A Closer Look at Diagnosis in Clinical Dental Practice: Part 5. Emerging Technologies for Caries Detection and Diagnosis

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Abstract

Parts 5 and 6 of this series examine innovations in diagnostic and management procedures and assess their potential to become everyday tools of the dental clinician. This paper examines some of the diagnostic tools supporting a philosophical shift in mainstream dental practice from concern with extensively decayed teeth to a focus on detecting incipient demineralized tissues. With the latter approach, the incipient carious process can be reversed by promoting enamel remineralization and thus eliminating the need for restorative intervention. Numerous methods and devices have been developed to detect, diagnose and monitor such lesions, and several have been produced in versions that may appeal to dental practitioners. This paper considers 3 of these methods and devices: the DIAGNODent laser device, quantitative light-induced fluorescence and the Digital Imaging Fiber-Optic Transillumination device. Each technique is illustrated, the research on its effectiveness is assessed to determine usefulness to the practitioner, and the comparative advantages of the 3 adjunct tools are discussed.

MeSH Key Words: *decision support techniques; dental caries/diagnosis; predictive value of tests; risk assessment methods*

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Despite a significant reduction in the prevalence of caries within some population subgroups in the Western world, this problem remains significant at the clinical and public health levels. Diagnostic devices have been developed with claims of detecting the earliest signs of enamel demineralization and thus affording the opportunity to intervene with aggressive therapies (mainly fluorides) at an incipient stage, arrest the lesion, encourage remineralization and avoid the need for restorative intervention. The extent of the epidemiological problem, along with this battery of new diagnostic tools, poses a challenge for the dental practitioner attempting to address the former while maximizing the scope for using the latter. An examination of the applications of these tools, and of the information they reveal, is in order.

In this paper, we examine techniques for detecting caries that are intended for, or currently available to, general dental practitioners. This information is presented in the context of the larger framework of diagnostic tests and management strategies discussed in the current series of articles.[1–4] Before the techniques are discussed in detail, however, we should define the clinical context into which they have been introduced. **Table 1** summarizes the evidence for the more conventional methods of detecting caries: visual, visual and tactile, and radiographic. This summary is based on 2 highly recommended reviews of the subject by Bader and others.[5,6] Although they are commonly used in dental practice and are reasonably reliable by today's standards, these conventional techniques leave room for improvement. This paper assesses whether any of the new systems fill that need.

A glossary, with concise definitions of terms, is available for the entire series (see **Appendix 1**, Glossary of epidemiology terms, at http://www.cda-adc.ca/jcda/vol-70/issue-4/251.html).

DIAGNODent Laser Device

The DIAGNODent laser device (KaVo, Lake Zurich, Ill.) uses laser fluorescence to detect incipient caries. The exact mechanism of detection has not been fully articulated,

Table 1 Effectiveness of common diagnostic tests for detection of caries[a]

Method, surface and extent	No. of studies	No. of examiners		Prevalence of lesions (%)		Sensitivity (%)		Specificity (%)	
		Mean	Median	Mean	Median	Mean	Median	Mean	Median
Visual									
Occlusal surfaces									
Cavitated	4	1	1	56	51	63	51	89	89
Dentinal	10	9	4	50	44	37	25	87	91
Enamel	2	2	2	21	21	66	66	69	69
Any	4	12	7	78	75	59	62	72	74
Visual-Tactile									
Occlusal surfaces									
Dentinal	2	12	6	29	29	19	19	97	97
Any	2	4	4	40	40	39	39	94	94
Proximal surfaces									
Cavitated	3	3	3	5	6	52	32	98	99
Radiographic									
Occlusal surfaces									
Dentinal	26	4	3	54	55	53	54	83	85
Enamel	4	2	2	18	18	30	28	76	76
Any	7	5	4	82	84	39	27	91	95
Proximal surfaces									
Cavitated	7	3	3	13	9	66	66	95	97
Dentinal	8	39	5	27	27	38	40	95	96
Enamel	2	10	10	25	25	41	41	78	78
Any	11	6	3	62	66	50	49	87	88

[a]*Modified from Bader and others*[5,6]

Figure 1a: *The DIAGNODent device showing the 2 light-emitting diode readouts.*

Figure 1b: *The B version of the DIAGNODent handpiece is used for occlusal pits and fissures. The broader, flatter version A (not shown) is used for smooth surfaces.*

but the device appears to measure the fluorescence of bacterial products within carious lesions — namely, porphyrins — rather than crystalline disintegration.[7] This theory is supported by the fact that the DIAGNODent device does not detect lesions produced in the laboratory by means of acidic buffers, which produce no microbiological activity.[8] The device generates a laser beam that is absorbed by materials within the tooth and is subsequently re-emitted as infrared fluorescence.

The DIAGNODent device (**Fig. 1a**) is compact, portable and fully compliant with cross-infection control directives. It consists of a control unit and a hand-held probe. The probe comes with 2 attachments, one with a small tip, for examining fissure caries, and the other with a larger, broader tip, for examining smooth surfaces (**Fig. 1b**).

Technique

After calibration, the appropriate probe is selected. For smooth surfaces, the probe is gently run over the surface of the tooth. For occlusal examinations, the probe should be moved (e.g., mesially to distally) and swayed bucolingually to ensure that all fissures are examined.

