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The diagnostic efficacy of quantitative light-induced fluorescence in detection of dental caries of primary teeth

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ABSTRACT

Objectives: To evaluate a quantitative light-induced fluorescence (QLF) caries detection method using a portable device under clinical conditions and present a QLF scoring index (QS-index) for primary teeth.
Methods: A total of 878 tooth surfaces (proximal and occlusal) of 44 children were studied. After visual inspection and radiographic examination, images of dental caries captured with the QLF device were classified according to caries progression stages and analyzed with a specialized software. Cut-off values, sensitivity, specificity, and area under the receiver operating characteristic curve (AUROC) were calculated for the QLF parameters: fluorescence loss (ΔF) and bacterial activity (ΔR). The reliability of logistic regression model to combine ΔF and ΔR was evaluated by the AUROC.
Results: QLF parameters showed a good sensitivity (0.72–0.91), specificity (0.74–0.96), and AUROC (0.861–0.940). The AUROC of logistic regression model (0.90–0.957) was higher than ΔF or ΔR average alone in all types of carious lesions. Every level of the QS-index was properly defined to represent the progression of dental caries with corresponding statistical significance.
Conclusions: The reliability of QLF for dental caries detection in primary teeth was similar to or slightly higher than that of the traditional diagnostic methods of visual inspection or radiographic examination in clinical conditions.
Clinical significance: The results of QLF were reliable in detecting all types of dental caries in primary teeth. The QLF method can provide visual images as well as quantitatively analyze the carious lesion.

1. Introduction

Dental caries is one of the most common oral diseases in patients across all ages; therefore, precise detection and appropriate treatment of dental caries are indispensable aspects of dentistry. Early detection and prompt treatment of dental caries are extremely important in primary dentition as primary teeth have reduced enamel thickness and easily accumulate dental plaque compared with permanent teeth. These differences render primary teeth weak against dental caries, leading to rapid disease progression [1,2]. Primary teeth health is crucial in pediatric industry as they are the foundation of permanent teeth. This necessitates periodic dental examinations in children to develop patient-specific treatment plans. Early caries detection coupled with active preventive intervention through regular screening and monitoring of dental caries progression helps re-establish healthy oral conditions [3]. Visual inspection and radiographic examination are widely used to detect caries. Although regarded as highly reliable diagnostic tools, the diagnostic accuracy of visual inspection and radiographic examination is markedly influenced by the varied anatomical morphologies of teeth. Therefore, much of the screening and final diagnosis of dental caries tend to rely on empirical evidence [4]. Quantitative light-induced fluorescence (QLF) has been introduced as a complement to basic dental examinations and aids in providing a precise diagnosis of dental caries. This technology detects quantitative fluorescence changes

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in the light reflected from the tooth surface when irradiated with visible blue light of 405 nm. It can determine the depth as well as the bacterial activity of dental caries simultaneously [5,6]. QLF detects fluorescence loss (ΔF) which is representative of the mineral loss of the examined tooth and thus, reveals the lesion depth [7–9]. QLF also detects red fluorescence (ΔR), which corresponds to the porphyrin derivatives of bacterial metabolism [10]. ΔR is usually increased in carious lesions, dental plaque, and dental calculus as these are formed by the aggregation of a plethora of microorganisms [11,12]. Recent studies have proved that ΔR is related with the lesion activity of dental caries [13–15]. QLF has the added benefit of being devoid of detrimental effects of radiation exposure that are associated with traditional radiographic examination and thus, is a better technique for caries screening and detection.

Based on the characteristics of the QLF method and results of previous QLF studies, it may be possible to use QLF for the detection of dental caries in primary teeth. We hypothesized that QLF could show a similar caries detection ability as conventional methods such as visual inspection or radiographic examination for primary teeth in children. The aim of this study is to evaluate the efficacy of QLF technology in diagnosis of dental caries in primary teeth and to extend the application of a quantitative light-induced fluorescence scoring index (QS-index) to primary teeth, that was originally introduced for clinical application on permanent teeth.

2. Materials and methods

This clinical study was granted ethical approval by the Institutional Review Board for clinical research in Yonsei University (IRB No. 2–2019–0022). The data for the study were collected at the Department of Pediatric Dentistry, Yonsei University Dental Hospital, Republic of Korea. Participating patients and their parents received information sheets regarding the procedure and informed consent was obtained prior to the study. Potential patients were recruited from September 2019 to March 2020. Distal surfaces of primary canines and occlusal and proximal surfaces (both mesial and distal) of primary first and second molars were included as eligible tooth surfaces. A total of 1232 tooth surfaces of 44 patients were evaluated in this study (Fig. 1). Patients with systemic diseases, tooth malformations, such as enamel hypoplasia or severe periodontitis, and those who were undergoing orthodontic treatment were excluded from the study. Restored tooth surfaces (direct restorations and crowns), extracted teeth, tooth surfaces without matched radiographic images, and low quality QLF images were also excluded.

A total of 44 patients (boys = 27, girls = 17, age range: 3 - 8 years, mean age: 6.02 years) and 1232 primary tooth surfaces were enrolled in this study (Fig. 1). In the final analysis, 878 tooth surfaces (occlusal surfaces = 251, proximal surfaces = 627) were selected.

2.1. Clinical examinations

The clinical examinations were conducted by two trained dentists in the department of pediatric dentistry. The included tooth surfaces were examined with a dental mirror, explorer, and air syringe and classified based on the International Caries Detection and Assessment System II as: 0 - Sound tooth surface; 1-Visible change in enamel only after prolonged air drying; 2 - Distinct visual change in enamel; 3 - Localized enamel breakdown because of caries with no visible dentin or underlying shadow; 4 - Underlying dark shadow from dentin with or without localized enamel breakdown; 5 - Distinct cavity with visible dentin; and 6 - Extensive distinct cavity with visible dentin. Inter examiner correlation coefficient was 0.702 ($p<.001$).

