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Clinical Trial of the Canary System for Proximal Caries Detection: A Comparative Study

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Background: Detecting initial caries on the proximal surfaces of teeth in an intact dentition is a problem in dental practice since radiograph has been shown to have poor sensitivity with this stage of caries lesions. Hence there is need for an alternative technology.
Objectives: The aim of this study was to investigate the efficacy of the Canary System (CS) to detect proximal caries in a clinical setting, comparing it with bitewing radiography (BWR).
Methodology: 33 subjects, age 18 years and above, were recruited from a mixed population of low, moderate, and high caries risk patients. BWR and the CS were used to detect proximal caries lesions in these subjects. Teeth were separated by 48 hours insertion of rubber rings, and the proximal surfaces were examined by direct visual examination using the International Caries Detection and Assessment System II (ICDAS-II) scoring system. The Sensitivity (se), specificity

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(sp), positive (ppv) and negative predictive (npv) values of the CS and BWR in detecting caries on proximal surfaces were calculated by evaluating each method alone against ICDAS-II system (used as bronze standard). The two methods were compared statistically using their Area Under the Receiver Operating Curve (AUC). The sensitivities and specificities were compared using a test of proportions and AUC values were compared using DeLong's method of nonparametric testing of AUC values.

Results: The se, sp, ppv and npv for the CS are 0.92, 0.78, 0.89, 0.84 respectively, and for BWR are 0.67, 0.54, 0.78, and 0.40 respectively. The AUC of the Canary System (0.77) was statistically significantly higher than the AUC of the radiography (0.53, $P < .001$).

Conclusions: This study demonstrated the efficacy of the Canary System in detecting proximal caries lesions to be greater than that of bitewing radiography.

Clinical Significance: The Canary System can be a valuable clinical device for detecting and monitoring proximal caries lesions in clinical practice.

Keywords: Bitewing radiography; canary system; proximal caries; caries diagnostics; caries detection; ICDAS-II system; sensitivity; specificity.

1. INTRODUCTION

The incidence and prevalence of dental caries have declined, and severity of caries has changed due to slow rate of progression of new lesions [1]. The detection of early caries lesions has been considered the cornerstone of cost-effective health care delivery and quality of dental care. In lesions that are detected at an early stage, preventive non-operative treatment is advocated, allowing lesion arrest and remineralization, which can prevent invasive procedures [2,3]. However, for such a treatment approach, accurate methods which allow detection of early lesions are needed.

The detection of caries lesions in inaccessible contacting proximal surfaces is more difficult than in readily visible surfaces. The most commonly used methods for detecting and assessing proximal caries, despite their limitations, are bitewing radiography [4] and visual examination with International Caries Detection and Assessment System II (ICDAS-II) [5]. For the radiographic method, researchers obtained higher specificity and lower sensitivity values in detecting early proximal caries [6]. It showed that the method is more accurate to detect more advanced caries lesions [4,7,8]. In addition, there are disadvantages associated with the use of ionizing radiation. Similarly, studies have presented low sensitivity and higher specificity for detecting early caries lesions on contacting proximal surfaces with visual examination [9,10], since the lesion can be viewed only from the buccal or lingual/palatal directions. In clinical practice, the use of orthodontic elastic O-rings has been recommended to temporarily separate the teeth to permit direct vision of a suspicious contact point [11], since this has been reported to result to high sensitivity and high specificity of the visual examination [7]; however, it takes at least 24 hours to achieve this teeth separation. There is therefore a need for more accurate methods for detecting both advanced and initial stage proximal caries lesions.

A promising alternative method could be a diagnostic tool based on combined frequency-domain laser-induced infrared photothermal radiometry (PTR) and modulated luminescence (LUM), the Canary System. 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) [12,13]. A Canary number, created from an algorithm combining four signals (PTR amplitude, PTR phase, LUM amplitude and LUM phase), is directly linked to the status of the tooth crystal structure.

The sensitivity of PTR-LUM in a study on occlusal caries using this device was reported to be much higher than those of a continuous laser-induced luminescence (DIAGNOdent), visual inspection, and radiographs [14]. Other studies have shown the ability of the Canary System to detect caries at all stages of development on occlusal surfaces [15], underneath opaque dental sealants [16], in remineralized natural early caries lesions on smooth surfaces *in vitro* [17], approximal surfaces of primary molars in children [18] and to detect secondary caries underneath composite restoration on proximal surfaces [19]. In our previous *in vitro* study on proximal caries using this device, with histological validation as a gold standard, the Canary System demonstrated greater accuracy in detecting proximal lesions

than visual examination and bitewing examination, although without significantly higher specificity [20].

