e-ISSN: 2582-5208
International Research Journal of Modernization in Engineering Technology and Science
(Peer-Reviewed, Open Access, Fully Refereed International Journal)
Volume:04/Issue:05/May-2022 Impact Factor- 6.752 www.irjmets.com

EFFECTIVENESS OF PHOTOTHERMAL RADIOMETRY AND MODULATED LUMINESCENCE IN THE DETECTION OF DENTAL CARIES: A SYSTEMATIC REVIEW

Nithyalakshmi Elango*1, Sindhu R*2, Gousalya V*3, Rajmohan M*4, Bharathwaj VV*5, Dinesh Dhamodhar*6, Prabu D*7

*1Undergraduate Student, Department Of Public Health Dentistry, SRM Dental College, Ramapuram, Chennai, Tamil Nadu, India.

*2,5Senior Lecturer, Department Of Public Health Dentistry, SRM Dental College, Ramapuram, Chennai, Tamil Nadu, India.

*3Post Graduate Student, Department Of Public Health Dentistry, SRM Dental College, Ramapuram, Chennai, Tamil Nadu, India.

*4,6Reader, Department Of Public Health Dentistry, SRM Dental College, Ramapuram, Chennai, Tamil Nadu, India.

*7Head Of The Department, Department Of Public Health Dentistry, SRM Dental College, Ramapuram, Chennai, Tamil Nadu, India.

ABSTRACT

Early dental caries cannot be detected by conventional methods, thereby necessitating for development of nonintrusive, non-contacting techniques. Photothermal radiometry and modulated luminescence (PTR-LUM) is a sensitive noninvasive technique for the early detection of carious lesions. To assess the effect of PTR-LUM as a non-invasive technique in detecting dental caries. An electronic literature search was performed using PubMed, Science Direct, Wiley Online Library, National Institutes of Health, PubMed Central-National Center for Biotechnology Information using MeSH terms- PTR-LUM, dental caries and caries detection. 125 were retrieved, and 119 articles were screened. 16 full-text articles were assessed for eligibility, and a total of 7 articles, whichever satisfied the inclusion criteria, were selected for this systematic review, and the results in these articles were analyzed. This systematic literature review was reported according to the PRISMA guidelines. Seven randomized control trials were included in the review process. Seven articles included in this review assessed the effectiveness of PTR-LUM in detecting dental caries. Six out of the seven articles supported that PTR-LUM was effective in detecting and monitoring dental caries. PTR-LUM was found to be effective in detecting dental caries. It is a sensitive adjunct and reliable nonintrusive dental probe for detecting and monitoring dental caries.

Keywords: PTR-LUM, DENTAL CARIES, CARIES DETECTION, DENTAL PROBE.

I. INTRODUCTION

The most frequent chronic ailment is dental caries in the world.[1] In dental diagnostic research, the detection and monitoring of early carious lesions are becoming significant. [2-7] The existence of caries could be detected by visual inspection; however, the initiation of caries prevention measures would be too late since the lesions would have grown large and, at times, even involved the dentin.[8] Small lesions having the potential to remineralize if preventive therapies are adopted in time have necessitated efforts to develop and enhance methods for diagnosis that enable the detection of early lesions which cannot be identified by visual inspection.[9]Earlier caries detection before substantial tooth damage allows for a minimal or non-invasive treatment.[10] Early dental caries that have just begun demineralization of the underlying enamel crystal structure cannot be detected by traditional caries detection methods such as visual, tactile, and radiographic examinations. [11-14] Thus, the requirement for early detection of small initial subsurface lesions has led to the development of non-intrusive, non-contacting techniques.[8] There has been a growing interest in nondestructive, noninvasive detection of incipient dental caries due to the emergence of evidence that early implementation of preventive strategies, at the expense of invasive reparative interventions, can promote the

e-ISSN: 2582-5208
International Research Journal of Modernization in Engineering Technology and Science
(Peer-Reviewed, Open Access, Fully Refereed International Journal)
Volume:04/Issue:05/May-2022 Impact Factor- 6.752 www.irjmets.com

reuptake of inorganic ions, i.e., remineralization, consolidation and arrest of the lesion.[15] The techniques capable of quantifying the extent of progression of the lesion while avoiding constant exposure to ionizing radiation, which is harmful, are crucial in advancing clinical detection and diagnosis of caries.[15] Transverse microradiography (TMR) is the gold standard for defining the extent of lesion, mineral loss and depth.[16] But, the requirement of thin sections averts its clinical applicability and the ability to examine intact teeth, as they would be present in their natural oral environment.[15] The phenomenon of laser-induced fluorescence of the enamel makes use of lasers for dental diagnostics of early carious lesions. [8,11] One such technology is the DIAGNOdent [17,18], which is based on the optical interaction with bacterial porphyrins and enamel and not on the amount of demineralization. [15,19] To assess the viability of using this instrument, several studies have been conducted [20-22] and have been evaluated as having the potential to enhance the assessment of caries in numerous ways. However, a review conducted by Tranæus et al. [7] on three of these new methods- quantitative light-induced fluorescence (QLF), DIAGNOdent, and electronic caries monitor (ECM)- for detection and quantification of caries has concluded that these techniques did not present sufficient evidence to be recommended as a substitute for conventional methods. Still, they might provide supplementary information to determine caries activity and risk assessment. An emerging sensitive methodology for the characterization of pathological dental tissues as a dental nondestructive technique is frequency-domain photothermal radiometry (PTR). [23-26] The application of the depth profilometric capability of frequency-domain PTR toward the inspection of dental defects was first reported by Mandelis et al. [27] and Nicolaides et al. [28]. The adaptation of this technique to the early detection of carious lesions in conjunction with modulated luminescence as a dual-probe technique has inherent advantages reported. [28-32] PTR-LUM, a nonintrusive energy conversion technology, monitors two phenomena: modulated thermal infrared radiation (PTR) and alternating current luminescence (LUM).[33] Laser light modulated at a specific frequency focused on a tooth results in the emission of radiation from the tooth at the same frequency, followed by radiative conversion of part of the incident optical energy to a longer wavelength(stokes shifted) LUM. Heat is released simultaneously at the same frequency in thermal infrared photons("blackbody" or Planck radiation), followed by non-radiative conversion of the remaining incident energy. Both PTR and LUM, a wave-based phenomenon, consist of amplitude and phase. The amplitude (PTR-A) is the overall signal magnitude for the duration the laser light shines on the tooth with the PTR signal. The phase (PTR-P) refers to the delay in collecting photothermal signals by the infrared detector concerning a reference signal. [10,34-39] A complimentary signal channel, modulated LUM (in the forms of LUM-A and LUM-P), in addition to heat, monitors the conversion of optical-to-radiative energy, where there is the absorption of laser light by chromophore molecules which get raised to a higher-energy state, and following their de-excitation there is the emission of a longer wavelength luminescent light. Being a purely light-based technique, the high scattering coefficients of sound and carious enamel limit its enamel depth resolution. PTR can reach deeper areas in the tooth alone than LUM since thermal energy, unlike optical energy, does not get scattered. [10,40] With the increased severity of the lesion, there is an analogous change in the amount of infrared radiation and luminescence collected. As there is a progression of remineralization, a signal reversal trend represents the improved structural organization of the tooth. The main advantage of PTR-LUM is that it ensures high contrast against a minimal or non-absorbent healthy dental enamel since carious lesions have coefficients of optical absorption greater than healthy dental enamel, thus effecting photonic devices using PTR-LUM apt for detection of small lesions. [10,33] The Canary System®, CS is a commercially available caries detection device employing PTR-LUM technology.[41] This paper aims to assess the effect of photothermal radiometry and modulated luminescence (PTR-LUM) as a noninvasive technique in detecting dental caries.

