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Proximal caries lesion detection using the Canary Caries Detection System: an *in vitro* study

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Abstract

Objective: This study investigated the accuracy of the Canary System (CS) to detect proximal caries lesions *in vitro*, and compared it with conventional methods: International Caries Detection and Assessment System (ICDAS) II and bitewing radiography (BW).

Methods: Visible proximal surfaces of extracted human teeth were assessed by ICDAS-II before setting them in five manikin mouth models. Then contacting proximal surfaces in mouth models were assessed by BW and CS. Histological validation with polarized-light microscopy served as a gold standard. Pairwise comparisons were performed on area under the curve (AUC), sensitivity, and specificity of the three methods, and corrected using Bonferroni's method. Sensitivities and specificities were compared using a test of proportions and AUC values were compared using DeLong's method.

Results: The CS presented significantly higher sensitivity (0.933) than ICDAS-II (0.733, $P = 0.01$) and BW (0.267, $P < 0.001$), and ICDAS-II higher sensitivity than BW ($P < 0.001$). There were no significant differences between their specificity values: 0.825 (CS), 0.65 (ICDAS-II), and 0.875 (BW). The AUC of CS (0.862) was significantly higher than of ICDAS-II (0.681, $P < 0.001$) and BW (0.577, $P < 0.001$).

Conclusion: The CS demonstrated greater accuracy in detecting proximal lesions than ICDAS-II and BW, although without significantly higher specificity.

Introduction

The importance of early detection and quantitative monitoring of caries lesions to facilitate preventive non-operative intervention before the development of irreversible damage is now generally accepted.[1–3] However, for such a treatment approach, accurate methods which allow detection of early lesions are required.[4]

Proximal caries lesions are usually difficult to detect, because they are not directly visible and accessible. The most commonly used methods for detecting and assessing proximal caries, despite their limitations, are bitewing radiography (BW)[5] and visual examination with the International Caries Detection and Assessment System (ICDAS) II.[6] Although BW has high specificity due to its ability to detect advanced lesions, it exhibits low sensitivity in detecting early proximal caries, in addition to its hazards of ionizing radiation.[5,7–9] Similarly, studies have presented low sensitivity and higher specificity for detecting early caries lesions on contacting proximal surfaces

with visual examination,[10,11] since the lesion can be viewed only from the buccal or lingual/palatal directions. Although temporary separation using orthodontic rubber rings is employed clinically to assist their detection,[12] this takes at least 24 h to achieve teeth separation. There is therefore a need for more accurate detection methods than traditional visual examination and BW.

Recently, a diagnostic tool based on combined frequency-domain laser-induced infrared photothermal radiometry (PTR) and modulated luminescence (LUM), the Canary System (CS), was introduced for early detection of dental caries.[13–17] The CS directly assesses the status of the tooth crystal structure by using photothermal radiometry-luminescence, an energy conversion technology. With this device, intensity-modulated laser light at a fixed frequency is shone on the tooth and the light is converted into heat (PTR) and light of longer wavelength (LUM), thereby generating thermal infrared and optical emissions at the same frequency.[15] These signals are captured by appropriate detectors and are demodulated by two lock-in amplifiers yielding two amplitudes and two phases. Therefore, the CS measures four signals: (a) the strength of the converted heat (PTR amplitude); (b) the time delay of the converted heat to reach the surface conductively (PTR phase); (c) the strength of the converted luminescent light (LUM amplitude); and (d) the time delay of the converted luminescent light (LUM phase). A Canary number, created from an algorithm combining these four signals (PTR amplitude, PTR phase, LUM amplitude, and LUM phase), is directly linked to the status of the tooth crystal structure. Specifically, the Canary number is determined by the PTR to LUM signals ratio. Early mineral loss from the tooth (incipient caries) causes small changes in the ultrastructure, creating a more porous, less dense environment. This increases the generated PTR signals and decreases LUM signals of the tooth, resulting in a corresponding increase in the Canary number. In contrast, as remineralization of the lesion progresses, there is a decrease in PTR signals and increase in LUM signals and a corresponding decrease in Canary number. By modulating the laser beam at low frequency (2 Hz), the CS is able to collect information from a hemispherical area beneath the 1.5 mm diameter laser beam that can be up to by 5 mm in depth[16] by means of scattered light in deep subsurface regions, which subsequently is converted to heat and luminescence in those regions. A previous study[13] on occlusal caries using this device, with the histological technique as the gold standard, reported that the sensitivity of PTR–LUM was much higher than those of a continuous laser-induced luminescence (DIAGNOdent), visual inspection, and radiographs. Other studies also assessed PTR–LUM to be capable of detecting artifi-