The objective of the present study was to investigate the accuracy of the Canary System (CS) to detect proximal dental caries in a clinical setting, comparing it with the accuracy of the bitewing radiography (BW). The accuracy will be assessed by determining the specificity and sensitivity of the two examination methods. The null hypothesis was that no significant difference exist in accuracy (Sensitivity and specificity) of the CS and BW in detecting proximal caries lesions. Furthermore, the data analysis in the present clinical study require some novel statistical methods. Considering that visual examination is not a perfect way of detecting caries, comparing the CS to the visual examination, such as ICDAS-II, would distort the estimates of the true accuracy of the CS to detect caries. We know how both the visual examination and the CS perform in an *in vitro* study compared to the histological method (gold standard) [20], thus we developed a novel method that used the data from the *in vitro* study to compensate for the less than perfect performance of the visual method when estimating the performance of the Canary method.

2. MATERIALS AND METHODS

2.1 Study Population and Subject Recruitment

The study was approved by the Institutional Review Board (Approval #: HSC20130286H) of the University of Texas Health San Antonio (UTHSA). The study was conducted at the clinical research facility of the UTHSA school of dentistry. Thirty three subjects (22 females, 11 males), aged 18 years and above, were recruited from different ethnic and socioeconomic status and a mixed population of low, moderate, and high caries risk subjects, at a percent distribution reflecting caries group demographics in the general population [21]. The caries risk status was assessed using the American Dental Association (ADA) caries risk assessment form [22] and categorized in accordance with the recommendation of ADA Council on Scientific Affairs [23]. Subjects were recruited through flyers that were posted in different locations. Written informed consent was obtained from all participants prior to their participation in the study. After providing informed written consent, subjects underwent a complete intra-oral examination and completed a medical/dental history questionnaire for inclusion and exclusion criteria. To be included in the study, the subject had to be at least 18 years of age and have at least 12 teeth to ensure an adequate number of surfaces for caries detection.

2.2 Study Procedures

To ensure accurate assessment for dental caries, the two examiners (JJ and WZWB) were calibrated for the study by a benchmark examiner (BTA), a Cariologist experienced in caries diagnosis. The first ten participants that were recruited into the study were used for the calibration exercise, and were later removed from full participation in the study. The agreement between the two examiners (inter-examiner reproducibility) and between the examiner's individual evaluations (intra-examiner reproducibility) were assessed using the unweighted kappa (κ) statistic. Kappa values for intra-examiner reproducibility for the two examiners were 0.80 and 0.83 respectively, and the inter-examiner reproducibility was 0.78. These values met the 0.70 pre-established value for qualification. Agreement of clinical assessments was therefore established to be good which validated the examination procedure.

Initial telephone or in-person screening preceded an enrolment visit to obtain consent and confirm eligibility according to the above inclusion and exclusion criteria.

2.2.1 Conventional visual examination (ICDAS II)

Following enrolment into the study on the first visit, orthodontic elastic O-rings, acting as spacers, were inserted by a qualified dentist between the posterior (premolars and molars) teeth. They were left in place for two days to space the teeth and provide direct visibility to the proximal surfaces of the teeth. On the third day, prior to examination, subjects brushed their teeth thoroughly with toothpaste and toothbrush for two minutes to remove any food particles and plaque. Each subject was examined by one of the trained and calibrated caries detection experts, who were calibrated on the use of the ICDAS-II for caries assessment. The teeth were first examined wet, then the surfaces were dried for 5 sec with a dental air–water syringe, and again examined dry. The examiner used a WHO ball-end probe, a non-magnifying plane mirror,

prism loupes, standard dental operating light and chair, to visually identify caries on the proximal surfaces of premolars and molars in each subject, excluding the anterior (incisors and canine) teeth. All levels of caries lesions ranging from initial (non-cavitated) to cavitated lesions were recorded. The examiner used the caries assessment criteria of the ICDAS II [24] to distinguish between initial (non-cavitated) caries lesions and developmental defects of enamel. The scoring criteria according to ICDAS-II were: score 0: sound tooth surface; score 1: first visual change (opacity or discoloration) in enamel hardly visible on the wet surface but distinctly visible after air drying; score 2: distinct visual change (opacity or discoloration) in enamel, visible without air drying; score 3: localized enamel breakdown without visible dentin; score 4: underlying dark shadow from dentin without cavitation; score 5: distinct cavity with visible dentin; score 6: extensive distinct cavity with visible dentin. Detected lesions were recorded in a specially designed case report form (CRF).

