

REVIEW ARTICLE

Unveiling the Incipient Caries by Quantitative Light-induced Fluorescence

¹Rahul Srivastava, ²Janhavi Dixit, ³Bhuvan Jyoti, ⁴Shobhit Pradhan

ABSTRACT

Dental caries is one of the most prevalent chronic diseases of humans worldwide. When different stages of the disease are taken into account, from the initial to the clinically manifesting lesion, very few individuals are truly unaffected. Quantitative light-induced fluorescence (QLF) is a prominent diagnostic technique in dentistry. The purpose of this article is to review the effectiveness of QLF system in early detection of carious lesions as well as its future clinical application in dentistry. The review article has been prepared doing a literature review from the world wide web and PubMed/medline.

Keywords: Dental caries, Diagnostic technique, Quantitative.

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INTRODUCTION

Dental caries (tooth decay) is a chronic disease, affecting a large number of population. The carious process affects the mineralized tissues of the teeth, enamel, dentin and cementum, caused by the action of microorganisms on fermentable carbohydrates in the diet. The disease is often described to be progressive and if not treated may expand in size and progress to the pulp leading to pulp inflammation thus pain and discomfort, and the end result will be loss of vitality followed by loss of the tooth.¹

Dental caries is the number one childhood disease in the United States. Although dental caries (tooth decay) is largely preventable, it remains the most common chronic disease of children aged 5 to 17 years.²

Once the caries has reached the cavitory stage, the only treatment option left is to restore the lesion because of irreversible nature of the disease. Till yesteryears, cavities were made using GV Black principle that dictate extension for prevention. This classical approach to treat dentinal lesion mandates removing all the infected and affected dentin.³

The clinical management of dental caries has progressed from extraction to restoration and recently from minimally invasive to maximally interceptive approaches. With the shift from operative to nonoperative intervention, the accurate early detection of caries lesions is a prerequisite for interceptive measures to arrest or reverse caries progression. Lesions are usually detectable first at the white spot stage, but may be more advanced; mineral loss in enamel lesions is not quantifiable, and changes in mineral content—loss or gain as a result of de- or remineralization—cannot be monitored. It is suggested that objective methods would enhance conventional intraoral examination and improve the potential for correct diagnosis, especially in caries-risk patients.⁴ Diagnostic techniques to support appropriate clinical decisions about management of the individual lesion, whether invasive therapy or a more conservative, noninvasive approach is indicated, are predominantly based on subjective interpretation of visual information: visual inspection, bitewing radiography, and the use of a dental explorer.⁵ Diagnosis of dental caries is often regarded as synonymous with the detection of the clinical signs of tissue damage caused by the disease, i.e. carious lesions and cavities.⁶

Dental radiographs are inadequate for detecting decay in occlusal surfaces until the lesion is well advanced through the enamel and in to the dentin. The clinician relies on visual observation of staining and clinical judgement based upon experience and on tactile sense, by probing with an explorer.⁷ In this context, QLF seems to be a promising method, which fulfills the essential requirements for detection, quantification and monitoring of caries lesions.⁴

^{1,4}Senior Lecturer, ²Senior Resident, ³Consultant

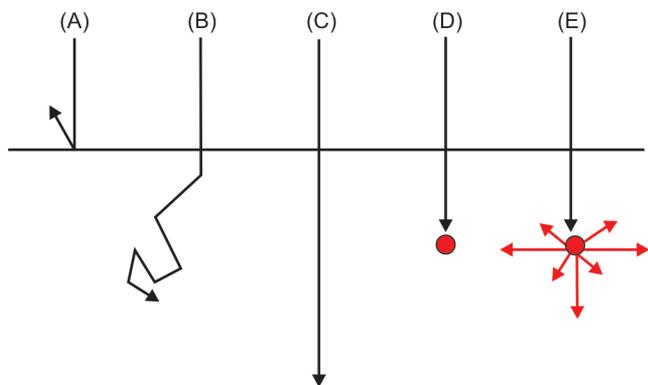
¹Department of Oral Medicine and Radiology, Rama Dental College Hospital and Research Centre, Kanpur, Uttar Pradesh India

