laser fluorescence-based (LF and LFpen) devices were tested.

2.2 Laser Fluorescence-Based Devices (DIAGNOdent and DIAGNOdent pen)

The first LF system and the LFpen function on the same principle, are based on the phenomenon of fluorescence, where absorption of light of a given wavelength by a fluorescent molecule is followed by the emission of light at longer wavelengths. These LF systems emit red light at a wavelength of 655 nm (≈ 1 mW power). A photodetector quantifies the fluorescence light passing through the filter and digitally displays a real time (moment) and a maximum (peak) value. In the LFpen device, the excitation and emission of fluorescence follow the same solid fiber tip, but in opposite directions.¹⁷ This is the main difference to the first one, which has different fibers for light excitation and emission.^{1,3}

The test sites were measured using both LF devices (LF and LFpen). The mode of calibration was the same for both. First, the devices were calibrated for every tooth using a ceramic standard in accordance with the manufacturer's instructions. The

fluorescence value of a sound part of the cuspal area on the buccal surface was also recorded (zero value) to be later subtracted from the peak value. For the measurements, the tip A (for the LF device) and a cylindrical sapphire fiber tip for occlusal surfaces (for the LFpen device) were used. The device was moved around the test site until the highest value was obtained. This ensured the tip picking up the highest value from the fissure wall, where the carious process often begins. The peak values were recorded and the zero values of fluorescence were subtracted.

2.3 Light-Emitting Diode-Based Devices (Midwest Caries and VistaProof)

Because healthy tooth structure is generally more translucent than decalcified enamel, there is a different optical signature between healthy and demineralized tooth structure. The MID (Fig. 1) is a handheld device that analyzes the reflectance and refraction of the emitted LED, which is captured by built-in fiber-optics and converted into an electrical signal that is analyzed. A microprocessor within the device contains a computer-based algorithm that differentiates the presence or absence of changes in optical translucency and opacity. The presence of demineralization activates a change in the LED from green to red with a concurrent audible signal, confirming the presence of caries.¹⁸ The tip of the device was positioned over the test site and the audible signal was classified into absent (0), moderate (1), or fast (2).

The fluorescence camera (VP) is an intra-oral camera with six blue GaN LEDs at 405 nm wavelength with an optical power of 60 mW. An optical long pass filter cut down the excitation light below 495 nm and the images are viewed through an optical lens and projected to a CCD sensor, which converted the image data into an electronic signal. The software DBSWIN (Dürr Dental, Bietigheim-Bissingen, Germany) has been used to create the images, resulting in a digitalization of this electronic signal. The images were composed of 720×576 pixels with 3×8 bit intensities of RGB-channels and a resolution of 72 pixels/inch. These images have been analyzed with the software, which translated the red and green correlation of fluorescence to numbers. This software shows the region of the teeth that emits fluorescence varying from green to red (approximately 510 nm and 680 nm wavelength, respectively) and values ranging from 0 to 3 corresponding to the lesion severity. The outcome parameter is calculated considering the intensity ratio of the red and green fluorescence. Caries lesions were determined when the red/green-ratio was higher than the red/green-ratio of sound tissue. To calculate the fluorescence ratio of caries lesions, the maximum of the red/green-ratio in the lesion was recorded. The images of the teeth were taken using the described FC system



Fig. 1 Newly developed device MIDWEST Caries ID.

and analyzed by the software, stored in the computer, and the values were recorded for further analysis.^{3,4}

2.4 Validation

After the assessments, the teeth were longitudinally grounded on a Knuth-Rotor polishing machine (Struers, Copenhagen, Denmark) using silicon carbide paper (60 μm of grain size) cooled under tap water. Progression of the grinding process was constantly checked under the microscope (magnification 6.25 \times) and compared to the initial pictures, where the test site had previously been identified. When the periphery of the site was reached by the grinding process, papers of grain size 30, 18, 8, and 5 μm were used. The occlusal cut surfaces were photographed to ensure that the caries lesion was not ground away. The teeth surfaces were then colored with saturated rhodamine B (Fluka, Buch, Switzerland). The histological examination was performed according to the rhodamine B penetration either into the enamel or both enamel and dentin tissues and considering as gold standard. The sites were assessed for caries extension (magnification 10 \times) as caries-free (0), caries extending up to halfway through the enamel (1), caries extending in the inner half of enamel (2), and caries in dentin (3) (Fig. 2).

