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Computer-aided proximal caries diagnosis: correlation with clinical examination and histology

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ABSTRACT

Purpose : To evaluate the performance of the LOGICON Caries Detector using RVG-4 and RVG-ui sensors, by comparing results of each detector to the results of clinical and histological examinations.
Materials and Methods : Pairs of extracted teeth were radiographed, and a total of 57 proximal surfaces, which included both carious and non-carious situations, were analyzed. The RVG-4 produced 8-bit images, while the RVG-ui unit produced 12-bit images, which were taken in the high sensitivity mode. The images produced by the LOGICON were evaluated by a trained observer using both automated and manual caries detection software modes. Ground sections of the teeth established the actual absence or existence of caries.
Results : LOGICON-aided caries detection and depth discrimination of the RVG-4 and RVG-ui sensors were equally inconsistent irrespective of whether the LOGICON software was set to the automated or manual mode. Sensitivity ranged from 50% to 57% for caries penetration of the enamel-dentin junction.
Conclusion : Care needs to be taken when using LOGICON in conjunction with RVG images as an adjunct for treatment planning dental caries. Even when applied by a trained observer, substantial discrepancies exist between the results of the LOGICON software-guided evalutations using RVG images and histologic examination. ***(Korean J Oral Maxillofac Radiol 2002; 32 : 187-94)***

KEY WORDS : dental caries; diagnosis, computer-assisted

One of the most frequent radiographic diagnostic tasks required of the dentist is determining the presence or absence of proximal dental caries and choosing an appropriate therapy when caries is determined to be present.[1] Dentists have used various diagnostic methods to detect carious lesions of the dental proximal surface. These methods include visual examination with, or without, the aid of a dental explorer, analog film and digital intraoral radiographs, laser fluorescence, and fiberoptic transillumination. Nevertheless, the task of accurate interpretation of proximal dental caries remains a challenge for dentists.[2-11]

Computer-based image analysis has been applied to examining the proximal carious lesions. Early in 1984, Pitts applied a computer-based system to detect and measure proximal enamel radiolucencies.[12] It was shown that consistent proximal radiolucency detection was possible using this system.[13, 14] Heaven, et al. (1992, 1994) also found that image analysis PC-based systems could be more accurate than, or equal to, clinicians in deciding whether the proximal dental caries was present or not.[15, 16] That image analysis and decision support systems could detect more proximal caries and make fewer incorrect treatment decisions, and provide better consistency in treatment decisions compared to the dental practitioner was the conclusion made by Duncan, et al. (1995) and Firestone, et al. (1998).[1, 17] Forner et al. (1999) agreed that a digital image analysis system could help dentists diagnose incipient proximal carious lesions.[18]

We have now entered an age in which improve provider and patient decision-making is being attempted using computed clinical decision support systems.[19] While there is still potential to further reduce errors and to improve quality of decision support systems, new obstacles also have emerged, including concern about data confidentiality and security and the potential for product liability claims.[19]

The LOGICON Caries Detector™ (Logicon Advanced Technology, Los Angeles, CA) is an FDA approved software decision aid for the diagnosis of proximal caries on digital intraoral radiographic image. It aims to discriminate between lesions that reach dentin and need restoration from those rest-

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ricted to enamel that do not require treatment. LOGICON was originally tested using the RVG-4 x-ray sensor (Trophy Radiology, Marne-la-Vallée, France). Trophy subsequently introduced the RVG-ui sensor and has made modification to the acquisition software both for the RVG-4 and the RVG-ui. The objective of the currently reported study is to evaluate LOGICON Caries Detector™ in conjunction both with the RVG4 and with the RVGui sensors, comparing to clinical and histological examinations.

Materials and Methods

1. Model construction

Thirty-six extracted teeth were used: three (3) incisors, three (3) canines, 18 premolars and 12 molars. The clinical appearance of the proximal surfaces ranged from sound to opaque white or brown discoloration with or without a cavity. Defective surfaces with large cavities or extensive were excluded from analysis as LOGICON is not meant to work in such situations. The teeth were disinfected by immersion in buffered 10% formalin solution for more than 2 weeks. The tooth root surfaces were coated with wax to simulate a periodontal ligament space and embedded in plaster with wide interproximal spacing permitting clear visual examination of the proximal surfaces. Each block had 2 similar sized teeth, resulting 18 blocks.