2.2.2 Radiographic examination (BW)

Bitewing radiographs of the posterior teeth of each patient were taken by a trained radiographer using the standard technique in routine clinical practice. In radiographic examination, using a radiographic film magnifier (magnification ×2) in a darkroom, the presence or absence of radiolucency (caries) on the proximal surfaces of the posterior teeth were determined and recorded by an oral radiologist (SMM) who was trained in caries detection, and who was different from both visual and Canary system examiners. The radiographic examiner recorded caries based on 4-grade classification as follows [25]: 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.

2.2.3 The Canary system examination (CS)

Following visual and radiographic examination, each subject was sent home for two days to enable the space created with elastic spacers to close up. This prevented the clinician using the Canary System from viewing the proximal surfaces of the teeth. On the examination day, a clinician trained on the use of the Canary System (Quantum Dental Technologies Toronto, ON, Canada), used the system to assess the proximal surfaces through the corresponding marginal ridge, the buccal and lingual embrasures (at the angle of the proximal and buccal or lingual surface) as described in previous studies [19,20,26]. The Canary system examiner was independent of the one who carried out the ICDAS-II examination and the one who carried out the radiographic examination. The Canary System 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 seconds using the dental airwater syringe, and then scanned with the Canary System and the Canary number recorded. The highest value from the three measurements of each surface was recorded in accordance with the manufacturer's instruction.

2.3 Sample Size Estimation

The sample size was calculated using PASS 11. The calculation is based on the following factors: (1) An adult patient with 16 posterior teeth, excluding wisdom teeth, represent a sample of 28 proximal surfaces with opposing teeth. (2) Population area under the receiver operating characteristic (ROC) curve for a clinically effective diagnostic tool is defined as 0.90. (3) Visual examination is projected to have an area under the ROC curve of 0.80. (4) The significance level for each of 5 possible pair wise z tests comparing areas under ROC curves is set at 1% level of significance (i.e. $\alpha = 0.01$) using the Bonferroni correction. (5) The power - this is the probability of detecting the chosen clinically relevant difference is set at 0.9 (i.e. $\beta=10\%$). (6) Using these criteria, 30 subjects providing sample size of at least 840 potential proximal lesions is determined to be sufficient for each pair wise z test comparing areas under ROC curves. However, 33 subjects were enrolled to provide for 10% dropouts.

2.4 Adjustment of the Visual Examination (ICDAS) Data to Serve as Reference Standard

At times, one must find a way of determining the performance of a novel test without the presence of a gold standard by which to test. We were involved in a study such as this to determine the specificity and sensitivity of a relatively new test (The Canary System) to detect dental caries. However, the only previous methods of detecting dental caries in a live patient (visual and

radiographic methods) have poor sensitivity and specificity with early caries and hidden caries, thus giving no gold standard by which to assess the accuracy of prediction. There is a gold standard by which it can be determined if a tooth has caries, but this gold standard (histological method) involves destroying the tooth in question, which is obviously not a feasible approach in practice. Instead, we would be forced to use a separate, less accurate test, which we refer to as a bronze standard (ICDAS-II). In addition to the data that was collected from the patients in the present study, we also received data from a previous *in vitro* study that collected data from the novel test (The Canary System), the bronze standard (ICDAS-II), and the gold standard (the histological method of Polarized Light Microscopy [PLM]) [20]. This section describes a correction for the bronze standard in the present clinical study based on the frequencies of the bronze standard, the Canary system, and the gold standard in the *in vitro* study [20].

The theory: Let *B* be the result of the ICDAS-II test (bronze standard), Y be the result of the Canary test (novel test), and D be the result of the PLM test (gold standard). In this study, true disease is assumed to be indicated by the PLM test.