Table 2 **Summary of studies assessing the DIAGNODent device**

Subject	Study	Main Findings
Root caries	Wicht and others[15]	Correlation of 0.45 with lesion depth
Active vs. arrested lesions	Pinelli and others[14]	Kappa statistic for agreement of operators 0.77, sensitivity 0.72, specificity 0.73
Clinical occlusal lesions	Sheehy and others[16]	Reported a tendency for device to overscore occlusal lesions and effect of stain
Smooth-surface lesions	Shi and others[17]	Good correlation with lesion depth (0.83); inter-observer agreement substantial (0.94)
Occlusal caries in primary teeth	Attrill and Ashley[11]	DIAGNODent device had highest sensitivity (0.78), but lowest specificity (0.83) relative to other devices tested
Validation of detection	Shi and others[17]	Strong correlation with total mineral loss (0.89)
Validation in occlusal surfaces	Lussi and others[12]	Sensitivity 0.96 (better than achieved with bitewing radiographs), specificity 0.86
Approximal caries	Shi and others[18]	Sensitivity 0.75, specificity 0.96
Occlusal caries	Shi and others[19]	Receiver operating characteristics analysis used; DIAGNODent device significantly better than radiography

The device displays the results in real time. The unit presents current and peak values from the time when the unit was last reset. Therefore, the unit should be reset between teeth, so that the peak value for each tooth can be recorded, along with notes as to the location on the tooth where the reading was taken. Further readings at recall appointments can be used to determine if the DIAGNODent value has increased, decreased or stabilized. Recent research has proposed indices for the interpretation of DIAGNODent values in relation to occlusal decay.[8,9]

Evidence

This device has generated a great deal of research interest.[10] Attrill and Ashley[11] compared it with clinical–visual and radiographic examinations of primary occlusal surfaces in vitro. Echoing previous findings, they discovered that radiography performed poorly, whereas the DIAGNODent device performed effectively, although not significantly better than the visual scale. Despite little statistical separation between the device and a clinical (visual) scale, the ability to quantify the result may be of great value for monitoring teeth longitudinally. Studies on occlusal surfaces in adults have shown that, for certain lesions, the DIAGNODent device offers significant advantages over conventional techniques.[12,13] With a sensitivity of 0.72 and a specificity of 0.73, the device might also be used for smooth-surface caries.[14] **Table 2** provides details of other studies that have assessed the sensitivity and specificity of the DIAGNODent device. The device may be used to detect demineralization that is developing beneath fissure sealants, although its diagnostic performance appears to depend to some degree on sealant colour.[20]

Summary

The DIAGNODent is probably a valuable device for the dental practitioner. It is relatively inexpensive and, when combined with a visual exam, improves the clinician's ability to detect demineralization, as well as to longitudinally monitor suspect lesions to determine the success of remineralization interventions. Its capacity to ascertain demineralization under sealants may be of particular appeal to pediatric dentists. The unit has been designed with general dental practice in mind, and its physical appearance, ease of use, compliance with cross-infection stipulations and capability for longitudinal recording of values are suitable for this setting.

Digital Imaging Fiber-Optic Transillumination Device

Illuminating teeth to determine the presence of demineralization is far from a novel approach to caries detection. However, the Digital Imaging Fiber-Optic Transillumination (DIFOTI) system (Electro-Optical Sciences, Irvington, NY; www.difoti.com), which allows images from all tooth surfaces to be digitally captured and stored, has made this technology accessible for practitioners and sophisticated enough for longitudinal evaluation of individual caries lesions. The principle behind transilluminating teeth is that demineralized areas of enamel or dentine scatter light (in this case a high-intensity white light) more than sound areas. Incipient caries appear as darker areas in the resultant images.

The user-friendly DIFOTI system consists of 2 handpieces (one for occlusal surfaces and one for smooth and interproximal areas), a disposable mouthpiece, a foot pedal for selecting the image of interest from the live pictures, and a computer system to capture and store the resulting image (**Fig. 2**). Examples of the images obtained are shown in **Fig. 3** (sound teeth), **Fig. 4** (early demineralization) and **Fig. 5** (larger lesions).

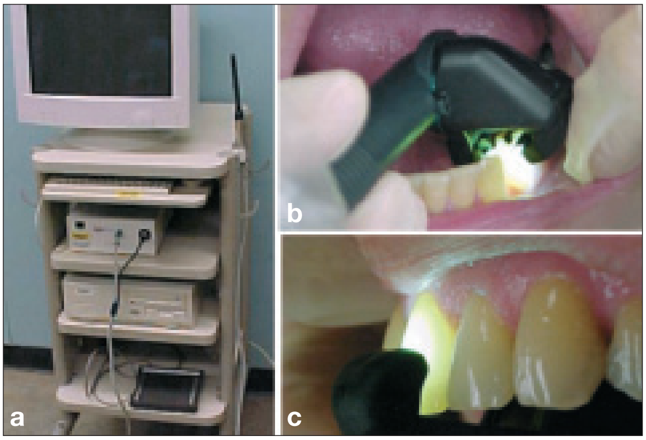

Figure 2: *a) The DIFOTI set up, including light box, computer and foot pedal. b) The occlusal handpiece, with illumination from the buccal and lingual aspects, imaged from above. c) The smooth surface handpiece, illuminated from the palatal aspect and imaged from the buccal surface.*

Technique

The appropriate handpiece is selected and placed over the tooth, and a live image appears on the screen. The software detects when the image is focused, and the operator selects images to be captured. The software automatically moves through the dental arch, and an entire mouth series can be captured in 10–15 minutes; the operator simply moves the handpiece over each tooth in sequence. DIFOTI is not a quantitative technique, and the software does not perform any analysis. Instead, the images must be analyzed by the clinician in the same way as radiographs (i.e., visual assessment of the light scattering relating to mineral loss).