²Department of Oral Pathology and Microbiology, King George Medical College, Lucknow, Uttar Pradesh, India

³Department of Dental Surgery, Ranchi Institute of Neuro-Psychiatry and Allied Sciences, Ranchi, Jharkhand, India

⁴Department of Oral Pathology and Microbiology, Mansarovar Dental College, Bhopal, Madhya Pradesh, India

Corresponding Author: Rahul Srivastava, Senior Lecturer Department of Oral Medicine and Radiology, 783/4 W-1, Saket Nagar, Juhi-2, Kanpur, Uttar Pradesh-208014, India, Phone: +91-9450326179, e-mail: drrahul_osmf@yahoo.com



Figs 1A to E: (A) Reflection, (B) scattering (C) transmission, (D) absorption and (E) absorption with fluorescence

EFFECT OF LIGHT TO DENTAL HARD TISSUES

When light interacts with dental hard tissue, it can produce following reactions:

- *Reflection:* In this process, photon is reflected by the material.
- *Scattering:* In this process, photon is scattered several times in the material.
- *Transmission:* In this process, photon is transmitted right through the material.
- *Absorption:* In this process, the photon is absorbed and then transformed in to heat.
- *Absorption with fluorescence:* In this process, electron in lower status are moved to higher status and when they fall back to original situation, energy is emitted from the light that is called fluorescence. In other words, fluorescence is result of interaction of electromagnetic radiation with molecule in the tissue⁷ (Figs 1A to E).

The fluorescence of tooth tissue has been known for a very long time. Spectra have been given by many authors. Three types of fluorescence have to be distinguished. The first is the blue fluorescence that is excited in the near ultraviolet. The second is the yellow and orange fluorescence excited in the blue and green.

The third is the fluorescence in the far red and near infrared that has recently received much attention for quantitative non-image diagnosis of caries lesions.⁶

The cause of enamel fluorescence is unclear, most of the fluorescence is induced by organic components proteinic chromophores but some is probably attributable to appetite. The fluorescence of dentin is proposed to be caused by in organic complexes as well as some organic component. In sound enamel, the path lengths are long with high probability that the photons will hit the chromophore. Thus, fluorescence is relatively intense.⁷

Demineralization of dental hard tissue results in loss of autofluorescence, the natural fluorescence. There are following possible mechanisms that contribute in decreased fluorescence of incipient lesions:

- The light scattering in the lesion causing light path to be much shorter than in sound enamel: the light absorption per volume is much smaller in the lesion and the fluorescence is weaker.
- The light scattering in the lesion act as a barrier for excitation light to reach the underlying fluorescing dentin, and a barrier for fluorescence light from dentin to reach the surface.
- Fluorescence is quenched by a change in molecular environment of the chromophore.
- Proteinic chromophores are removed by the caries process.⁵⁻⁷

QUANTITATIVE LIGHT-INDUCED FLUORESCENCE

The phenomenon of tooth autofluorescence has long since been suggested to be useful as a tool for the detection of dental caries.⁵

Natural fluorescence of teeth was studied by Stubell and Benedict in ultraviolet light and they determined clearly reduced fluorescence in carious teeth surface compared to sound hard tooth tissue. A study of initial carious lesions was carried out by Alfano and Yao with help of ultraviolet light and visible light, in visible light great differences in fluorescence were registered and, as a result, a higher diagnostic significance for distinguishing between sound and carious hard tooth tissue.⁸

Bjerkhagen and Sundstrom and later de Josselin de Jong et al developed a technique based on this optical phenomenon, making the difference in fluorescence radiance between the carious and sound tooth structure quantitative. This has been termed quantitative light-induced fluorescence (QLF).⁵