2.2. Radiographic examinations

Digital periapical radiographic images of primary canines, first and second primary molars of every patient were taken by a professional radiologist at Yonsei University Dental Hospital using the dental x-ray machine (Kodak 2200 Intraoral X-ray System, Eastman Kodak Co., Rochester, NY, USA) and extension cone paralleling system. Two trained pediatric dentists scored all periapical radiographs according to the International Caries Classification and Management System (ICCMS) as follows: 0 - No radiolucency; 1 - Radiolucency in the outer 1/2 of the enamel; 2 - Radiolucency in the inner 1/2 of enamel (to dentino-enamel junction); 3 - Radiolucency limited to the outer 1/3 of the dentin; 4 -

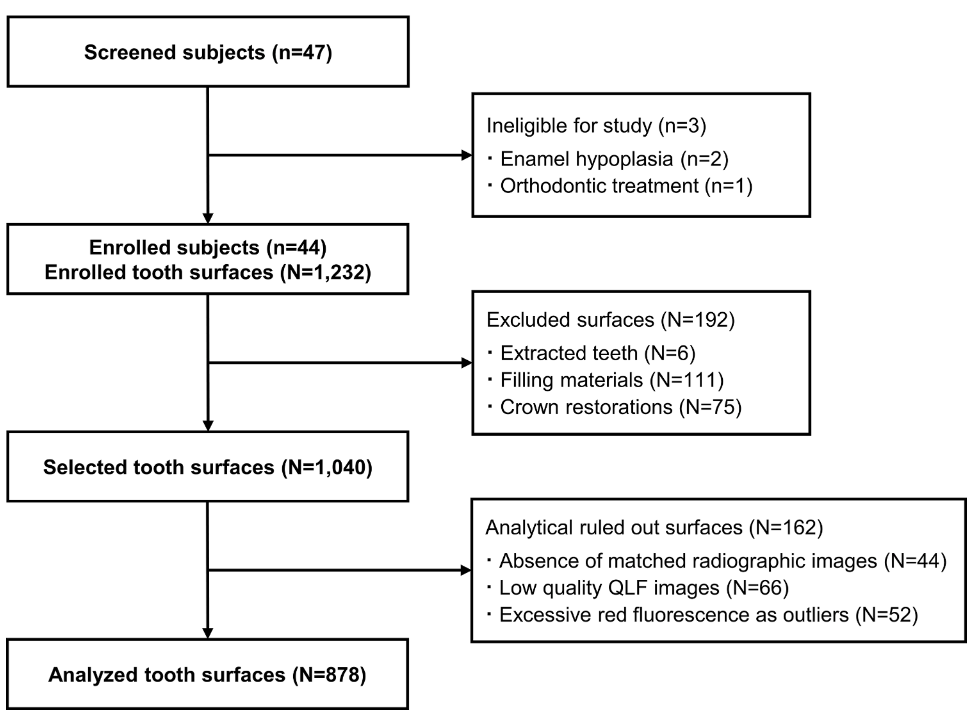

Fig. 1. Flow diagram of patient enrollment and inclusion and exclusion process for tooth surfaces in primary teeth (n = number of patients, N = number of tooth surfaces).

Radiolucency reaching the middle 1/3 of the dentin; and 5 - Radiolucency coming to the inner 1/3 of the dentin. Inter examiner correlation coefficient was 0.819 ($p<.001$).

2.3. Acquisition of QLF images and assessments

Qraypen C (AIOBIO, Seoul, Republic of Korea), the device used in this study is a portable QLF device. It has the same appearance as a dental curing light and works like an oral camera. When the LED light (405 nm) from the device falls on tooth surfaces, the scattered light is detected through a special double filter to create fluorescence images. White light images and QLF images can be taken consecutively with auto focusing function (1280 × 720 output resolution, 53.05° for the horizontal and 41.14° for the vertical field of view). Two pediatric dentists each captured QLF images of the carious lesions of different patients using the QLF device after cleaning the tooth surfaces with a rubber cup, brush, low speed handpiece, and dental floss to remove plaque or food debris as these could affect the analysis. All images were taken in a darkened room and under the same lighting conditions. Soft tissues and lips were retracted with air blowing by a 3-way syringe to maximize the quality of QLF images.

Since Qraypen C can take multiple shots in a short time, QLF images of the same carious lesions with the best quality were selected for analysis by the dentist who obtained the QLF images. These were classified by a single examiner (one of the pediatric dentists who examined the patients) in accordance with the QS-Occlusal (Fig. 2) and QS-Proximal (Fig. 3) levels. QS-Occlusal classification is as follows: Level 0 (sound): No fluorescence loss and no red fluorescence increase in pits and/or fissures. Level 1 (suspected or initial caries): Fluorescence loss and red fluorescence present as a line or spot in pits and/or fissures. Level 2 (enamel caries): Fluorescence loss and red fluorescence glow extend around pits and fissures. Level 3 (Dentin caries): Red fluorescence glow extend around pits and fissures and a dark shadow from dentin is present. QS-Proximal classification is as follows: Level 0: No dark shadow and no red fluorescence. Level 1: Irregular dark shadow but no red fluorescence. Level 2: Faint red fluorescence limited to 1/3 of the bucco-lingual width. Level 3: Strong red fluorescence over 1/3 of the bucco-lingual width. Intra examiner coefficient was 0.797 ($P<.001$).