From the *in vitro* experiment, we can determine the probabilities of true disease as determined by the gold standard based on the results of the novel test and the bronze standard. Let:

$$\acute{\omega}_a = P(D \mid B, Y)$$
$$\acute{\omega}_b = P(D \mid \overline{B}, Y)$$
$$\acute{\omega}_c = P(D \mid B, \overline{Y})$$
$$\acute{\omega}_d = P(D \mid \overline{B}, \overline{Y})$$

Now, for the clinical study, we would like to be able to create the following table:

	D	$\overline{D}$	
Y	a'	b'	$a' + b'$
$\overline{Y}$	c'	d'	$c' + d'$

but, as we explained, this is not directly observable, so we will estimate it based on the table below, which we can observe from the data:

	B	$\overline{B}$	
Y	a	b	$a + b$
$\overline{Y}$	c	d	$c + d$

We can now take the information that we collected from the *in vitro* study and adjust the values for the bronze standard.

We will insert an asterisk (*) to denote the tests and values after the adjustment.

	B^*	$\overline{B}^*$	
Y	a^*	b^*	$a^* + b^*$
$\overline{Y}$	c^*	d^*	$c^* + d^*$

Where

$$a^* = \acute{\omega}_a a + \acute{\omega}_b b$$
$$b^* = (1 - \acute{\omega}_a) + (1 - \acute{\omega}_b) b$$
$$c^* = \acute{\omega}_c c + \acute{\omega}_d d$$
$$d^* = (1 - \acute{\omega}_c) c + (1 - \acute{\omega}_d) d$$

Because the applied adjustment does not affect the categorization from the model test, the number of caries positive tests of the adjusted table ($a^* + b^*$) is equal to the number of caries positive tests of the original, unadjusted bronze standard table ($a + b$).

$$a^* + b^* = \acute{\omega}_a a + \acute{\omega}_b b + (1 - \acute{\omega}_a) + (1 - \acute{\omega}_b) b$$
$$= (\acute{\omega}_a + (1 - \acute{\omega}_a)) + (\acute{\omega}_b + (1 - \acute{\omega}_b)) b$$

Therefore, we know that:

$$\left[\frac{a^*}{a^* + b^*}\right] = \left[\frac{a^*}{\mathrm{a} + \mathrm{b}}\right]$$

We use this to solve for the expected value of the adjusted positive predictive value (PPV)

$$E\left[\frac{a^*}{a^* + b^*}\right] = E\left[\frac{a^*}{a+b}\right]$$

$$= E\left[\frac{\acute{\omega}_a \mathrm{a} + \acute{\omega}_b \mathrm{b}}{a+b}\right]$$

$$= E\left[\acute{\omega}_a\left(\frac{a}{a+b}\right) + \acute{\omega}_b\left(\frac{b}{a+b}\right)\right]$$
$$= E\left[\acute{\omega}_a\left(\frac{a}{a+b}\right)\right] + E\left[\acute{\omega}_b\left(\frac{b}{a+b}\right)\right]$$
$$= \left(\frac{a}{a+b}\right)E\left(\acute{\omega}_a\right) + \left(\frac{b}{a+b}\right)E(\acute{\omega}_b)$$
$$= P(B\,|Y)P(D\,|B,Y) + P(\overline{B}|Y)P(D\,|\overline{B},Y)$$
$$= P(B|Y)\frac{P(B|D,Y)}{P(B|Y)} + P(\overline{B}|Y)\frac{P(\overline{B}|D,Y)}{P(\overline{B}|Y)}$$
$$= P(B\,|D,Y)P(D|Y) + P(\overline{B}|\mathrm{D},Y = \check{\mathrm{D}})P(D|Y)$$
$$= [P(B\,|D,Y) + P(\overline{B}|\mathrm{D},Y)]P(D|Y)$$
$$= P(D|Y)$$

From this, we can now solve for [a^*]

$$E[a^*] \;= E[a^*]\left(\frac{a+b}{a+b}\right)$$

$$= E\left[\frac{a^*}{\mathrm{a}+\mathrm{b}}\right](\mathrm{a}+b)$$

$$= E\left[\frac{a^*}{a^*+b^*}\right](\mathrm{a}^*+\mathrm{b}^*)$$

$$= P(D|Y)(\mathrm{a}^*+\mathrm{b}^*)$$

$$= P(D|Y)P(Y)N$$

$$= P(D,Y)N$$

$$= a'$$

This logic follows for the estimation of b*, c* and d* as well.

Therefore, the adjusted values are estimators of the true disease and these values can be used to estimate the sensitivity and specificity of the novel test (The Canary System).