II. MATERIAL AND METHODS

STUDY DESIGN: Systematic review

ELIGIBILITY CRITERIA:

Inclusion criteria:

- Randomized control trials and pilot studies from 2008 onwards till the recent update.
- Full-text article available in the search engine mentioned in the search strategy was included.
- Studies in which PTR-LUM was used as one of the diagnostic methods for detecting dental caries.

e-ISSN: 2582-5208
International Research Journal of Modernization in Engineering Technology and Science
(Peer-Reviewed, Open Access, Fully Refereed International Journal)
Volume:04/Issue:05/May-2022 Impact Factor- 6.752 www.irjmets.com

Exclusion criteria:

- Non-randomized studies
- Studies without PTR-LUM for the detection of caries were excluded.
- Animal studies

SEARCH STRATEGY

Published literature on assessing the effect of photothermal radiometry and modulated luminescence (PTR-LUM) as a noninvasive technique for caries detection, which includes original articles and research papers in databases such as PubMed, Science Direct, Wiley Online Library, Cochrane Library, National Institutes of Health (NIH), PubMed Central-National Center for Biotechnology Information (PMC-NCBI) were taken into study for review from October to November 2021. A literature search was done to collect relevant data was performed using MeSH terms "PTR-LUM, dental caries and caries detection".

SEARCH ENGINE

- PubMed
- Science Direct
- Wiley Online Library
- Cochrane Library
- National Institutes of Health (NIH)
- PubMed Central-National Center for Biotechnology Information (PMC-NCBI)

RESULTS

The search yielded 125 records, and 16 full-text articles were independently assessed. Among these 16 articles, seven articles were included for the review.

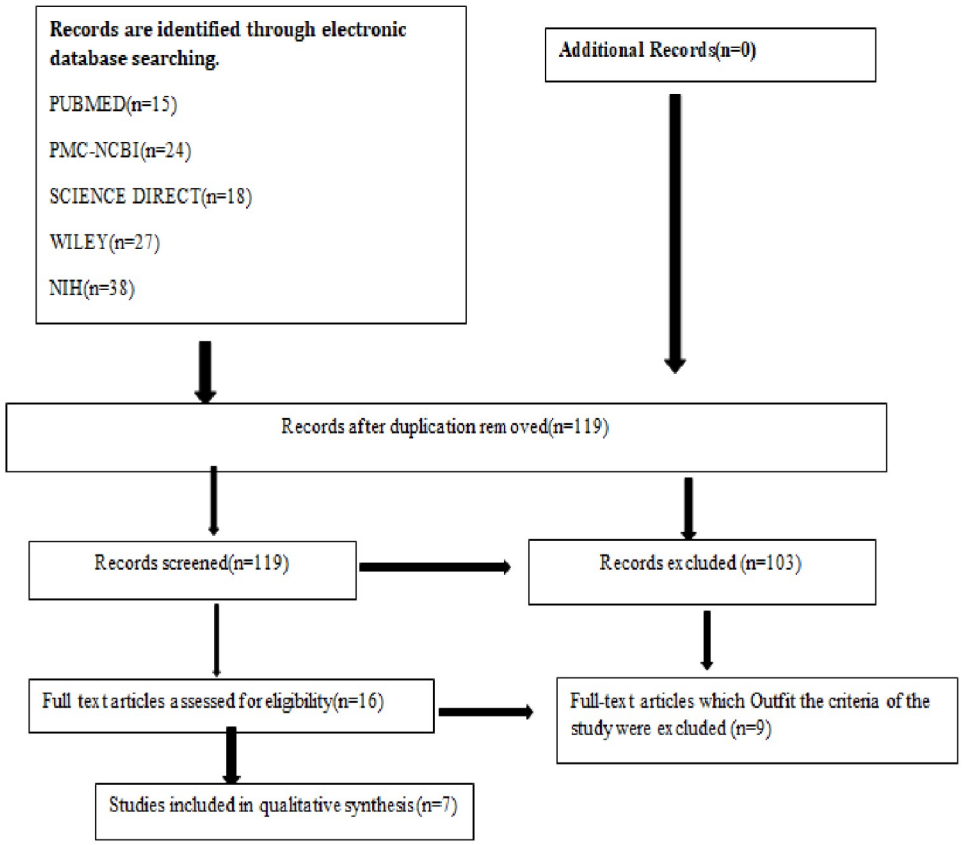

Figure 1: Flow diagram showing the number of studies identified, screened, assessed for eligibility, excluded and included in the systematic review

e-ISSN: 2582-5208
International Research Journal of Modernization in Engineering Technology and Science
(Peer-Reviewed, Open Access, Fully Refereed International Journal)
Volume:04/Issue:05/May-2022 Impact Factor- 6.752 www.irjmets.com

Table 1: Characteristics Of The Interventions In The Included Studies

S.NO	AUTHOR NAME	YEAR	TYPE OF STUDY	MATERIALS AND SAMPLE SIZE	METHODOLOGY	
					Pre-experimental interventions	Experimental interventions
1	Mahmoud Jallad et al. [42]	2015	Randomized control trial	60 human non restored posterior teeth with equal no. of molars and premolars were selected with occlusal surface sites ranging from sound to non-cavitated lesions (ICDAS 0-4), which had fully formed roots and no lesions beyond ICDAS score three on either smooth or proximal surfaces.	0.1% thymol solution is used to store the teeth initially. Then, a bristle brush mounted on a slow-speed rotary handpiece is used for cleaning, after which the teeth are rinsed with deionized water (DI) 20 times for 14 days and later stored in DI water temperature of 4°C.	**The Canary System ®:** The examiner dried the occlusal surface of teeth with canned-gas air for 5 secs. The canary wand tip was placed perpendicular and as near as possible to the site that had to be examined. The measurement was recorded on a scale of 0 to 100(Canary number, CN) through the quick scan mode. **Other diagnostic methods:** a) **International Caries Detection and Assessment System (ICDAS) criteria** Two quantitative light-induced fluorescence (QLF) systems – **Inspektor TM Pro** and **QLF-D Biluminator TM 2** (Inspektor Research Systems B.V., Amsterdam, The Netherlands)
2	R.J. Jeon et al. [43]	2004	Randomized control trial	Fifty-two extracted human teeth, 25 molars, 21 bicuspids and six primary molars were	0.9% sodium chloride is used to store the tooth samples in vials before the experiment to avoid dehydration and	**PTR and LUM scanning:** The tooth was placed on the sample stage, and the laser was focused on the