Quantitative light-induced fluorescence (QLF) is a novel method for detecting caries and bacterial activity of teeth. A recent National Institutes of Health and National Institute of Dental and Craniofacial Research (NIH) report has noted that flipping a coin may provide as much sensitivity and specificity as current methods for diagnosing caries.⁹

Quantitative light-induced fluorescence is based on autofluorescence of teeth. When the teeth are illuminated with high intensity blue light, the resultant autofluorescence of enamel is detected by an intraoral camera which produces a fluorescent image. The emitted fluorescence has a direct relationship with the mineral content of the enamel. Thus, the intensity of the tooth image at a demineralised area is darker than the sound area. The software of QLF systems can process the image to provide user quantitative parameters, such as lesion area, lesion depth and lesion volume.¹⁰ Thus, QLF is a powerful tool

which makes it possible to diagnose the degree of demineralization in a nondestructive way.¹¹

HOW DOES IT WORK?

The QLF equipment is comprised of a light box containing a xenon bulb and a handpiece, similar in appearance to an intraoral camera (Figs 2 and 3). Light is passed to the handpiece via a liquid light guide and the handpiece contains the bandpass filter. Quantitative light-induced fluorescence is a visible light system that offers the opportunity to detect early caries and then longitudinally monitor their progression or regression. Using two forms of fluorescent detection (green and red) it may also be able to determine if a lesion is active or not, and predict the likely progression of any given lesion. In the case of the QLF the visible light has a wavelength (λ) of 370 nm, which is in the blue region of the spectrum. The resultant autofluorescence of human enamel is then detected by filtering out the excitation light using a bandpass filter at $\lambda > 540$ nm by a small intraoral camera. This produces an image that is comprised of only green and red channels (the blue having been filtered out) and the predominate color of the enamel is green.¹² An image of the tooth must be acquired with the intraoral camera held in the hand.¹³

Live images are displayed via a computer and accompanying software enables patient's details to be entered and individual images of the teeth of interest to be captured and stored. Once an image of a tooth has been captured, the next stage is to analyse any lesions and produce a quantitative assessment of the demineralization status of the tooth. This is undertaken using proprietary software and involves using a patch to define areas of sound enamel around the lesion of interest. Following this the software uses the pixel values of the sound enamel to reconstruct the surface of the tooth and then subtracts those pixels which are considered to be lesion. This is controlled by a threshold of fluorescence loss, and

is generally set to 5%. This means that all pixels with a loss of fluorescence greater than 5% of the average sound value will be considered to be part of the lesion. Once the pixels have been assigned 'sound' or 'lesion' the software then calculates the average fluorescence loss in the lesion, known as $\% \Delta F$, and then the total area of the lesion in mm^2 , the multiplication of these two variables results in a third metric output, ΔQ (Figs 4A to D). When examining lesions longitudinally, the QLF device employs a video repositioning system that enables the precise geometry of the original image to be replicated on subsequent visits.¹²

SMOOTH SURFACE LESIONS AND QLF

The QLF method provides a fluorescence image of a smooth surface caries lesion that quantifies the mineral loss and size of the lesion. Accordingly, the method is suitable for quantitative assessment of early enamel lesions in visually accessible surfaces. It may be used for quantitative monitoring of mineral changes (regression or progression) over just a few months.⁶

Clinician situations can be compared with QLF method (Figs 5A and B). The fluorescence image clarifies the difference between view in visible light and QLF light. Figure 5 A shows facial aspect of permanent upper front teeth in which right upper lateral incisor has metal porcelain crown. Figure 5B shows fluorescence images taken with help of QLF method. The sound hard tooth tissue appears greenish-yellow on QLF images, metal porcelain crown cannot be seen in QLF images due to lack of fluorescence. Because of increased fluorescence composite material appears brighter than surrounding enamel.⁸