Evidence

Table 3 summarizes the one research employing FOTI and DIFOTI methods. These results suggest that the technique is highly specific and sensitive, especially in the diagnosis of occlusal caries. The current clinical environment is influenced by the inherent difficulties of diagnosing mineral loss in occlusal caries;[29] therefore, the observation in one study of an area under the curve of 0.85 in a receiver operating characteristics (ROC) analysis of DIFOTI[24] suggests that there is a basis for using this device in diagnostic dentistry.

Summary

The DIFOTI system has been developed with the dental practitioner in mind. It is simple to use, and the instantly available images are easily interpreted.[30] It can also be used as a patient education tool, since the images can be readily understood by the layperson. The ability to combine an image from, for example, an intraoral camera with the DIFOTI image can help patients target their oral hygiene to at-risk areas.[30]

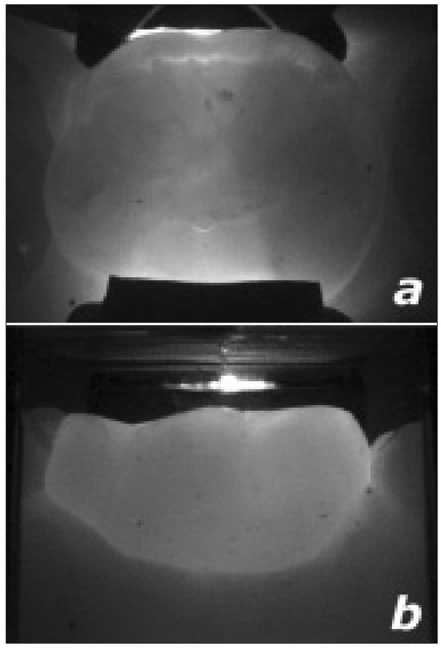

Figure 3: *a) Sound occlusal surface as seen with the occclusal handpiece of the DIFOTI. b) Buccal view of the same tooth demonstrating lack of demineralization.*

One potential problem with DIFOTI relates to image interpretation. Because the results are not directly quantified, the clinician must perform the analysis, with all the advantages and disadvantages that such analyses entail.[28] Furthermore, the content of the images should not be considered equivalent to what appears in radiographs. Specifically, areas of radiotranslucency appearing in radiographs should generally be restored. However, areas detected with the DIFOTI system are generally incipient lesions that are amenable to remineralization therapies.

Quantitative Light-induced Fluorescence

Quantitative light-induced fluorescence (QLF) is the newest technology in the field. The theory behind QLF has been amply discussed in recent publications,[31–34] and is briefly summarized here. Under certain conditions, human enamel autofluoresces. Bjelkhagen and others[35] were the first to describe the reduction of fluorescence seen in demineralized enamel, and Angmar-Månsson and ten Bosch[36] suggested that the increased porosity of carious lesions leads to a decrease in the refractive index.

Use of this theory to develop a viable technique[37] was followed by the capture of images on charge coupled device (CCD) cameras, which enabled longitudinal monitoring of individual carious lesions.[38] An existing method for quantifying mineral loss from lesions[39] was improved by substituting the cumbersome laser-based system with a portable arc-lamp unit.[40,41] A commercial device and software (including an image subtraction system

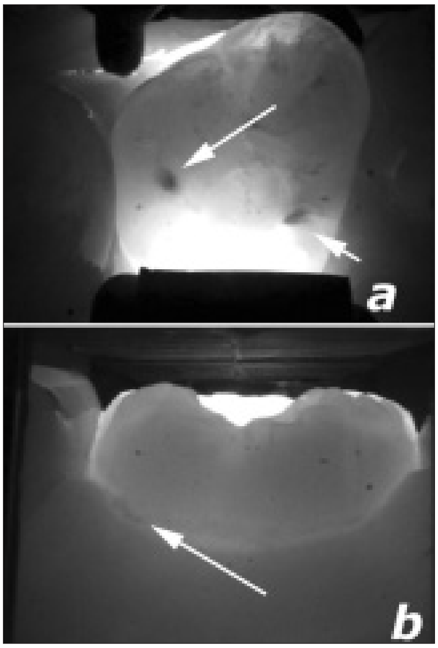

Figure 4: *a) Arrows point to areas of light scattering, which indicates mineral loss on the (a) occlusal and (b) buccal surfaces. These are both early lesions that may respond to a fluoride remineralization therapy.*

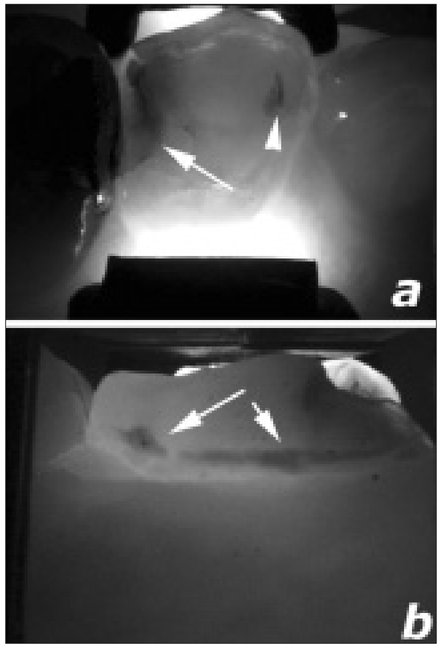

Figure 5: *Arrows indicate more severe scattering and hence greater mineral loss on the occlusal (a) and buccal (b) surfaces. Such lesions may require minimal restorative intervention (i.e., enamel biopsy).*

