Journal of Dentistry 90 (2019) 103221

Contents lists available at ScienceDirect

Journal of Dentistry

journal homepage: www.elsevier.com/locate/jdent

Detection ability and direction effect of photothermal-radiometry and modulated-luminescence for non-cavitated approximal caries

Haixia Xing[a,b], George J. Eckert[c], Masatoshi Ando[b,*]

[a] Department of General Dentistry, Peking University School and Hospital of Stomatology, Beijing, China
[b] Department of Cariology, Operative Dentistry and Dental Public Health, Indiana University School of Dentistry, Indianapolis, IN, USA
[c] Department of Biostatistics, Indiana University School of Medicine, Indianapolis, IN, USA

A R T I C L E I N F O

Keywords:
Photothermal-radiometry and modulated-luminescence (PTR/LUM)
Approximal
Non-cavitated caries
Detection
Scanning direction
Scanning geometry

A B S T R A C T

Objective: The objective was to evaluate the ability of photothermal-radiometry and modulated-luminescence (PTR/LUM) to detect non-cavitated approximal caries lesions, including the effect of scanning direction.

Methods: Thirty human extracted premolars were selected based on micro-computed tomography [μ-CT: μ-CT = 0: sound (n = 12), μ-CT = 1: lesions into outer-half of enamel (n = 6), μ-CT = 2: lesions into inner-half of enamel (n = 6), and μ-CT = 3: lesions into outer one-third of dentine (n = 6)]. Teeth were mounted in a custom-made device to simulate approximal contact. Each tooth was scanned from three directions: buccal, lingual, and occlusal, then repeated 48 h later. Statistical analyses were performed by bootstrap analyses using average and maximum values across all directions. Sensitivity, specificity, area under ROC-curve (AUC), intraclass correlation coefficient (ICC) and correlation with μ-CT were calculated. Sensitivity was further evaluated based on lesion extension.

Results: Using the manufacturer-suggested lesion cut-off, overall sensitivity ranged from 3%–61%, where the maximum value of all measurements (All-max) showed higher sensitivity (61 %) than other measurements except the buccal direction, which was also higher than the lingual and occlusal directions. As μ-CT score increased from μ-CT = 1–3, the sensitivity of All-max also increased from 50 % to 74 %. Specificity was 100 % regardless of direction, and AUC ranged from 0.65 to 0.88. All-max had the highest ICC (0.74). PTR/LUM values showed weak to moderate correlations with μ-CT.

Conclusion: Within the limitations of this *in vitro* study, PTR/LUM non-cavitated approximal caries lesion detection achieved best individual results from the buccal direction, while using the maximum value from all directions might improve performance.

Clinical significance: Non-cavitated approximal caries detection is a challenging procedure. PTR/LUM is a non-destructive, no ionized-radiation caries detection method that can scan from buccal, lingual, and occlusal directions of an approximal surface. PTR/LUM seems suitable to detect deeper non-cavitated approximal caries. The maximum PTR/LUM value from three directions may be optimal.

1. Introduction

In the past decades, dental caries as one of the most common diseases, affects 60–90 % of children and nearly 100 % of adults worldwide [1]. Although many efforts are used to improve oral health, the prevalence of dental caries still significantly increased [2]. In 2010, 2.4 billion adults suffered from untreated dental caries, while 621 million children suffered from untreated deciduous teeth caries [3]. The complications caused by dental caries not only include teeth pain, teeth loss, but also may cause systemic infection [4], which negatively impacts quality of life. Therefore, management of dental caries amongst the world population is still a huge challenge for all dental professionals.

Dental caries is determined by the balance of pathological factors and protective factors [5]. Dental caries can exist under intact tooth surfaces, which is called non-cavitated caries [6]. Intervention methods depend upon the extension of dental caries. At non-cavitated stages, also known as early stage caries, lesions were from the first signs of demineralization through to the presence of dentinal lesions, non-invasive and micro-invasive treatment methods should be considered in

* Corresponding author at: Masatoshi Ando Department of Cariology, Operative Dentistry and Dental Public Health, Indiana University School of Dentistry, 415 Lansing Street, Indianapolis, IN, 46202 USA.
E-mail address: mando@iu.edu (M. Ando).

https://doi.org/10.1016/j.jdent.2019.103221
Received 15 August 2018; Received in revised form 31 July 2019; Accepted 25 October 2019
0300-5712/

order to maximize preservation of dental tissue [7]. In order to apply those treatment methods, detecting dental caries as early as possible is required.

Visual examination, tactile assessment, and radiographs are the three common and traditional methods to detect dental caries. For approximal caries detection, the adjacent teeth make visual examination difficult [8]. Tactile assessment means using dental sharp explorer/periodontal probe/CPI probe to feel the texture of teeth surfaces. Using the probe to determine the softness or tackiness of dental caries is subjective [9,10]. For bitewing radiographs (BW), the sensitivity is 50–70% and specificity is 70–97% when detecting lesions reaching into the dentine (both approximal and occlusal), which still means around half of approximal caries were missed by BW [11]. Digital radiographs (DR) are more and more popular in recent years, and may perform better than conventional film radiography when detecting approximal surfaces [12]. However, when detecting non-cavitated approximal caries, both BW and DR showed similar sensitivity, only 45%–55% [13].