cial demineralized and remineralized caries lesions on root dentin and enamel.[14,17]

The objective of the present study, therefore, was to investigate the accuracy of the PTR–LUM-based CS in detecting proximal dental caries *in vitro*, comparing it with that of the conventional visual and BW examinations, and using polarized light microscopy (PLM) as the histological validation of the presence or absence of caries. The null hypothesis was that there would be no significant difference in accuracy between the CS, visual examination, and BW for detection of proximal caries lesions.

Material and methods

Teeth selection

Seventy extracted human permanent molars, premolars, canines, and incisors with or without proximal caries were selected and coded by a Cariologist experienced in caries diagnosis and the ICDAS-II caries assessment criteria. Carious teeth were selected such that the caries lesions were either cavitated or non-cavitated lesions at varying levels of severity that cut across the seven ICDAS-II codes (0 through 6). However, teeth with extensive cavitation visible from the buccal, lingual, and/or occlusal surfaces of the tooth were excluded. Stains and calculus on the teeth were left intact as would be encountered clinically in oral cavity.

Visual examination

Following selection, the proximal surfaces of each tooth (except the incisors) were examined independently by two trained and calibrated caries detection experts, and in case of dispute the examiners re-examined the surface until consensus was reached. Calibration among the examiners was conducted prior to the study by the cariologist, who selected the teeth in accordance with the above criteria. Weighted Cohen's kappa values for intraexaminer reproducibility were 0.87 and 0.91, and for interexaminer reproducibility 0.81 (any score >0.70 was considered to be acceptable as adequate agreement). The examiners used a CPITN-E probe, a non-magnifying plane mirror, prism loupes, and standard dental operating light, to visually assess the status of proximal surfaces of each tooth by using the caries assessment criteria of the ICDAS-II.[18] Visual examination is suitable for making clinical inferences, while histological validation served as a positive reference. All levels of caries lesions ranging from early (non-cavitated) to cavitated lesions were recorded to ensure the variation in the severity of the caries lesions used in the study and the inclusion of early

non-cavitated caries lesions. The scoring criteria were: 0, sound tooth surface; 1, first visual change (opacity or discoloration) in enamel hardly visible on the wet surface but distinctly visible after air drying; 2, distinct visual change (opacity or discoloration) in enamel, visible without air drying; 3, localized enamel breakdown without visible dentin; 4, underlying dark shadow from dentin without cavitation; 5, distinct cavity with visible dentin; 6, extensive distinct cavity with visible dentin. Prior to examination, all teeth were kept in water, and for examination, each tooth was picked up from water, and each surface examined while still wet. Then the surfaces were dried for 5 sec with a dental air–water syringe, and again examined dry. In this way, factors that may confound caries detection in a live mouth were closely replicated. On proximal surfaces without caries, a spot recognized by the examiners as non-carious was defined and marked. Detected lesions were recorded in a specially designed case report form.