Distribution of ICCMS and ICDAS II scores according to dental caries severity in primary teeth based on QS level in Table 4 shows how the QS index corresponds with other scoring systems (ICCMS and ICDAS II). For the quantification of fluorescence changes, QLF images were analyzed by the same single examiner using QA2 software (v.1.39, Inspektor Research Systems BV, Amsterdam, The Netherlands). Four types of QLF parameters (ΔF average, ΔF max, ΔR average, and ΔR max) can be obtained through the QLF analysis process using QA2 software, and the numeric results of each QLF parameter are displayed. QA2 software represents ΔF values indicating a decrease in fluorescence as negative values and ΔR values indicating an increase in red fluorescence as positive values.

2.4. Statistical analysis

The means and standard deviations of QLF parameters by QS-index were compared using analysis of variance and Scheffe's post-hoc analysis. Box whisker's plots were made to compare median values of ΔF and ΔR average based on the ICCMS using Kruskal-Wallis test and Mann-Whitney post hoc analysis. For the evaluation of the detection performance of QLF parameters, sensitivity, specificity, and area under the receiver operating characteristic curve (AUROC) were calculated with cut-off values for each type of incipient and moderate caries in primary teeth (95% confidence interval [CI]). Logistic regression analysis was used to estimate the relationship between ΔF average or ΔR average and each type of dental caries. The AUROC of the logistic regression model for ΔF average combined with ΔR average were also obtained to compare the caries detection performance of each QLF parameter. In ROC analyses, both visual inspections (ICDAS II) and radiographic examinations (ICCMS) were considered as references to establish the criteria for enamel caries or dentin caries as follows. Level 0 of both ICDAS II and ICCMS was regarded as normal surface. Level 1–2 of ICDAS II or ICCMS was regarded as incipient caries (If one of them was level 0 and the other was level 1, it was regarded as a normal surface considering clinical judgment and the possibility of false positives). Greater than level 3 of ICDAS II or ICCMS was regarded as moderate caries. Cohen's kappa coefficient values were used to confirm the intra- and inter examiner reliability. p-values less than 0.05 were considered statistically significant. SPSS Statistics 25.0 (IBM Corporation, Armonk, NY, USA), R version 4.0.3 (The R Foundation, Vienna, Austria) and R-studio version 1.3.1093 (Rstudio, Boston, MA, USA) were used for all statistical analyses.

Fig. 2. Quantitative light-induced fluorescence score for occlusal caries (QS-Occlusal).

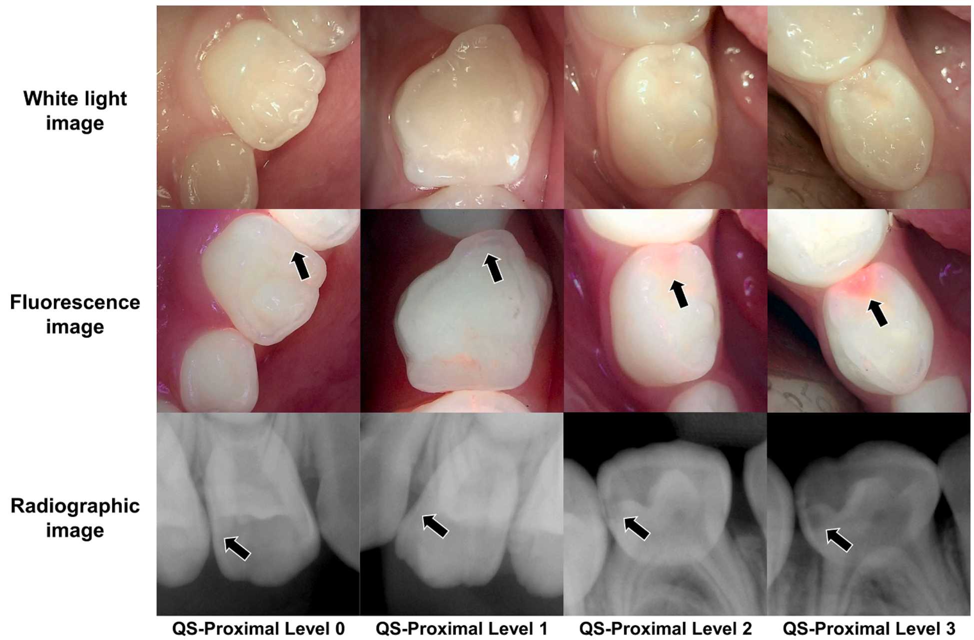

Fig. 3. Quantitative light-induced fluorescence score for proximal caries (QS-Proximal).

3. Results

Table 1 presents that mean values of ΔF and ΔR average increased with an increase in the QS-level. There were significant differences in the QS-levels of all carious lesions ($p < .005$). ΔF average decreased with the ICCMS score increase (Fig. 4a) and ΔR average increased with the ICCMS score increase (Fig. 4b). Statistically significant differences appeared at each score ($p < .005$) except between 4 and 5, which indicates severe dental caries in both QLF parameters.