Table 3 **Summary of studies assessing FOTI/DiFOTI devices**

Subject	Study	Main findings
Occlusal caries	Cortes and others[21]	Receiver operating characteristic 0.85, kappa statistic 0.87
FOTI in general practice	Davies and others[22]	Practitioners reported enhanced detection with FOTI
Inter-observer agreement	Cleaton-Jones and others[23]	Excellent agreement between observers (>90%)
Occlusal caries	Fennis-le and others[24]	Inter-observer reproducibility 0.79
Occlusal and approximal surfaces	Schneiderman and others[25]	Sensitivity 0.67 for occlusal surfaces and 0.56 for aproximal surfaces; radiography had sensitivity of 0.18 and 0.21 respectively
In vitro use	Peers and others[26]	Sensitivity 0.67, specificity 0.97
Occlusal caries	Mitropoulos[27]	Sensitivity 0.85, specificity 1.00
Buccal surfaces	Sidi and Naylor[28]	Sensitivity 0.74, specificity 0.99

for in vivo longitudinal assessment) are now available (QLFPatient, Inspektor Research Systems BV, Amsterdam, The Netherlands); the system includes cameras suitable for intraoral use and a repositioning system to ensure that images are correctly aligned.[42] With the addition of a fluorescent dye, QLF can be used to detect early demineralization in dentine.[39,43–45] In addition to its use in detecting incipient caries in permanent teeth, adjacent to restorations and orthodontic brackets, in primary teeth and in clinical trials of dentifrice products,[34,41,43,46–50] QLF can be used to detect failing fissure sealants, to measure planimetric plaque[41,48,51] and to monitor enamel erosion in vitro.[52]

Technique

The QLF device consists of the light source and the intraoral camera (**Fig. 6** illustrates how the system works, and clinical examples are shown in **Figs. 7** and **8**). The QLF technique is a 2-stage process. First, an image of the tooth must be acquired with the intraoral camera held in the hand. Then, both qualitative and quantitative assessments of mineral loss are obtained. The enhanced contrast (more than 20 times that which can be detected clinically) between sound and demineralized enamel enables the clinician to identify areas of concern. Longitudinal monitoring of lesions with the QLF analysis software can be used to quantitatively measure mineral loss (**Fig. 9**).

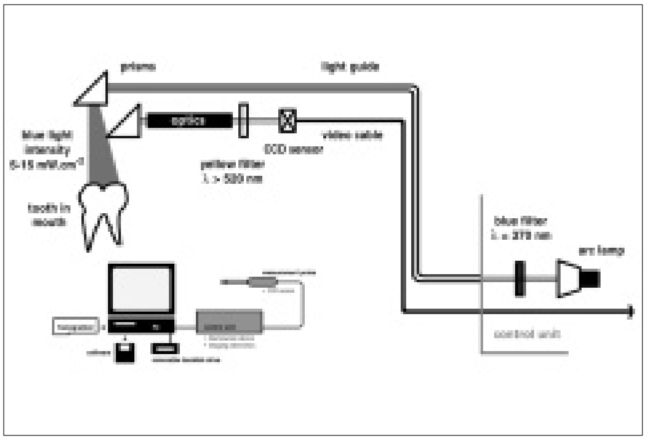

Figure 6: *Diagrammatic representation of the QLF system.*

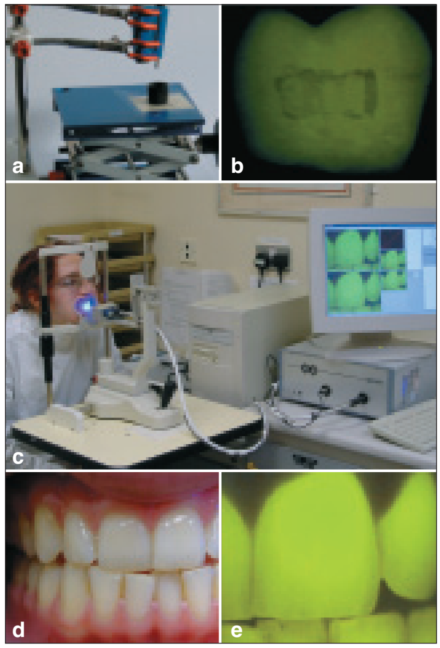

Figure 7: *a) Quantitative light-induced fluorescence (QLF) camera in an in vitro set-up. b) An image captured in vitro. c) The VidRep system used with the QLF handpiece held on a headrest. d) White light image. (e) The QLF image taken using this system.*

Evidence

Table 4 summarizes the evidence supporting the use of QLF to detect caries, both the initial validation studies and more recent work to ascertain sensitivity and specificity. **Table 5** outlines how QLF compares with other systems for detection of occlusal caries. **Table 6** summarizes predictive values for detecting caries on occlusal and smooth surfaces, caries adjacent to a variety of restorative materials (secondary caries), root caries and demineralization adjacent to orthodontic brackets and bands, giving examples for both high-and low-risk populations.

Summary

QLF is a more versatile system than either DIAGNODent or DIFOTI and can measure absolute mineral loss along with a number of other applications. Research suggests that the correlation between QLF and absolute mineral loss (as measured by a radiographic gold standard) may be as high as $r = 0.92$.[63] The ability to visualize bacterial products, which appear as red fluorescence, may be used to determine the activity of lesions.[64] QLF can be considered a diagnostic system, rather than simply a detection device. The feasibility of using QLF to detect root caries[45] and early orthodontic demineralization[65] will be of interest to specialists treating patients with these kinds of lesions. It is likely that, within the next few years, general practitioners will become more familiar with how QLF applies to their clinical work, and the unit will become more affordable for general clinical use.

Discussion

Because this is a narrative rather than a systematic review, we cannot say unequivocally that these devices offer clear improvements over the more traditional systems. They do, however, offer distinct advantages. For example, QLF and DIFOTI images can be stored and viewed at a later date. The DIAGNODent device generates a simple numeric index of demineralization that can be entered into the patient's notes and monitored over time. Ultimately, however, the plethora of methods, validating systems and (often) arbitrary gold standards makes comparisons difficult and poses a challenge for the dental practitioner who is trying to stay abreast of technological developments.