Radiographic examination

Following visual examination, an independent technician, who was not involved in the study, used these teeth to construct five manikin jaw models. Incisors were included, even though not scored, as we wanted to replicate the detection in a live mouth. Also, close proximal contacts with adjacent teeth were kept. Bitewing radiographs were taken by a trained radiographer of all teeth in each manikin jaw using the standard technique in routine clinical practice. Then, using a radiographic film magnifier (magnification ×2) in a darkroom, the presence or absence of radiolucency (caries) on the proximal surfaces of the teeth (except the incisors) were determined and recorded by a dental radiologist who was trained in caries detection, and who was different from both visual and CS examiners. The radiologist recorded caries as follows:[19] score 0, no radiolucency; score 1, radiolucency in the enamel; score 2, radiolucency in the outer one-half of the dentin; score 3, radiolucency in the inner one-half of the dentin.

The Canary System examination

Following radiographic examination, a clinician trained on the use of the CS (Quantum Dental Technologies Toronto, ON, Canada), used the system to assess the proximal surfaces of all teeth (except the incisors). He was independent of the one who selected the teeth and the one who carried out the ICDAS-II evaluation. The examiner assessed the proximal surfaces through the corresponding marginal ridge, the buccal and lingual surfaces (at the angle of the proximal and buccal or lingual surface). The CS indicates the presence or absence of caries using a Canary scale with Canary numbers ranging from 0 to 100. Canary numbers ≤20 signify absence of caries lesion while numbers above 20 signify presence of varying levels of caries lesion. Prior to imaging, each surface was dried for 5 sec using a dental air–water syringe as recommended by the manufacturer, and then scanned with the CS and the Canary number recorded. The highest value from the three measurements of each surface was recorded in accordance with the manufacturer's instruction.

Histological examination by PLM

Following the CS scanning, a tooth slice (100 μm thick) was cut perpendicularly to the surface of all detected lesions and all marked non-carious spots on the proximal surfaces of each tooth to histologically confirm that the surface was sound. Each slice was imbibed with water and histologically examined using polarized-light microscopy (PLM; Model BH-2, Olympus, Japan) with a rotating stage, polarizer, and analyzer at a magnification of 450×: the images of each slice were captured by a digital camera (Axio Cam ICc 1; Zeiss, Oberkochen, Germany) connected to the microscope. The image of each slice was assessed independently but in identical position by two technicians, who had been previously trained and calibrated on the use of PLM, in order to assess carious demineralization of tooth tissue and to estimate the severity of the lesions through measurement of the lesion depth. Measurements of lesion depth were made (Fig-
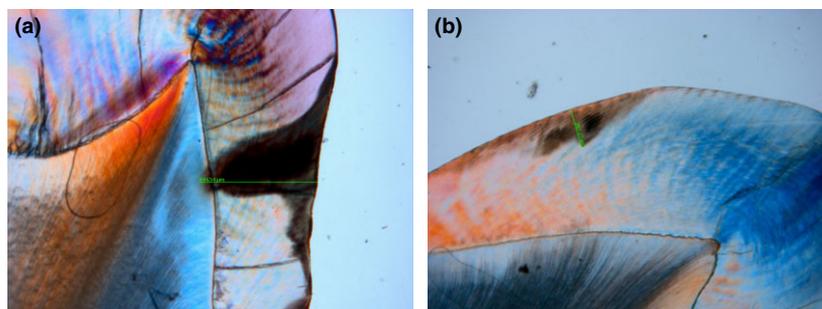
Figure 1. Two PLM images showing the measurement of the lesion depth.

ure 1) and assessment for caries was carried out with histologic scores as follows:[20] 0, caries-free; 1, caries extending as much as halfway through the enamel; 2, caries extending into the inner one-half of the enamel; 3, caries in the outer one-half of the dentin; 4, deep dentin caries involving the inner one-half of the dentin. If they disagreed about a lesion, they re-examined that slice together and discussed their findings until they reached a consensus. All evaluations in this study were blind.