2.5 Application/Example

From the *in vitro* study, we find:

For those with D:

	B	$\overline{B}$	
Y	42	14	56
$\overline{Y}$	2	2	4

For those with $\overline{D}$:

	B	$\overline{B}$	
Y	6	1	7
$\overline{Y}$	8	25	33

From this, we can solve:

$$\acute{\omega}_a = P(D\,|B,Y) = \frac{42}{48}$$
$$\acute{\omega}_b = P(D\,|\overline{B},Y) = \frac{14}{15}$$
$$\acute{\omega}_c = P(D\,|B,\overline{Y}) = \frac{2}{10}$$
$$\acute{\omega}_d = P(D\,|\overline{B},\overline{Y}) = \frac{2}{27}$$

Also, let's solve for the performance measures of the novel test (The Canary System) based on the gold standard (PLM) for reference:

Sensitivity (*Se*) = $\frac{56}{60}$ = 0.93

Positive Predictive Value (*PPV*) = $\frac{56}{63}$ = 0.89

Specificity (*Sp*) = $\frac{33}{40}$ = 0.83

Negative Predictive Value (*NPV*) = $\frac{33}{37}$ = 0.89

From the present clinical study, we find:

	B	$\overline{B}$	
Y	a = 158	b = 42	a+b = 200
$\overline{Y}$	c = 64	d = 29	c+d = 93

If we stopped here and use the bronze standard (ICDAS-II), we would have the following performance measures:

$$Se = \frac{158}{222} = 0.71$$

$$PPV = \frac{158}{200} = 0.79$$

$$Sp = \frac{29}{71} = 0.41$$

$$NPV = \frac{29}{93} = 0.31$$

These values make the test out to be a much poorer predictor of caries than the *in vitro* study suggested, because of the inaccuracies of the bronze standard.

However, if we continue to solve for the adjusted values.

$$a^* = \acute{\omega}_a a + \acute{\omega}_b b = \left(\frac{42}{48}\right)(158) + \left(\frac{14}{15}\right)(42) = 177.45$$

$$b^* = (1-\acute{\omega}_a) + (1-\acute{\omega}_b) b = \left(1-\frac{42}{48}\right)(158) + \left(1-\frac{14}{15}\right)(42) = 22.55$$

$$c^* = \acute{\omega}_c c + \acute{\omega}_d d = \left(\frac{2}{10}\right)(64) + \left(\frac{2}{27}\right)(29) = 14.95$$

$$d^* = (1-\acute{\omega}_c) + (1-\acute{\omega}_d) d = \left(1-\frac{2}{10}\right)(64) + \left(1-\frac{2}{27}\right)(29) = 78.05$$

	B^*	$\overline{B}^*$	
Y	a^* = 177.45	b^* = 22.55	a^*+b^* = 200
$\overline{Y}$	c^* = 14.95	d^* = 78.05	c^*+d^* = 93

we find the following adjusted performance measures:

$$Se^* = \frac{177.45}{192.40} = 0.92$$

$$PPV^* = \frac{177.45}{200} = 0.89$$

$$Sp^* = \frac{78.05}{100.60} = 0.78$$

$$NPV^* = \frac{78.05}{93} = 0.84$$

which are very similar to the values from the *in vitro* study.

2.6 Statistical Analysis

All statistical analyses were performed using R 3.0.1 (The R Foundation for Statistical Computing, Vienna, Austria). The diagnostic quality of each method was further assessed based on the area under the Receiver Operating Curves values defined by the sensitivity and specificity values. Pairwise comparisons were performed on the area under the curve (AUC), sensitivity and specificity of the two caries diagnostic methods (CS and BW), and were corrected for multiple comparisons using Bonferroni's method. Using their AUC values, the CS and BW were compared statistically using DeLong's method of non-parametric testing of AUC values, and the sensitivity and specificity values were compared using a test of proportions [27].

3. RESULTS

A flow diagram of the study is shown in Fig. 1. Fifty subjects were screened for the study, and thirty three met the inclusion criteria and were enrolled into the study. Seven subjects later withdrew from the study due to discomfort from the O-ring, and were excluded from the analysis due to incomplete data. The 26 subjects included in the data analysis provided 293 suitable proximal tooth surfaces (144 distal, 149 mesial). Of the 293 surfaces, ICDAS-II, CS and BW respectively indicated 222, 200, and 179 surfaces to be carious, and 71, 93 and 114 surfaces respectively to be non-carious surfaces. Table 1 showed the distribution of the 200 carious lesions and 93 non-carious surfaces detected by CS as identified by ICDAS and BW. Bitewing radiograph detected only 66.5% of the total caries lesion detected by CS (Table 1 and 2). Table 2 showed the radiographic severity (depth) categorization of 200 carious lesions and 93 non-carious surfaces detected by CS.