In order to accurately detect the initial signs of enamel demineralization, objective and non-invasive detection methods have been developed and investigated over the past decades [14]. Photothermal radiometry and modulated luminescence system (PTR/LUM) is one of the methods which has the ability to detect early caries lesions without ionizing radiation [15]. Briefly, the principle of PTR/LUM is when low pulses of laser are absorbed by a tooth, some of the light is converted to heat, and other is emitted back. Measurement of the reflected heat and light provide information about the severity of tooth demineralization [16]. When using PTR/LUM to detect pit and fissure caries, it showed higher sensitivity and specificity than traditional methods, *e.g.* visual examination, radiography and red laser fluorescence device [17]. A multi-center clinical evaluation of PTR/LUM showed it was safe for clinical application during a 17-month span and also could distinguish healthy smooth and occlusal surfaces [International Caries Detection and Assessment System II (ICDAS II) score 0] from caries surfaces [18]. In another *in vitro* study, a total of 60 occlusal surfaces ranging from sound to non-cavitated lesions (ICDAS II scores 0–4) were assessed. The sensitivity of PTR/LUM was 85 %, and the specificity was only 43 % [19].

PTR also showed the ability to detect approximal artificial demineralized lesions in simulated approximal contact area [20,21]. When detecting approximal caries in primary molars as compared with BW *in vivo*, the sensitivity of PTR/LUM (81 %) was similar, and the specificity of PTR/LUM (35 %) was significantly lower than BW [22]. Another study showed that the sensitivity of PTR/LUM (93.3 %) was better than ICDAS II and BW; the specificity of PTR/LUM (82.5 %) was not significantly different from ICDAS II and BW [23]. These results indicated controversial findings. Therefore, the ability of PTR/LUM to detect approximal caries appears to need further evaluation, especially non-cavitated approximal caries.

Besides these controversial results, it is also not clear which scanning direction, buccal, lingual and/or occlusal, performs better and/or which value is reliable. According to the manufacturer's instruction, PTR/LUM should be scanned from occlusal, buccal and lingual surfaces to locate approximal caries. In that way, the examiner would get at least three PTR/LUM values. However, the manufacturer did not mention about how to choose appropriate PTR/LUM values, *e.g.* the real measurement value, the average value, or the maximum value. One study scanned from two directions: two scans from the buccal approximal area and two scans from the lingual approximal surfaces and then accepted the maximum value of those four measurements [24]. Another study scanned at the corresponding marginal ridge, at the angle of buccal and lingual surface and then accepted the maximum value of those three measurements [23]. Since there is no standard procedure for scanning direction and how to evaluate the measurement values, they need to be evaluated.

The primary purpose of this study was to assess the ability of PTR/LUM to detect non-cavitated approximal caries in premolars. The secondary purpose was to evaluate the most effective measurement direction for detection.

2. Materials and methods

2.1. Teeth preparation and model assembly

Thirty human extracted premolars were selected (sound to non-cavitated lesions into the outer one-third of the dentine) based on micro-computed tomography (μ-CT).

2.1.1. Teeth selection

Extracted human teeth had been collected from dental practitioners across the State of Indiana and transported in 0.1 % thymol solution. A total of 50 premolars that had sound or non-cavitated caries on approximal surfaces were selected. Teeth with visible defects, stains, obvious fluorosis or cracks on any surfaces were excluded. All teeth were cleaned with Robinson's brush under water on a slow speed rotary handpiece. All teeth were kept separately in 0.1 % thymol solution in an air-tight humid container at 4 °C. The collection of human teeth for use in dental laboratory research had been approved by the Indiana University Institutional Review Board.

2.1.2. Initial μ-CT image acquisition

To estimate the lesion extension, all teeth were scanned using μ-CT. The teeth were mounted and secured on Lego® bricks (The LEGO Group, Billund, Denmark) using utility wax (Heraeus Kulzer Inc., Lafayette, IN, USA). The μ-CT images were acquired using a Skyscan μ-CT instrument (Skyscan 1172, Kontich, Belgium) at 80 kV, 134 μe, 8.9 μm pixel size resolution with an Al + Cu filter. Using NRecon version 1.6.6 software (Bruker microCT, Kontich, Belgium), a two-dimensional (2D) image was reconstructed. The axial views of the 2D images were observed and scored using image display software (CT-Analyser, Bruker microCT, Kontich, Belgium) by two experienced examiners independently according to the criteria previously described [25]. The deepest lesion extension was used to determine lesion extension. In case of disagreement, the examination was performed again until consensus agreement was achieved. Among the selected 50 teeth, thirty teeth were included in this study. The final distribution of the 30 study teeth was as follows: sound surface (μ-CT = 0: n = 12), lesion in the outer half of the enamel (μ-CT = 1: n = 6), lesion in the inner half of the enamel but not extending beyond the dentin-enamel junction (μ-CT = 2: n = 6), and lesions in the outer one third of the dentin (μ-CT = 3: n = 6). Two additional sound premolars were also selected as neighbor teeth for the model.

2.1.3. Model assembly

The 30 study teeth and additional two neighbor sound teeth were then mounted and secured on plastic Lego® bricks using Triad® visible light cure resin (DENTSPLY International, Inc., York, USA). The resin was applied around the root and the cervical part of the teeth at the level of the cemento-enamel junction to resemble the thickness and anatomy of the gingiva. Approximal contact against the sound neighbor tooth was confirmed using dental floss. Fig. 1 shows the three views of simulated model. The assembled models were kept in a container with wet gauze to maintain humidity.

2.1.4. Final μ-CT image acquisition as a gold standard

To confirm the lesion depth and acquire the standardized μ-CT images, all study teeth were scanned again using μ-CT as described previously in *1.2 Initial μ-CT image acquisition*.

