Development of a fluorescence-image scoring system for assessing noncavitated occlusal caries

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ABSTRACT

Background: This study aimed (1) to develop a scoring system based on a quantitative light-induced fluorescence (QLF) score for the occlusal caries (QS-Occlusal) that standardizes the fluorescence properties of noncavitated lesions from QLF images, (2) to confirm the validity and reliability of QS-Occlusal, and (3) to determine whether it is possible to replace existing clinical examinations by image evaluations based on the developed QS-Occlusal for assessing occlusal caries lesions.

Methods: This clinical study investigated 791 teeth of 94 subjects. The teeth were assessed by visual and tactile examinations using ICDAS criteria and quantitative light-induced fluorescence-digital (QLF-D) image examinations. QS-Occlusal was divided into four stages (from 0 to 3) based on the progression level of the lesion and the fluorescence loss and red fluorescence on captured QLF-D images. Two trained examiners who were not involved in the visual examination evaluated occlusal fluorescence images using QS-Occlusal. The maximum loss of fluorescence (ΔFmax) and the maximum change in the ratio of red and green fluorescence (ΔRmax) were quantitatively analyzed by the QA2 software to detect differences between the QS-Occlusal groups. The modalities were compared in terms of sensitivity, specificity, and area under the receiver operating characteristics (AUROC) curve for three different thresholds of the ICDAS codes: 0 vs 1–4 (D1), 0–2 vs 3/4 (D2), and 0–3 vs 4 (D3).

Results: ΔFmax increased significantly by about 4.7-fold (from 15.94 to 75.63) when QS-Occlusal increased from 0 to 3. ΔRmax was about 6.2-fold higher for QS-Occlusal = 1 (49.74) than for QS-Occlusal = 0 (8.04), and 21.6-fold higher for QS-Occlusal = 3 (P < 0.05). The new QS-Occlusal showed an excellent AUROC (ranging from 0.807 to 0.976) in detecting occlusal caries when optimum cutoff values were applied. The intra- and inter-examiner agreements indicated excellent reliability, with ICC values of 0.94 and 0.86, respectively.

Conclusions: The QS-Occlusal proposed in this study can be used in the clinical detection of noncavitated lesions with an excellent diagnostic ability. This makes it possible to replace clinical examinations and intuitively evaluate the lesion severity and status relatively easily and objectively by applying this scoring system to fluorescence images.

1. Introduction

The prevalence of dental caries is decreasing worldwide along with the increased use of fluoride and interest in oral health, whereas the relative prevalence of noncavitated caries lesions is increasing [1]. These changes require nonoperative preventive dentistry and the early detection and evaluation of lesions, with accurate diagnoses being essential [2]. However, clinical signs usually appear in the visual and radiographic examinations that are commonly used for detecting caries lesions, but only after a lesion has progressed considerably into the dentin due to the anatomical structure of the lesion going downward from the pits and fissures in occlusal caries [3–5]. In particular, visual examinations for detecting noncavitated lesions reportedly exhibit problematic variations in sensitivity (0.20–0.96), specificity (0.50–1.00), and diagnostic mismatches between examiners. Radiographs also exhibit low sensitivity (0.14–0.38) and high specificity.
In the clinic, and so a simplified, it is difficult to intuitively understand the status of caries lesions for using visual and radiographic examinations [7]. A recently developed system based on QLF technology, called qualitative light-induced fluorescence-digital bitumination 2+ (QLF-D, Inspektor Research Systems BV, Amsterdam, The Netherlands), produces high-resolution images with the aid of a digital SLR camera. In a conventional QLF image, the sound tooth surface exhibits green fluorescence, and the initial caries area appears as a black shadow. In a QLF-D image, sound teeth appear similarly as in original images obtained using a double filter. This is more useful for lesion detection because the fluorescence change is more pronounced in the presence of tooth demineralization or caries surfaces [9,10]. In addition, it is possible to obtain a white-light image simultaneously with a fluorescence image, which overcomes problems associated with anatomical structures and debris when evaluating occlusal dental caries using fluorescence images alone. In particular, the QLF-D image can be used to assess the dental caries severity by detecting the red fluorescence from porphyrin, which is produced by oral bacteria and penetrates into the tooth surface, as well as oral bacteria structures such as plaque and calculus [11–13]. Moreover, in QLF-D it is possible to detect caries lesions easily with the naked eye by presenting not only fluorescence, which is related to changes in conventional mineral contents [14], but also the bacteria metabolic activity based on increases in the red fluorescence [15]. In addition, it is possible to objectively quantify the lesion status using various quantitative QLF parameters (e.g., ΔF, ΔQ, and ΔR) as calculated using provided software, so that minute changes can be monitored in order to ensure that the applied preventive treatments are appropriate for the lesion status [16–18].