The mean (SD) age of the recruited subjects was 39.5 (14.0) years, and the distribution of the subjects according to caries risk status were, low (12%), moderate (29%), and high (59%) caries risk. The ethnic distribution of the subjects was as follows; Hispanic 19 (58%), Black (not Hispanic) 3 (9%), White (not Hispanic) 8 (24%), Asian 3 (9%).

Following the adjustment of the ICDAS-II data to serve as the Reference standard (i.e. standard for performance measurement), the sensitivity, specificity, positive predictive and negative predictive values of the CS relative to ICDAS-II were 0.92, 0.78, 0.89 and 0.84 respectively, while those of the BW are 0.67, 0.54, 0.78, and 0.40 respectively. The sensitivity of the CS (0.92) was statistically significantly higher than that of the BW (0.67, $P < .001$). There was no statistical significance difference in specificity of the CS (0.78) and the BW (0.54, $P = .25$). The area under the ROC (AUC) was taken as another variable to compare the diagnostic methods. The AUC of the CS (0.77) was statistically

significantly higher than the AUC of the BW (0.53, $P < .001$).

4. DISCUSSION

The present study investigated the accuracy of the CS in detecting proximal caries lesions in a clinical setting and compared it with conventional radiographic method. Visual examination was used as a reference bronze standard. The CS, a caries detection system based on photothermal radiometry and modulated luminescence (PTR/LUM), presented significantly higher sensitivity than radiographic method. A high sensitivity can often be obtained at the expense of a reduced specificity, which may lead to unnecessary overtreatment. In the present study, specificity reached higher values than bitewing radiography, although not significantly, thus corroborating the findings of our previous study in which a histological gold standard was used [20].

This high sensitivity could be attributed to the ability of the CS to detect early changes in the tooth crystal structure. Caries modifies the thermal properties (PTR) and luminescence (LUM) of healthy teeth, the CS is able to collect information from a hemispherical area of 1.5 mm in diameter, up to 5 mm below the tooth surface [14]. In fact, the CS was used for quantitative monitoring of the remineralization of early caries lesions of enamel following administration of a therapeutic noninvasive intervention [28]. As remineralization progresses and enamel prisms start to reform their structure, the thermal and luminescence properties begin to revert towards those of healthy tooth structure. Furthermore, a recent study on smooth and occlusal surfaces of extracted human teeth demonstrated that this method correlates well with a histological gold standard [29]. The CS and ICDAS II exhibited much higher correlation with caries lesion depth than DIAGNOdent. Also, their sensitivity for caries detection, compared to DIAGNOdent, was higher. All the three methods showed high specificity.

Among proximal surfaces without radiographic radiolucencies, the CS identified almost 60 percent as having carious lesions (Table 1). Similar results were obtained in another in vivo study in primary molars [18], where the CS identified 65 percent of teeth without radiographic radiolucencies as having approximal carious lesions, indicating the CS is detecting lesions earlier than radiographs. Their overall sensitivity of the CS was 81%, with bitewing radiographs as the gold standard. However, the specificity of the CS was lower than in our study, only 35%**,** indicating controversial findings.

The low sensitivity and higher specificity values of the BW observed are in line with findings from previous studies. According to a recent meta-analysis in a systematic review [30], the pooled sensitivity for radiography to detect any kind of proximal lesions under clinical settings was reported to be 24%, and specificity 97%. In our current study, the sensitivity value for BW was higher (67%), and specificity lower (54%). A possible explanation may be due to distribution of the extents of the lesions in the study sample. When the authors of the systematic review evaluated the accuracy of detecting dentin and cavitated lesions, the mean sensitivity was increased to 36% and 64%, respectively. For BW, a sensitivity of 67% in the current study indicates that nearly a third of lesions were underdiagnosed, and therefore undertreated. If carious lesions can be detected early, noninvasive treatment can be rendered to stop the progression of the carious lesion [2,3].