2.2. PTR/LUM examination

The PTR/LUM instrument (Canary System®, Quantum Dental

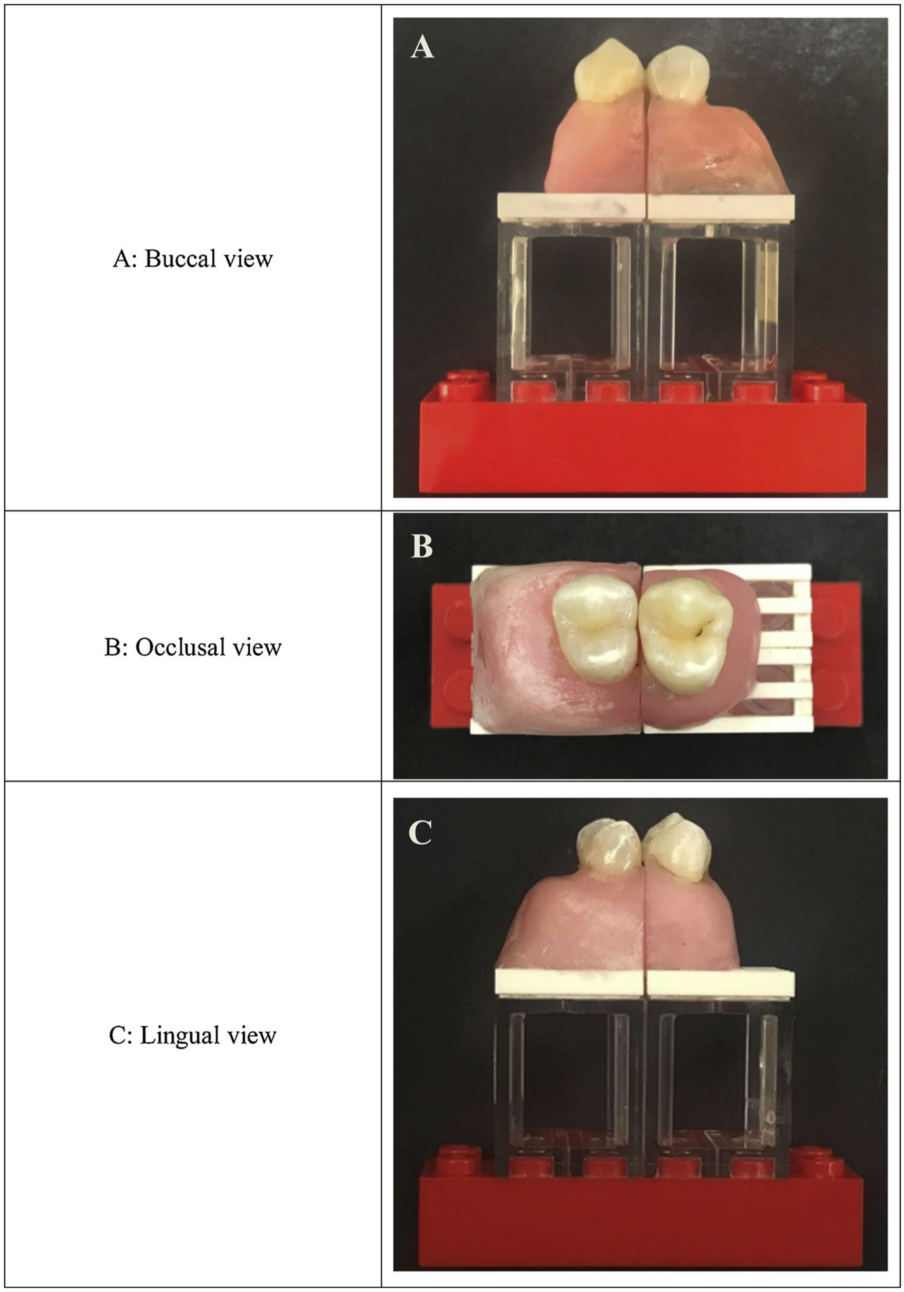


Fig. 1. This figure shows a model to simulate approximal contact: A) buccal view, B) occlusal view, and C) lingual view.

Technologies, Toronto, Ont., Canada) was used with the quick scan setting under the manufacturer's instruction. The examiner, who was trained to perform PTR/LUM examination, was independent of the one who selected teeth and the two who scored the teeth by μ-CT criteria. The model was assembled immediately after the tooth was taken out of the container. Each tooth was scanned from three directions: buccal, lingual, and occlusal [three occlusal locations: perpendicular to the marginal ridge just above contact point (Occlusal-middle) and 1 mm shifted to buccal (Occlusal-buccal) and 1 mm shifted to lingual (Occlusal-lingual)]. To make this 1 mm shift, the precision microscope mechanical stage was used to locate the scanning points (Fig. 2). This mechanical stage includes controls that allow precise movement of the specimen slide.

Each PTR/LUM scan was given a number rating (Canary Number, 0–100). Based on the manufacturer's instruction, the healthy zone (Canary Number: 0–20) indicates no evidence of caries lesions, Canary Number 21–70 indicates decay, while Canary Number 71–100 indicates advanced decay [16]. For each scan, PTR/LUM value was recorded. Before scanning, to standardize hydration, the buccal and lingual surfaces and the marginal ridge were moistened by cotton pellet with deionized water for 1 min. The manufacturer recommended PTR/LUM could be used for detection on a wet surface, just avoiding pools of water or saliva, because PTR/LUM value showed no significant difference in signal whether the tooth surface was wet or not [26]. In order to evaluate intra examiner repeatability, all measurements were repeated 48 h later.