However, there are still limitations in terms of cost and time when applying specific software in a busy clinic to obtain specific quantitative values for each lesion [19]. Also, even if quantitative values are obtained, it is difficult to intuitively understand the status of caries lesions in the clinic, and so a simplified score is required. Moreover, a small number of examiners must examine a large number of subjects in a large-scale epidemiological survey, and in some cases this can be expensive and time-consuming since the examiners must directly visit the different sites where the subjects live. These problems could be overcome if clinical data are acquired through image-taking and these images can be evaluated by other dental professionals, making it possible to accumulate the data without limitations of the examination space or number of visits. This approach could be used both clinically and in education, including in large-scale epidemiology surveys [20,21]. In particular, a scoring system requiring only images obtained from objective detection equipment would reduce mismatches in diagnostic criteria and inconsistent results from different examiners. It would also be possible to intuitively evaluate the condition and depth of a lesion using a relatively objective and simple method that can replace clinical evaluations.

The aim of this study was to determine the clinical usefulness of a proposed QLF scoring system that reflects the fluorescence properties of noncavitated occlusal caries lesion, and also measure its validity and reliability.

2. Materials and methods

This study was approved by the Yonsei University Institutional Review Board (IRB No. 2-2015-0030) and conformed to the tenets of the Declaration of Helsinki. Clinical data were collected during a clinical study performed from March to November 2016 at Yonsei University Dental Hospital, South Korea, and followed the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines. Patients with systematic disease, those who underwent orthodontic treatments, had a temporomandibular joint disorder, severe periodontitis, bleeding symptoms on the oral mucosa, and pregnant women were excluded based on preinterview surveys. All subjects who visited a dental hospital were given an explanation about the objectives and procedures of this clinical study. Those who subsequently provided written agreement to participate and were aged over 18 years and in good general health (n = 180) were included in the study (Fig. 1). Teeth with cavitated surfaces or proximal caries, primary teeth, restored teeth that included pit and fissure sealant, teeth with hypoplasia or fluorosis, third molars, and teeth with other characteristics that may have affected the study results were excluded based on visual examinations and the results of QLF image-taking. This procedure resulted in the final inclusion of 791 teeth of 94 subjects (Fig. 1).

2.1. Clinical examination

Two trained dental hygienists conducted full-mouth professional tooth cleaning with a toothbrush, rubber cup, and low speed handpiece prior to performing the clinical examinations and QLF-D image-taking in order to remove debris or plaque that could have affected the study results. The clinical examinations were performed in a clinical environment by a single calibrated examiner, using the findings coded in accordance with the ICADS II criteria. The code (0) refers to sound, the code (1) to first visual change in enamel, the code (2) to distinct visual change in enamel when viewed wet, the code (3) to localized enamel breakdown due to caries with no visible dentin, the code (4) to underlying dark shadow from dentin with or without localized enamel breakdown, the code (5) to distinct cavity with visible dentin, and the
code (6) to extensive distinct cavity with visible dentin [22]. The examiner conducted visual and tactile examinations with the aid of a dental mirror, air syringe, and ball-type probe in order to assess the surface characteristics. We applied the criteria conservatively, with lower grades applied when it was difficult to distinguish lesions clearly. The intraexaminer reproducibility of the visual examination using ICDS on occlusal surfaces was assessed in a second examination of 10 randomly selected subjects (representing 10% of the total subjects), which confirmed the presence of high repeatability with an ICC value of 0.964.

2.2. Obtaining quantitative light-induced fluorescence images

The white-light and fluorescence images were obtained by two trained examiners using a quantitative light-induced fluorescence-digital Biluminator 2+ (QLF-D) in a dark room in order to maintain the quality of the images. The occlusal surfaces were dried sufficiently using compressed air before taking images. A fluorescence image and a white-light image were captured in a single shooting using a digital SLR camera (model 550D, Canon, Tokyo, Japan) under the following conditions: aperture values of 8.0 (white-light image) and 5.0 (fluorescence image), shutter speed of 1/30 s, focal length of 0.32 mm, and ISO speed of 1600. The camera was positioned vertically over the occlusal surface using an intraoral mirror. The images were automatically stored in bitmap format.