Sample size estimation

The sample size was calculated using PASS 11. The calculation was based on the following factors: (a) an adult jaw model with 10 teeth, excluding 2 wisdom teeth and 4 incisors, represent a sample of 20 proximal surfaces; (b) five jaw models represent sample size of 100 proximal surfaces; (c) population area under the receiver operating characteristic (ROC) curve for a clinically effective diagnostic tool was defined as 0.90 ± 0.09; (d) visual examination was projected to have an area under the ROC curve of 0.80 ± 0.1; (e) the significance level (α) for the five possible pairwise z-tests comparing areas under ROC curves was set at a 0.05, and the Bonferroni correction was used to correct for multiple testing; (f) the power, the probability of detecting the chosen clinically relevant difference, was set at 90% (i.e., $\beta = 10\%$); (g) using these criteria, five jaw models providing sample size of at least 100 proximal surfaces (about 50 carious and 50 sound) were determined to be sufficient for each pairwise z-test comparing areas under ROC curves.

Statistical analysis

The categorical outcomes were summarized with counts and percentages. Comparisons of variables by the status of caries/no caries were carried out using Fisher's exact and Pearson's chi-squared tests. Pairwise comparisons were performed on the area under the curve (AUC), sensitivity and specificity of the three tests (CS, ICDAS-II and BW), and were corrected for multiple comparisons using Bonferroni's method. The sensitivities and specificities were compared using a test of proportions and AUC values were compared using DeLong's method of non-parametric testing of AUC values.[21] All analyses were performed using R 3.0.1 (The R Foundation for Statistical Computing, Vienna, Austria).

Results

The histological examination (PLM severity score), which was used to determine the severity of the lesions used in this study, showed that the samples comprised of 40

caries-free surfaces, 31 surfaces with lesions into the outer half of the enamel, 16 surfaces with lesions into the inner half of the enamel, 10 surfaces with lesions into the outer half of the dentin, and 3 surfaces with lesions into the inner half of the dentin. Measurements were taken from two surfaces of each of 50 teeth (wisdom teeth and incisors excluded) from five jaw models resulting in a sample size of 100 measurements for each test. Of the 60 caries lesions detected, 11 were located in canines (7 in upper, 4 in lower), 26 in premolars (8 in upper first premolars, 5 in upper second premolars, 5 in lower first premolars, 8 in lower second premolars), and 23 in molars (4 in upper first molars, 6 in upper second molars, 8 in lower first molars, 5 in lower second molars). The difference between PLM caries status by tooth location reached statistical significance ($P = 0.03$). Lesions were evenly distributed among distal and mesial surfaces. However, the mean $\pm$ SD values of the lesion depth determined from PLM for carious proximal surfaces were 559.9 ± 536.9 μm (range 63.0–2852.9 μm). The difference in PLM caries status was not statistically significant among the different jaw models ($P = 0.1$) or between the marginal ridge and buccal or lingual surface measurement locations ($P = 1.0$).

The overall distribution of scores by using each method is presented in Table 1. As determined by the manufacturer, the caries cut-off value for the CS was >20. Canary numbers ≤20 signify absence of caries lesion while numbers above 20 signify presence of varying severity levels of caries lesion. According to ICDAS-II scoring criteria (0–6), 0 signifies absence of caries while numbers 1 through 6 signify varying severity of caries. For statistical purposes, the authors represented the absence and presence of caries in bitewing radiograph and PLM tests with 0 and 1 respectively.

Table 1. Distribution of caries scores of the proximal surfaces by each method (PLM was the reference standard)

Test method (score criteria)	Caries	No caries
Canary System (scores: ≤20 = no caries; >20 = caries)		
Mean ± SD	45.4 ± 18.1	24.2 ± 15.3
Median [Q1, Q3]	40 [34, 54]	19 [17, 20]
Minimum, maximum	19, 100	11, 81
ICDAS-II test (scores: 0 = no caries; ≥ 1 = caries)		
Mean ± SD	1.56 ± 1.14	0.57 ± 0.84
Median [Q1, Q3]	2 [0, 2]	0 [0, 1]
Minimum, maximum	0, 5	0, 2
Radiograph test (scores: 0 = no caries; ≥1 = caries)		
Mean = SD	0.37 = 0.68	0.12 = 0.33
Median [Q1, Q3]	0 [0, 1]	0 [0, 0]
Minimum, maximum	0, 3	0, 1