				assessed.	contamination. After removal from the vial, the sample tooth was rinsed thoroughly with clean water for more than 20s and later dried with pressurized air.	sample tooth by adjusting a three-axis micrometre stage. The PTR and LUM signals sources were two semiconductor lasers of wavelength 659nm (maximum power 30 mW; Mitsubishi ML1016R-01) and 830 nm (maximum power 100 mW Sanyo DL-7032–001). First, a diode laser driver (Coherent 6060) was used for the laser, activated by the lock-in amplifier's internal function generator (Stanford Research SR83), which modulated the laser current harmonically. Next, a frequency scan was done, measuring the PTR and LUM signals at each measurement point by varying frequency from 1Hz to 1kHz. **Other diagnostic methods:** **Visual inspection** **b) Radiographic examination** **c) DIAGNOdent**
3	Josh D. Silvertown et al. [44]	2016	Randomized control trial	Forty extracted permanent human teeth, including molars and premolars, were selected. Of the 40 teeth,	0.1% thymol is used to store the teeth in vials. After removing the vial, each tooth sample is rinsed thoroughly with clean distilled water for the 20s and air-	**The Canary System:** Under the manufacturer's operating instructions, The Canary System (L-CS-CO-001;

				105 occlusal surfaces without debris, stains, restorations, sealants, plaque or cavitations were chosen, which had statuses of visually-sound enamel and early caries lesions. One of 4 opaque sealant groups was randomly assigned to the selected teeth (10 teeth/group): (a) Delton (Dentsply International, York, PA, USA); (b) Embrace WetBond (Pulpdent, Watertown, MA, USA); (c) Helioseal F (Ivoclar Vivadent, Amherst, NY, USA); and (d) Ultradent Products (South Jordan, UT, USA).	dried for 5s before scanning. Photographs were taken of the occlusal surfaces on which the positions of the examined sites were marked clearly. In addition, landmarks with known distances were made on each tooth surface from the scanned spots.	Qantram Dental Technologies, Toronto, Canada) is used to obtain the CN readings before and after applying sealant from the occlusal surface. Over the examination sites, the cone of the disposable plastic tip on the handpiece was positioned, and scanning was done with The Canary System. Following scanning, teeth in each treatment group were sealed with the corresponding sealant. After sealant application, scanning is repeated. Three measurements were taken for each site, and the mean CN calculation was done. **Other diagnostic methods:** • **DIAGNOdent**
4	R.J. Jeon et al. [45]	2008	Randomized control trial	Seventeen pairs of extracted human teeth with healthy mesial and distal surfaces, which had no visible defects, cracks or stains, were selected.	After careful cleaning of each pair with a toothbrush and polishing paste (Temrex), mounting on LEGO blocks (15.8mm(W)* 15.8mm(D)* 9.5mm(H)) allowed the separation of teeth. During	Two semiconductor lasers of wavelengths 670nm(450mW) and 659nm(80Mw) were the sources of PTR and LUM signals. After collecting the

					repeated measurements, the teeth were remounted into the exact position. Preliminary tests were performed to assess the ability of PTR to detect mechanical holes that were generated by ¼-round carbide dental burs, and 37% phosphoric acid is etched for 20secs on the inter-proximal contact spots. Inter-proximal caries simulation is done using a partially saturated acidic buffer system containing 2.2Mm potassium phosphate, monobasic (KH_2PO_4), 50Mm acetic acid (NaOAc), 2.2 mM of 1M calcium chloride (CaCl2), 0.5 ppm fluoride (F−), and potassium hydroxide (KOH) for balancing out the pH at 4.5. the treated area is located at the contact point with the adjacent tooth and is approximately 2≈3mm. Examination of each sample pair is done before and after micro-machining or treatment at sequential treatment periods of duration 6 hours to 30 days is	modulated infrared PTR signal from the tooth, it was focused by two off-axis paraboloidal mirrors onto a Mercury Cadmium Telluride detector. A photodetector of spectral bandwidth 300nm≈1.1µm was used to monitor the modulated luminescence. Two lock-in amplifiers are connected and controlled by the computer via RS-232 ports to measure PTR and LUM signals. With each sample, three kinds of experiments were performed: 1)an interproximal scan was taken. 2)a line scan was performed. 3)a frequency scan in which the PTR and LUM signals were measured at the centre of the treated area by frequency varying between 1Hz to 1kHz.

e-ISSN: 2582-5208
International Research Journal of Modernization in Engineering Technology and Science
(Peer-Reviewed, Open Access, Fully Refereed International Journal)
Volume:04/Issue:05/May-2022 Impact Factor- 6.752 www.irjmets.com

					performed.	
5	Janja Jan et al. [46]	2015	Randomized control trial	Seventy extracted human permanent teeth, including molars, premolars, canines, and incisors with or without caries, were evaluated. In the carious teeth selected, the carious lesions were either cavitated or non-cavitated with varying levels of severity that cut across the seven ICDAS-II codes (0 to 6). Teeth with extensive cavitation visible from the buccal, lingual, and occlusal tooth surfaces were excluded.	Each tooth surface is dried for 5 secs using a dental air-water syringe before imaging.	**The Canary System** (Quantum Dental Technologies Toronto, ON, Canada) assessed the proximal surfaces via the corresponding marginal ridge at the angle of the buccal and lingual surfaces, and the Canary number was recorded. Then, following the manufacturer's instructions, the highest value from the three measurements of each surface was recorded. **Other diagnostic methods:** a) **International Caries Detection and Assessment System (ICDAS) II** b) **Bitewing radiography (BW)**
6	Adeyinka F. Dayo et al. [47]	2019	Randomized control trial	Fifty-four extracted human teeth with 35 carious surfaces, and 35 non-carious surfaces were used. In selecting teeth, extracted molar or premolar teeth without any defects apart from caries limited	The extracted teeth were collected, cleaned, immersed in 10% formalin for two weeks and stored in 0.1% thymol solution to maintain the tissue hydration and bacterial growth prevention. The samples are washed with distilled water and then stored in distilled water	**The PTR/LUM system** was set on a quick scan mode, and scanning of the gingival floors of the restored teeth was done by placing the tip of the PTR/LUM handpiece on the occlusal surface of the marginal ridge of the restoration, perpendicular and as close as possible