The cut-off values, sensitivity, specificity, and AUROC of QLF parameters (ΔF and ΔR average) to detect incipient caries (Table 2) and moderate caries (Table 3) in primary teeth were calculated. For detection of incipient caries, cut off values were determined for QLF parameters (ΔF average = −7.75, and ΔR average = 20.5). For moderate caries, the cut-off value in case of occlusal surface (ΔF average = −10.85, and ΔR average = 22.5) was slightly higher than that of proximal surface (ΔF average = −9.15, and ΔR average = 21.5). Sensitivity to detect incipient caries was good (0.72–0.88, ΔR average of proximal surface was the lowest value). All results of sensitivity analysis were better for moderate caries (0.81–0.91, ΔF average more than 0.90). Specificity of QLF parameters also demonstrated good results (0.74–0.96, ΔR average in proximal caries more than 0.90), but the results of ΔF average for proximal caries (0.74 for both incipient and moderate caries) and ΔR average for occlusal moderate caries (0.76) were relatively low.

The AUROC for detection of incipient caries was reliable for both surfaces (0.861–0.940). In moderate caries, the surfaces showed higher AUROC values (0.912–0.940) than in incipient caries. In both incipient and moderate caries, QLF parameters of occlusal surfaces showed higher AUROC values than proximal surfaces. We also examined caries detection ability through a receiver operating characteristic (ROC) analysis of logistic regression model with combined ΔF and ΔR. When values of ΔR average were added to ΔF average, the AUROC was increased significantly for occlusal moderate (Fig. 5b, 0.943, $p < .001$), proximal incipient (Fig. 5c, 0.902, $p < .001$), and proximal moderate caries (Fig. 5d, 0.940, $p < .001$). In occlusal incipient caries, the AUROC was increased, but the increase was not statistically significant (Fig. 5a, 0.957, $p = .388$). There were more improvements in the AUROC with the logistic regression model of QLF parameters in case of proximal caries than occlusal caries.

4. Discussion

QLF analysis can provide information regarding quantitative changes taking place during dental caries progression. Among the QLF parameters obtained through our analysis, ΔF average and ΔR average

Table 1
Means and standard deviation values of QLF parameters in the different lesions of dental caries depending on each level of the QS-index in primary teeth.

	QLF parameters			
	Occlusal		Proximal	
	|ΔF average|	ΔR average	|ΔF average|	ΔR average
QS-level 0	2.35 ± 3.03[a] (1.58 – 3.13)	0 ± 0[a] (0 – 0)	3.93 ± 3.26[a] (3.54 – 4.30)	0.16 ± 1.86[a] (0.06 – 0.38)
QS-level 1	7.46 ± 2.17[b] (6.98 – 7.95)	6.75 ± 11.16[b] (4.25 – 9.25)	7.09 ± 2.39[b] (6.75 – 7.43)	4.18 ± 8.72[b] (2.93 – 5.42)
QS-level 2	9.66 ± 2.94[c] (8.94 – 10.38)	22.62 ± 12.86[c] (19.46 – 25.78)	9.96 ± 3.42[c] (9.16 – 10.76)	19.04 ± 11.77[c] (16.28 – 21.81)
QS-level 3	16.52 ± 6.98[d] (14.43 – 18.62)	39.27 ± 14.87[d] (34.80 – 43.73)	18.78 ± 9.62[d] (16.69 – 20.86)	39.83 ± 19.47[d] (35.61 – 44.06)

Data are mean ± SD values.
Different letters within the same column indicate significant differences between groups by Scheffe's post-hoc analysis (cut off α of significant differences is 0.005).
The ranges of numbers in parentheses mean minimum and maximum values for 95% confidence intervals.

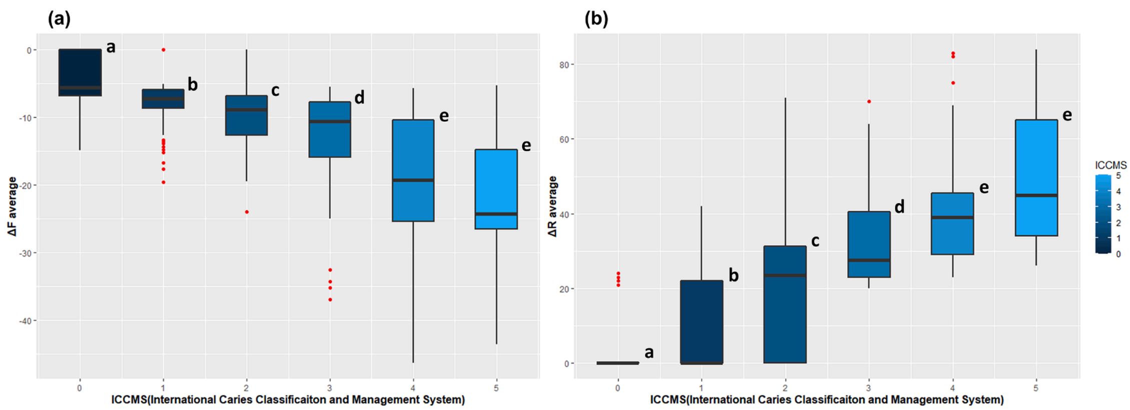

Fig. 4. Box-whisker plots of quantitative light-induced fluorescence parameters - ΔF average (A) and ΔR average (B) related to the International Caries Classification and Management System (ICCMS). The boxes mean the upper and lower quartile and horizontal lines show the median values. Different letters within the same graph indicate significant differences between groups (Using Kruskal-Wallis test with Mann-Whitney U test for post hoc, $p < .005$).

Table 2
The cut-off value, sensitivity, specificity, and AUROC of QLF parameters to detect incipient caries in primary teeth.

	QLF parameters (Incipient dental caries)			
	Occlusal		Proximal	
	ΔF average	ΔR average	ΔF average	ΔR average
Cut-off value	−7.75	20.5	−7.75	20.5
Sensitivity	0.88	0.83	0.83	0.72
Specificity	0.82	0.93	0.74	0.96
AUROC	0.940	0.911	0.866	0.861
(95% CI)	(0.913–0.967)	(0.872–0.950)	(0.835–0.897)	(0.824–0.898)

AUROC, area under the receiver operating characteristic curve; CI, confidence interval.