Table 2 presents sensitivity and specificity values for all three detection tests. The sensitivity of the CS (0.933) was statistically significantly higher than that of the ICDAS-II (0.733; $P = 0.01$) and BW (0.267; $P < 0.001$) methods. The sensitivity of the ICDAS-II test was statistically significantly higher than that of the BW ($P < 0.001$). There was no statistically significant difference in specificity of the CS (0.825) and that of ICDAS-II (0.65; $P = 0.25$) and BW (0.875; $P = 1.0$) methods. Similarly, there was no difference ($P = 0.07$) in specificity between ICDAS-II and BW tests.

The calculated negative predictive value (NPV), a chance that a proximal surface classified as sound with CS test truly presented no caries lesions after histological examination, was 89.2% (Table 2). A chance that a surface with a positive CS test truly presented caries (positive predictive value, PPV) was 88.9%. The calculated NPV and PPV for the ICDAS-II test and for BW were lower.

Using sensitivity and specificity, ROC curves and areas for each test were calculated to express their accuracy for caries detection. The ROC curves are displayed in Figure 2. The area under the curve (AUC) was taken as a variable to compare curves. The AUC of the CS (0.862) was statistically significantly higher than that of the ICDAS-II (0.681, $P < 0.001$) and the BW (0.577, $P < 0.001$) methods. The difference in AUC values of the ICDAS-II test and the BW was not statistically different ($P = 0.1$).

Discussion

The present study investigated the performance of the CS in detecting proximal caries lesions *in vitro* and compared it with other conventional methods, namely, visual examination and BW. Histological (PLM) examination was used as a reference standard for the presence or absence of caries lesion. The number of false negative diagnoses of the CS was the lowest, and its positive and negative predictive values the highest (Table 2). Furthermore, AUC of the CS was the highest (Figure 2).

The significantly higher sensitivity exhibited by the CS over the two conventional methods, visual and BW (Table 2), is in agreement with results of Jeon *et al.*[13] that examined the occlusal caries diagnostic ability of PTR–LUM, and reported sensitivities of 81% and 79% and specificities of 87% and 72% for caries in enamel and dentin, respectively.

Compared with the other two tests, the number of false negative diagnoses of the CS test was the lowest (Table 2), the CS was able to identify proximal lesions without increasing the number of carious surfaces incorrectly identified as sound. The number of false positive diagnoses was only slightly higher than for BW, which is a highly specific method.[5] Of the seven false-positive readings of the CS test, five were given a Canary number below 50, one 62,

Table 2. Validity of the CS, ICDAS-II, and bitewing radiograph tests of carious lesions on proximal surfaces using the histological examination as the validating criterion

Parameters	Canary System	ICDAS-II test	Radiograph test
False positive	7	14	5
False negative	4	16	44
Positive predictive value	0.889	0.759	0.762
Negative predictive value	0.892	0.619	0.443
Sensitivity	0.933†,‡	0.733†,§	0.267‡,§
Specificity	0.825	0.65	0.875