Appropriate assessment of the many studies in the literature and the barrage of marketing messages from the industry is of critical importance. It is also worthwhile to examine motivations for supplementing, or even replacing, well-established diagnostic methods in dental practice. A new approach or technique must perform substantially better in diagnosing the status of carious lesions if it is to be adopted.

One of the components of diagnostic thinking is information, which is also the basis of the Bader and Shugars[66] model of decision making in dental practice. These authors focused on creating a system composed of many pieces of information and proposed that clinicians resort to inventories, or "caries scripts," to match each clinical case with profiles. Clinical and nonclinical items are used to modify the profiles; in particular, patient factors may include relatively abstract concepts within the consultation environment (such as treatment preferences) or highly specific, tangible information (such as changes in tooth colour that indicate decay). The highly specific pieces of information that connote dental caries were considered as patient factors at the tooth or mouth level in the Bader and Shugars[66]

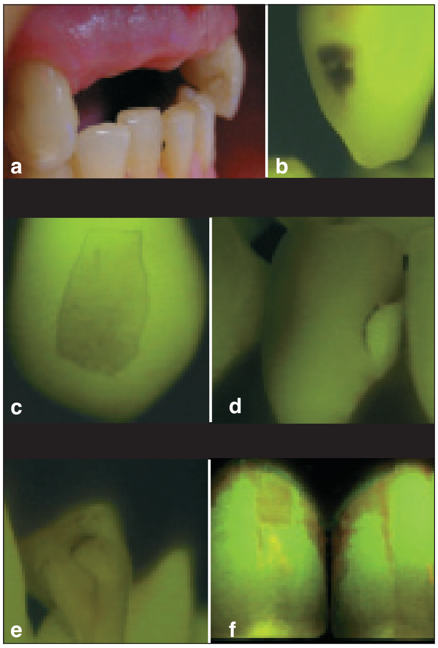

Figure 8: a) Clinical example of a lesion on the mesial surface of the canine associated with partial denture wear. b) The QLF image showing enhanced contrast between sound and demineralized enamel; note the lack of reflections. c) An example of an in vitro artificial lesion imaged by QLF. d) An example of secondary caries imaged by QLF; note the failing composite. e) Further example of secondary caries. f) Plaque imaged by QLF.

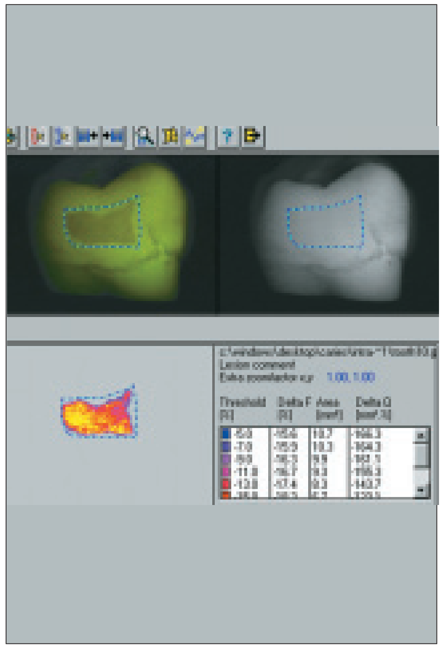

Figure 9: Example of QLF image analysis.

Table 4 Summary of studies assessing quantitative light-induced fluorescence device

Subject	Study	Main findings
Occlusal caries	Pretty and others[8] Ando and others[53] ten Cate and others[54]	Strong correlation with histologic findings (0.82) Sensitivity 0.76 with plaque-covered surface Sensitivity 0.77, specificity 0.71
Reliability	Tranaeus and others[55]	Intra-observer agreement 0.96, inter-observer agreement 0.97
Secondary caries	DeSchepper and others[56] Benedict and others[57]	Sensitivity 0.88, specificity 0.85 Sensitivity 0.95, specificity 0.85
Root caries	Pretty and others[45] Gonzalez-Cabezas and others[58]	Correlation with gold standard 0.89 Receiver operating characteristic value of 0.78
Smooth surface caries	Hall and others[59] Shi and others[18]	Sensitivity 0.75, specificity 0.90 Sensitivity 0.76, specificity 0.92

Table 5 Effectiveness measures for a variety of diagnostic methods applied in the detection of occlusal caries

Diagnostic system	Study	Sensitivity	Specificity	Youden's J
Electronic caries monitor	Ashley and others[60]	0.65	0.73	0.38
Visual	Ashley and others[60]	0.60	0.73	0.33
Fibreoptic transillumination	Ashley and others[60]	0.21	0.88	0.09
Bitewing radiographs	Ashley and others[60]	0.19	0.80	0.01
Quantitative light-induced fluorescence	Pretty and others[8]	0.68	0.70	0.38
Visual	Alwas-Danowska and others[61]	0.50[a]	0.91[a]	0.41[a]
DIAGNODent	Alwas-Danowska and others[61]	0.94[a]	0.52[a]	0.46[a]
	Bamzahim and others[62]	0.8	1	0.80
Electronic caries monitor	Bamzahim and others[62]	0.75	0.88	0.63

[a]*Calculated from reference.*

Table 6 Positive and negative predictive values of QLF on various surfaces

	High risk population (0.8)[a]		Low risk population (0.1)[a]	
Surface	**PPV**	**NPV**	**PPV**	**NPV**
Smooth	0.95	0.43	0.36	0.96
Occlusal	0.90	0.35	0.20	0.95
Secondary caries	0.96	0.70	0.40	0.98
Orthodontic	0.98	0.62	0.65	0.98
Root caries	0.97	0.74	0.64	0.99