2.3. Assessment of occlusal caries using fluorescence images

Selected teeth were graded according to ICDAS code (the gold standard) as evaluated in visual examinations, with 10 representative QLF images being selected for each ICDAS code to define the fluorescence properties. These QLF images were selected by four clinicians (who did not participate in the clinical examinations) based on the teeth assigned with the same ICDAS codes based on white-light images. The fluorescence properties (fluorescence loss and red fluorescence) of selected teeth in the fluorescence images were listed. The common characteristics were categorized into four stages in order to yield the quantitative light-induced fluorescence score for the occlusal caries (QS-Occlusal) (Table 1). All fluorescence images of the occlusal surface of the teeth selected in this study were classified by two calibrated examiners. The presence of factors that may influence the evaluation of fluorescence images such as staining and debris during the examination process was confirmed using white-light images. To assess the reproducibility of QS-Occlusal, one examiner reevaluated all of the images 1 week later. The same examiner then performed quantitative analyses to obtain the fluorescence parameters of all occlusal surfaces included in this study using Q2A software (version 1.25, Inspektor Research Systems BV). For the fluorescence images, an analysis area was delimited by drawing a border that encompassed sound parts without caries lesions from pits and fissures in accordance with manufacturer recommendations. The fluorescence changes of occlusal surfaces were calculated automatically by the Q2A software algorithm. Considering the typical features of occlusal caries, the maximum loss of fluorescence ($|\Delta F_{\text{max}}|$) and the maximum change in the ratio of red and green fluorescence ($\Delta R_{\text{max}}$) were used to represent pit and fissure lesions, because they show an inverted V-shape with a narrow entrance and a progressively wider area to the dentioenamel junction.

2.4. Histological validation of representative tooth samples

To confirm the histological lesion depths for the clinically separate QS-Occlusal values, 30 extracted human teeth were randomly selected (IRB No. 2-2014-0042). Debris and calculus were removed using hand scalers and tooth brushes. The cleaned teeth were stored in a black container to block external light and then frozen at $-20\, ^\circ C$ until they were used (within 1 month). The white-light and fluorescence images were obtained using QLF-D. Three teeth that were representative of each QS-Occlusal value were then selected from the obtained images. The selected teeth were sectioned buccolingually into 1-mm-thick specimens using a microtome (TechCut 4™, Allied High Tech Products, California, USA), and the specimens were ground with silicon carbide paper (600 grit, SiC Sand Paper, R&B, Daejeon, South Korea) to a thickness of 200 micrometers and then photographed at 40× magnification for histological examination with a polarized-light microscope (CX31-P, Olympus, Tokyo, Japan).

Table 1

<table>
<thead>
<tr>
<th>QS-Occlusal value</th>
<th>Description</th>
<th>Score examples</th>
<th>Fluorescence images</th>
<th>White-light images</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No fluorescence loss and no red fluorescence increase in pits and/or fissures</td>
<td><img src="image1.jpg" alt="Image" /></td>
<td><img src="image2.jpg" alt="Image" /></td>
<td><img src="image3.jpg" alt="Image" /></td>
</tr>
<tr>
<td>1</td>
<td>Fluorescence loss and red fluorescence present as a line or spot in pits and/or fissures</td>
<td><img src="image4.jpg" alt="Image" /></td>
<td><img src="image5.jpg" alt="Image" /></td>
<td><img src="image6.jpg" alt="Image" /></td>
</tr>
<tr>
<td>2</td>
<td>Fluorescence loss and red fluorescence glow extending around pits and fissures</td>
<td><img src="image7.jpg" alt="Image" /></td>
<td><img src="image8.jpg" alt="Image" /></td>
<td><img src="image9.jpg" alt="Image" /></td>
</tr>
<tr>
<td>3</td>
<td>Red fluorescence glow extending around pits and fissures and a dark shadow from dentin present</td>
<td><img src="image10.jpg" alt="Image" /></td>
<td><img src="image11.jpg" alt="Image" /></td>
<td><img src="image12.jpg" alt="Image" /></td>
</tr>
</tbody>
</table>
2.5. Statistical analysis