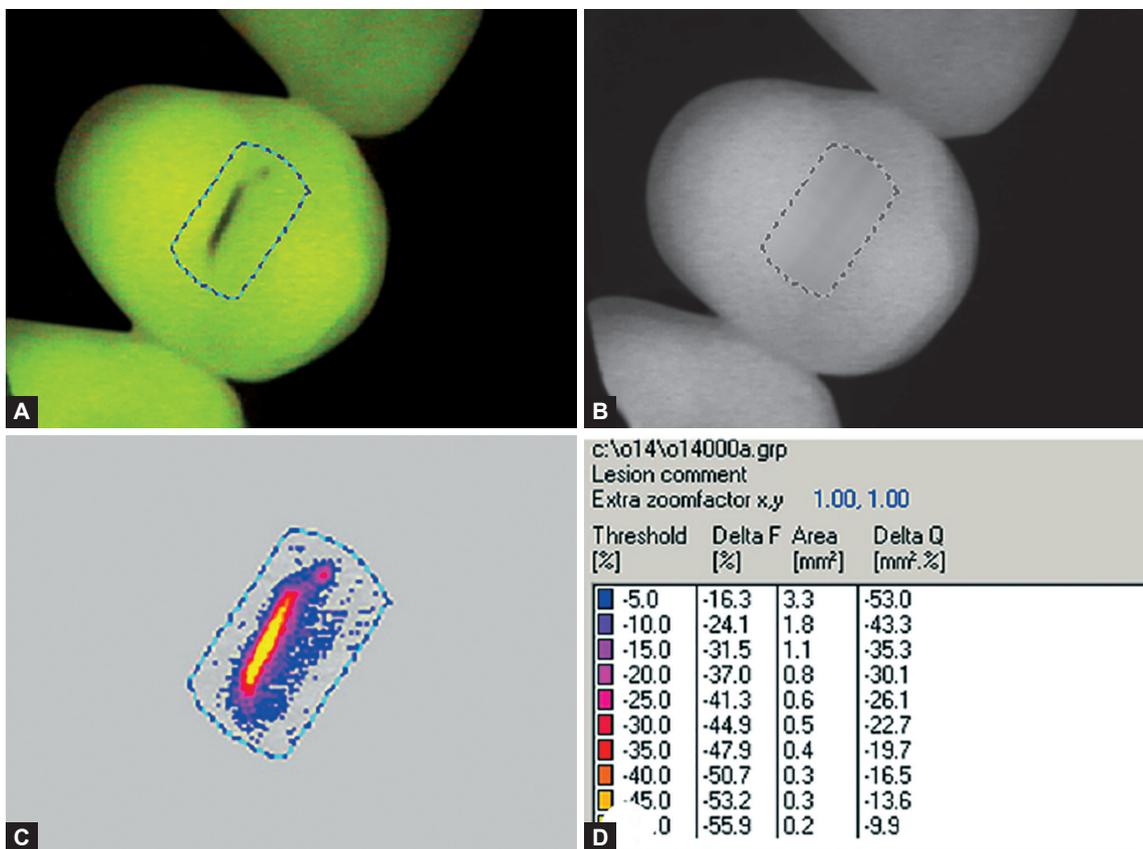
The quantitative laser/light-induced fluorescence method (QLF) is reported to be valuable tool for the detection and quantification of initial caries lesions and for monitoring de- or remineralization on smooth surfaces.⁴ Restored 52 and 61 shows the increased