2.3. Statistical analysis

Statistical analyses were performed using the following nine values: Buccal, Lingual, Occlusal-middle, Occlusal-buccal, Occlusal-lingual, average (Occlusal-average) and maximum value (Occlusal-max) of three occlusal locations, average value (All-average) and maximum value (All-max) of all measurements. Intraclass correlation coefficients

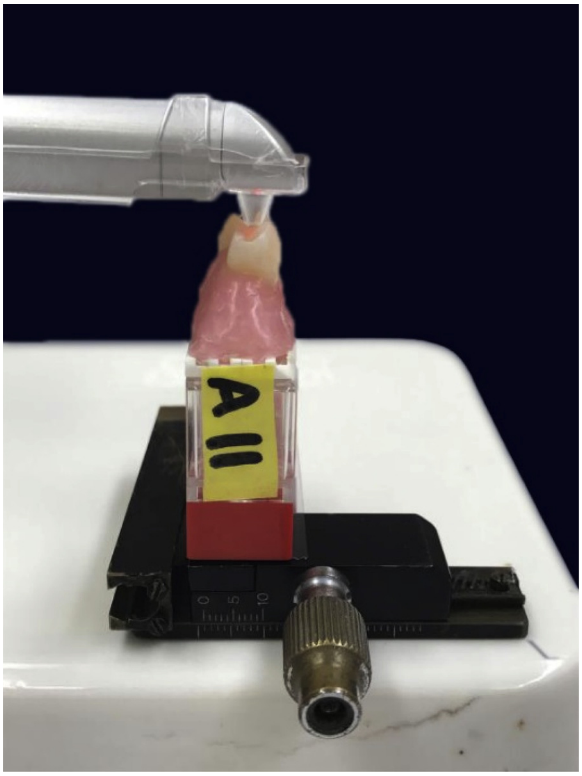


Fig. 2. This figure shows how precision of occlusal scanning was performed. A microscope mechanical stage was used to locate the scanning points.

(ICC) were used to evaluate intra examiner repeatability. Sensitivity, specificity, area under ROC curve (AUC), correlation with μ-CT and were calculated using bootstrap analyses.

2.4. Sample size calculation

Data from previous studies indicated a correlation of approximately 0.7 between methods. With a sample size of 10 sound teeth and 5 teeth for each of E1, E2, and D1, the study was designed to have 80 % power to detect a difference in the area under the ROC curve of 0.23 (0.67 *vs.* 0.90), assuming a two-sided test with a 5 % significance level.

3. Results

Summary statistics of PTR/LUM values for each direction were shown in Table 1. Typical cross-sectional images of μ-CT images were presented in Fig. 3.

3.1. Sensitivity

Overall sensitivity was shown in Fig. 4 and Table 2, and sensitivity at three μ-CT thresholds were presented in Fig. 4.

For overall sensitivity, All-max measurements (61 %) was significantly higher than Lingual, Occlusal-middle, Occlusal-buccal, Occlusal-lingual, Occlusal-average, Occlusal-max, and All-average measurements ($p < 0.001$). Overall sensitivity for Buccal (47 %) was significantly higher than Lingual ($p = 0.015$), Occlusal-middle ($p = 0.009$), Occlusal-buccal ($p = 0.010$), Occlusal-lingual ($p = 0.001$), Occlusal-average ($p = 0.015$), Occlusal-max ($p = 0.050$), and All-average measurements ($p = 0.002$).

As for the sensitivity at three μ-CT scores, it increased as μ-CT score increased for Buccal and All-max measurements. For μ-CT = 1, sensitivity was significantly higher for All-max measurements (50 %) than for Occlusal-middle ($p = 0.027$) and Occlusal-lingual ($p = 0.027$). For both μ-CT = 2/μ-CT = 3, sensitivity was significantly higher for All-max measurements (58 %/74 %) than for Lingual ($p = 0.006/0.007$), Occlusal-middle ($p = 0.046/0.001$), Occlusal-buccal ($p = 0.020/0.001$), Occlusal-lingual ($p = 0.006/0.001$), Occlusal-average ($p = 0.046/0.001$), Occlusal-max ($p = 0.046/0.007$), and All-average measurements ($p = 0.006/0.007$). For μ-CT = 2, sensitivity was significantly higher for Buccal (42 %) than for Lingual ($p = 0.046$), Occlusal-lingual ($p = 0.046$), and All-average measurements ($p = 0.046$). As for μ-CT = 3, sensitivity was significantly higher for Buccal (66 %) than for Occlusal-middle ($p = 0.034$), Occlusal-buccal ($p = 0.007$), Occlusal-lingual ($p = 0.034$), and Occlusal-average ($p = 0.034$) measurements.

3.2. Specificity, AUC, correlation with μ-CT, and ICC

Specificity, AUC, correlation with μ-CT, and ICC are presented in Table 1. Specificity of all measurements was 100 %. The AUC ranged from 0.65 to 0.88. Fig. 5 shows the ROC curves for each probing direction. AUC was significantly lower for Occlusal-buccal than Occlusal-average ($p = 0.032$), All-average ($p = 0.006$), and All-max measurements ($p = 0.025$). For Lingual, AUC was significantly lower than All-average measurements ($p = 0.021$). PTR/LUM showed weak to moderate correlations with μ-CT scores. Among all measurements, All-max had the highest ICC (0.74), while the ICC of the other measurements were 0.24-0.64.

Table 1
Summary statistics of PTR/LUM values for each probing direction.

Probing Direction	N	Mean (SD)	Median (Q1, Q3)	Min	Max
Buccal	30	18.2 (3.8)	18 (15, 20)	12	26
Lingual	30	17.2 (3.5)	18 (16, 19)	11	26
Occlusal-middle	30	16.7 (3.7)	17 (14, 19)	9	28
Occlusal-buccal	30	15.3 (3.3)	15 (14, 17)	9	23
Occlusal-lingual	30	14.8 (3.9)	16 (12, 18)	7	24
Occlusal-average	30	15.6 (3.1)	16 (13, 18)	9.7	23.7
Occlusal-max	30	17.7 (3.3)	18 (15, 19)	11	28
All-average	30	16.4 (2.7)	18 (14, 18)	10.8	23.2
All-max	30	19.9 (3.6)	19 (17, 23)	13	28

4. Discussion

Technology-based caries detection methods, such as Quantitative light-induced fluorescence (QLF), red laser fluorescence device (DIAGNOdent: DD, KaVo, Biberach, Germany), near infrared light transillumination (NILF), and optical coherence tomography (OCT), have been developed in the past years. When detecting approximal enamel and dentinal caries, QLF has comparable performance to the visual inspection and radiography [27]. DD has better value when detecting occlusal caries rather than approximal surfaces [28]. NILF has similar sensitivity and specificity to DR when detecting non-cavitated approximal caries [29]. OCT can be used in many aspects, *e.g.* indicating tooth demineralization [30], measuring enamel thickness [31], monitoring early enamel occlusal caries and lesion progression over time [32,33]. However, there are no published studies about using OCT to detect non-cavitated approximal caries of posterior teeth, especially with the adjacent teeth existing.