2.4.1 Statistical analysis

Optimal cut-off limits for MID and VP were determined considering the point where the sum of sensitivity and specificity was the highest. For all methods, sensitivity, specificity, accuracy, and area under the ROC curve (AUC) were calculated at D_1 threshold (0 = sound; 1 to 3 = decayed), and D_3 threshold (0 to 2 = sound, 3 = decayed). Spearman's rank correlations (95% confidence interval) with histology were obtained. Intraclass-correlation (ICC) was calculated to assess inter- and intra-examiner reproducibility.

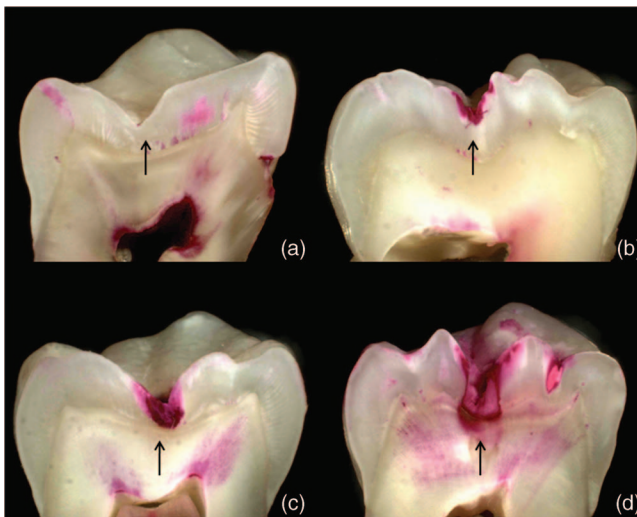


Fig. 2 Histological examination. (a) Caries-free, (b) caries extending up to halfway through the enamel, (c) caries extending in the inner half of enamel, and (d) caries in dentin.

Table 1 Specificity, sensitivity, accuracy, and area under the ROC curve (A_z) of the methods for the detection of occlusal caries. [D_1 : 0 = sound; 1 to 3 = decayed. D_3 : 0 to 2 = sound; 3 = decayed.]

	Specificity		Sensitivity		Accuracy		A_z	
	D_1	D_3	D_1	D_3	D_1	D_3	D_1	D_3
LF ^a	76.5	88.6	70.0	63.0	71.1	81.5	0.72	0.85
LFpen ^a	76.5	87.1	62.5	63.0	65.0	80.4	0.72	0.85
MID ^b	94.1	90.0	31.2	70.4	42.2	84.5	0.67	0.87
VP ^b	70.6	70.0	75.0	96.3	74.2	77.3	0.76	0.89

^aCut-off proposed by Lussi and Hellwig (Ref. 10).

^bOptimal cut-off (Table 1).

3 Results

From the 97 occlusal test sites analyzed in this study (one site in each tooth), the histological examination revealed that 17 of them were caries free, 21 had caries extending up to halfway through the enamel, 32 had caries extending in the inner half of enamel, and 27 had dentin caries.

Specificity, sensitivity, accuracy, and area under the ROC curve (A_z) are shown in Table 1, where the accuracy of the tested methods compared with the gold standard can be observed. Table 2 shows the optimal cut-off values for MID and for VP. Spearman's rank correlations with histology, as well as ICC for inter- and intra-examiner reproducibility, and the 95% confidence interval for all of the methods are shown in Table 3.

4 Discussion

Caries lesions on occlusal surfaces are the most readily seen manifestation of the disease in children and young adults.¹⁹ Because of the special morphology of the pits and fissures and the difficulty of plaque removal, occlusal caries are difficult to detect.²⁰ Furthermore, occlusal dentin caries has been observed under a fissure that seems intact to the naked eye due to the use of fluorides making the detection of such lesions difficult by conventional methods (visual examination and radiography).^{1,3} For this reason, the importance of early detection of occlusal caries and the development of new auxiliary methods has grown in the last years.^{20,21}

Some studies have assessed the performance of both LF devices as auxiliary methods for occlusal as well as for

Table 2 Optimal cut-off limits of the LED-based devices.

Histology	MID	VP
0 (sound)	0 (no audible signal)	0 to 1.2
1 (enamel)	0 (moderate audible signal)	1.2 to 1.4
3 (dentin)	1 (moderate audible signal)	>1.4

Table 3 Spearman's rank correlation with histology and ICC for inter- and intraexaminer reproducibility as well as 95% confidence interval for LF, LFpen, MID, and VP.