Table 3
The cut-off value, sensitivity, specificity, and AUROC of QLF parameters to detect moderate caries in primary teeth.

	QLF parameters (Moderate dental caries)			
	Occlusal		Proximal	
	ΔF average	ΔR average	ΔF average	ΔR average
Cut-off value	−10.85	22.5	−9.15	21.5
Sensitivity	0.90	0.89	0.91	0.81
Specificity	0.83	0.76	0.74	0.91
AUROC	0.940	0.920	0.912	0.921
(95% CI)	(0.908–0.973)	(0.872–0.968)	(0.884–0.941)	(0.887–0.955)

AUROC, area under the receiver operating characteristic curve; CI, confidence interval.

Table 4
Distributions of ICCMS and ICDAS II scores according to the severity of the dental caries in primary teeth based on QS-level.

QS-level	N	ICCMS score						ICDAS II score						
		0	1	2	3	4	5	0	1	2	3	4	5	6
0	341	251	83	5	1	1	0	337	4	0	0	0	0	0
1	270	95	123	36	15	0	1	24	227	19	0	0	0	0
2	138	13	74	33	15	3	0	0	3	120	15	0	0	0
3	129	5	19	22	26	37	20	0	2	7	43	31	24	22

were mainly used in this study because they are considered to be more representative.

When ΔF average and ΔR average were compared to the ICCMS radiographic scores, they showed the same tendency. QLF results increased with the severity of dental caries according to the ICCMS level and were appropriately distributed to each level with statistically significant differences. Thus, it could be said that QLF can indicate the states of carious lesions in primary teeth similar to the radiographic examination which is still considered as the gold standard for caries detection. In addition, it was thought that these analytic results of QLF can distinguish the progression of dental caries at dentin level better than others because the difference between the mean values corresponding to level 3 and 4 of ICCMS was the largest.

QLF in this study showed excellent caries detection ability with good sensitivity (0.72–0.91), specificity (0.74–0.96), and AUROC values (0.861–0.940) under clinical conditions. Although there may be some differences in the execution, these results can be compared with those of other previous studies. An in vitro study for detection of occlusal caries in primary molars reported that ΔF has a sensitivity of 0.68, specificity of 0.80, and accuracy (with McNemar test) of 0.71 in D1 threshold

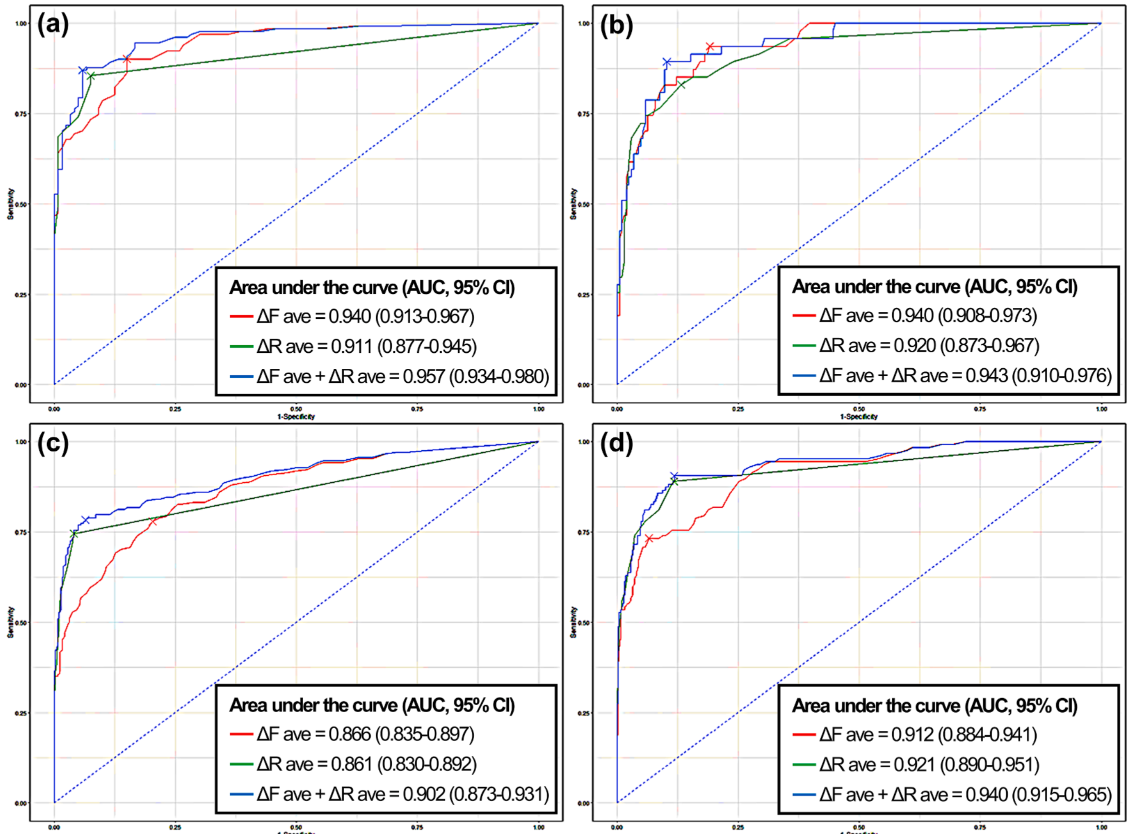

Fig. 5. Receiver operating characteristic (ROC) curves and corresponding areas under the curve (AUCs) of quantitative light-induced fluorescence parameters (ΔF average and ΔR average) in dental caries of primary teeth following locations and depth of caries lesions – occlusal incipient caries (a), occlusal moderate caries (b), proximal incipient caries (c), and proximal moderate caries (d). ΔF average + ΔR average show AUCs of logistic regression models for ΔF average together with additional predictors ΔR average. CI, confidence interval.