[a]*Prevalence of the disease within the population.*

model. It is in this domain of information that new devices such as the DIAGNODent can help to improve diagnostic performance: the pieces of information they can provide (in this case, quantifiable records depicting caries status, which are amenable to comparison with observations made during subsequent periodic recall appointments) become valuable building blocks in better performance.[67–69] But these pieces of information are just that: building blocks that ought to be interpreted by the clinician in the context of a core set of themes employed in the appraisal of restorative needs.[67,70] A clinician cannot rely totally on one diagnostic system or another, but must assimilate all the information available, modify it in light of the patient's particular situation, then formulate a treatment plan. The way information is assimilated by clinicians is likely to be quite diverse and will depend on various settings and levels of clinical expertise. Kay and Nuttall[71] showed that neither clinicians' stated therapeutic criteria, nor their stated therapeutic attitudes, corresponded to their clinical decisions.

In conclusion, the DIAGNODent, DIFOTI and QLF devices may improve decision making by affording more sophisticated diagnostic and management capabilities (through more detailed information) and by providing a clearly stated measure of longitudinal lesion activity that can be incorporated into a diagnostic heuristic (thus making consultation patterns closely relevant to the natural history of dental caries). However, responsibility for making the "right" decision (i.e., correctly combining the various pieces of information into a treatment plan that satisfies the patient's personal preferences, attends to sociobehavioural aspects and takes care of the patient's biomedical needs) will continue to rest with the clinician. ❖

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References

1. Pretty IA, Maupome G. A closer look at diagnosis in clinical dental practice: Part 1. Reliability, validity, specificity and sensitivity of diagnostic procedures. *J Can Dent Assoc* 2004; 70(4):251–5.
2. Pretty IA, Maupome G. A closer look at diagnosis in clinical dental practice: Part 2. Using predictive values and receiver operating characteristics in assessing diagnostic accuracy. *J Can Dent Assoc* 2004; 70(5): 313–6.
3. Pretty IA, Maupome G. A closer look at diagnosis in clinical dental practice: Part 3. Effectiveness of radiographic diagnostic procedures. *J Can Dent Assoc* 2004; 70(6):388–94.
4. Maupome G, Pretty IA. A closer look at diagnosis in clinical dental practice: Part 4. Effectiveness of Nonradiographic diagnostic procedures and devices in dental practice. *J Can Dent Assoc* 2004; 70(7):470–4.
5. Bader JD, Shugars DA, Bonito AJ. A systematic review of the performance of methods for identifying carious lesions. *J Public Health Dent* 2002; 62(4):201–13.
6. Bader JD, Shugars DA, Bonito AJ. Systematic reviews of selected dental caries diagnostic and management methods. *J Dent Educ* 2001; 65(10):960–8.
7. Ross G. Caries diagnosis with the DIAGNOdent laser: a user's product evaluation. *Ont Dent* 1999; 76(2):21–4.
8. Pretty IA, Lalloo A, Smith PW, Higham SM. Development of an occlusal caries index for Quantitative Light-induced Fluorescence and DiagnoDent. *J Dent Res* 2003; 82(Spec Issue C):475.
9. Lussi A, Imwinkelried S, Pitts N, Longbottom C, Reich E. Performance and reproducibility of a laser fluorescence system for detection of occlusal caries in vitro. *Caries Res* 1999; 33(4):261–6.
10. Tam LE, McComb D. Diagnosis of occlusal caries: Part II. Recent diagnostic technologies. *J Can Dent Assoc* 2001; 67(8):459–63.
11. Attrill DC, Ashley PF. Occlusal caries detection in primary teeth: a comparison of DIAGNOdent with conventional methods. *Br Dent J* 2001; 190(8):440–3.
12. Lussi A, Megert B, Longbottom C, Reich E, Francescut P. Clinical performance of a laser fluorescence device for detection of occlusal caries lesions. *Eur J Oral Sci* 2001; 109(1):14–9.
13. Sanchez-Figueras A Jr. Occlusal pit-and-fissure caries diagnosis: a problem no more. A science-based diagnostic approach using a laser-based fluorescence device. *Compend Contin Educ Dent* 2003; 24(5 Suppl):3–11.
14. Pinelli C, Campos Serra M, de Castro Monteiro Loffredo L. Validity and reproducibility of a laser fluorescence system for detecting the activity of white-spot lesions on free smooth surfaces in vivo. *Caries Res* 2002; 36(1):19–24.
15. Wicht MJ, Haak R, Stutzer H, Strohe D, Noack MJ. Intra- and interexaminer variability and validity of laser fluorescence and electrical resistance readings on root surface lesions. *Caries Res* 2002; 36(4):241–8.
16. Sheehy EC, Brailsford SR, Kidd EA, Beighton D, Zoitopoulos L. Comparison between visual examination and a laser fluorescence system