The visual examinations and image classification were performed for sound or noncavitated occlusal surfaces independently. The mean values of QLF parameters according to QS-Occlusal classifications were compared using one-way ANOVA and Tukey’s post-hoc analysis. The Spearman correlation coefficient was used to investigate the correlation between the findings of the visual examination using ICDAS criteria and QS-Occlusal, and the distribution was confirmed using cross-tabulation. The sensitivity, specificity, and the area under the receiver operating characteristics (AUROC) curve were calculated for caries for three different thresholds of the ICDAS codes: 0 vs 1–4 (D1), 0–2 vs 3/4 (D2), and 0–3 vs 4 (D3). The cutoff points for the new QS-Occlusal scoring system corresponding to D1, D2, and D3 were 0/1, 1/2, and 2/3, respectively. To evaluate the reproducibility and reliability of the imaging test results using QS-Occlusal, the intra- and interexaminer reliabilities were assessed using the ICC. The significance cutoff for all the statistical tests was set at α = 0.05 (version 23.0, PASW Statistics, SPSS, Chicago, IL, USA).

3. Results

In total, 791 teeth of 94 participants (aged 29.2 ± 10.2 years, mean ± SD) were analyzed (Fig. 1). The mean value of the QLF parameter was compared between the QS-Occlusal groups in order to assess the fluorescence changes of the occlusal surface. This revealed that $\Delta F_{\text{max}}$ increased significantly by about 4.7-fold (from 15.94 to 75.63) when QS-Occlusal increased from 0 to 3. In particular, a much larger difference was observed between QS-Occlusal = 0 and QS-Occlusal = 1 (34.27) compared to the other scores (0.68-fold change for QS-Occlusal = 1 and 2, and 0.65-fold change for QS-Occlusal = 2 and 3) due to a 2.1-fold increase in the fluorescence loss. $\Delta R_{\text{max}}$ was about 6.2-fold higher for QS-Occlusal = 1 (49.74) than for QS-Occlusal = 0 (8.04), and the red fluorescence intensity was 10.5-fold higher for QS-Occlusal = 2. In particular, for QS-Occlusal = 3, the red fluorescence intensity was 21.6-fold higher than for a sound tooth surface and 3.5-fold higher than for QS-Occlusal = 1 (Table 2, $P < 0.001$).

For QS-Occlusal = 1, lesions progressed to the enamel outer half along a pit or fissure and extended from side to side along the progression direction of occlusal caries lesions that simultaneously progressed to the enamel inner half for QS-Occlusal = 2. The lesions for which QS-Occlusal = 3 had progressed to dentin (Fig. 2).

The distribution of the depth of caries in the included teeth was evaluated using ICDAS criteria. Most of the teeth (n = 419, 53.0%) were classified as ICDAS code 0. The caries lesions were the next most common, with 186 teeth (23.5%) classified as ICDAS code 2, while teeth classified as ICDAS code 4 were the least common (5.6%). The tooth classifications based on QS-Occlusal in QLF images showed a moderate positive correlation with tooth evaluations using the ICDAS criteria (r = 0.64, P < 0.001; Table 3). QS-Occlusal = 0 (35%) was less common than ICDAS code 0 (53%). Approximately 33% of the ICDAS code 0 teeth were scored as QS-Occlusal = 1, and 10% were scored as QS-Occlusal = 2, and we confirmed that fluorescence changes were detected using QS-Occlusal even when they were classified as sound teeth based on ICDAS criteria. In addition, the proportions of teeth with QS-Occlusal = 1 (36%) and classified as an ICDAS score of 1 or 2 (33%) were similar, as were those for QS-Occlusal = 3 (11%) and ICDAS scores of 3 and 4 (14%).

Table 4 presents the sensitivity, specificity, and AUROC values for the optimal cutoff point calculated from the three ICDAS diagnostic thresholds. At the D1 diagnostic threshold (ICDAS code 0 vs 1–4), the optimum sensitivity and AUROC (0.807) were obtained using a QS-Occlusal cutoff value of 0/1, for which a moderate specificity (0.563) was obtained. At the D2 diagnostic threshold (ICDAS code 0–2 vs 3/4), an excellent AUROC (0.929) was obtained using a QS-Occlusal cutoff value of 1/2. At the D3 diagnostic threshold (ICDAS code 0–3 vs 4), QS-Occlusal exhibited the highest sensitivity, specificity, and AUROC (0.976).