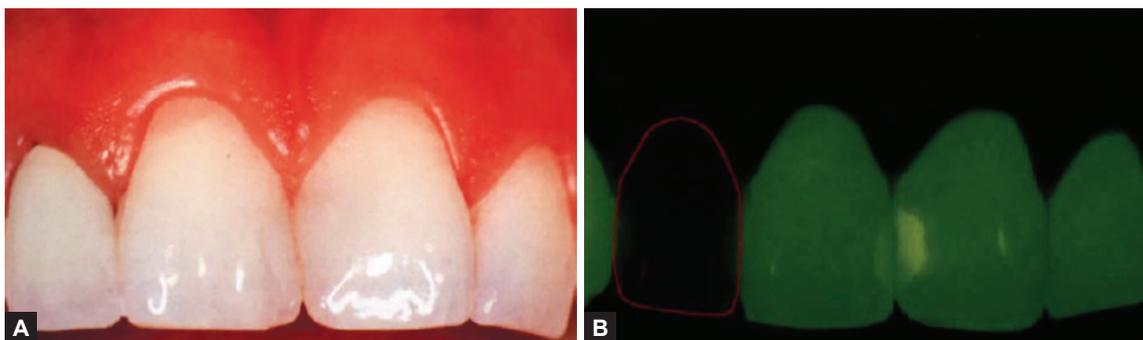
Fig. 2: The QLF unit light box demonstrating the handpiece and liquid light guide



Fig. 3: QLF equipment close-up of the intraoral camera featuring a disposable mirror tip that also acts as an ambient light shield



Figs 4A to D: Analysis of lesion using QLF (A) lesion on the occlusal surface of a premolar is identified and the analysis patch placed on sound enamel, (B) the reconstruction demonstrates correct patch placement as the surface now looks homogenous, (C) the 'subtracted' lesion is demonstrated in false color indicating the severity of the demineralization, (D) the quantitative output from this analysis at a variety of fluorescent threshold levels



Figs 5A and B: (A) Clinical image of buccal surfaces of maxillary anteriors, tooth 12 has been taken care of with metal porcelain crown, (B) montage of fluorescence images shows a clear fluorescence of composite fillings in mesial surface of middle incisors. The metal porcelain crown does not show any fluorescence and appears black

fluorescence whereas the mesial surface of tooth 51 shows an active initial caries characterized by red fluorescence of attached plaque⁸ (Fig. 6).

Amaechi BT, Higham SM monitored development of caries-like lesions and subsequent remineralization of the lesions by QLF. They also quantified the change in stain intensity of teeth were whitened with a bleaching agent. They concluded that QLF could be used to detect and longitudinally monitor the progression or remineralization of incipient caries, however lesion detection may be limited by the presence of saliva or plaque and enhanced by staining. The change in shade of discolored teeth by

whitening agents could be quantitatively measured by QLF.¹⁴

DEVELOPMENTAL DISORDERS AND CARIOUS LESION

Amelogenesis imperfecta hereditaria presents with characteristic amber-like tooth color along with frontal open bite. The QLF images of teeth shows the fluorescence of lower front teeth largely remains, in amber colored area the fluorescence has been reduced due to increase light absorption.⁸ An increased caries susceptibility was observed in the case of a hypoplastic type of amelogenesis

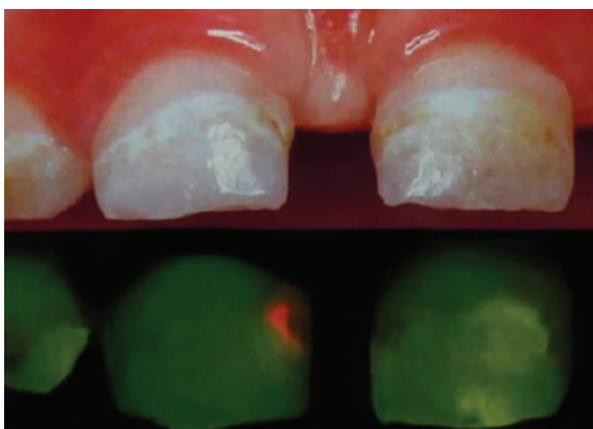


Fig. 6: Clinical and fluorescence images (montage) of initial carious lesions of deciduous front teeth. Restored 52 and 61 shows the increased fluorescence. Fifty-one shows an active initial caries characterized by red fluorescence of attached plaque

imperfect classic example of inheritable enamel defects. The crowns contained a very thin or nonexistent enamel layer (Figs 7A and B). The accumulation of plaque on the porous enamel encouraged the carious process, as well as enamel fragmentation, which rapidly exposed the underlying dentin.¹⁵