regarding enamel caries. For dentin caries (D3 threshold), it showed a high sensitivity, specificity, and accuracy (0.93, 0.87, and 0.88) [16]. Another in vitro study using permanent teeth found that QLF can detect proximal caries with a sensitivity of 0.64– 0.75, specificity of 0.84–0.88, and an AUROC of 0.76–0.80 in for incipient and moderate caries [17]. A clinical study on adult patients reported that ΔF / ΔR had sensitivity of 0.825 / 0.842, specificity of 0.816 / 0.879, and AUROC of 0.860 / 0.902 when detecting dentin caries on proximal surfaces [18]. It was found that results about caries detection ability of QLF in this study were similar or even higher than those obtained in the other studies employing QLF for caries detection.

On the other hand, cut-off values of QLF in our study were similar to those in the previous studies conducted on primary teeth, and slightly lower than those of permanent teeth. The cut-off values of ΔF were −7.4 for enamel caries (D1 threshold) and −13.8 for dentin caries (D3 threshold) as reported in a recent in vitro study on primary teeth [16]. An in vivo study of permanent teeth reported cut-off values of −12.4 (ΔF) and 23.3 (ΔR) for proximal dentinal caries [19]. Another clinical study on treatment decision making with regard to dental caries in permanent teeth showed that a ΔF cut-off values of −12 for incipient caries needed preventive resin restoration only whereas a value of −23 for moderate caries needed operative treatments [20]. Taken together, QLF showed similar or better detection ability and lower cut off values compared to previous studies. We inferred the reason from the histological difference between primary and permanent teeth. The histological features of primary teeth such as thin enamel layer or less mineralization that may allow the QLF device to detect fluorescence changes better when compared with permanent teeth. This may be because light entering enamel easily reaches the level of DEJ (Dento-enamel junction) and dentin where the chance of light absorption by fluorophores which remit the fluorescence is a magnitude higher [5]. If QLF can catch smaller changes of fluorescence of the carious lesion in primary teeth than in permanent teeth, it could be more efficient to use QLF as a caries detection method for children. Moreover, the results of QLF for the caries detection were comparable with the results of visual inspections or radiographic examinations [21,22]. It is encouraging that QLF showed similar caries detection ability to the conventional methods.

Taking a closer look at the results of this study, sensitivity, specificity, and AUROC values of the evaluated QLF parameters for incipient caries were higher for occlusal surfaces than proximal surfaces indicating a high caries detection ability of QLF for occlusal carious lesions. The lesions on occlusal surfaces can be confirmed directly; however, in case of proximal surfaces, fluorescence from the carious lesions can only be seen through the marginal ridge. It is hard to detect minute changes in the fluorescence of the proximal lesions because as the enamel becomes thicker the reflected fluorescence is correspondingly reduced [23]. It is problematic to detect proximal incipient caries using QLF due to the difficulty in accessing lesions under proximal contact points of teeth with the QLF device. A previous study pointed out that 75% of proximal carious lesions exist at the proximal contact area and 25% are below the contact point [24]. The closer carious lesions are to the marginal ridge, the better detection of proximal caries with QLF in the occlusal direction [17]. For the same reason, the specificity and AUROC of ΔR were better than ΔF in proximal moderate caries.

In case of occlusal moderate caries, the specificity and AUROC of ΔF revealed higher values than those of ΔR. The relatively low specificity and AUROC of ΔR in occlusal caries may be due to red fluorescence from the plaques in pits and fissures which can lead to false positive results in the QLF analysis. Although it has been shown that red fluorescence has a positive relation with caries activity [12,15,25], red fluorescence released from the remaining plaque can give rise to a false perception of increased cariogenic potential of a lesion. Although we cleaned patient's teeth thoroughly with professional instruments before commencement of the study to minimize the effect of debris and plaque, it is impossible to completely remove bacteria and their metabolites in pits and fissures [26]. Despite of these variations, QLF parameters showed excellent AUROC values in all types of carious lesions.

In all types of dental caries, the AUROC of the logistic regression model were higher than the results obtained with ΔF or ΔR alone. These differences were more significant for proximal caries. Thus, it can be said that it is efficient and accurate to check the bacterial activity expressed by red fluorescence combined with mineral loss. Since there were the differences in detection ability of ΔF or ΔR between enamel and dentin caries, the importance of each parameter should be set differently according to the depth of the carious lesion when considering two QLF parameters together (for example, ΔF values would be more important in enamel caries, both ΔF and ΔR should be considered equally for dentin caries). Through subsequent studies, if a method is developed which can appropriately combine ΔF and ΔR to show comprehensive figures according to the types of dental caries, we believe that it will markedly improve the caries detection ability of QLF.