2. Image acquisition

A plaster mold was made to accommodate and reposition the RVG-4 (also known as RVG-XL for the sensor size used) or RVG-ui size #2 sensors (Trophy Radiology, Marne-la-Vallée, France). To ensure constant beam geometry, the sensor was set on an optical bench and held in the plaster mold. The source-to-sensor distance was 42 cm, and the sensor lay immediately against the teeth being examined. A 1 cm thick acrylic plate was placed between the cone and the block to replicate soft tissue scatter (Fig. 1).

A Trophy CCX x-ray generator (Trophy Radiology, Marne-la-Vallée, France), set at 70 kVp and 8 mA with 2.5 mm Aluminum equivalent filtration, was used as the x-ray source for digital RVG imaging. Images were obtained both with the RVG-4 and the RVG-ui sensors using Trophy Windows v.4.1 g software, images being acquired 8-bit for the RVG-4 and 12-bit for the RVG-ui, the latter using the Endo mode. The exposure time range from 0.05-0.12 seconds for the RVG-ui sensor and 0.12-0.23 seconds for RVG-4 sensor. These exposure times translated to entrance doses of 57-117 μGy for the RVG-ui and 117-224 μGy for the RVG-4.

3. LOGICON analysis

The proximal surfaces of each image made with the RVG-4 and the RVG-ui sensors were analyzed 3 times both with manual and with automatic modes for proximal caries detection utilizing the LOGICON Caries Detector™ (three analyses each × 2 image sensors × 2 modes of image analysis = 12 analyses per proximal surface). The operation of the LOGICON Caries Detector™ was by an experienced examiner trained by the manufacturer of the system. LOGICON Caries Detector™ provided readouts that aimed to discriminate between lesions that reached dentin (and requiring treatment) from those restricted to enamel and not requiring restoration. Discrimination between enamel and dentin lesions was made based upon the lesion probability exceeding a set threshold probability. The

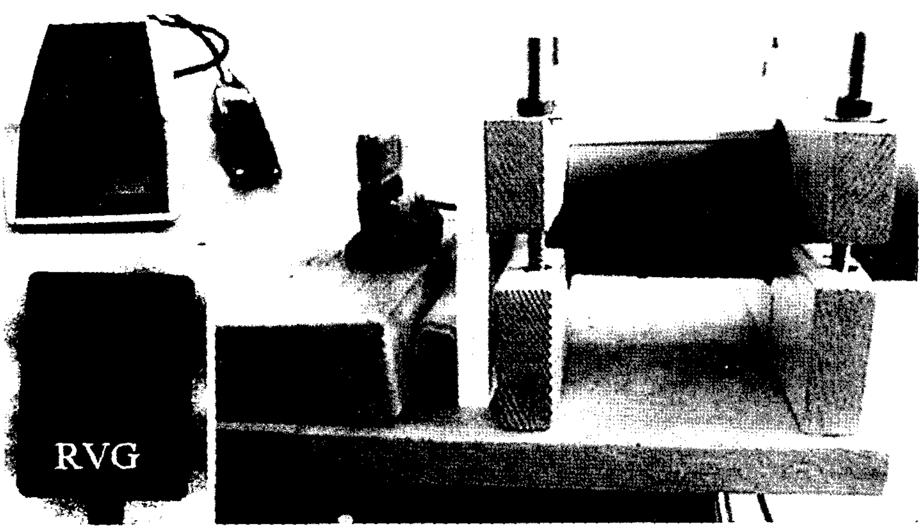

Fig. 1. An optical bench was used for constant geometry. This photo shows the orientation of the RVG sensor, the tooth model, and the dosimeter.

default values for decision thresholds were set at 15% false positive.