PTR/LUM is another non-invasive, non-ionizing radiation, non-contacting method to detect caries. PTR/LUM value (Canary Number) are calculated from PTR-amplitude response, PTR-phase response, LUM-amplitude response, and LUM-phase response, which measure the reflected heat and light [18]. PTR/LUM value showed good correlation with volume of demineralized tissue and the lesion depth measured with TMR results [20,34] and μ-CT mineral loss measurements [20], when detecting smooth surface and occlusal caries. Based on the manufacturer's instruction, the decay zone (Canary Number: 21–70) indicates lesions with depth of 532 ± 322 μm, and the advanced decay

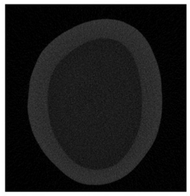
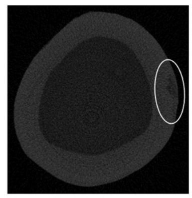
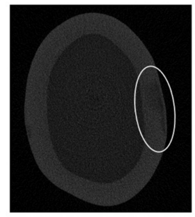
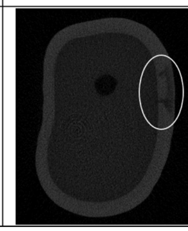
μ-CT=0	μ-CT=1	μ-CT=2	μ-CT=3
Canary Number 0-20	Canary Number 21-100		
Sound surface	Lesion in the outer half of the enamel	Lesion in the inner half of the enamel	Lesions in the outer one third of the dentin
			

Fig. 3. This figure represents typical cross-sectional images of μ-CT image for each category. White circle indicates location of caries lesion.

zone (Canary Number: 71–100) indicates lesion depth of 1057 ± 441 μm [35].

4.1. Ability of PTR/LUM for detection of non-cavitated approximal caries

The overall sensitivity of All-max was 61 % in this current study. As the severity of caries increased (from μ-CT = 1–3), the sensitivity of All-max increased from 50 % to 74 %. Overall sensitivity for Buccal was 47 %, it also increased from 33 % to 66 % as the severity of caries increased. There are no published articles mentioning that deeper caries appeared to be detected easier than enamel lesion by PTR/LUM. This current study clarified that PTR/LUM might be more reliable to detect deeper approximal lesions, especially dentinal lesions. For the occlusal direction, the three locations (perpendicular to the marginal ridge just above contact point, 1-mm shifted to buccal and 1-mm shifted to lingual) did not show significant differences for sensitivity. Occlusal-max had the highest sensitivity value (16 %) among all occlusal measurements. Since natural caries does not develop as uniformly as artificial caries, it's impossible for an examiner to know the location and the geometry of natural caries [36]. Therefore, scanning multiple locations and using the highest value will be recommended.

When comparing the results across studies, multiple factors need to be considered [37]: 1) *in vivo* or *in vitro* studies; 2) the method for obtaining a 'gold standard'; 3) the origin of the study teeth; 4) prevalence of caries in the *in vivo* samples, or simulation techniques applied in *in vitro* studies; 5) disease cut-off value. Taking into consideration of those factors, we compared this current study with two prior studies. PTR/LUM showed higher sensitivity (93.3 %) than this current study in one *in vitro* study [23], possibly due to the sample population. The prior study included all types of extracted teeth with cavitated and non-cavitated lesions. As this current study demonstrated that PTR/LUM may be more suitable for deeper caries detection, another study concluded deeper dentinal caries and cavitated lesions may be the reason for achieving higher sensitivity [38], which may explain the higher sensitivity of PTR/LUM than found in current study. For another *in vivo* study [22], the sensitivity of PTR/LUM was 81 % when detecting approximal caries of primary molars, with bitewing radiographs as the gold standard. In this current study, when the caries extended to the outer one-third of dentine, the sensitivity of All-max was 74 %, which was comparable to that *in vivo* study. They included more than half of teeth with no radiographic radiolucency, and only 4 % of teeth (3/75) with dentinal radiographic radiolucency. The sample population was quite opposite with this current study, which included more than half of teeth with non-cavitated caries. This result may remind researchers to do more research based on different caries extensions.

4.2. Repeatability of PTR/LUM

Intraclass correlation coefficients (ICC) were used to evaluate intra examiner repeatability. This current study showed the lowest ICC was 0.24 (Occlusal-lingual) and the highest ICC was 0.74 (All-max). This indicates that PTR/LUM may not be able to repeat, which is supported by others. *In vitro* detection of occlusal caries on permanent teeth

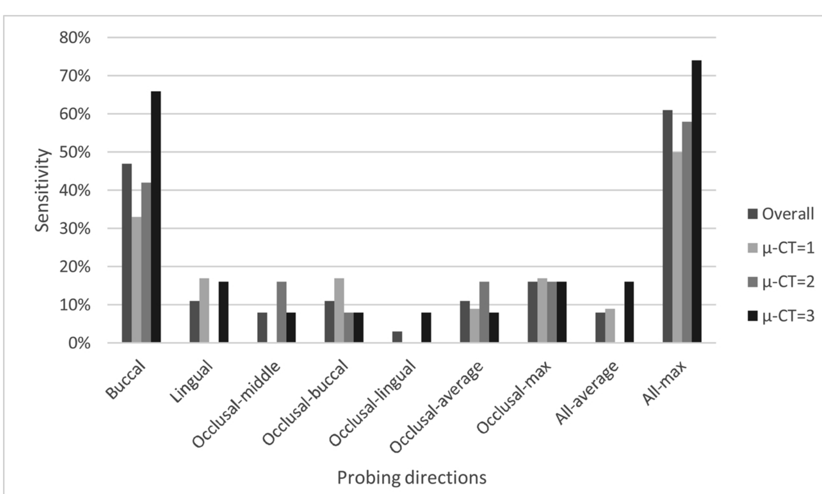


Fig. 4. Overall sensitivity and sensitivity based on μ-CT lesion extension.