for in vivo diagnosis of occlusal caries. *Caries Res* 2001; 35(6):421–6.
17. Shi XQ, Tranaeus S, Angmar-Mansson B. Validation of DIAGNOdent for quantification of smooth-surface caries: an in vitro study. *Acta Odontol Scand* 2001; 59(2):74–8.
18. Shi XQ, Tranaeus S, Angmar-Mansson B. Comparison of QLF and DIAGNOdent for quantification of smooth surface caries. *Caries Res* 2001; 35(1):21–6.
19. Shi XQ, Welander U, Angmar-Mansson B. Occlusal caries detection with KaVo DIAGNOdent and radiography: an in vitro comparison. *Caries Res* 2000; 34(2):151–8.
20. Takamori K, Hokari N, Okumura Y, Watanabe S. Detection of occlusal caries under sealants by use of a laser fluorescence system. *J Clin Laser Med Surg* 2001; 19(5):267–71.
21. Cortes DF, Ellwood RP, Ekstrand KR. An in vitro comparison of a combined FOTI/visual examination of occlusal caries with other caries diagnostic methods and the effect of stain on their diagnostic performance. *Caries Res* 2003; 37(1):8–16.
22. Davies GM, Worthington HV, Clarkson JE, Thomas P, Davies RM. The use of fibre-optic transillumination in general dental practice. *Br Dent J* 2001; 191(3):145–7.
23. Cleaton-Jones P, Daya N, Hargreaves JA, Cortes D, Hargreaves V, Fatti LP. Examiner performance with visual, probing and FOTI caries diagnosis in the primary dentition. *SADJ* 2001; 56(4):182–5.
24. Fennis-Ie YL, Verdibschot EH, van't Hof MA. Performance of some diagnostic systems in the prediction of occlusal caries in permanent molars in 6- and 11-year-old children. *J Dent* 1998*;* 26(5-6):403–8.
25. Schneiderman A, Elbaum M, Shultz T, Keem S, Greenebaum M, Driller J. Assessment of dental caries with Digital Imaging Fiber-Optic Transillumination (DIFOTI): in vitro study. *Caries Res* 1997; 31(2):103–10.
26. Peers A, Hill FJ, Mitropoulos CM, Holloway PJ. Validity and reproducibility of clinical examination, fibre-optic transillumination, and bitewing radiology for the diagnosis of small approximal carious lesions: an in vitro study. *Caries Res* 1993; 27(4):307–11.
27. Mitropoulos CM. A comparison of fibre-optic transillumination with bitewing radiographs. *Br Dent J* 1985; 159(1):21–3.
28. Sidi AD, Naylor MN. A comparison of bitewing radiography and interdental transillumination as adjuncts to the clinical identification of approximal caries in posterior teeth. *Br Dent J* 1988; 164(1):15–8.
29. Angmar-Mansson B, ten Bosch JJ. Advances in methods for diagnosing coronal caries — a review. *Adv Dent Res* 1993; 7(2):70–9.
30. Young DA. New caries detection technologies and modern caries management: merging the strategies. *Gen Dent* 2002; 50(4):320–31.
31. Tranaeus S, Heinrich-Weltzien R, Kuhnisch J, Stosser L, Angmar-Mansson B. Potential applications and limitations of Quantitative Light-induced fluorescence in dentistry. *Med Laser Appl* 2001; 16:195–204.
32. van der Veen JH, Ferreira Zandona AG, de Josselin de Jong E, Stookey GK. Clinical evaluation of an intra-oral quantitative light-induced fluorescence camera. *Caries Res* 1998; 32:296.
33. Angmar-Mansson B, ten Bosch JJ. Quantitative light-induced fluorescence (QLF): a method for assessment of incipient caries lesions. *Dentomaxillofac Radiol* 2001; 30(6):298–307.
34. van der Veen MH, de Josselin de Jong E. Application of quantitative light-induced fluorescence for assessing early caries lesions. *Monogr Oral Sci* 2000; 17:144–62.
35. Bjelkhagen H, Sundstrom F, Angmar-Mansson B, Ryden H. Early detection of enamel caries by the luminescence excited by visible laser light. *Swed Dent J* 1982; 6(1):1–7.
36. Angmar-Mansson B, ten Bosch JJ. Optical methods for the detection and quantification of caries. *Adv Dent Res* 1987; 1(1):14–20.
37. Sundstrom F, Hafstrom-Bjorkman U, Strom J, Angmar-Mansson B, Frostell G, Takazoe I. Evaluation of a model for short-term clinical testing of cariogenicity. *J Biol Buccale* 1989; 17(2):115–20.
38. Hafstrom-Bjorkman U, Sundstrom F, de Josselin de Jong E, Oliveby A, Angmar-Mansson B. Comparison of laser fluorescence and longitudinal microradiography for quantitative assessment of in vitro enamel caries. *Caries Res* 1992; 26(4):241–7.
39. de Josselin de Jong E, Sundstrom F, Westerling H, Tranaeus S, ten Bosch JJ, Angmar-Mansson B. A new method for in vivo quantification of changes in initial enamel caries with laser fluorescence. *Caries Res* 1995; 29(1):2–7.
40. al-Khateeb S, Oliveby A, de Josselin de Jong E, Angmar-Mansson B. Laser fluorescence quantification of remineralisation in situ of incipient enamel lesions: influence of fluoride supplements. *Caries Res* 1997; 31(2):132–40.
41. Ando M, van der Veen M, Schemehorn BR, Stookey G. Comparative study to quantify demineralised enamel in deciduous and permanent teeth using laser- and light-induced fluoresence. *Caries Res* 2001; 35(6):464–70.
42. de Josselin de Jong E, van der Veen JH. Video Repositioning of QLF images. Proceedings of Optical Methods in Caries Detection, Groningen, 2000.
43. Amaechi BT, Higham SM. Quantitative light-induced fluorescence: a potential tool for general dental assessment. *J Biomed Opt* 2002; 7(1):7–13.
44. Ando M, Hall AF, Eckert GJ, Schemehorn BR, Analoui M, Stookey GK. Relative ability of laser fluorescence techniques to quantitate early mineral loss in vitro. *Caries Res* 1997; 31(2):125–31.
45. Pretty IA, Ingram G, Agalamanyi EA, Edgar WM, Higham SM. The use of fluorescein-enhanced quantitative light-induced fluorescence to monitor de- and re-mineralisation of in vitro root caries. *J Oral Rehabil* 2003; 30(12):1151–6.
46. Lagerweij M, Beiswanger AJ, van der Veen M, Ferreira Zandona AG, Stookey G. Interexaminer variability of analysis of QLF images obtained from a patient. *J Dent Res* 1998; 77:713.
47. Pretty IA, Edgar WM, Higham SM. Detection of in vitro demineralization of primary teeth using quantitative light-induced fluorescence (QLF). *Int J Paediatr Dent* 2002; 12(3):158–67.
48. Amaechi BT, Higham SM. Development of a quantitative method to monitor the effect of a tooth whitening agent. *J Clin Dent* 2002; 13(3):100–3.
49. Ando M, van Der Veen MH, Schemehorn BR, Stookey GK. Comparative study to quantify demineralized enamel in deciduous and permanent teeth using laser- and light-induced fluorescence techniques. *Caries Res* 2001; 35(6):464–70.
50. Tranaeus S, Al-Khateeb S, Bjorkman S, Twetman S, Angmar-Mansson B. Application of quantitative light-induced fluorescence to monitor incipient lesions in caries-active children. A comparative study of remineralisation by fluoride varnish and professional cleaning. *Eur J Oral Sci* 2001; 109(2):71–5.
51. Pretty IA, Edgar WM, Higham SM. The use of QLF to quantify in vitro whitening in a product testing model. *Br Dent J* 2001; 191(10): 566–9.
52. Pretty IA, Edgar WM, Higham SM. The validation of quantitative light-induced fluorescence to quantify acid erosion of human enamel. *Arch Oral Biol* 2004; 49(4):285–94.
53. Ando M, Analoui M, Schemehorn BR, Eggertsson H, Stookey GK. In vitro comparison of three caries diagnosis techniques. *Caries Res* 1999; 33(3):298.
54. ten Cate JM, Lagerweij MD, Wefel JS, Angmar-Mansson B, Hall AF, Ferreira Zandona AG, and others. In vitro validation studies of Quantitative Light-induced Fluoresence. Early detection of dental caries II. Proceedings of the 4th Annual Indiana Conference, 2000, Indiana University Press; 230–46.
55. Tranaeus S, Shi XQ, Lindgren LE, Trollsas K, Angmar-Mansson B. In vivo repeatability and reproducibility of the quantitative light-induced fluorescence method. *Caries Res* 2002; 36(1):3–10.
56. DeSchepper EJ, Hall AF, Ando M, Beiswanger BB. Secondary caries detection: laser fluorescence imaging versus traditional clinical examination. *Caries Res* 1996; 30:273–4.
57. Benedict SL, DeSchepper EJ, Hall AF, Analoui M, Willis G, Dixon S, Eckert G, and other. Laser fluorescence and secondary caries detection. *J Dent Res* 1996; 75:86.
58. Gonzalez-Cabezas C, Dunn E, Ando M, Eggertsson H, Eckert G, Fontana M, Stookey G. Detection of small carious lesions on root surfaces of extracted teeth. *Caries Res* 2001; 35:282.
59. Hall AF, DeSchepper E, Ando M, Stookey GK. Dye-enhanced laser fluorescence method. Presented at 1st Annual Indiana Conference. Indianapolis, 1996a., Indiana University Press; 156–71.
60. Ashley PF, Blinkhorn AS, Davies RM. Occlusal caries diagnosis: an in vitro histological validation of the Electronic Caries Monitor (ECM) and other methods. *J Dent* 1998; 26(2):83–8.