4. Clinical evaluation

Following the LOGICON Caries Detector™ analysis, the teeth were separated from the plaster blocks. Using a 0.1-mm scaled No 5 explorer under a 500 g load, the depths of the white or discolored and cavitated caries lesion were measured according to the method described by Kang et al. (1996).[3] Lesions were classified clinically as follows: 0 = sound proximal tooth surface, 1 = non-cavitated, white opaque, or brownish discolored caries, 2 = minimally cavitated carious lesion with measured depths exceeding 0.1 mm but not reaching 0.2 mm, 3 = cavitated caries with depths of 0.2 mm or greater depth (up to 1.6 mm) (Table 1).

5. Histologic evaluation

After cutting the root, each tooth crown was embedded into transparent acrylic resin and cut with a water-cooled, diamond -wafering blade (Buehler Ltd., Lake Bluff, Illinois, USA) into mesiodistal sections of 76 μm thickness. The sections were viewed using an inverted metallurgical microscope (EPIPHOT -TME, Nikon Inc., NY., USA) at (15 magnification. Carious demineralization, defined as opaque or brownish discolorations, was scored on a scale from 0 to 2, where 0 = sound, 1 = caries restricted to enamel, 2 = caries extending into dentin.[20] The histological truth was compared to the LOGICON Caries Detector™ analysis-aided decision (Table 1).

6. Statistical analysis

Using the histological examination as gold standard, sensitivity and specificity was determined for the LOGICON Caries Detector™ in indicating the presence or absence of proximal dental caries. These sensitivities and specificities derived for the LOGICON Caries Detector™ (three time consensus, two time consensus, and first analysis with the RVG-4 and RVG-ui images) were compared using the Chi-square test. This was then repeated for determination of dentin penetration comparing LOGICON results to the histological gold standard.

Table 1. Recording scales and scoring criteria used for clinical and histological and LOGICON Caries Detector™ analyses

Clinical examination with a scaled explore
Disease severity scale
- 0 = sound
- 1 = non-cavitated caries: whitish and discolored carious lesion
- 2 = minimal cavitated caries: explored less than 0.2 mm in depth
- 3 = cavitated caries: explored 0.2 mm or more in depth

Histological examination and Logicon Caries Detector™ analysis
Depth scale
- 0 = sound
- 1 = caries in enamel
- 2 = caries in dentin

Results

1. Clinical depth measurement

Excluding 15 defective or large C4 caries surfaces, the 57 proximal surfaces included in this study were: 17 sound, 19 white opaque or discolored non-cavitated proximal surfaces, 12 white opaque or discolored proximal surfaces with 0.1 mm deep cavities reaching 0.2 mm, and 9 proximal carious cavities of greater depth (Table 2).

2. Histological determination

Histological examination revealed the 57 proximal surfaces to include 17 sound proximal surfaces, 26 carious lesions penetrating into the enamel, and 14 carious lesions penetrating into dentin. Among 19 clinically non-cavitated whitish or discolored proximal carious lesions, 11 lesions (58%) extended into the enamel, and 8 lesions (42%) had penetrated dentin (Fig. 2). The 21 cavitated caries included 6 proximal carious lesions (29%) extending into dentin. The relationship between the clinical and histological examinations is shown on Table 3.

The histological treatment decision criteria for dentin extension was compared with clinical treatment decision criteria of

Table 2. Number of proximal surfaces with each cavity depth

Depth (mm)	0	0.1	0.2	0.3	0.4	0.7	1.4	1.6	Total
No. surfaces	36*	12	3	1	2	1	1	1	57

* Includes 17 sound and 19 non-cavitated caries proximal surfaces.

Table 3. Clinical examination vs. histological examination

Clinical examination		Histological examination	
Disease severity scale	No of surfaces	No of surfaces	Depth scale
0 = sound surface	17	17	0
1 = non-cavitated caries	19	11 8	1 2
2 = minimal cavitated caries (< 0.2 mm depth)	12	11 1	1 2
3 = cavitated caries (0.2-1.6 mm depth)	9	4 5	1 2

cavitation in terms of sensitivity and specificity, since such cavitation was taken to indicate that a restoration was required (Table 4, 5).[10, 21-27] The clinical decision criteria were divided into two, setting the clinically diagnosed cavity (minimal cavitated caries and cavitated caries of 0.2 mm or greater) and the clinically diagnosed cavity excluding minimal cavitated caries. The sensitivities (0.43 and 0.36) using the different clinical treatment decision criteria showed no differences ($\chi^2 = 0.144$, df = 1, $p < .05$). However, the 0.90 specificity determined for the treatment decision criteria "cavitated caries" was higher than the specificity of 0.65 for "minimally cavitated caries" ($\chi^2 = 7.705$, df = 1, $p < .05$).