In an in vitro study of Dayo and coworkers [19], proximal surfaces were assessed for the presence of caries under composite restorations. Average sensitivities for PTR/LUM and digital intraoral radiography were 89% and 38%, while average specificities were 83% and 80%, respectively. These results were comparable with those obtained for PTR/LUM in the present study, only slightly lower in terms of sensitivity and higher in terms of specificity. BW in the present study produced higher sensitivity and lower specificity. On the other hand, the CS presented low performance in an in vitro study evaluating detection of occlusal caries on permanent teeth [15]. Specificity was lower (43%) than for visual examination and quantitative light-induced fluorescence (QLF) systems. In another in vitro study that examined the occlusal caries diagnostic ability of PTR-LUM, they reported sensitivity of 81% / 79% and specificity of 87% / 72% for caries level of enamel and dentin, respectively [12]. Two other studies also presented that the severity of caries lesions in the study sample can affect performance of the CS, as the CS sensitivity values reported were higher in lesions with deeper caries, measured either by histological [15] or μ-CT scores [31].

The great variability in the reported validity parameters of diagnostic tests between studies might be due to underlying clinical or methodological heterogeneity [30,32]. Of the approximal dental surfaces included in the present study, 24% were identified by the ICDAS-II as sound (Table 1), and only 6% were radiographically classified as radiolucency in the inner one-half of the dentin (Table 2). Caries present in the study sample reflected the currently low prevalence of deep dentin caries observed in the general population [1,21], which could be the reason for the observed low sensitivity of the BW that is especially suitable for detecting more advanced caries lesions [4,30]. This finding is also illustrated by the agreement observed between the radiographic and the CS findings, which was better for the detection of more advanced caries lesions than for early stages (Table 2).

