Original Article

Retrospective longitudinal observation of caries around restorations by quantitative light-induced fluorescence

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ABSTRACT

Caries lesions that develop around restorations (CARS) are the main reason for restoration replacement. The aim of this study was to assess whether surfaces that developed CARS and progressed to cavitation have a different fluorescent profile than surfaces that have restorations and no associated lesions. Quantitative light-induced fluorescence (QLF) images of occlusal, buccal, or lingual surfaces of permanent molars from 569 consented children followed up for 48 months as part of a longitudinal study (Ferreira Zandoná *et al*, 2010, 2013) with an amalgam restoration and no associated caries lesion at baseline as determined by visual examination using the International Caries Detection and Assessment System (ICDAS) were selected. Surfaces ($n = 22$) that progressed to cavitation (ICDAS ≥5) at follow-up and randomly selected surfaces ($n = 22$) with no change at follow-up were analyzed for QLF parameters: area (A [mm^2]), fluorescence loss (ΔF [%]), and ΔQ [% × mm^2]. Single, calibrated, and masked examiner (CPP) analyzed the images. Means and slopes between progressed and nonprogressed surfaces were compared using linear mixed effects models. ΔF, ΔQ, and ΔA increased significantly ($P \leq 0.0001$) at a faster rate for surfaces that developed CARS and progressed to cavitation compared to restorations with no associated lesions. Surfaces with amalgam restorations that developed associated caries and progressed to cavitation have a different fluorescent profile than surfaces that have amalgam restorations and no associated lesions. Within the limitations of this study, QLF could assess the development of CARS *in vivo*. Analyses of amalgam restorations with associated lesions that do not progress to cavitation are warranted.

Key words: Caries around restoration, caries detection, international caries detection and assessment system, quantitative light-induced fluorescence, secondary caries

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INTRODUCTION

Development of caries around restorations (CARS) has been extensively studied and documented.[1-5] The success of a dental restoration lies on the physical properties of the restorative material, marginal integrity of restoration,[6] and patient risk factors.[5] Over 70% of restorative procedures are done on previously treated teeth,[7] and CARS is the main reason for restoration replacement.[8] Retreatment due to CARS is a major dental care expense.[9]

CARS consist of two carious lesions: outer (enamel or cementum) and inner/wall (interface where restoration and dentin or enamel meet).[10] Both carious lesions (outer and wall) can be present as isolated or concurrent lesions.[1,11] Most CARS lesions have an outer lesion which is more demineralized than the wall lesion.[10] Outer lesions have been

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shown to be the precursor for the wall lesion. A wall lesion without an outer lesion is extremely difficult to demonstrate through *in vitro* experiments.[3] Earlier studies suggest that primary and CARS spread through enamel rods.[5] Therefore, CARS can develop as initial demineralization of enamel/cementum and formation of outer lesion, which spreads through enamel rods to the interface or wall region. This outer lesion rapidly progresses through the restoration–tooth interface or wall lesion leading to an eventual restoration failure requiring an operative intervention. Early identification of such lesions is important for better prognosis.

Quantitative light-induced fluorescence (QLF) uses visible light in the violet-blue spectrum (290–450 nm) to excite enamel autofluorescence. This autofluorescence can be detected after filtering the excitation light using a high bandpass filter. Normal enamel will appear green after violet-blue light filtration, and demineralized enamel will have decreased autofluorescence. QLF is a quantitative method which allows longitudinal observation of a carious lesion.[12,13] The sensitivity and specificity of QLF in permanent teeth for detecting pit and fissure lesions has been reported to be 0.68 and 0.70, respectively; whereas reliability for smooth surface lesions on permanent teeth using image analysis was 0.93 for intraexaminer and 0.92 for interexaminer comparisons.[14]