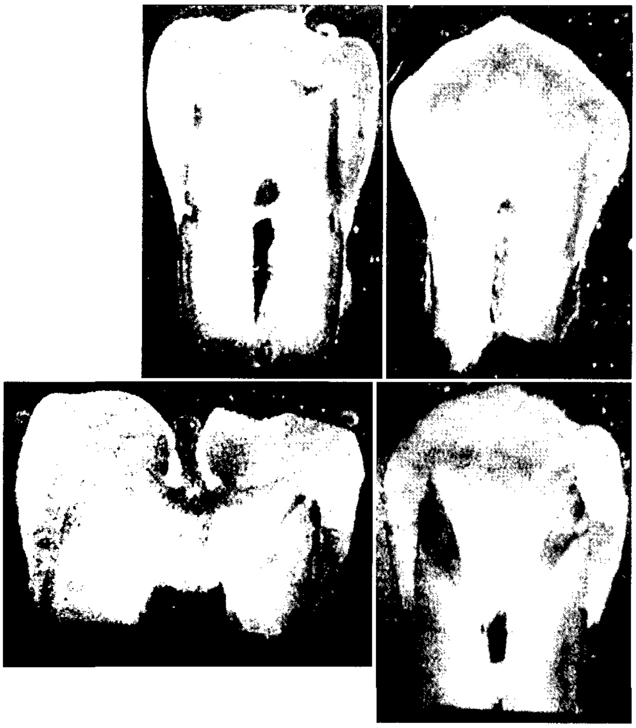

Fig. 2. Histological (ground) sections of non-cavitated teeth. The upper two teeth show caries penetrating enamel and the lower two teeth show caries into dentin.

Table 4. Comparison of clinical and histological decisions setting any depth of cavitation as the treatment criterion

		Histological examination	
		Treatment	No treatment
Clinical examination	Treatment	6	15
	No treatment	8	28

Table 5. Comparison of clinical and histological decisions setting cavitation of 0.2 mm or greater as the treatment criterion.

		Histological examination	
		Treatment	No treatment
Clinical examination	Treatment	5	4
	No treatment	9	39

3. Histological gold standard versus LOGICON Caries Detector™

The comparisons between this histological gold standard and the LOGICON Caries Detector™ analyses are shown Tables 6-9.

1) Caries presence or absence

LOGICON readouts are illustrated in figure 3. With the histological examination as gold standard, sensitivities and specificities for the LOGICON Caries Detector™ for determination

Table 6. Histological examination vs. LOGICON Caries Detector™ manual analysis for RVG-4 images

Histological examination		Logicon Caries Detector analysis			
Depth scale	No of surfaces	No of surfaces: 3 time consensus	No of surfaces: 2 time consensus	No of surfaces: first analysis	Depth scale
0 = sound	17	12	6	6	0
		3	8	7	1
		2	3	4	2
1 = caries in enamel	26	12	4	3	0
		6	8	8	1
		8	14	15	2
2 = caries in dentin	14	7	5	5	0
		1	0	0	1
		6	9	9	2
Total	57	57	57	57	

Table 7. Histological examination vs. LOGICON Caries Detector™ automatic analysis of RVG-4 images

Histological examination		Logicon Caries Detector analysis			
Depth scale	No of surfaces	No of surfaces: 3 time consensus	No of surfaces: 2 time consensus	No of surfaces: first analysis	Depth scale
0 = sound	17	15	10	12	0
		2	5	2	1
		0	2	3	2
1 = caries in enamel	26	12	11	12	0
		6	7	2	1
		8	8	12	2
2 = caries in dentin	14	8	6	6	0
		0	0	0	1
		6	8	8	2
Total	57	57	57	57	