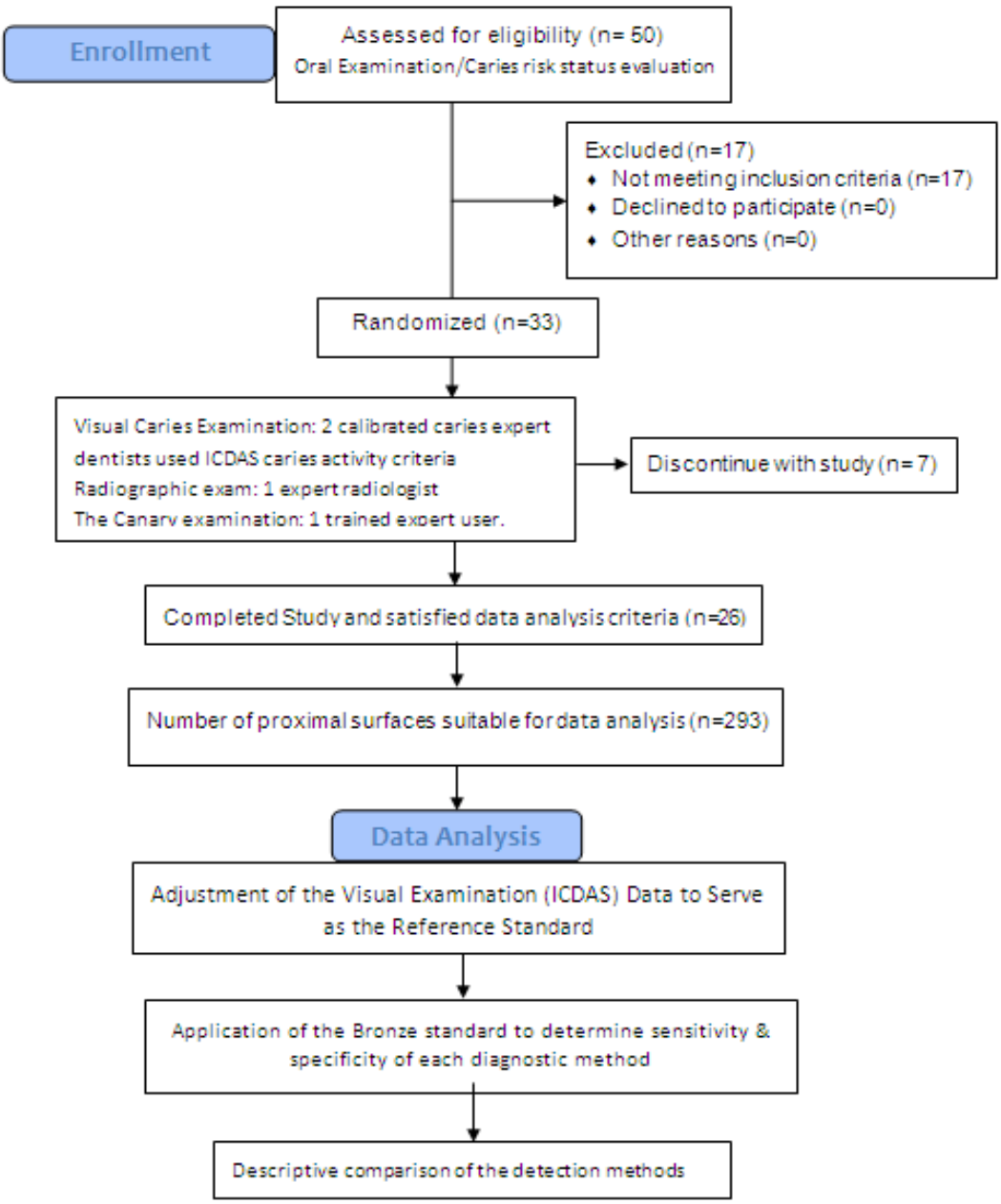

Fig. 1. A flow diagram of the study protocol

Table 1. The distribution of the 200 carious lesions and 93 non-carious surfaces detected by The Canary System as identified by the ICDAS-II and the Bitewing radiograph

	The Canary System		
	Caries (N = 200)	No caries (N = 93)	Total (N = 293)
ICDAS-II			
Caries	158	64	222
No caries	42	29	71
Total	200	93	293
Bitewing Radiograph			
Caries	133	46	179
No caries	67	47	114
Total	200	93	293

Table 2. The Radiographic classification of the 200 carious lesions and the 93 non-carious surfaces detected by The Canary System

Radiograph Severity Categories	Caries (N = 200)	No caries (N =93)	Total (N = 293)
0: No caries (No Radiolucency)	67	47	114
1: Radiolucency in the enamel	55	23	78
2: radiolucency in the outer one-half of the dentin	62	21	83
3: radiolucency in the inner one-half of the dentin	16	2	18
Total	200	93	293

Detection accuracy in the form of AUC, a more comprehensive measure of diagnostic performance than single values for sensitivity and specificity [33] was significantly higher for the CS than for the BW. From a clinical perspective, where predictive values (NPV and PPV) of the caries detection test are more interesting, higher values in our study sample were calculated for the Canary System test. In 84% of cases, a negative Canary System test result was indeed indicative of a sound surface, and in almost 90% a positive Canary System test result could be trusted. Such a good detection ability of the Canary System could be attributed to the combined PTR and LUM sensitivity and specificity [12]. The calculated NPV and PPV for BW, which is a highly specific method [4], were 40% and 78%, respectively. More than half of carious surfaces were incorrectly identified as sound. Similar results were obtained in our previous in vitro study [20].

PTR/LUM can have moderate [19] or low intraexaminer repeatability [15,31]. Two potential reasons for lower repeatability were suggested, strict scanning diameter of PTR/LUM and nonuniform characteristics of natural caries lesions [31]. A recent in vitro study showed the scanning direction can have an effect on PTR/LUM detection performance [31]. Therefore, the authors recommended to scan multiple locations/directions to obtain the maximum PTR/LUM value. In previous studies, researchers used different scanning procedures and evaluated the measurement values differently. This might be one of the reasons for different detection performances observed. In the current study, the highest value from the three measurements of each surface was recorded as the final result.

In our previous in vitro study a histological gold standard (PLM) was used [20]. Usually, in vivo designs use relatively weak validation methods when compared to in vitro settings [33]. In the current study, the visual-tactile examination (ICDAS-II) was the reference bronze standard, after performing temporary tooth separation. Previous studies reported improved sensitivity and accuracy values for ICDAS-II assessment on proximal surfaces of primary molars after temporary tooth separation [34,35], providing improved accessibility for direct examination [11,36]. To further improve the accuracy of our bronze standard, adjustment of the visual examination data to serve as reference standard was performed.

In our future clinical trial, this adjustment of the visual examination data to serve as reference

standard, will be applied in conducting a large multicentre clinical trial to produce more high strength evidence in support of the efficacy of the Canary System in detecting proximal caries.

5. CONCLUSIONS

This study demonstrated the accuracy of the Canary System in detecting proximal caries to be greater than that of bitewing radiography. Thus, the Canary System can be a valuable clinical device for proximal caries diagnosis.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

CONSENT

As per international standard and our university standard, patients' written consent has been collected and preserved by the authors.

ETHICAL APPROVAL

The approval of our Institutional Review Board (ethics committee) was obtained (Approval #: HSC20130286H) prior to teeth collection.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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