There are few studies that have used QLF to monitor caries lesions progression around restorations.[3,12,15] All these previously published studies presented *in vitro* data for the use of QLF for the detection of caries lesion in permanent teeth. These studies demonstrated that QLF is comparable to conventional caries detection techniques such as visual examination and radiography or detecting secondary caries. In addition, Lenzi *et al.* detected caries around tooth-colored restorations in primary molars through an *in vitro* experiment[15] with similar results. Ferreira Zandoná *et al.* previously presented data on the effectiveness of QLF in the early detection of primary caries lesions on permanent teeth in an *in vivo* longitudinal study.[16,17] To our knowledge, there are no published studies presenting *in vivo* longitudinal data on the detection of caries around amalgam restorations. In this 48-month, retrospective, longitudinal study, we conducted an analysis of available QLF images of surfaces restored with amalgam that did or did not progress to cavitation. The hypothesis of the study was that surfaces with amalgam restorations that developed caries lesion and progressed to cavitation have a different fluorescent profile than surfaces that have amalgam restorations and no associated lesions.

MATERIALS AND METHODS

Experimental participants

This retrospective study assessed available images from children that had been recruited for a previous study (16,17). As previously published (16, 17) the original study recruited children (n = 569) from kindergarten to 9th grade public schools (5–13 years old) in the area of Aguas Buenas,Puerto Rico, with at least one permanent tooth and one unrestored surface.[16,17] All children received oral hard and soft tissue examination by a calibrated examiner[18] at 0, 8, 12, 16, 20, 24, 28, 32, 36, 40, 44, and 48 months. Guidelines for full mouth hard tissue examination using the International Caries Detection and Assessment System (ICDAS)[19] were followed. The ICDAS detection criteria for CARS are[10] (0) sound tooth surface with restoration or sealant, (1) first visual change in enamel, (2) distinct visual change in enamel/dentin adjacent to a restoration/sealant margin, (3) carious defects of `0.5 mm with the signs of code 2 adjacent to a restoration/sealant margin, (4) caries in enamel/dentin/cementum adjacent to restoration/sealant with underlying dark shadow from dentin, (5) distinct cavity adjacent to restoration/sealant, and (6) extensive distinct cavity with visible dentin adjacent to restoration/sealant. As Per protocol,[17] all buccal and occlusal surfaces of permanent posterior teeth and lingual surfaces of upper molars were imaged by QLF (QLF Pro, Inspektor Research systems, Amsterdam, The Netherlands) in a dark environment at regular intervals over a 48-month period using the repositioning function of the software.

Quantitative light-induced fluorescence

QLF images were generated by exposing the tooth surface to 13 mW/cm^2 of violet-blue light (290–450 nm). Images were captured and stored using a unique identification number. All imaged surfaces that fit the inclusion criteria, that is, an amalgam restoration and no associated caries at baseline by visual examination using the ICDAS;[17] at least consecutive 3 visits, with progression to cavitation (ICDAS ≥5), were included in the study. These restored surfaces were considered the test group (n = 22), (progression group). A randomly selected equal number of restored surfaces, matched for age and gender and type of surface (n = 22) that remained sound at follow-up, were included as the control/no-progression group. QLF images from both groups were analyzed to generate three QLF parameters: area (A [mm^2]), fluorescence loss (ΔF [%]), and ΔQ [% × mm^2].

The QLF parameters were generated using the white spot lesion module in the Inspektor Pro image analysis software (Inspektor Research Systems BV, Amsterdam, The Netherlands). All QLF images were analyzed in a dark room by a single, masked, calibrated examiner as previously described.[16] The fluorescence threshold was set at 5%.