				to the crown were included. Teeth with root caries, forceps marks, cracks, abrasion, endodontic treatment, stains, gross tooth structure loss, non-carious cervical lesions, and fractures were excluded.	before scanning. On the proximal surfaces of all 70 teeth, class 2 composite restorations were prepared. To simulate the proximal contact points, mounting of teeth in sets of four to five on a 1*1*3 cm^2 rectangular block of Sil-Tech condensation silicone with thirteen blocks was done for the study.	to the examination site. Under the manufacturer's instructions. The device automatically generated the Canary Numbers (CN). Each surface of the restored tooth was scanned three times, and the average CN was recorded. To assess intra-observer agreement, eleven of the surfaces. (6 carious and five sound) were rated twice with an interlude of one week. **Other diagnostic methods:** **Digital intraoral radiography (IR)** **b) Cone-beam computed tomography (CBCT)**
7	Haixia Xinga et al. [48]	2019	Randomized control trial	Based on micro-computed tomography (< UNK>- CT), thirty extracted human premolars with sound or non-cavitated lesions into the outer one-third of the dentine were selected based on micro-computed tomography(μ-CT). Teeth with	Robinson's brush is used to clean all teeth under water on a slow speed rotary handpiece. The samples are stored in 0.1% thymol solution in an air-tight humid container at 4°C. To simulate approximal contact, Triad® visible light cure resin (DENTSPLY International, Inc., York, USA) to mount and secure the 30 study teeth and two neighbour sound	Under the manufacturer's instructions, the PTR/LUM instrument (Canary System®, Quantum Dental Technologies, Toronto, Ont., Canada) was used with the quick setting. Scanning of each tooth was done from three directions: buccal, lingual and occlusal [three occlusal positions: perpendicular to

e-ISSN: 2582-5208
International Research Journal of Modernization in Engineering Technology and Science
(Peer-Reviewed, Open Access, Fully Refereed International Journal)
Volume:04/Issue:05/May-2022 Impact Factor- 6.752 www.irjmets.com

				any visible defects, stains, fluorosis or cracks were excluded.	teeth on plastic Lego® bricks.	the marginal ridge just above the contact point (Occlusal-middle) and 1 mm shifted buccally (Occlusal-buccal) and 1 mm shifted lingually (Occlusal-lingual)]. A precision microscope mechanical stage was used to locate the scanning points to make the 1mm shift. The PTR/LUM value was recorded for each scan. All measurements were repeated 48h later for evaluation of intra examiner repeatability.

Table 1 shows the information on the final included studies, such as the author's name, study design, number of teeth, and descriptive information on the intervention done for each study.

Table 2: Outcome Data As Reported In Included Studies

S. No	Author Name	Year	Outcome Assessment	Results
1	Mahmoud Jallad et al. [42]	2015	The combination of sensitivity and specificity was best for ICDAS, followed by QLF-D Biluminator TM 2 at an optimum threshold.	i. For the canary system: At standard threshold [CN (20)], sensitivity=0.85 and specificity=0.43. At optimum threshold [CN (25)], sensitivity=0.75 and specificity=0.64. p=0.0005 ii. For ICDAS: At a sound threshold, sensitivity=0.82 and specificity=0.86 p=0.0023 For (QLF) Inspektor ™ Pro: At standard threshold [ΔF (5%)] sensitivity=0.89 and specificity=0.60. At optimal threshold [ΔF (7%)], sensitivity=0.87 and specificity=0.82. P=0.0214 For QLF-D Biluminator™ 2: At optimal threshold [ΔF (5%)], sensitivity=0.96 and specificity=0.57. At optimal threshold [ΔF (7%)], sensitivity=0.84 and specificity=0.89.

				Correlating the histological scores of ICDAS, Inspektor TM Pro and QLF-D Biluminator TM 2, $p < 0.001$ and for histological depth $p < 0.0001$. Correlating the histological scores and depths of The Canary System ® $p > 0.10$.
2	R.J. Jeon et al. [43]	2004	Combined PTR and LUM have an excellent potential for diagnosing near-surface or deep subsurface carious lesions as a sensitive, nonintrusive dental probe.	For PTR and LUM combined: At the caries level of enamel, sensitivity=0.81 and specificity=0.87. At the caries level of dentin, sensitivity=0.79 and specificity=0.72. For PTR only: At the caries level of enamel, sensitivity=0.69 and specificity=0.86. At the caries level of dentin, sensitivity=0.52 and specificity=0.72. For LUM only: At the caries level of enamel, sensitivity=0.60 and specificity=0.81. At the caries level of dentin, sensitivity=0.58 and specificity=0.77. For Visual inspection: At the caries level of enamel, sensitivity=0.51 and specificity=1.00. At the caries level of dentin, sensitivity=0.36 and specificity=1.00. For Radiograph: At the caries level of enamel, sensitivity=0.29 and specificity=1.00. At the caries level of dentin, sensitivity=0.36 and specificity=0.85. For DIAGNOdent: At the caries level of enamel, sensitivity=0.60 and specificity=0.78. At the caries level of dentin, sensitivity=0.76 and specificity=0.85.
3	Josh D. Silvertown et al. [44]	2016	The Canary System could serve as a clinical tool for dental professionals to detect and monitor the status of carious lesions and tooth structure beneath sealant. However, intrinsic auto-fluorescence of sealant filler and opacifying agents increases the likelihood of false-positive diagnoses with	Sound and carious tissue underneath opaque sealants were distinguished by The Canary System and DIAGNOdent with an accuracy(N=105) of 76% and 59%, respectively. i. For the Canary system, Before sealant application, the specificity of sound samples(N=17) is 100%, and the sensitivity of carious samples (N=88) is 78%. After sealant application, the specificity of sound samples(N=17) is 94%, and the sensitivity of carious samples (N=88) is 65%.

e-ISSN: 2582-5208
International Research Journal of Modernization in Engineering Technology and Science
(Peer-Reviewed, Open Access, Fully Refereed International Journal)
Volume:04/Issue:05/May-2022 Impact Factor- 6.752 www.irjmets.com

			DIAGNOdent, which may limit its use as a tool to detect caries beneath opaque sealants.	c) p<0.05 ii. For DIAGNOdent, Before sealant application, the specificity of sound samples(N=17) is 100%, and the sensitivity of carious samples (N=88) is 27%. After sealant application, the specificity of sound samples(N=17) is 0%, and the sensitivity of carious samples(N=88) is 94%. c) p<0.05
4	R.J. Jeon et al. [45]	2008	PTR has exhibited the sufficient contrast required to detect very early interproximal lesions. In addition, excellent signal reproducibility and consistent changes in signal due to the presence of interproximal demineralized lesions were shown by the technique rendering PTR a reliable probe for detection of early interproximal demineralized lesions that conventional X-rays cannot detect. Simultaneous measurement of modulated luminescence was also measured, but compared to PTR, it showed a relatively lower ability to detect interproximal demineralized lesions.	An analytical caries detection tool developed by PTR and LUM of combined sensitivity and specificity was considerably better than the DIAGNOdent, radiographic, and visual methodologies.
5	Janja Jan et al. [46]	2015	Although without substantially higher specificity, the Canary System with the highest sensitivity demonstrated greater accuracy in detecting proximal lesions than ICDAS-II and Bitewing	The Canary System (CS) presented statistically significantly higher sensitivity than ICDAS-II and BW methods. • Sensitivity of CS=0.933 • Sensitivity of ICDAS-II=0.733 • Sensitivity of BW=0.267 There was no statistically significant difference in their specificity values.