QS-index is a scoring process of QLF images to infer progression of dental caries easily without the use of any specific software. It can indicate the severity of carious lesion and related bacterial activity together. Recent study on permanent teeth have reported that QS-index is cost-effective, timesaving, and highly reproducible. In addition, the sensitivity was 0.895–0.912, specificity was 0.563–0.839, and AUROC was 0.807– 0.929 for detecting occlusal caries [27]. For proximal caries, the sensitivity was 0.702–0.894, specificity was 0.835–0.951, and AUROC was 0.826–0.864 [18]. As per the results of this study, QLF analysis results were evenly distributed according to the QS index levels. On confirming the relation between the QS index and other scoring systems (ICCMS and ICDAS II), the QS index showed a tendency to increase with increasing ICCMS and ICDAS scores. This indicates that the QS index can represent dental caries severity in primary teeth similar to other detection methods. However, a weakness of the QS index is that each level of that was oversimplified, especially for dental caries with greater severity than moderate caries. The number of tooth surfaces for QS level 3 corresponded to several levels of other scoring systems representing deep carious lesions (levels 3–5 of ICCMS or 4–6 of ICDAS II). Nevertheless, we hope that QS-index of primary teeth, which was introduced in this study at first can be helpful in the clinical judgement about dental caries in children.

The QLF technology also has its limitations in the use of QLF devices and analysis procedures. It is difficult to be free from the effects of the accumulated dental plaque on the final results. Excessive tooth cleaning or flossing for better quality of analysis induced bleeding which is again disadvantageous. We tried to establish the same conditions for every patient included in the study while using QLF detection, but problems arose because of variability in level of cooperation of every child and contrasts of light or shadow in QLF images. These factors could have led to skewed results from the actual state of dental caries. Another weakness of this study was the relatively low values of inter examiner coefficients of ICDAS II or ICCMS because these scoring systems served as the basis for many analysis processes. In the ROC analysis, for example, the diagnosis of enamel caries or dentin caries was determined using ICCMS (radiographic examinations) and ICDAS II (visual inspections) together for greater reliability. Both visual inspections and radiographic examinations (available as gold standards for caries detection) were considered in the analysis procedure, but if repeated tests show different results of these scoring systems for the same carious lesion, the reliability of the diagnostic criteria may decrease. Establishing more reliable standards such as 3D radiographic data using CT radiography or histological analysis data will be needed in subsequent studies.

Visual inspection and radiographic examination are considered basic caries detection methods and will remain an essential part of the dental examination process. However, the guideline of the American Dental Association does not recommend radiography for dental caries screening [28]. As such, the QLF method may be a reliable method for screening and detecting dental caries in children. This method can complement visual inspection and may serve as a good alternative to radiographic examination, which has known detrimental health effects due to associated radiation exposure.

5. Conclusion

This study assessed the caries detection ability of QLF technology in primary teeth using a portable device (Qraypen C) and presented the QS index for primary teeth. The reliability of the QLF method in clinical conditions was found to be similar or slightly higher than those of the basic caries detection methods and results obtained in previous QLF studies. In addition, the results of QLF analysis (i.e., ΔF or ΔR values) and QS index for primary teeth can satisfactorily represent the progression of dental caries. Although it can be difficult sometimes to obtain good quality images in children, detection with the portable QLF device is a useful and harmless way for caries screening. Thus, QLF used together with traditional caries detection methods can make the caries detection process more efficient and precise.

CRediT authorship contribution statement

Kyung Hyun Cho: Conceptualization, Methodology, Software, Writing – original draft. **Chung-Min Kang:** Data curation, Supervision, Writing – original draft. **Hoi-In Jung:** Investigation, Visualization. **Hyo-Seol Lee:** Supervision. **Koeun Lee:** Data curation, Software, Validation. **Tae Yang Lee:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **Je Seon Song:** .

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jdent.2021.103845.

References

[1] P. Wilson, A. Beynon, Mineralization differences between human deciduous and permanent enamel measured by quantitative microradiography, Arch. Oral Biol. 34 (2) (1989) 85–88, https://doi.org/10.1016/0003-9969(89)90130-1.
[2] K.H. Mo, J.H. Yoon, S.G. Kim, S.H. Lee, Detection of proximal caries using laser fluorescence, J. Korean Acad. Pedtatric Dent. 31 (2) (2004) 323–330.
[3] O. Fejerskov, B. Nyvad, E. Kidd, Dental caries: the Disease and Its Clinical Management, John Wiley & Sons, 2015. Third ed.
[4] J.H. Lee, D.H. Kim, S.N. Jeong, S.H. Choi, Detection and diagnosis of dental caries using a deep learning-based convolutional neural network algorithm, J. Dent. 77 (2018) 106–111, https://doi.org/10.1016/j.jdent.2018.07.015.
[5] M. Van der Veen, E.d.J.de Jong, Application of quantitative light-induced fluorescence for assessing early caries lesions, Monogr. Oral. Sci. 17 (2000) 144–162, https://doi.org/10.1159/000061639.
[6] B. Angmar-Månsson, J.Ten Bosch, Quantitative light-induced fluorescence (QLF): a method for assessment of incipient caries lesions, Dentomaxillofac. Radiol. 30 (6) (2001) 298–307, https://doi.org/10.1038/sj/dmfr/4600644.