†,‡,§Different symbols show statistical differences between detection tests ($P < 0.05$).
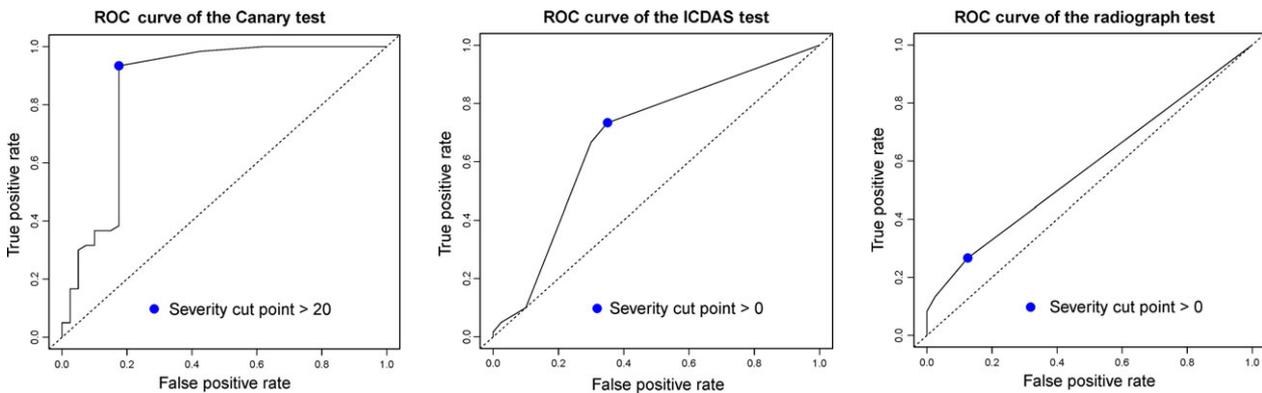
Figure 2. Receiver operating characteristic (ROC) curves for the CS, ICDAS-II, and radiograph tests.

and one 81 (Table 1). At the moment, Canary numbers above 20 signify presence of varying levels of caries lesion, but there is still a lack of a scale for their interpretation, with cut-off points to define the lesion severity.

Published validity parameters of diagnostic tests are difficult to compare: a large variation can be the result of differences in the samples used.[22] In the present study, the sample was selected with prevailing early non-cavitated lesion in order to reflect the currently low prevalence of dentin caries observed in the population.[1] The CS showed detection accuracy superior to that of BW and visual examination. The results showing high sensitivity of the CS support previous findings that PTR–LUM are able to detect lesions which are neither yet visible, nor detectable with BW or DIAGNOdent,[13] or not even with microcomputed tomography and transverse microradiography analyses.[14]

From a clinical perspective, where a predictive value (positive and negative) of the caries detection test is more interesting, the highest values in our *in vitro* sample were calculated for the CS test (Table 2). In 89% of cases, a positive CS test result could be trusted and a negative CS test result was indeed indicative of a sound surface. Such a good detection ability of the CS could be attributed to the combined PTR and LUM sensitivity and specificity.[13]

The CS examination was performed in mouth models, where teeth were mounted into close proximal contact with adjacent teeth. Therefore, it was not possible to directly assess proximal surfaces, but only through the corresponding marginal ridge and the buccal and lingual surfaces. Thickness of healthy enamel between the tip of the handpiece and the carious region could therefore influence the detection accuracy of the CS on proximal surfaces. This factor is likely to decrease the Canary number readings. Nevertheless, the CS was able to detect proximal caries with similar sensitivity and specificity as simultaneous measurements of PTR and LUM on occlusal surfaces.[13] Our results support the finding that at least up to 5 mm below the enamel surface is able to be examined and probed when the wavelength and modulation frequency of the PTR signal are optimized.[13] Furthermore, no differences in PLM caries status were observed between different measurement locations. Another factor that might confound caries lesion detection in the present study was stains and calculus on the teeth. Removing spots of calculus and stains on proximal surfaces in everyday general practice is difficult and it is not easy to see whether it has been achieved. As we wanted to replicate the detection in a clinical setting, they were not removed in this study. It is known for DIAGNOdent, another laser device, that such deposits can cause fluorescence and give false-positive readings.[20,23] However, it is expected that the PTR signal can distinguish between caries, stains on

tooth surface, and developmental white spots, as the PTR signal consists of both surface and subsurface responses of dental tissue.[13]