			radiography (BW).	• Specificity of CS=0.825 • Specificity of ICDAS-II=0.65 • Specificity of BW=0.875 When the Canary system was compared to ICDAS-II, p=0.01 and bitewing radiography, p<0.001.
6	Adeyinka F. Dayo et al. [47]	2019	The PTR/LUM system involving non-ionizing radiation serves as a sensitive adjunct in detecting and monitoring early caries, particularly among high caries risk patients. Despite being valuable in detecting advanced caries, radiographs are of less sensitivity in detecting early lesions or recurrent lesions under restorations. When used in conjunction with intraoral radiography and visual examination, PTR/LUM could have value. Although, this requires to be validated by further clinical research. CBCT has a higher radiation dose and low sensitivity and specificity, prohibiting its routine use to detect caries.	The sensitivity of PTR/LUM was statistically greater than that of IR and CBCT. • Sensitivity of PTR/LUM=0.89 • Sensitivity of IR=0.38 • Sensitivity of CBCT=0.40 There was no statistical difference in specificity values. • Specificity of PTR/LUM=0.83 • Specificity of IR=0.80 • Specificity of CBCT=0.70 kappa=0.56
7	Haixia Xinga et al. [48]	2019	Non-cavitated approximal caries lesions were detected with the best individual results from the buccal direction by PTR/LUM, although using the maximum value from all directions might enhance performance. PTR/LUM seems more suitable for detecting non-cavitated	The overall sensitivity for the following probing directions was: • Buccal=47% • Lingual=11% • Occlusal-middle=8% • Occlusal-lingual=3% • Occlusal-buccal=11% • Occlusal-average=11% • Occlusal-max=16% • **All-average=8%** • **All-max=61%** •

e-ISSN: 2582-5208
International Research Journal of Modernization in Engineering Technology and Science
(Peer-Reviewed, Open Access, Fully Refereed International Journal)
Volume:04/Issue:05/May-2022 Impact Factor- 6.752 www.irjmets.com

			approximal dentinal caries than enamel caries.	Regardless of direction, the specificity was 100%. The p values obtained for each probing direction are: • Buccal: p<0.001 • Lingual: p=0.072 • Occlusal-middle: p<0.001 • Occlusal-lingual: p=0.007 • Occlusal-buccal: p=0.324 • Occlusal-average: p<0.001 • Occlusal-max: p=0.001 • **All-average: p<0.001** • **All-max: p<0.001**

Table 2 shows the author's name, the year the studies were conducted, the outcome assessed and the results.

Table 3: Bias Analysis Of Included Studies

S.NO	AUTHOR AND YEAR	RANDOM SEQUENCE GENERATION	ALLOCATION CONCEALMENT	SELECTIVE REPORTING	INCOMPLETE OUTCOME DATA	BLINDING OF OUTCOME ASSESSMENT	BLINDING PARTICIPANTS AND PERSONALS
1	Mahmoud Jallad et al. [42]	++	?	-	++	?	?
2	R.J. Jeon et al. [43]	?	-	++	++	?	?
3	Josh D. Silvertown et al. [44]	++	?	++	++	?	?
4	R.J. Jeon et al. [45]	?	?	++	++	?	?
5	Janja Jan et al. [46]	?	?	++	++	?	?
6	Adeyinka F. Dayo et al. [47]	?	?	++	++	?	?
7	Haixia Xinga et al. [48]	-	?	++	++	?	?

++ low risk of bias; - high risk of bias; ? unclear risk of bias

III. DISCUSSION

In this systematic review, 119 articles were screened from various search engine databases, and seven relevant articles were selected. All articles selected analyzed the effect of photothermal radiometry and modulated luminescence in detecting dental caries. In this review, the seven articles included were randomized control trials. The exclusion was then carried out based on the relevance to the subject matter. There has been a shift towards lesser interventional approaches in managing dental caries, with preventive interventions emphasising inducing the remineralization of lesions at an earlier disease stage. This necessitates the requirement of accurate and valid early caries detection devices.[42]

The PTR-LUM modality is one such noninvasive energy conversion technology which provides combined optical and thermal data regarding the state of the tooth microstructure [54]. The strength of the energy

converted, i.e., the converted heat and light from the laser beam with intensity modulation and time delay for heat conduction is measured by the PTR-LUM. It has a probing area of a diameter of 1.5mm and an effective probing depth of up to 5mm beneath the tooth's surface. A healthy tooth structure is indicated by a Canary number less than or equal to 20, whilst a large carious lesion has a Canary number greater than 70. Early carious lesions or cracks that may require treatment are indicated by Canary numbers between 20 and 70 [47,55,56]. Adeyinka F. Dayo et al. reported a statistically significant greater sensitivity of PTR/LUM than intraoral radiography and cone-beam computed tomography. However, there was no statistical difference in their specificity values.[47] A review article of alternative methods to radiographic and visual examinations for proximal caries detection by Abogazalah and Ando implied objective quantification of caries lesions and differentiation between developmental and caries defects and the potential to be objective quantification of caries lesions and differentiation between developmental for assessment of caries lesion can be done with PTR/LUM.[49] A study conducted by Abrams et al. [50] on the correlation of various diagnostic systems with caries lesion depth presented a high correlation between the PTR/LUM system about the depth of decay, demonstrating that this technique may provide information regarding the size and position of caries and thus could aid in monitoring treatment.[47] For the PTR/LUM system, a large range in CN can exist among the canary scans taken per study tooth [53] since it is angulation sensitive [51,52]. Thus, training and calibration before initiation of the study ensure the strict adherence of the examiner to the protocol given by the manufacturer for placing the probe in a perpendicular direction to the surface under examination.[47] Constraints of this in vitro study impact its clinical implications and, hence, are considered to be done while extrapolating the study results. Limitations include, for instance, in vitro studies being conducted in ideal laboratory conditions, which do not represent practical clinical usage. Mahmoud Jallad et al. reported that ICDAS remained acceptable for caries detection within the constraints of the in vitro conditions compared to the Canary system, which is based on the PTR-LUM technology. [42] R.J. Jeon et al. reported that the combined PTR and LUM approach yielded a higher statistical sensitivity than visual inspection, DIAGNOdent and radiograph, which indicates its excellent potential for diagnosing near-surface or deep subsurface carious lesions as a sensitive, nonintrusive dental probe.[43] An adjunct method for detecting and monitoring pit and fissure caries beneath opaque sealants is required since the opacity of the sealant often masks the caries lesions. In a study conducted by Josh D. Silvertown et al., it was reported that the Canary System based on the PTR-LUM modality could serve as a clinical tool to detect and monitor the status of carious lesions and tooth structure beneath the sealant. An increased likelihood of false-positive diagnoses due to intrinsic autofluorescence of sealant filler and opacifying agents limits the use of DIAGNOdent as a caries detection tool under opaque sealants.[44] Janja Jan et al. reported that under in vitro conditions, the Canary system demonstrated greater accuracy in proximal lesions detection when compared with ICDAS-II and Bitewing radiography, with the highest sensitivity but without substantially higher specificity. However, further investigations are required to assess the accuracy of the Canary System for clinical usage.[46] Haxia Xinga et al. reported that non-cavitated approximal caries lesions were detected with best individual results from the buccal direction with PTR/LUM. However, using the maximum value from all directions might enhance performance. He concluded that PTR/LUM seemed more suitable for detecting non-cavitated approximal dentinal caries than enamel caries. An increase in the sensitivity for the maximum value of all scanning directions was observed as lesions became deeper. PTR/LUM value exhibited weak to moderate correlations with the extent of severity of lesions. The buccal direction had a significantly higher sensitivity than the lingual and occlusal.[48] There is conclusive evidence that Photothermal radiometry and modulated luminescence (PTR-LUM) are effective in detecting dental caries if used as a diagnostic method. It is also evident that PTR-LUM has statistically higher sensitivity than DIAGNOdent, ICDAS-II, intra-oral radiography, cone-beam computed tomography and visual methods.