Excellent intraexaminer reliability was confirmed by an ICC of 0.94 (95% confidence interval [CI] = 0.93–0.95, P < 0.001) in image evaluations using QS-Occlusal. The interexaminer reliability was also high, with an ICC of 0.86 (95% CI = 0.84–0.88, P < 0.001).

4. Discussion

The aim of this study was to develop diagnostic criteria for occlusal caries lesions using QLF technology for possible use in teledentistry and large-scale epidemiology surveys based on the analysis of images only. We also wanted to determine whether a scoring system that standardizes the QLF properties of noncavitated occlusal lesions could replace existing clinical examinations based on simply evaluating fluorescence images obtained in the clinic.

The newly proposed QS-Occlusal parameter divides the caries depth into four stages according to standardized fluorescence changes detectable using QLF technology (Table 1). Excellent validity and reliability were observed based on ICDAS results, which are commonly used to assess the clinical severity of caries, and on comparisons with histological test results. The findings confirm the possibility of assessing occlusal noncavitated lesions using fluorescence images.

The scoring system proposed in this study is based on an intuitive classification that utilizes two fluorescence parameters (fluorescence loss and red fluorescence) to assess the fluorescence pattern according to the caries severity. The QLF parameter averages for each QS-Occlusal value were compared to verify that this can be used to assess the depth of a lesion. $|\Delta F_{\text{max}}|$ was found to increase significantly with QS-Occlusal (Table 2). Several previous studies have demonstrated that $\Delta F$ (reflecting the degree of mineral loss) is an index that accurately reflects the histologically measured depth of a lesion [23]. In particular, a recent study found that $\Delta F_{\text{max}}$ reflects the depth of tooth cracks by quantifying the maximum fluorescence loss of the lesion [24]. According to the same principle, $\Delta F_{\text{max}}$ can be used to detect the fluorescence loss of a deep lesion below a pit or fissure on the occlusal surface [25,26]. Thus, the differences in fluorescence loss for different QS-Occlusal values indicates that this parameter is appropriate for grading the stage of a lesion in terms of its depth and progression. In addition, a previous study found that $\Delta F$ could be used to ensure that appropriate treatment is provided according to the lesion severity [27]. It is therefore expected that the findings of the present study can be used to develop objective criteria for decision-making when ensuring the optimal treatment is provided for caries prevention and management by calculating the $\Delta F$ value for lesions classified according to QS-Occlusal. Moreover, $\Delta R_{\text{max}}$ (another QLF parameter used in this study) can be used to evaluate the depth of the lesion due to the distinct differences evident between each score. It was found that $\Delta R$ increased more clearly than did $\Delta F$, and so changes in $\Delta R$ may be better for distinguishing the lesion depth (Table 2).

Few studies have investigated how the characteristics of red

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Table 2  Fluorescence parameters obtained from fluorescence images according to the severity of caries lesion classified using QS-Occlusal.

| QS-Occlusal | QLF parameters | $|\Delta F_{\text{max}}|$  | $\Delta R_{\text{max}}$ |
|------------|----------------|--------------------------|---------------------|
| 0          |                | 15.94 ± 0.61$^a$         | 8.04 ± 1.01$^a$      |
| 1          |                | 33.65 ± 0.81$^b$         | 49.74 ± 3.27$^b$     |
| 2          |                | 49.73 ± 1.36$^c$         | 84.57 ± 4.40$^c$     |
| 3          |                | 75.63 ± 1.17$^d$         | 173.87 ± 18.36$^d$   |

Data are mean ± SD values.