Table 2
Overall sensitivity, specificity, Area under ROC curve (AUC), correlation with μ-CT scores, and Intraclass Correlation Coefficient (ICC).

Probing direction	Overall sensitivity	Specificity	AUC	Correlation with μ-CT scores	P value	ICC
Buccal	47%	100%	0.81	0.60	< .001	0.45
Lingual	11%	100%	0.71	0.31	0.072	0.47
Occlusal-middle	8%	100%	0.78	0.51	< .001	0.37
Occlusal-buccal	11%	100%	0.65	0.17	0.324	0.48
Occlusal-lingual	3%	100%	0.78	0.41	0.007	0.24
Occlusal-average	11%	100%	0.81	0.48	< .001	0.54
Occlusal-max	16%	100%	0.79	0.49	0.001	0.63
All-average	8%	100%	0.88	0.61	< .001	0.64
All-max	61%	100%	0.86	0.62	< .001	0.74

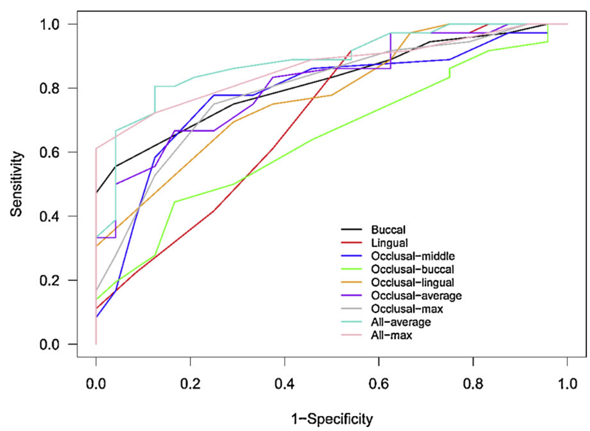


Fig. 5. ROC curves of the PTR/LUM examination for each probing direction.

showed that the ICC value of intra-examiner repeatability ranged from 0.33 to 0.63, which was similar with this current study [19]. An *in vivo* study showed that the diff ;erence of maximum and minimum PTR/LUM values per study tooth ranged from 2 to 52 [22]. There are two potential reasons for presenting lower repeatability. One can be the strict scanning diameter of PTR/LUM and the other reason can be characteristics of natural caries lesions, which is natural caries lesion do not develop uniformly. The scanning diameter of PTR/LUM is 1.5 mm. It is not easy to reposition the PTR/LUM handpiece at the same location exactly over and over. Additionally, the shape of a caries lesion is not uniform so that different locations may have different depth/severity of caries lesion. Since All-max showed the highest ICC, this suggests the maximum value from multiple scanning directions should be considered as the final result.

4.3. Effect of scanning direction

For scanning direction, overall sensitivity for Buccal, Lingual, and Occlusal-max was 47 %, 11 %, and 16 % separately. When scanning approximal surfaces from buccal or lingual directions, the laser beam transmitted from teeth embrasures, not directly from the tooth surface. PTR/LUM collects infrared radiation emitted from the tooth surface by an infrared detector. The angle between the infrared detector and the laser beam was designed as 80° [17]. This restriction indicates that signals from a narrow entrance would not be all detected, such as signals from fissures and contact area [17]. Therefore, when detecting approximal surfaces, some signals may be blocked by the neighbor tooth which can decrease the PTR/LUM value. Another potential reason can be the thickness of sound enamel from tooth surface to approximal caries. The PTR amplitude decreases as the thickness of the enamel increases [16]. Since it is impossible to directly assess/scan approximal surfaces, but only through the corresponding marginal ridge, buccal and lingual surfaces, the sound enamel existing from the contact area to the tooth surface would decrease the PTR/LUM value.

Although overall sensitivity for Buccal, Lingual, and Occlusal-max were not high, the buccal direction still showed significantly higher sensitivity than lingual and occlusal directions. That might because the location of approximal caries might not be only in the contact area, but also in subcontact area and cervical area. The bucco-lingual extension of lesions mostly is near the buccal surface [36]. As thickness of sound enamel from the surface to caries lesion might be thinner and the distance between the handpiece and the surface was shorter than other directions, the PTR/LUM value increases as mentioned earlier. Those could increase sensitivity from the buccal direction. Despite the locations of approximal caries, scanning/assessment from buccal surface may be better than other directions. However, there are some issues need to be considered. It's not easy to scan/probe PTR/LUM from buccal direction compared to the occlusal direction. One of the reasons is that it is difficult to place the PTR/LUM handpiece tip to the buccal embrasure space. Another challenge is that the examiner carefully evaluates the location of the approximal contact area to make sure the tip scanning/probing the contact area as close as possible.

Therefore, when detecting approximal caries, even though the performance of scanning from the buccal direction was better than from the occlusal and lingual directions, scanning from all three directions (buccal, lingual and occlusal directions) is recommended. Since All-max of PTR/LUM values presented the highest overall sensitivity in this current study, it is recommended to scan multiple locations/directions to obtain the maximum PTR/LUM value.