IV. CONCLUSION

The combined effect of Photothermal radiometry and modulated luminescence (PTR-LUM) system, which involves non-ionizing radiation, has an excellent potential to serve as a sensitive adjunct and reliable nonintrusive dental probe for the detection and monitoring of dental caries, which otherwise cannot be detected by conventional dental radiographs.

V. REFERENCES

[1] Gomez J, "Detection and diagnosis of the early caries lesion", BMC oral health., vol. 15, no.1, pp. 1-7, Dec, 2015. https://doi.org/10.1186/1472-6831-15-S1-S3

[2] G. N. Jenkins, "Recent changes in dental caries", Br. Med. J, vol. 291, no. 6505, pp. 1297-1298, Nov, 1985. doi: 10.1136/bmj.291.6505.1297

[3] D. Ricketts, E. Kidd, K. Weerheijm, and H. de Soet, "Hidden caries: What is it? Does it exist? Does it matter?", Int. Dent. J, vol.47, no. 5, pp. 259-265, Oct, 1997. https://doi.org/10.1002/j.1875-595X.1997.tb00786.x

[4] D. McComb and L. E. Tarn, "Diagnosis of occlusal caries: Part I. conventional methods", J. Can. Dent. Assoc, vol.67, no. 8, pp. 454-457, Sept, 2001. http://www.cda-adc.ca/jcda/vol-67/issue-8/454.pdf

[5] K. J. Anusavice: Need for early detection of caries lesions.in A United States Perspective in Early Detection of Dental Caries II, Proc. 4th Annual Indiana Conf., G. Stookey, Ed.2001; pp. 13–30

[6] Zandoná AF, Zero DT, " Diagnostic tools for early caries detection", The Journal of the American Dental Association. vol.137, no. 12, pp. 1675-1684, Dec, 2006. https://doi.org/10.14219/jada.archive.2006.0113

[7] Tranæus S, Shi XQ, Angmar-Månsson B, "Caries risk assessment: methods available to clinicians for caries detection", Community dentistry and oral epidemiology, vol. 33, no. 4, pp. 265-273, Aug, 2005. https://doi.org/10.1111/j.1600-0528.2005.00234.x

[8] Raymond J. Jeon, Andreas Mandelis, Victor Sanchez, Stephen H. Abrams, "Nonintrusive, noncontacting frequency-domain photothermal radiometry and luminescence depth profilometry of carious and artificial subsurface lesions in human teeth", Journal of Biomedical Optics, vol. 9, no. 4, pp. 804-819, Jul, 2004. https://doi.org/10.1117/1.1755234

[9] Angmar-Månsson BE, Al-Khateeb S, Tranaeus S, "Caries diagnosis. Journal of dental education", , vol. 62, no. 10, pp. 771-780, Oct, 1998. https://doi.org/10.1002/j.0022-0337.1998.62.10.tb03245.x

[10] Silvertown JD, Abrams SH, Sivagurunathan KS, Kennedy J, Jeon J, Mandelis A, Hellen A, Hellen W, Elman G, Ehrlich R, Chouljian R, "Multi-centre clinical evaluation of photothermal radiometry and luminescence correlated with international benchmarks for caries detection", The open dentistry journal, no. 11, pp. 636-647, Dec, 2017. doi: 10.2174/1874210601711010636

[11] Jeon RJ, Hellen A, Matvienko A, Mandelis A, Abrams SH, Amaechi BT,"In vitro detection and quantification of enamel and root caries using infrared photothermal radiometry and modulated luminescence", Journal of biomedical optics, vol.13, no. 3, pp. 034025, May, 2008. https://doi.org/10.1117/1.2942374

[12] Dove SB, "Radiographic diagnosis of dental caries", J Dent Educ, vol.65, no. 10, pp. 985-990, Oct, 2001. https://doi.org/10.1002/j.0022-0337.2001.65.10.tb03474.x

[13] Pretty IA, Maupomé G, "A closer look at diagnosis in clinical dental practice: Part 3. Effectiveness of radiographic diagnostic procedures" Journal-Canadian Dental Association, no. 1, pp.388-396, Jun, 2004. http://www.cda-adc.ca/JCDA/vol-70/issue-6/388.pdf

[14] Jan J, Wan Bakar WZ, Mathews SM, Okoye LO, Ehler BR, Louden C, Amaechi BT,"Proximal caries lesion detection using the Canary Caries Detection System: an in vitro study", Journal of investigative and clinical dentistry, vol.7, no. 4, pp. 383-390, Nov, 2016. https://doi.org/10.1111/jicd.12163

[15] Hellen A, Mandelis A, Finer Y, Amaechi BT, "Quantitative evaluation of the kinetics of human enamel simulated caries using photothermal radiometry and modulated luminescence", Journal of biomedical optics, vol.16, no. 7, pp. 071406, Jul, 2011. https://doi.org/10.1117/1.3564909

[16] Damen JJ, Exterkate RA, Ten Cate JM, " Reproducibility of TMR for the determination of longitudinal mineral changes in dental hard tissues", Advances in dental research, vol.11, no. 4, pp. 415-419, Nov, 1997. https://doi.org/10.1177%2F08959374970110040601