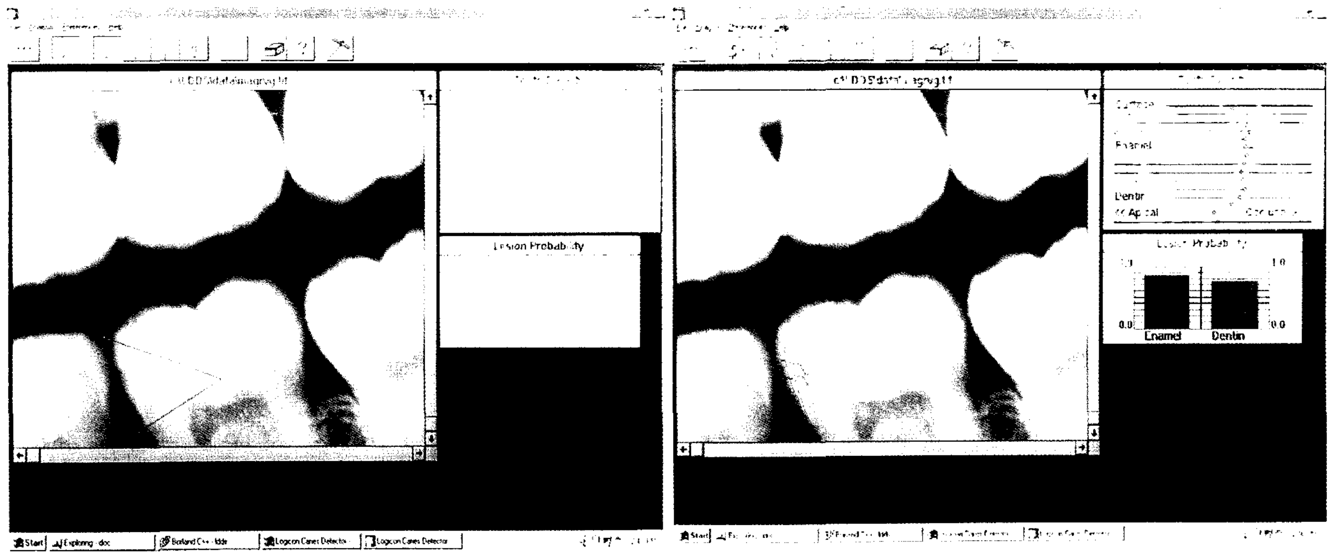

Fig. 3. LOGICON^{TM} operation. Using the V-tool the software shows the outline of the cavity and the probability of the caries in enamel and dentin.

Table 8. Histological examination vs. LOGICON Caries Detector^{TM} manual analysis of RVG-ui images

Histological examination		Logicon Caries Detector analysis			
Depth scale	No of surfaces	No of surfaces: 3 time consensus	No of surfaces: 2 time consensus	No of surfaces: first analysis	Depth scale
0 = sound	17	10	6	6	0
		3	5	5	1
		4	6	6	2
1 = caries in enamel	26	13	4	4	0
		5	10	7	1
		8	12	15	2
2 = caries in dentin	14	7	5	4	0
		0	0	0	1
		7	9	10	2
Total	57	57	57	57	

Table 9. Histological examination vs. LOGICON Caries Detector^{TM} automatic analysis of RVG-ui images

Histological examination		Logicon Caries Detector analysis			
Depth scale	No of surfaces	No of surfaces: 3 time consensus	No of surfaces: 2 time consensus	No of surfaces: first analysis	Depth scale
0 = sound	17	12	8	7	0
		4	6	5	1
		1	3	5	2
1 = caries in enamel	26	16	11	12	0
		4	6	6	1
		6	9	8	2
2 = caries in dentin	14	6	3	4	0
		0	0	0	1
		8	11	10	2
Total	57	57	57	57	

of the presence or absence of proximal dental are shown in Table 10. This includes separate information related to the number of attempts using LOGICON, the type of RVG sensor used and the mode of LOGICON applied (manual tracing versus automatic) The overall proximal caries diagnostic sensitivity ranges were 0.50-0.80. Overall specificity ranges were 0.35-0.88. The sensitivities and specificities for manual and the automatic modes of analysis with LOGICON for the RVG -4 or RVG-ui images were not significantly different ($p > 0.05$). The sensitivities determined using a ×3 consensus, irrespective of whether LOGICON was used in automatic or