Different letters within the same column indicate significant differences between groups by Tukey’s post-hoc analysis with a significance cutoff of α = 0.05.
fluorescence varies with the caries severity. Although some previous studies have found that the red fluorescence intensity varies with the depth of a caries lesion, it was difficult to observe slight differences in the fluorescence properties in noncavitated lesions, since cavitated lesions were assessed retrospectively [28, 29]. In contrast, the present study used extracted teeth and assessed their fluorescence images using QS-Occlusal. The results confirmed that the intensity and range of red fluorescence increased with the lesion progression and depth, based on the results of histological analyses (Fig. 2). The red fluorescence properties could be categorized into three levels of lesion severity: with/without fluorescence expression (QS-Occlusal = 0/1), with/without extension of fluorescence expression (QS-Occlusal = 1/2), and with/without red fluorescence glow and dark shadow (QS-Occlusal = 2/3). The variations in the red fluorescence properties with lesion severity were similar to a previous retrospective study finding that the intensity and area of red fluorescence increased with the lesion activity when comparing with the baseline red fluorescence value [12].

Red fluorescence is produced by the metabolites of bacteria such as porphyrin, and it increases with the cariogenicity [15]. The relation between caries lesions and red fluorescence can be explained as follows: as the depth of a caries lesion increases, the lesion pore widens and deepens, allowing bacteria to penetrate more deeply into the pore, which increases metabolic activity according to the bacterial composition (greater pathogenicity and anaerobicity), and the red fluorescence intensity and range are thereby increased [30]. Previous studies have also shown that this red fluorescence tends to be more prominent in active lesions [12, 27, 30]. However, in order to clearly demonstrate the mechanisms underlying the expression of red fluorescence in caries lesions, it is necessary to confirm the relationship between changes in the mineral loss of the lesions and the type of bacteria and the metabolic activity present in lesions according to their severity. Since the red fluorescence intensity increases with the cariogenicity of the biofilm [31], the red fluorescence depends on lesion severity, which is determined by the composition of the internal bacteria and the metabolic activity during caries progression. In addition, although it is

### Table 3

<table>
<thead>
<tr>
<th>ICDAS</th>
<th>QS-Occlusal value</th>
<th>Total (%)</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>0</td>
<td>236</td>
<td>139</td>
<td>43</td>
</tr>
<tr>
<td>1</td>
<td>18</td>
<td>40</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>19</td>
<td>91</td>
<td>65</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>11</td>
<td>24</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total (%)</td>
<td>275 (34.8)</td>
<td>281 (35.5)</td>
<td>145 (18.3)</td>
</tr>
</tbody>
</table>

$r$ is the Spearman correlation coefficient for the correlation between ICDAS and QS-Occlusal.

$*$ $P < 0.001$

### Table 4

<table>
<thead>
<tr>
<th>Diagnostic thresholds</th>
<th>$D_1$</th>
<th>$D_2$</th>
<th>$D_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutoff value</td>
<td>0/1</td>
<td>1/2</td>
<td>2/3</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.895</td>
<td>0.912</td>
<td>0.977</td>
</tr>
<tr>
<td>Specificity</td>
<td>0.563</td>
<td>0.839</td>
<td>0.957</td>
</tr>
<tr>
<td>AUROC</td>
<td>0.807</td>
<td>0.929</td>
<td>0.976</td>
</tr>
</tbody>
</table>

$D_1$, 0 vs 1–4; $D_2$, 0–2 vs 3/4; $D_3$, 0–3 vs 4.
difficult to identify the relationship between the caries activity and the presence of red fluorescence in this study, if this is confirmed, it will be possible to assess the caries status and provide appropriate treatment by evaluating the level of red fluorescence detected from the lesions in the future.

Our comparison of the distribution according to QS-Occlusal values in this study (Table 3) revealed that using QS-Occlusal simplified the ICDA diagnostic criteria and allowed the lesion severity to be classified objectively. The proportion of lesions with QS-Occlusal = 1 was similar to the sum of ICDA codes 1 and 2 (32.6%), which corresponds to early-stage enamel caries (Table 3). It is known that ICDA code 2 can be easily distinguished by visual examination, and can be detected more easily than ICDA codes 1 and 3, which are ambiguous diagnostic criteria [32]. This may have contributed to the lesion proportion being highest for ICDA code 2 in the visual examinations. On the other hand, the newly proposed criteria can distinguish differences between lesions more objectively due to use of changes in the fluorescence properties from the teeth as the diagnostic criteria. Dental devices such as a dental unit-chair with an air compressor are needed to blow air over the teeth when distinguishing caries lesions according to ICDA criteria during a clinical examination [33]. However, if examiners has access to a computer, QS-Occlusal can be used for cost-effective and timesaving tele-dentistry without such dental devices because this method detects caries lesions using images that have already been taken. The proportion of teeth with QS-Occlusal = 3 (11.4%) was similar to the sum of ICDA codes 3 and 4 (14.4%), which corresponds to progression to dentin. QS-Occlusal was equal to 2 for about 35% of those with ICDA code 2 and about 34% of those with ICDA code 3, so this diagnostic criterion is an indicator of a definite caries lesion after the initial caries stage. Also, based on the result that more than 43% of those with ICDA code 0 had QS-Occlusal = 1 or 2, we confirmed that fluorescence changes could be detected in fluorescence images even though no surface changes of the teeth were evident in visual examinations (Table 3). This reconfirms certain problems: even if there are reliable criteria (i.e. ICDA) for diagnosing noncavitated lesion, it is difficult to make a clear judgment, which increases the false-negative rate and results in low validity and reliability [34]. These limitations can be easily overcome by objectively evaluating fluorescence images in order to detect the presence or absence of a lesion.