[17] Hibst R, Konig K, inventors; Kaltenbach, Voigt GmbH, assignee, "Device for detecting dental caries", United States patent US 5,306,144, April, 1994. https://patents.google.com/patent/US5306144A/en

[18] Hibst R, Gall R, Klafke M, inventors; Kaltenbach, Voigt GmbH, assignee. Device for the recognition of caries, plaque or bacterial infection on teeth. United States patent US 6,024,562, Feb, 2000. https://patents.google.com/patent/US6024562A/en

[19] Alwas-Danowska HM, Plasschaert AJ, Suliborski S, Verdonschot EH, "Reliability and validity issues of laser fluorescence measurements in occlusal caries diagnosis", Journal of Dentistry, vol.30, no. 4, pp. 129-134, May, 2002. https://doi.org/10.1016/S0300-5712(02)00015-5

[20] Lussi A, Imwinkelried S, Pitts NB, Longbottom C, Reich E, "Performance and reproducibility of a laser fluorescence system for detection of occlusal caries in vitro", Caries research, vol.33, no. 4, pp. 261-266, 1999. https://doi.org/10.1159/000016527

[21] Shi XQ, Welander U, Angmar-Månsson B, " Occlusal caries detection with KaVo DIAGNOdent and radiography: an in vitro comparison", Caries research, vol.34, no. 2, pp. 151-158, 2000. https://doi.org/10.1159/000016583

[22] Shi XQ, Tranaeus S, Angmar-Mansson B, "Comparison of QLF and DIAGNOdent for quantification of smooth surface caries", Caries Research, vol.35, no. 1, pp. 21, Feb, 2001. https://search.proquest.com/openview/aceb364940ac911c8e3abc7bff4d60a8/1?pq-origsite=gscholar&cbl=34578

[23] Jeon RJ, Han C, Mandelis A, Sanchez V, Abrams SH, "Diagnosis of pit and fissure caries using frequency-domain infrared photothermal radiometry and modulated laser luminescence", Caries research, vol.38, no. 6, pp. 497-513, 2004. https://doi.org/10.1159/000080579

[24] Raymond J. Jeon, Andreas Mandelis, Victor Sanchez, Stephen H. Abrams, "Nonintrusive, noncontacting frequency-domain photothermal radiometry and luminescence depth profilometry of carious and artificial subsurface lesions in human teeth", Journal of Biomedical Optics, vol. 9, no. 4, pp. 804-819, Jul, 2004. https://doi.org/10.1117/1.1755234

[25] Jeon RJ, Matvienko A, Mandelis A, Abrams SH, Amaechi BT, Kulkarni G, "Detection of interproximal demineralized lesions on human teeth in vitro using frequency-domain infrared photothermal radiometry and modulated luminescence", Journal of biomedical optics, vol. 12, no. 3, pp.034028, May, 2007. https://doi.org/10.1117/1.2750289

[26] R. J. Jeon, A. Hellen, A. Matvienko, A. Mandelis, S. H. Abrams and B. T. Amaechi, "In vitro detection and quantification of enamel and root caries using infrared photothermal radiometry and modulated luminescence", J. Biomed. Opt, vol. 13, no. 3, pp.034025, May, 2008. https://doi.org/10.1117/1.2942374.

[27] Mandelis A, Nicolaides L, Feng C, Abrams SH, "Novel dental depth profilometric imaging using simultaneous frequency-domain infrared photothermal radiometry and laser luminescence", InBiomedical Optoacoustics, vol. 3916, pp.130-137, May, 2000. https://doi.org/10.1117/12.386313

[28] L. Nicolaides, A. Mandelis, and S. H. Abrams, "Novel dental dynamic depth profilometric imaging using simultaneous frequency-domain infrared photothermal radiometry and laser luminescence", J. Biomed. Opt, vol. 5, no. 1, pp.31-39, Jan, 2000. https://doi.org/10.1117/1.429965

[29] Mandelis A, "Progress in theoretical, experimental, and computational investigations in turbid tissue phantoms and human teeth using laser infrared photothermal radiometry", Thermosense XXIV, vol. 4710, pp.373-383, Mar, 2002. https://doi.org/10.1117/12.459586

[30] Jeon RJ, Han C, Mandelis A, Sanchez V, Abrams SH, "Diagnosis of pit and fissure caries using frequency-domain infrared photothermal radiometry and modulated laser luminescence", Caries research, vol.38, no. 6, pp. 497-513, 2004. https://doi.org/10.1159/000080579

[31] Raymond J. Jeon, Andreas Mandelis, Victor Sanchez, Stephen H. Abrams, "Nonintrusive, noncontacting frequency-domain photothermal radiometry and luminescence depth profilometry of carious and artificial subsurface lesions in human teeth", Journal of Biomedical Optics, vol. 9, no. 4, pp. 804-819, Jul, 2004. https://doi.org/10.1117/1.1755234

[32] Jeon RJ, Matvienko A, Mandelis A, Abrams SH, Amaechi BT, Kulkarni G, "Detection of interproximal demineralized lesions on human teeth in vitro using frequency-domain infrared photothermal radiometry and modulated luminescence", Journal of biomedical optics, vol. 12, no. 3, pp.034028, May, 2007. https://doi.org/10.1117/1.2750289

[33] Garcia JA, Mandelis A, Abrams SH, Matvienko A, "Photothermal radiometry and modulated luminescence: Applications for dental caries detection", Handbook of biophotonics, pp. 1047-52, , Jan 2013. https://doi.org/10.1002/9783527643981.bphot078

[34] Matvienko A, Jeon J, Mandelis A, Arvizu G, Gomez AE, Abrams SH, Amaechi BT, "Dental biothermophotonics: A quantitative photothermal analysis of early dental demineralization", The European Physical Journal Special Topics, vol. 153, no. 1, pp. 463-465, Jan, 2008. https://link.springer.com/article/10.1140/epjst/e2008-00485-5

[35] Nicolaides L, Feng C, Mandelis A, Abrams SH, "Quantitative dental measurements by use of simultaneous frequency-domain laser infrared photothermal radiometry and luminescence", Applied optics, vol. 41, no. 4, pp. 768-777, Feb, 2002. https://doi.org/10.1364/AO.41.000768

[36] Nicolaides L, Chen Y, Mandelis A, Vitkin IA, "Theoretical, experimental, and computational aspects of optical property determination of turbid media by using frequency-domain laser infrared photothermal radiometry", J Opt Soc Am A Opt Image Sci Vis, vol.18, no. 10, pp. 2548-2556, Oct, 2001. DOI: 10.1364/josaa.18.002548

[37] L. Nicolaides, A. Mandelis, and S. H. Abrams, "Novel dental dynamic depth profilometric imaging using simultaneous frequency-domain infrared photothermal radiometry and laser luminescence", J. Biomed. Opt, vol. 5, no. 1, pp.31-39, Jan, 2000. https://doi.org/10.1117/1.429965