Table 10. Sensitivity and specificity of the LOGICON Caries Detector^{TM} for presence or absence of proximal dental caries (%)

	Manual RVG-4	Auto RVG-4	Manual RVG-ui	Auto RVG-ui
Sensitivity				
× 3 consensus	53	50	50	45
× 2 consensus	78	58	78	65
First analysis	80	55	80	60
Specificity				
× 3 consensus	71	88	59	71
× 2 consensus	35	59	35	47
First analysis	35	71	35	41

Table 11. Sensitivity and specificity of the LOGICON Caries Detector™ for the caries treatment decision-penetration of dentin (%)

	Manual RVG-4	Auto RVG-4	Manual RVG-ui	Auto RVG-ui
Sensitivity				
×3 consensus	43	43	50	57
×2 consensus	64	57	64	79
First analysis	64	57	71	71
Specificity				
×3 consensus	77	81	72	84
×2 consensus	60	77	58	72
First analysis	56	65	51	70

manual mode - and irrespective of whether RVG-4 or RVG-ui images were studies, , were significantly lower than using an ×2 consensus or ×1 analysis ($p < 0.05$). The specificities for the ×3 consensus were, irrespective of the LOGICON mode of analysis or sensor generation used, significantly higher than those for the ×2 consensus or ×1 analysis ($p < 0.05$).

2) Caries extension into dentin (treatment decision threshold)

Using histology as the gold standard, sensitivities and specificities for the LOGICON Caries Detector™ in determining dentin penetration are shown in Table 11. The sensitivity range was 0.43-0.79. The specificity range was 0.51-0.81. Comparing manual and the automatic modes of analysis and RVG-4 versus RVG-ui images, the sensitivity differences for LOGICON were not significantly different ($p > 0.05$). The specificity with the automatic mode of LOGICON analysis of RVG-ui images was significantly greater than that for the LOGICON manual analysis of RVG-ui images ($p < 0.05$). However, the specificity of the LOGICON automatic analysis of RVG-ui images was not significantly greater than that determined for either manual or automatic analysis of RVG-4 images ($p > 0.05$).

Irrespective of the LOGICON mode of analysis, and whether the RVG-4 or the RVG-ui sensor was employed, the sensitivities for the ×3 consensus, the ×2 consensus, and the ×1 analyses did not significantly differ ($p > 0.05$). The specificity for the ×3 consensus was significantly higher than that for the ×1 analysis. ($p < 0.05$), but not significantly different from the ×2 consensus ($p > 0.05$).

Discussion

As shown in Tables 2 and 3, the teeth utilized in this study had a relatively low ratio for mineral loss in comparison with sound tooth substance. Most could be described as early proximal carious lesions. When dentin penetration was present it was relatively early (C3 rather than C4). The LOGICON Caries Detector™ measures the variation in tooth density levels from the enamel surface to the dentin in order to calculate probabilities of the proximal enamel and dentin lesions. Perhaps the database of teeth originally used was less exacting on the system, or perhaps there have been changes in the RVG acquisition software that confuse the LOGICON software. This may explain the low sensitivities of proximal caries detection we determined for the LOGICON Caries Detector™.

The density of the proximal surfaces on radiograph might be affected by various dental anomalies such as hypoplastic pits or concavities produced by wear on the proximal surfaces as well as from dental caries. Hence, any the decision-making program based on the distribution of radiographic density differences alone may necessarily result in some false positive results. Our study indicates that if one adopts an ×3 consensus for caries presence or absence, the LOGICON Caries Detector™, provides a high specificity. This high specificity is at the expense of a low sensitivity in caries detection. Perhaps as a second look tool, this sensitivity would be improved if used in conjunction with the clinical evaluation of the patient's mouth by the trained dentist.