61. Alwas-Danowska HM, Plasschaert AJ, Suliborski S, Verdonschot EH. Reliability and validity issues of laser fluorescence measurements in occlusal caries diagnosis. *J Dent* 2002; 30(4):129–34.
62. Bamzahim M, Shi XQ, Angmar-Mansson B. Occlusal caries detection and quantification by DIAGNOdent and Electronic Caries Monitor: in vitro comparison. *Acta Odontol Scand* 2002; 60(6):360–4.
63. Heinrich-Weltzien R, Kuhnisch J, van der Veen M, de Josselin de Jong E, Stosser L. Quantitative light-induced fluorescence (QLF) — a potential method for the dental practitioner. *Quintessence Int* 2003; 34(3):181–8.
64. de Josselin de Jong E, Buchalla W, van der Veen M. QLF: New Developments. in Early Caries Detection III. 2003. Indiana, Indianapolis: Indiana University Press. In press.
65. Pretty IA, Pender N, Edgar WM, Higham SM. The in vitro detection of early enamel de- and re-mineralization adjacent to bonded orthodontic cleats using quantitative light-induced fluorescence. *Eur J Orthod* 2003; 25(3):217–23.
66. Bader JD, Shugars DA. What do we know about how dentists make caries-related treatment decisions? *Community Dent Oral Epidemiol* 1997; 25(1):97–103.
67. Gale J, Marsden P. Medical diagnosis. 1983, Oxford: Oxford University Press.
68. Thompson R. The psychology of thinking. 1959, Harmondsworth: Penguin.
69. Maupome G, Sheiham A. Explanatory models in the interpretations of clinical features of dental patients within a university dental education setting. *Eur J Dent Educ* 2002; 6(1):2–8.
70. Maupome G, Sheiham A. Clinical decision-making in restorative dentistry. Content-analysis of diagnostic thinking processes and concurrent concepts used in an educational environment. *Eur J Dent Educ* 2000; 4(4):143–52.
71. Kay EJ, Nuttall NM. Relationship between dentists' treatment attitudes and restorative decisions made on the basis of simulated bitewing radiographs. *Community Dent Oral Epidemiol* 1994; 22(2):71–4.