Statistical analyses

The progression (test) and the no-progression (control) groups had eight time variables or values: 0, 8, 12, 16, 20,

24, 28, 32, 36, 42, and 48 months. The interval between the first and the second records was 8 months. The time intervals between the other consecutive records were all 4 months. Surfaces in either groups were followed for the duration of the study (48 months). The model was fitted with a random intercept and a random slope. Ignoring the random terms, the marginal models had the following form:

Model 1: $\Delta F = \beta_1 \times test_i + \beta_2 \times control_i + \beta_3\ test_i \times time_{ij} + \beta_4 \times control_i \times time_{ij}$

Model 2: $\Delta Q = \beta_1 \times test_i + \beta_2 \times control_i + \beta_3\ test_i \times time_{ij} + \beta_4 \times control_i \times time_{ij}$

Model 3: $\Delta A = \beta_1 \times test_i + \beta_2 \times control_i + \beta_3\ test_i \times time_{ij} + \beta_4 \times control_i \times time_{ij}$

Here, time = j^{th} time value (in months) for the corresponding i^{th} subject; $F/Q/A_{ij}$ = value of $\Delta F/\Delta Q/\Delta A$ for i^{th} subject at $time_{ij}$ in models 1, 2, and 3, respectively; $test_i$ = 1, if i^{th} subject is in progression group and 0, if the i^{th} subject is in the no progression group; $control_i$ = 1, if i^{th} subject is in no progression group and 0, if the i^{th} subject is in the progression group.

Data were analyzed using SAS software (version 9.4, SAS Institute, Cary, NC, USA). $P < 0.05$ was considered statistically significant.

RESULTS

Both groups, progression (test) and no-progression (control), had an average of six visits. Both progression (test) and no-progression (control) groups (n=22) had 20 occlusal surfaces and 2 buccal or lingual surfaces with restoration extending from occlusal surface into the buccal or lingual groove.

Fluorescence loss (mean ΔF) increased from baseline through follow-up visits until 48 months in the progression group whereas it did not increase significantly from baseline over the 48 months in the no-progression group [Figure 1]. Area (mean A) increased from baseline through the follow-up visits in the progression group. However, area (mean A) was constant over the study duration in the no-progression group [Figure 2]. A similar trend was observed for the ΔQ (which is the product of the ΔF and A). Mean ΔQ increased from baseline through the follow-up visits in the progression group whereas mean ΔQ was constant over the study duration in the no-progression group [Figure 3]. The selected QLF images of surfaces unrestored and restored with no-progression and progression are shown in [Figure 4].

Estimated slopes (per month change over time) of the QLF parameters such as (area [A (mm^2)], fluorescence loss [ΔF (%)], and ΔQ [% × mm^2]) were statistically significantly different than 0 in the progression groups but not in the no-progression groups [Table 1]. In addition, estimates of all the three QLF slopes in the progression group (ΔF: 13.64% ± 1.01%, A: 0.93 ± 0.16 mm^2, and ΔQ: 12.57% ± 3.34% mm^2) were statistically significantly

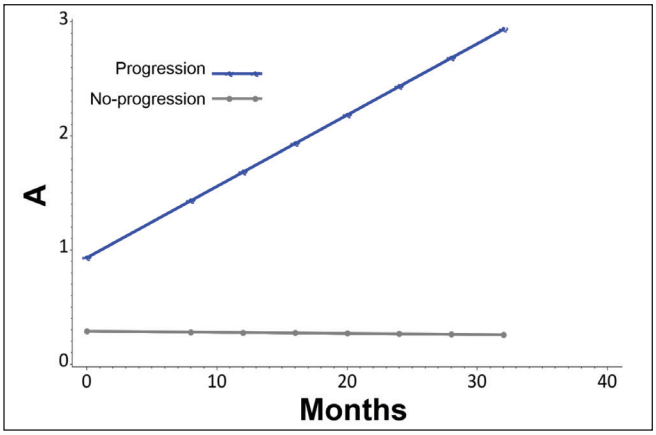

Figure 2: Fitted model for mean A (area) plotted against time (blue line = progression and black line = no-progression)