4.4. PTR/LUM cut-off/threshold issue

AUC is a more comprehensive measurement of diagnostic performance than single values of sensitivity and specificity [37]. For this current *in vitro* study, even though the sensitivity was not high, the AUC was ranged from 0.65 to 0.88. Based on the manufacturer's cut-off, the specificity of all scanning directions was 100 % in this current study. These results suggest a need to determine optimal cut-off values. When the cut-off value of PTR/LUM decreased from 25 to 20 on smooth surfaces, the sensitivity increased from 75 % to 85 %, while the specificity decreased from 64 % to 43 % [19]. The same issue was observed for DD, which outputs DD numbers 0-99. Cut-off values for DD selected by manufacturers are 0–9: sound/early enamel caries; 10–17: enamel caries; 18–99: dentinal caries [39]. However, based on the correlation between the measured values and demineralization depth, other study found that the optimal cut-off values between enamel caries to dentinal caries should be different from fissure caries (DD: 16–21) to smooth surface caries (9–11) [40]. Considering factors which would decrease PTR/LUM values when detecting approximal caries, *e.g.* the thickness of sound enamel between the handpiece and the caries, and the incident angle of the laser beam, the optimal cut-off values of PTR/LUM in approximal caries might be different from smooth surface, as happened for DD. Further study is needed to determine the optimal cut-off values of PTR/LUM for not only approximal caries, but also smooth surfaces.

In summary, the maximum measurement value of all scanning directions showed significantly higher sensitivity than other measurements except for the buccal direction. As lesions got deeper, the sensitivity for the maximum value of all scanning directions increased. PTR/LUM-value showed weak to moderate correlations with severity of lesions. Sensitivity was significantly higher from buccal direction than from lingual and occlusal.

5. Conclusion

Within the limitations of this *in vitro* study, PTR/LUM non-cavitated approximal caries lesion detection achieved best individual results from the buccal direction, while using the maximum value from all directions might improve performance. PTR/LUM appears more suitable to detect non-cavitated approximal dentinal caries rather than enamel caries.

Declaration of Competing Interest

The authors declare no conflict of interest.