[38] Matvienko A, Jeon RJ, Mandelis A, Abrams SH, Amaechi BT, "Photothermal detection of incipient dental caries: Experiment and modeling", InSmart Biomedical and Physiological Sensor Technology V, vol. 6759, pp.104-113, Oct, 2007. https://doi.org/10.1117/12.734987

[39] Matvienko A, Mandelis A, Abrams S, "Robust multiparameter method of evaluating the optical and thermal properties of a layered tissue structure using photothermal radiometry", Applied optics, vol. 48, no. 17, pp.3192-31203, Jun, 2009. https://doi.org/10.1364/AO.48.003192

[40] Raymond J. Jeon, Andreas Mandelis, Victor Sanchez, Stephen H. Abrams, "Nonintrusive, noncontacting frequency-domain photothermal radiometry and luminescence depth profilometry of carious and artificial subsurface lesions in human teeth", Journal of Biomedical Optics, vol. 9, no. 4, pp. 804-819, Jul, 2004. https://doi.org/10.1117/1.1755234

[41] Jeon RJ, Sivagurunathan K, Garcia J, Matvienko A, Mandelis A, Abrams S, "Dental diagnostic clinical instrument (" Canary") development using photothermal radiometry and modulated luminescence", InJournal of Physics: Conference Series, vol. 214, no. 1, pp. 012023, Mar, 2010. https://iopscience.iop.org/article/10.1088/1742-6596/214/1/012023/meta.

[42] Jallad M, Zero D, Eckert G, Zandona AF, "In vitro detection of occlusal caries on permanent teeth by a visual, light-induced fluorescence and photothermal radiometry and modulated luminescence methods", Caries Research, vol. 49, no. 5, pp. 523-530, 2015. https://doi.org/10.1159/000437214

[43] Jeon RJ, Han C, Mandelis A, Sanchez V, Abrams SH, "Diagnosis of pit and fissure caries using frequency-domain infrared photothermal radiometry and modulated laser luminescence", Caries research, vol.38, no. 6, pp. 497-513, 2004. https://doi.org/10.1159/000080579

[44] Silvertown JD, Wong BP, Abrams SH, Sivagurunathan KS, Mathews SM, Amaechi BT, "Comparison of The Canary System and DIAGNO dent for the in vitro detection of caries under opaque dental sealants", Journal of investigative and clinical dentistry, vol. 8, no. 4, pp. e12239, Nov, 2017. https://doi.org/10.1111/jicd.12239

[45] Jeon RJ, Matvienko A, Mandelis A, Abrams SH, Amaechi BT, Kulkarni G, "Interproximal dental caries detection using Photothermal Radiometry (PTR) and Modulated Luminescence (LUM)", The European Physical Journal Special Topics, vol.153, no. 1, pp. 467-469,Jan, 2008. https://link.springer.com/article/10.1140/epjst/e2008-00486-4

[46] Jan J, Wan Bakar WZ, Mathews SM, Okoye LO, Ehler BR, Louden C, Amaechi BT, "Proximal caries lesion detection using the Canary Caries Detection System: an in vitro study", Journal of investigative and clinical dentistry, vol.7 no. 4, pp. 383-390, Nov, 2016. https://doi.org/10.1111/jicd.12163

[47] Dayo, A.F., Amaechi, B.T., Noujeim, M., Deahl, S.T., Gakunga, P. and Katkar, R, "Comparison of photothermal radiometry and modulated luminescence, intraoral radiography, and cone beam

computed tomography for detection of natural caries under restorations", Oral Surgery, Oral Medicine, Oral Pathology and Oral Radiology, vol.129 no. 5, pp. 539-548, May, 2020. https://doi.org/10.1016/j.oooo.2019.09.006

[48] Xing H, Eckert GJ, Ando M, "Detection ability and direction effect of photothermal-radiometry and modulated-luminescence for non-cavitated approximal caries", Journal of Dentistry, vol.90, pp. 103221, Nov, 2019. https://doi.org/10.1016/j.jdent.2019.103221

[49] Abogazalah N, Ando M, "Alternative methods to visual and radiographic examinations for approximal caries detection", Journal of Oral Science, vol.59 no. 3, pp. 315-322, 2017. https://doi.org/10.2334/josnusd.16-0595.

[50] Abrams SH, Sivagurunathan KS, Silvertown JD, Wong B, Hellen A, Mandelis A, Hellen WM, Elman GI, Mathew SM, Mensinkai PK, Amaechi BT, "Correlation with caries lesion depth of the canary system, DIAGNOdent and ICDAS II", The Open Dentistry Journal, vol.11, pp. 679, Dec, 2017. https://dx.doi.org/10.2174%2F1874210601711010679

[51] Abrams TE, Abrams SH, Sivagurunathan KS, Silvertown JD, Hellen WMP, Elman GI, Amaechi BT, " In Vitro Detection of Caries Around Amalgam Restorations Using Four Different Modalities", The Open Dentistry Journal, vol.11,pp. 609-620, 2017. https://dx.doi.org/10.2174%2F1874210601711010609

[52] Jallad M, Zero D, Eckert G, Zandona AF, "In vitro detection of occlusal caries on permanent teeth by a visual, light-induced fluorescence and photothermal radiometry and modulated luminescence methods", Caries Research, vol. 49, no. 5, pp. 523-530, 2015. https://doi.org/10.1159/000437214

[53] Herzog K, D'Elia M, Kim A, Slayton RL, "Pilot study of the canary system use in the diagnosis of approximal carious lesions in primary molars", Pediatric dentistry, vol. 37, no.7, pp.525-529, Dec, 2015. https://www.ingentaconnect.com/content/aapd/pd/2015/00000037/00000007/art00006

[54] Mandelis A, Abrams S, Jeon JS, Kulkarni K, Matvienko A, inventors; Quantum Dental Technologies Inc, assignee, "Method and apparatus using infrared photothermal radiometry (PTR) and modulated laser luminescence (LUM) for diagnostics of defects in teeth", United States patent US 8,306,608. 2012 Nov 6. https://patents.google.com/patent/US8306608B2/en

[55] Sivagurunathan K, Abrams SH, Garcia J, Mandelis A, Amaechi BT, Finer Y, Hellen WM, Elman G, "Using PTR-LUM (The Canary System™) for in-vivo detection of dental caries: Clinical trial results", Caries Res,vol. 44, pp.171-247, 2010. http://www.thecanarysystem.com/pdfs/conferences/2010-02-ORCA.pdf

[56] Silvertown JD, Abrams SH, Sivagurunathan KS, Kennedy J, Jeon J, Mandelis A, Hellen A, Hellen W, Elman G, Ehrlich R, Chouljian R, "Multi-centre clinical evaluation of photothermal radiometry and luminescence correlated with international benchmarks for caries detection", The open dentistry journal, no. 11, pp. 636-647, Dec, 2017. doi: 10.2174/1874210601711010636