[7] H.E. Kim, H.K. Kwon, B.I. Kim, Recovery percentage of remineralization according to severity of early caries, Am. J. Dent. 26 (3) (2013) 132–136.
[8] M. Jallad, D. Zero, G. Eckert, A.F. 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, https://doi.org/10.1159/000437214.
[9] R. Gmür, E. Giertsen, M.H. van der Veen, E.d.J.de Jong, M. Jacob, B. Guggenheim, In vitro quantitative light-induced fluorescence to measure changes in enamel mineralization, Clin. Oral. Investig. 10 (3) (2006) 187–195, https://doi.org/10.1007/s00784-006-0058-z.
[10] C.M. Volgenant, M.H. van der Veen, J.J. de Soet, J.M. ten Cate, Effect of metalloporphyrins on red autofluorescence from oral bacteria, Eur. J. Oral Sci. 121 (3pt1) (2013) 156–161, https://doi.org/10.1111/eos.12045.
[11] M. Ando, A.G. Ferreira-Zandoná, G.J. Eckert, D.T. Zero, G.K. Stookey, Pilot clinical study to assess caries lesion activity using quantitative light-induced fluorescence during dehydration, J. Biomed. Opt. 22 (3) (2017), 035005, https://doi.org/10.1117/1.JBO.22.3.035005.
[12] E.S. Lee, S.M. Kang, H.Y. Ko, H.K. Kwon, B.I. Kim, Association between the cariogenicity of a dental microcosm biofilm and its red fluorescence detected by Quantitative Light-induced Fluorescence-Digital (QLF-D), J. Dent. 41 (12) (2013) 1264–1270, https://doi.org/10.1016/j.jdent.2013.08.021.
[13] A. Lennon, W. Buchalla, L. Brune, O. Zimmermann, U. Gross, T. Attin, The ability of selected oral microorganisms to emit red fluorescence, Caries Res. 40 (1) (2006) 2–5, https://doi.org/10.1159/000088898.
[14] H.E. Kim, B.I. Kim, Analysis of orange/red fluorescence for bacterial activity in initial carious lesions may provide accurate lesion activity assessment for caries progression, J. Evid. Based Dent. Pract. 17 (2) (2017) 125–128, https://doi.org/10.1016/j.jebdp.2017.03.010.
[15] G.F. Gomez, G.J. Eckert, A.F. Zandona, Orange/red fluorescence of active caries by retrospective quantitative light-induced fluorescence image analysis, Caries Res. 50 (3) (2016) 295–302, https://doi.org/10.1159/000441899.
[16] M.B. Diniz, P.H. Campos, S. Wilde, L.C. Rita de Cássia, A.G. Zandona, Performance of light-emitting diode device in detecting occlusal caries in the primary molars, Laser. Med. Sci. 34 (6) (2019) 1235–1241, https://doi.org/10.1007/s10103-019-02717-4.
[17] 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, https://doi.org/10.1016/j.jdent.2015.02.010.
[18] E.S. Kim, E.S. Lee, S.M. Kang, E.H. Jung, E.d.J.de Jong, H.I. Jung, B.I. Kim, A new screening method to detect proximal dental caries using fluorescence imaging, Photodiagn. Photodyn. Ther. 20 (2017) 257–262, https://doi.org/10.1016/j.pdpdt.2017.10.009.
[19] J.W. Lee, E.S. Lee, B.I. Kim, Can red fluorescence be useful in diagnostic decision making of residual dentin caries? Photodiagn. Photodyn. Ther. 26 (2019) 43–44, https://doi.org/10.1016/j.pdpdt.2019.02.016.
[20] M. Alammari, P. Smith, E.d.J.de Jong, S. Higham, Quantitative light-induced fluorescence (QLF): a tool for early occlusal dental caries detection and supporting decision making in vivo, J. Dent. 41 (2) (2013) 127–132, https://doi.org/10.1016/j.jdent.2012.08.013.
[21] T. Gimenez, C. Piovesan, M. Braga, D. Raggio, C. Deery, D. Ricketts, K.R. Ekstrand, F.M. Mendes, Visual inspection for caries detection: a systematic review and meta-analysis, J. Dent. Res. 94 (7) (2015) 895–904, https://doi.org/10.1177/0022034515586763.
[22] J. Gomez, M. Tellez, I. Pretty, R. Ellwood, A. Ismail, Non-cavitated carious lesions detection methods: a systematic review, Commun. Dent. Oral. Epidemiol. 41 (1) (2013) 55–66, https://doi.org/10.1111/cdoe.12021.
[23] M. Ando, B. Schemehorn, G. Eckert, D. Zero, G. Stookey, Influence of enamel thickness on quantification of mineral loss in enamel using laser-induced fluorescence, Caries Res. 37 (1) (2003) 24–28, https://doi.org/10.1159/000068229.
[24] W. Arnold, P. Gaengler, L. Kalkutschke, Three-dimensional reconstruction of approximal subsurface caries lesions in deciduous molars, Clin. Oral. Investig. 2 (4) (1998) 174–179, https://doi.org/10.1007/s007840050066.
[25] T.F. Novaes, A. Reyes, R. Matos, L.R. Antunes-Pontes, R.P.d.S. Marques, M. M. Braga, M.B. Diniz, F.M. Mendes, Association between quantitative measures obtained using fluorescence-based methods and activity status of occlusal caries lesions in primary molars, Int. J. Paediatric Dent. 27 (3) (2017) 154–162, https://doi.org/10.1111/ipd.12242.
[26] D.J. Manton, L.B. Messer, Pit and fissure sealants: another major cornerstone in preventive dentistry, Aust. Dent. J. 40 (1) (1995) 22–29, https://doi.org/10.1111/j.1834-7819.1995.tb05608.x.
[27] E.H. Jung, E.S. Lee, H.I. Jung, S.M. Kang, E.d.J.de Jong, B.I. Kim, Development of a fluorescence-image scoring system for assessing noncavitated occlusal caries, Photodiagn. Photodyn. Ther. 21 (2018) 36–42, https://doi.org/10.1016/j.pdpdt.2017.10.027.
[28] A.D.A.C.o.S. Affairs, The use of dental radiographs: update and recommendations, J. Am. Dent. Assoc. 137 (9) (2006) 1304–1312, https://doi.org/10.14219/jada.archive.2006.0393.