References

[1] P.E. Petersen, D. Bourgeois, H. Ogawa, S. Estupinan-Day, C. Ndiaye, The global burden of oral diseases and risks to oral health, Bull. World Health Organ. 83 (9) (2005) 661–669.
[2] R.A. Bagramian, F. Garcia-Godoy, A.R. Volpe, The global increase in dental caries. A pending public health crisis, Am. J. Dent. 22 (1) (2009) 3–8.
[3] N.J. Kassebaum, E. Bernabé, M. Dahiya, B. Bhandari, C.J.L. Murray, W. Marcenes, Global burden of untreated caries: a systematic review and metaregression, J. Dent. Res. 94 (5) (2015) 650–658.
[4] K.V. Arunkumar, Orbital infection threatening blindness due to carious primary molars: an interesting case report, J. Maxillofac. Oral Surg. 15 (1) (2016) 72–75.
[5] J.D.B. Featherstone, The continuum of dental caries-evidence for a dynamic disease process, J. Dent. Res. 83 (1_suppl) (2004) 39–42.
[6] R.H. Selwitz, A.I. Ismail, N.B. Pitts, Dental caries, Lancet 369 (9555) (2007) 51–59.
[7] J.E. Frencken, M.C. Peters, D.J. Manton, S.C. Leal, V.V. Gordan, E. Eden, Minimal intervention dentistry for managing dental caries–a review: report of a FDI task group, Int. Dent. J. 62 (5) (2012) 223–243.
[8] H. Hintze, A. Wenzel, B. Danielsen, B. Nyvad, Reliability of visual examination, fibre-optic transillumination, and bite-wing radiography, and reproducibility of direct visual examination following tooth separation for the identification of cavitated carious lesions in contacting approximal surfaces, Caries Res. 32 (3) (1998) 204–209.
[9] K.R. Ekstrand, S. Martignon, D.J.N. Ricketts, V. Qvist, Detection and activity assessment of primary coronal caries lesions: a methodologic study, Oper. Dent. 32 (3) (2007) 225–235.
[10] J.C. Hamilton, G. Stookey, Should a dental explorer be used to probe suspected carious lesions? J Am Dent Assoc. 136 (11) (2005) 1526–1532.
[11] A. Wenzel, Bitewing and digital bitewing radiography for detection of caries lesions, J. Dent. Res. 83 (1_suppl) (2004) 72–75.
[12] J.D. Bader, D.A. Shugars, A.J. Bonito, Systematic reviews of selected dental caries diagnosis and management methods, J. Dent. Educ. 65 (2001) 960–968.
[13] F. Abesi, A. Mirshekar, E. Moudi, M. Seyedmajidi, S. Haghanifar, N. Haghighat, A. Bijani, Diagnostic accuracy of digital and conventional radiography in the detection of non-cavitated approximal dental caries, Iran. J. Radiol. 9 (1) (2012) 17.
[14] J. Gomez, Detection and diagnosis of the early caries lesion, BMC Oral Health 15 (1_Suppl) (2015) S3.
[15] S. Abrams, Overcoming the challenges of caries detection using the Canary System, Oral Health 101 (12) (2011) 17.
[16] L. Nicolaides, C. Feng, A. Mandelis, S.H. Abrams, Quantitative dental measurements by use of simultaneous frequency-domain laser infrared photothermal radiometry and luminescence, Appl. Opt. 41 (4) (2002) 768–777.
[17] R.J. Jeon, C. Han, A. Mandelis, V. Sanchez, S.H. Abrams, Diagnosis of pit and fissure caries using frequency-domain infrared photothermal radiometry and modulated laser luminescence, Caries Res. 38 (6) (2004) 497–513.
[18] J.D. Silvertown, S.H. Abrams, K.S. Sivagurunathan, J. Kennedy, J. Jeon, A. Mandelis, A. Hellen, W. Hellen, G. Elman, R. Ehrlich, R. Chouljian, Y. Finer, B.T. Amaechi, Multi-centre clinical evaluation of photothermal radiometry and luminescence correlated with international benchmarks for caries detection, Open Dent. J. 11 (2017) 636–647.
[19] M. Jallad, D. Zero, G. Eckert, A. Ferreira Zandona, In vitro detection of occlusal caries on permanent teeth by a visual, light-induced fluorescence and photothermal radiometry and modulated luminescence methods, Caries Res. 49 (5) (2015) 523–530.
[20] R.J. Jeon, A. Matvienko, A. Mandelis, S.H. Abrams, B.T. Amaechi, G. Kulkarni, Detection of interproximal demineralized lesions on human teeth in vitro using frequency-domain infrared photothermal radiometry and modulated luminescence, J. Biomed. Opt. 12 (3) (2007) 034028-13.
[21] R.J. Jeon, A. Matvienko, A. Mandelis, S.H. Abrams, B.T. Amaechi, G. Kulkarni, Interproximal dental caries detection using Photothermal Radiometry (PTR) and modulated Luminescence (LUM), Eur. Phys. J. Spec. Top. 153 (1) (2008) 467–469.
[22] K. Herzog, M. D'Elia, A. Kim, R.L. Slayton, Pilot study of the canary system use in the diagnosis of approximal carious lesions in primary molars, Pediatr. Dent. 37 (7) (2015) 525–529.
[23] J. Jan, W.Z. Wan Bakar, S.M. Mathews, L.O. Okoye, B.R. Ehler, C. Louden, B.T. Amaechi, Proximal caries lesion detection using the Canary Caries Detection System: an in vitro study, J. Investig. Clin. Dent. 7 (4) (2016) 383–390.
[24] K. Herzog, M. D'Elia, A. Kim, R.L. Slayton, Pilot study of the canary system use in the diagnosis of approximal carious lesions in primary molars, Pediatr. Dent. 37 (7) (2015) 525–529.
[25] K.R. Ekstrand, D.N. Ricketts, E.A. Kidd, Reproducibility and accuracy of three methods for assessment of demineralization depth of the occlusal surface: an in vitro examination, Caries Res. 31 (3) (1997) 224–231.
[26] Quantum Dental Technologies. QDT-101 Clinical Trial, (2015) Available at: "http://www.thecanarysystem.com/researchstudies-qdt101.php ". Accessed November 10, 2015. (Archived by WebCite® at: http://www.webcitation.org/6cWqBdCkS).
[27] H.Y. Ko, S.M. Kang, H.E. Kim, H.K. Kwon, B.I. Kim, Validation of quantitative light-induced fluorescence-digital (QLF-D) for the detection of approximal caries in vitro, J. Dent. 43 (5) (2015) 568–575.
[28] A. Lussi, R. Hibst, R. Paulus, DIAGNOdent: an optical method for caries detection, J. Dent. Res. 83 (1_suppl) (2004) 80–83.
[29] N. Abogazalah, G.J. Eckert, M. Ando, In vitro performance of near infrared light transillumination at 780-nm and digital radiography for detection of non-cavitated approximal caries, J. Dent. 63 (2017) 44–50.
[30] D.P. Popescu, M.G. Sowa, M.D. Hewko, L.P. Choo-Smith, Assessment of early demineralization in teeth using the signal attenuation in optical coherence tomography images, J. Biomed. Opt. 13 (5) (2008) 054053.
[31] A. Algarni, H. Kang, D. Fried, G.J. Eckert, A.T. Hara, Enamel thickness determination by optical coherence tomography: in vitro validation, Caries Res. 50 (4) (2016) 400–406.
[32] R.S. Jones, C.L. Darling, J.D. Featherstone, D. Fried, Imaging artificial caries on the occlusal surfaces with polarization-sensitive optical coherence tomography, Caries Res. 40 (2) (2006) 81–89.
[33] M.H. Le, C.L. Darling, D. Fried, Automated analysis of lesion depth and integrated reflectivity in PS-OCT scans of tooth demineralization, Lasers Surg. Med. 42 (1) (2010) 62–68.
[34] R.J. Jeon, A. Hellen, A. Matvienko, A. Mandelis, S.H. Abrams, B.T. Amaechi, In vitro detection and quantification of enamel and root caries using infrared photothermal radiometry and modulated luminescence, J. Biomed. Opt. 13 (3) (2008) 034025.
[35] S.H. Abrams, K.S. Sivagurunathan, J.D. Silvertown, B. Wong, A. Hellen, A. Mandelis, W.M.P. Hellen, G.I. Elman, S.M. Mathew, P.K. Mensinkai, B.T. Amaechi, Correlation with caries lesion depth of the canary system, DIAGNOdent and ICDAS II, Open Dent. J. 11 (1) (2017) 679–689.
[36] W.H. Arnold, P. Gaengler, E. Saeuberlich, Distribution and volumetric assessment of initial approximal caries lesions in human premolars and permanent molars using computer-aided three-dimensional reconstruction, Arch. Oral Biol. 45 (12) (2000) 1065–1071.
[37] H.M. Van Rijkom, E.H. Verdonschot, Factors involved in validity measurements of diagnostic tests for approximal caries–a meta-analysis, Caries Res. 29 (5) (1995) 364–370.
[38] M.C. Huysmans, C. Longbottom, The challenges of validating diagnostic methods and selecting appropriate gold standards, J. Dent. Res. 83 (1_suppl) (2004) 48–52.
[39] D.C. Attrill, P.F. Ashley, Diagnostics: Occlusal caries detection in primary teeth: a comparison of DIAGNOdent with conventional methods, Br. Dent. J. 190 (8) (2001) 440–443.
[40] T. Shinohara, Y. Takase, T. Amagai, C. Haruyama, A. Igarashi, N. Kukidome, J. Kato, Y. Hirai, Criteria for a diagnosis of caries through the DIAGNOdent, Photomed. Laser Surg. 24 (1) (2006) 50–58.