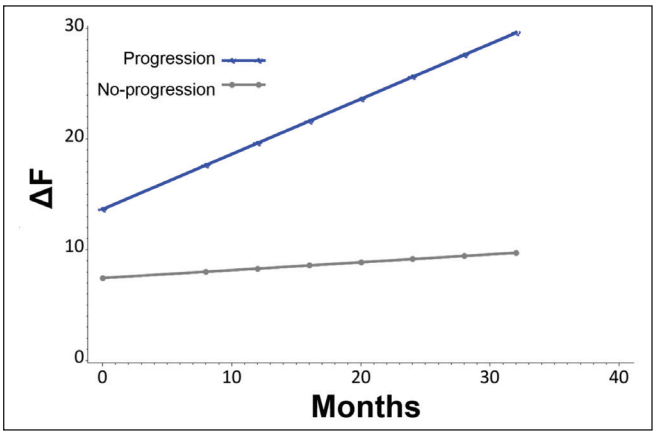

Figure 1: Fitted model for mean ΔF (fluorescence loss) plotted against time (blue line=progression and black line = no-progression)

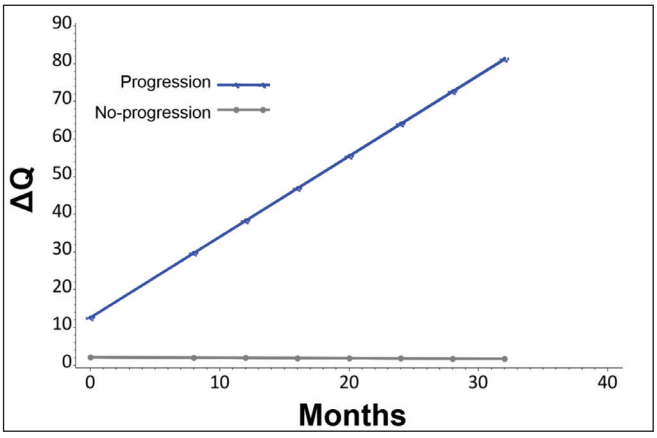

Figure 3: Fitted model for mean ΔQ (fluorescence loss vs. area) plotted against time (blue line = progression and black line = no-progression)