Cavity depth affects the odds of diagnosis of proximal carious lesions, with deeper lesions being more readily detected than more superficial ones.[3,4,6] Sensitivity and specificity results for the LOGICON Caries Detector™ in the determination of dentin penetration are important as they affect the decision to provide restorative treatment. These ranged from 0.43-0.79 for sensitivity and 0.51-0.81 for specificity. According to Verdonschot, et al. (1999), the provision of restorative care based on inadequate diagnostic evidence, particularly an imperfect specificity of the diagnostic test, may cause a tremendous amount of over-treatment.[10] Some dentists consider that the progression of caries in dentin might also be reasonably slow, so they would not automatically restore a primary proximal caries lesion if its radiographic appearance did not show obvious progression in the outer third to one-half the dentin.[23] Obviously, dental caries is not life threatening disease, so it might be reasoned that underestimation might be better than overestimation for proximal caries treatment decision. Comparing histological examination, dentists significantly underestimate proximal caries depth with radiographic images.[28] With the LOGICON Caries Detector™ a high value of specificity could be obtained at the expense of a low specificity by using an ×3 consensus.

It should be remembered that different studies use different teeth and that the degree of difficulty will vary depending upon what lesions are included. Therefore, one should be circumspect when comparing sensitivities and specificities determined in this study using the LOGICON Caries Detector™ with the results of other studies in which the degree of diagnostic difficulty may have differed.

LOGICON™ is a promising attempt at solving a useful diagnostic problem, but the accuracy of this program needs to be higher than demonstrated by the results of this study using a trained expert observers. In view of the discrepancy between our results and those presented for FDA approval, it is important to determine what factors have changed since the introduction of LOGICON that have effectively invalidated its use. The problem would not seem to be the introduction of the RVG-ui sensor, as the current results were equally bad using the RVG-4 sensor. The alternatives left are that the current Trophy RVG acquisition software is altered in such a way as it no longer provides the same density variations necessary to detect dental caries, that the new software conflicts with the LOGICON software in some other way confusing the LOGICON caries detection algorithms. A final possibility is that the lesions we examined differed significantly from those previously used to validate LOGICON. We are in process of an extensive observer study of ability to detect proximal caries on the same images with RVG-ui and RVG-4, but without LOGICON. It should be noted that there has been one previous report that has suggested RVG-ui inadequacies in dental caries detection, but in that earlier report a discrepancy was only demonstrated histologically for one tooth.[29]

Clinical cavitation is taken to indicate that a restoration is required, since, once the tooth surface is broken down, it is no longer possible to prevent plaque accumulation. The principal role of operative treatment as far as caries control is concerned is to eliminate traps that promote the collection of dental plaque.[26,27] Apart from clinically diagnosed cavity, the general threshold for treatment of a proximal carious lesion is the obvious progression in dentin.[10,21-24] In the current study, 42% of clinically non-cavitated white opaque or discolored proximal carious lesions had penetrated dentin (Fig. 2). Conversely, only 29% of the clinically cavitated lesions had penetrated dentin. Hence, treatment decision criteria based on histological depth might lead to different treatment decisions than would be the case if cavitation were the criterion employed.

Cavity size might give a good guideline for the dentists to make a decision of restoration.[30] However, it would not be easy to measure the cavity size in three dimensions when teeth are in proximal contact and the radiograph is essentially a two-dimensional shadow. We measured only the histological depth of the lesions, not the volume of the carious lesion. The cavity depth measured with the scaled explore under constant force, positively affected the odds of diagnosis of proximal carious lesions, i.e., the deeper lesions could be easily detected.[3,4,6] This might be the reason the specificities determined for LOGICON in the treatment decision criteria of cavitated caries (equal to or deeper than 0.2 mm) was higher than the specificity of that of minimally cavitated caries (equal to or deeper than 0.1 mm but less than 0.2 mm). Perhaps cavity depth determination is a more reliable index for evaluation than is caries histological depth.

The overall sensitivities and specificities regarding both caries diagnosis and the treatment decision showed no difference in diagnostic performance between RVG- and RVG-ui sensors for the LOGICON Caries Detector™.

The decision of proximal surface treatment should not depend exclusively on an analysis made using the LOGICON Caries Detector™. The LOGICON Caries Detector™ should be used merely as an adjunct to traditional diagnostic methods to identify proximal carious lesions and to determine the appropriate treatment.

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