	Spearman's rank correlation	ICC – Interexaminer	ICC – Intraexaminer
LF	0.56 (0.41 to 0.69)	0.89 (0.83 to 0.92)	0.89 (0.84 to 0.93)
LFpen	0.51 (0.34 to 0.64)	0.86 (0.77 to 0.91)	0.83 (0.74 to 0.88)
MID	0.55 (0.39 to 0.67)	0.85 (0.78 to 0.90)	0.83 (0.75 to 0.88)
VP	0.58 (0.43 to 0.70)	0.87 (0.81 to 0.91)	0.90 (0.85 to 0.93)

approximal caries detection, but very few have evaluated the newly developed fluorescence camera,^{3,4,14} and none have evaluated the LED-based device MIDWEST. For this reason, the present investigation aimed to evaluate their performance. Some studies cite the terms validity or accuracy, meaning performance. However, in this study, the authors defined performance as the association of two important characteristics of a method: accuracy and reproducibility.

Both LF and LFpen devices have shown good results of reproducibility and accuracy, mainly for the detection of dentin caries.^{1,3,9,11,22} In the present investigation, both LF devices performed better at D₃ threshold, which is in accordance to the literature. In spite of being lower, however, high values of sensitivity, specificity, and accuracy were found at the D₁ threshold as well, as observed in Table 1. These results seem to be important mainly when we look at the specificity. High specificity means that a great number of sound sites were correctly classified as sound and this could avoid a possible unnecessary intervention or an overtreatment on the tooth. The AUC also showed good performance of these methods, confirming their indication as auxiliary tools to the conventional methods for the detection of occlusal caries. However, it must be emphasized that this kind of analysis takes into account several cut-off limits, not considering a stipulated value for the calculation.²³ The advantage of ROC analysis is that positive and negative predictive values are independent of prevalence of the disease.²⁴

It is important to point out that a high value of fluorescence may indicate caries as changes in the physical properties in the tooth structure, such as the presence of stains, disturbed tooth development, or mineralization, which could increase the value of sensitivity as a false-positive result.³ Therefore, in the present study, teeth with such alterations were not included in the sample.

Reproducibility was assessed by means of ICC for both intra- and inter-examiner agreement. High ICC values varying from 0.83 to 0.90 were observed for all devices. These results are in accordance to other recently published studies that also found high values.^{3,4,10,20,25,26} Jablonski-Momeni et al.⁴ found ICC values for VP varying from 0.76 to 0.95 and Rodrigues et al.³ from 0.76 to 0.85. The good reproducibility means that the devices could be used for monitoring the carious process.¹⁰ However, it should be pointed out that the reproducibility only represents the ability of a method in reproduce similar results or near values, but does not necessarily mean that these results are correct or in agreement to the histological lesion's depth. Therefore, Spearman's rank correlation with histology was also

calculated for all methods, and values from 0.51 to 0.58 were found. According to Cohen,²⁷ values between 0.30 and 0.50 are considered as a moderate correlation and values from 0.50 to 1.0 as strong. Because the values are in the lower border of this interval, they should be carefully interpreted as strong.

The cut-off limits of the LED devices tested should also be considered with caution. The VP device does not seem to present trustworthy cut-off values for its clinical use as of yet. The range of values observed between the different histological classifications seems to be very close to each other, limiting its indication. Similar values were also found by other authors.^{3,4} The principle of fluorescence, on which the VP device is based, seems to have great potential for the detection of occlusal caries as well for monitoring purposes. However, the present observations suggest that the software used to analyze the digital images should be reviewed by the manufacturer in order to provide useful values for clinical practice.

The same could be stated for the MID device, which showed the same cut-off limits for caries-free sites and enamel caries. This means that the MID device was not able to differentiate those lesions from sound surfaces. This could also be stated by looking at the sensitivity (31.2) and specificity (94.1) values at D₁ threshold. Besides, the audible signal is very subjective, making the assessment and classification of occlusal lesions difficult and time-consuming.

Both LED and laser-based technologies are potential tools for the detection and quantification of dental caries. However, some of the devices still need to be further studied and improved by the manufacturers before being on the market. From the present study, it can be concluded that both LF devices are suitable for the detection of occlusal caries and are useful auxiliary tools to the conventional methods, presenting good inter- and intra-examiner reproducibility and better accuracy at the D₃ threshold. Concerning the LED-based devices, MID was not able to differentiate sound surfaces from enamel caries and VP still needs improvement on the cut-off limits for its use.

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