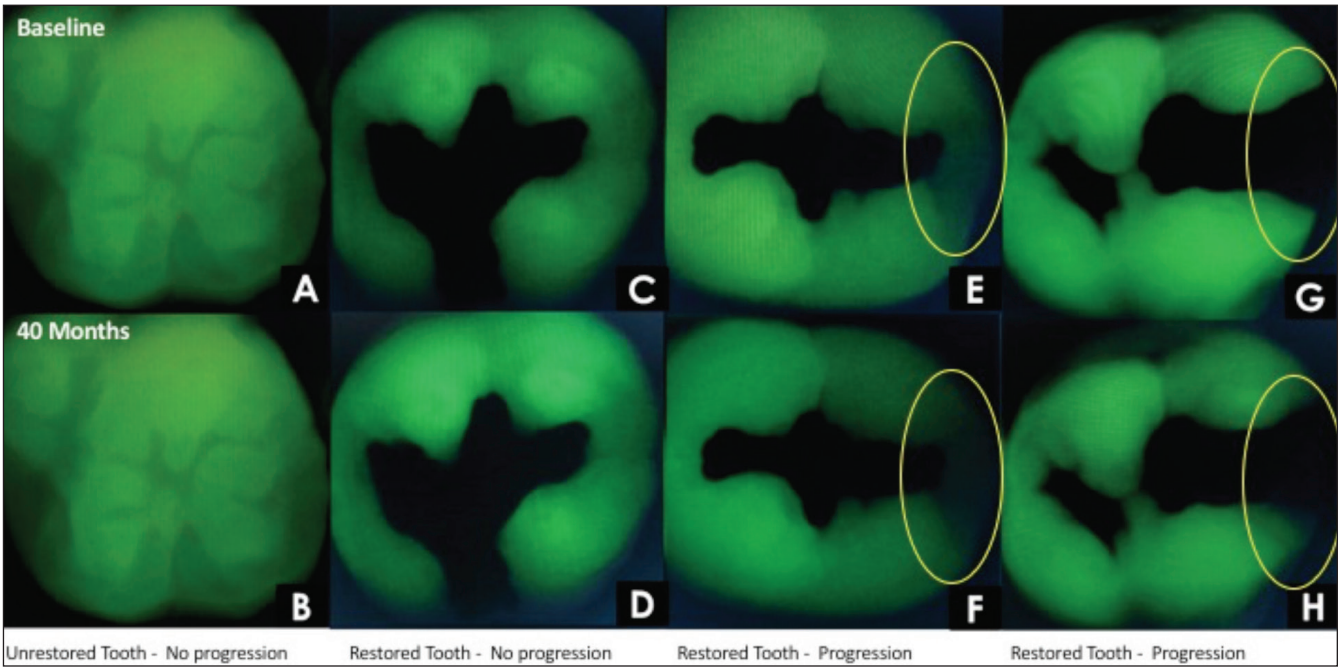

Figure 4: Example of surfaces that did not cavitate (no-progression) versus surfaces that did cavitate (progression)

Table 1: Linear Mixed Model Parameter Estimates (Standard Errors) for ΔF, A, and ΔQ

QLF Parameters	ΔF		A		ΔQ	
	Test	Control	Test	Control	Test	Control
Intercept	13.645 (1.012)*	7.443 (1.003)*	0.932 (0.163)*	0.288 (0.161)	12.578 (3.341)*	2.107 (3.288)
Slope	0.499 (0.055)*	0.072 (0.052)	0.063 (0.008)*	−0.001 (0.007)	2.145 (0.293)*	−0.015 (0.287)

[1]Intercepts are baseline mean, slopes are changes in mean outcome per 1 month, *P ` 0.001

higher (P ` 0.0001) as compared to slopes in the no-progression group (ΔF: 7.44% ± 1.00%, A: 0.28 ± 0.16 mm^2, and ΔQ: 2.10% ± 3.28% mm^2).

DISCUSSION

Early detection of caries is paramount for the interception of the vicious circle of caries-restoration-caries-retreatment. Visual and radiographic methods have been commonly employed in the past, but angulation of the teeth to the observer can be a confounding factor for clinical diagnosis of CARS. In addition, angulation and overlapping can undermine the diagnostic ability of a radiograph owing to the radiodensity of amalgam restorations. A recent systematic review and meta-analyses of caries detection around restorations found that few studies have investigated the ability of different methods to detect CARS[20] and most were done *in vitro* which further limits the clinical interpretation of the results.

A quantifiable method such as QLF provides a powerful tool to observe and longitudinally document the process of demineralization after the restoration is placed. Various clinical studies in children have employed QLF in the past for diagnosing caries in primary teeth[21] or permanent teeth.[16] QLF has been used for studying caries progression *in vitro*[15] and *in vivo*.[22] Use of QLF has been broadened recently to assess the efficacy of fluoride and dentifrices.[23] In addition, QLF has been used to quantify dental stains and determine the efficacy of whitening treatment.[24]

QLF provides a noninvasive yet quantitative tool for the detection of CARS. Pretty *et al*. used QLF to detect CARS including tooth-colored and amalgam restorations, finding it effective for the detection of CARS[25] in an *in vitro* study. Another *in vitro* study suggested similar results of efficacy of QLF in detecting CARS.[3] Ando *et al.* in an *in vitro* study assessed various methods of detecting CARS and provided evidence that QLF is a viable alternative for objectively determining and documenting CARS.[26] Lenzi *et al*. in an *in vitro* study on primary molars with tooth-colored resin composite restorations found that QLF was comparable to conventional caries detection methods including radiography and visual examination.[15]

Similar to the previously published data, our study supports the reliability of the QLF in detecting CARS.