Detection accuracy in the form of AUC, a more comprehensive measure of diagnostic performance than single values for sensitivity and specificity,[24] was significantly highest for the CS, followed by visual examination and BW (Figure 2). The correlation of the lesion depth with the Canary numbers was not calculated in the present study since our previous pilot studies[14,17] demonstrated that the Canary number does not depend only on the lesion depth but rather on the volume of demineralized tissue, the main property of caries lesions that indicates the severity.[25] In these two studies, in which artificial enamel lesions in the proximal contact area of extracted human teeth were used, microcomputer tomography[14] and transverse microradiography[17] analyses demonstrated good correlation of mineral loss with PTR signals but not lesion depth.

The ICDAS-II direct visual examination in the present study was used to indicate the variation in the severity of the caries lesions used in the study, and to ensure the inclusion of early non-cavitated caries lesions. It is more suitable for making clinical inferences than validation of histological sections that served as a reference standard. The teeth were viewed directly prior to setting in the model since we considered that in clinical practice, some practitioners do use the orthodontic elastomeric ring (O-ring) to separate the teeth to visualize a suspicious contact point. Thus, in this *in vitro* study, instead of mounting the teeth first, and then using an instrument to separate the teeth for direct visual examination, we decided to conduct visual examination before mounting. When free proximal surfaces were examined by direct visual examination under optimal conditions, the number of false positive diagnoses was twice as high as for the CS test (Table 2). A greater number of lesions were detected than by BW, but still smaller than by the CS test. Our results are in line with the results of Mitropoulos *et al.*[9] and Ekstrand *et al.*,[26] who evaluated the uses of conventional BW and the visual caries classification system ICDAS-II for diagnosis of caries on free proximal surfaces. They found ICDAS-II was better in sensitivity, but BW was better than ICDAS-II in specificity. Their sensitivities recorded for diagnosis of caries for ICDAS-II were higher. This may be attributed to the severity of caries lesions used in the study. More advanced lesions may have been used in their studies, which enhanced the sensitivity,[9] while in our present study we used mostly early non-cavitated lesions that we presumed the dentist should need the aid of a device to detect. Obviously, less severe (earlier stages) caries are more difficult to detect. It is interesting to note that Jeon *et al.*[13] reported much lower sensitivities and specificities for visual examination. The

reason can be that clinicians, assessing the occlusal surfaces of extracted teeth, did not use ICDAS-II, and as such did not include early stage caries but only lesions at the restorative treatment stage.

Sensitivity of the BW, the most widely used diagnostic method for the detection of proximal caries lesions, was low (Table 2), and almost three-quarters of lesions would remain undetected. The low sensitivity observed is in line with findings from most previous studies where histological appearance of the proximal surfaces was the validating criterion against which the diagnostic tests were assessed. Researchers obtained lower sensitivity and higher specificity values for the radiographic method, and showed that it is more efficient to detect more advanced caries lesions.[5,7,9] In the present study, 86.4% were non-cavitated lesions restricted to the enamel (ICDAS-II scores 1 and 2), which could be the reason for the observed low sensitivity of the BW that performs better in dentinal caries lesions.[5] In the studies of Mitropoulos et al.[9] and Ekstrand et al.[26] sensitivities recorded for BW were higher than in our study. The differences could be attributed to

their experimental set-up, where no proximal contacts and consequently no proximal overlapping was present. The AUC values of BW observed in the present study were lower than those of the CS and ICDAS-II (Figure 2). They were comparable to that reported by Hintze et al.[7] and Li et al.[8]

In summary, our data show that under *in vitro* conditions, the accuracy of the CS in detecting proximal caries lesions is greater than that of the conventional ICDAS-II and BW. The CS presented the highest sensitivity among the investigated methods but without significant differences in specificity. Therefore, it is reasonable to conclude that the CS can be a valuable method for proximal caries lesions detection. Further studies are needed to explore the accuracy of the CS in a clinical setting.

Conflict of interest and sources of funding statement

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