The results for the diagnostic accuracy at each threshold confirmed that the characteristics of the fluorescence parameter from QS-Occlusal can be used to distinguish the level of caries progression. The high sensitivity, specificity, and AUROC at optimum cutoff values (QS-Occlusal = 1/2) found for the D2 threshold of ICDA codes 2 and 3 allowed early-stage decay and established decay to be distinguished. This result confirms the validity of using the red fluorescence extending around pits and fissures as a criterion for clinically distinguishing between early-stage and definite caries lesions (Table 4). Also, the QS-Occlusal cutoff of 2/3 produced the highest diagnostic accuracy for the D3 diagnostic threshold (ICDA code 0–3 vs 4). In order to distinguish QS-Occlusal = 3, we confirmed that the proposed fluorescence properties (dark shadow as fluorescence loss and high intensity of red fluorescence) are useful parameters for detecting advanced caries at the dentin level. On the other hand, using a QS-Occlusal cutoff value of 0/1 for the D1 threshold (ICDA code 0 vs 1–4) to discriminate sound surfaces from initial (or suspected) caries lesions showed high sensitivity and relatively low specificity. Although professional tooth cleaning was performed to minimize the effects of debris and plaque on the evaluation results, it was not possible to completely remove the bacteria and their metabolites (porphyrin) from pits or fissures [35]. This meant that they manifested as red fluorescence, which might have affected the study results. In other words, the plaque in pits and fissures that is difficult to observe with the naked eye would appear as red fluorescence on the QLF-D image, which would impair the ability to distinguish between QS-Occlusal values of 0 and 1. However, it is generally, it is recommended for the sound surface or early stage caries to receive preventive care such as using fluoride or sealant, rather than irreversible surgical procedures [36,37]. Considering that the presence of plaque increases the risk of caries, this protocol may be effective for preventing early caries in clinical applications.

Finally, the intra- and interexaminer reliabilities were checked to determine whether the proposed QS-Occlusal would be useful in clinical practice—they showed high reproducibility, with ICC values of 0.94 (95% CI = 0.93–0.95) and 0.86 (95% CI = 0.84–0.88), respectively. Although visual examination is still the most commonly used method for caries detection, this is associated with wide variability in the reproducibility (0.34–0.96) between examiners [6]. In particular, detecting an early lesion on the occlusal surface is difficult, as indicated by a low sensitivity of less than 20% even when accompanied by a tactile examination [7]. On the other hand, it is expected that the use of QS-Occlusal—which is based on a clinical classification system for occlusal noncavitated lesions can achieve results comparable to a visual examination using images alone and therefore reduce the diagnostic inconsistencies that are common among clinicians [19,22,24]. Despite the recent emergence of telemedicine, which combines rapid Internet transfers and image analysis, there has been very little research into the use of such images for diagnosis in dentistry [38]. Nevertheless, the use of QLF images as in the present study could yield results for detecting noncavitated occlusal caries comparable to those obtained in direct oral examinations. Considering that a clinical evaluation based on images is an inexpensive, practical, and reliable method, it could also be a valid and practical method for performing large-scale epidemiological surveys involving numerous subjects across different clinical sites.

Conflicts of interest

The authors declare that there are no conflicts of interest related to the present study

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Photodiagnosis and Photodynamic Therapy 21 (2018) 36–42