However, our study provides long-term (4 years), longitudinal, *in vivo* evidence to support the validity of QLF for the detection of CARS. The "ΔF" parameter of QLF refers to the percent loss of fluorescence or depth of the demineralized lesion which increased over time in the progression group as compared to the no-progression group. This demonstrates that the development of clinical cavitation in subsequent visits (ICDAS ≥5) can be detected at an early stage using QLF. The area of the lesion increased over time in progression group as compared to the no-progression group. This suggests that if no preventive intervention is put in place, a lesion that is consistently increasing in size may eventually cavitate as seen in this study. The "ΔQ" is the mathematical product of the ΔF and A. In other words, ΔQ is the volume of the lesion. The volume of the lesion also increased over time in the progression group suggesting that QLF can be predictably used for the detection of early CARS even before the clinical cavitation is seen. Thus, fluorescent profile of the surfaces that progressed to cavitation was significantly different than the surfaces that did not progressed to cavitation.

Restorative material properties, quality of the restoration, restoration interface (enamel or dentin), and patient risk factors, including fluoride exposure[9] and diet, are often intricately involved in the caries process.[27] It was not possible for the authors to control these factors due to the study design since this was a retrospective study looking at existing data from an original study that did not include treatment. The restorations were placed by dentists in the community where the participants were located with no intervention whatsoever from the study personnel. However, this study provided us a rather important insight in studying the natural course of the lesion progression after the placement of restoration. Our *in vivo* study shows that QLF can serve a clinical tool to detect the CARS early. Thereby, patient factors such as diet and fluoride exposure can be modified early through home care and professional dental care. This may help the clinician to identify high-risk surfaces and address the risk factors that are contributing to the lesion progression.

It is worthwhile to know that although QLF serves a valuable and promising tool for the diagnosis of CARS, it has some shortcomings. QLF angulation and dehydration may affect the outcome of QLF parameters.[28,29] Therefore, QLF images should be generated at 90° to the surface imaged. Variations of more than 20° can generate unreliable results.[28] In addition, saliva and plaque can lead to decreased sensitivity by QLF whereas stains can decrease specificity.[30,31] Hence, for reliable results, the surface must be free of plaque and dried with compressed air before QLF imaging. We included all the protocols in our study to minimize errors in image generation, data collection, and analysis. Furthermore, a limitation of QLF is its ability to only capture visible surfaces (nonproximal surfaces) and most CARS occur at the cervical margins of interproximal restorations.[5] Further investigation between the progression of lesions on the surfaces visible by QLF and progression of lesions on associated proximal surfaces is warranted. Brouwer *et al.*[20] in their systematic review stated that there would be no benefit in using QLF as it has high sensitivity and low specificity and could lead to unwarranted retreatment. Although we agree in principle, the results of this study indicate that if QLF is used to detect and monitor early lesion progression around restorations, there is a great potential to avoid restorative retreatment and apply preventive interventions early on.

Finally, this *in vivo* study provides evidence for the effectiveness of longitudinal use of QLF for 4 years in children. Within the limitations of this study, it can be said that fluorescent profiles of surfaces that progressed to cavitation were different from the fluorescent profile of the surfaces that did not progressed to cavitation. Hence, QLF can serve as a quantitative tool to objectively diagnose and document initiation and progression of CARS. Such an early diagnosis of noncavitated CARS lesion can help the clinician to institute preventive measures and save dental health-care expense by delaying or avoiding cavitation and retreatment.

Study significance

The study is the first ever longitudinal *in vivo* demonstration that QLF can be reliably used to determine the initial demineralization in permanent molars restored with amalgam. The detection of initial demineralization in a tooth restored with amalgam can be challenging with visual and radiographic examination. Use of QLF might provide us with a clinical solution to diagnose and detect the presence of initial demineralization or development of CARS. Preventive intervention in such cases might reduce the burden on dental health-care expenses due to restorative procedures undertaken after the development of clinical cavitation.

Role of authors

All authors participated in the study design and manuscript preparation. In addition, CPP analyzed the images and interpreted the data, HB and JP analyzed the data, and AFZ interpreted the data and finalized the draft of the manuscript.

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Conflicts of interest
There are no conflicts of interest.

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