DETECTION OF BACTERIAL ACTIVITY AND EVALUATION OF PLAQUE REMOVAL

QLF is a useful tool to visualize plaque that is not clinically visible in daylight, but clearly visible on the computer screen. In some QLF images, areas on the teeth displayed a red hue that ranged from barely noticeable to very pronounced. This red light was also fluorescence, but not emanating from the teeth themselves. Research has shown the red fluorescence to be caused by certain by products of bacterial metabolism, mainly porphyrins. In general, this red fluorescence corresponds with mature plaque (older than 3 to 5 days), calculus, or gingivitis, independent of gross deposited food particles.⁹

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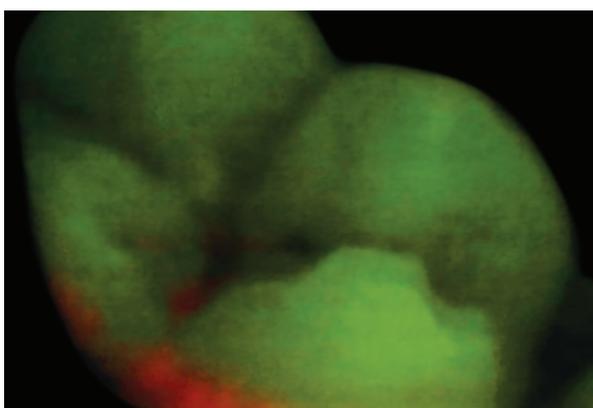
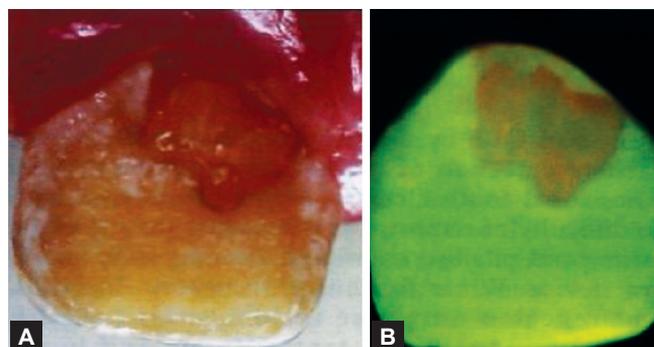


Fig. 8: Fluorescence image of a plaque covered occlusal surface of mandibular molar. Dental plaque is clearly visible without disclosing agent



Figs 7A and B: Clinical (A) and fluorescence (B) images of the palatal surface of a maxillary incisor with amelogenesis imperfecta attacked by a carious lesion

computer screen. As demonstrated in (Figs 8 and 9) QLF images support the understanding of site-specific guided instructions for plaque removal.¹⁵

DETECTION OF OCCLUSAL CARIES

The phenomenon of so called hidden caries makes occlusal caries detection much more difficult. Clinically the carious process develops below a sound appearing layer of enamel, which may hide a dentinal lesion of even considerable size.^{16,17} Tranaeus et al compared visual inspection, the radiographic procedure, electrical resistant measurement and QLF in terms of their accuracy in detection of occlusal caries. Using a fluorescence loss of 20% as the cut-off to detect dental caries, QLF showed a sensitivity of 71% and specificity of 73%.¹⁸ In a case of dark brown discolored fissure where distinction between caries in enamel or dentin and discolored fissure is difficult both clinically and QLF, the dentinal caries can be seen more clearly with help of QLF light than visible light after minimal opening of fissure⁸ (Figs 10A and B, 11A and B) Van Der Veen Mh, de Josselin de Jong E stated that QLF technique can be used *in vitro*, *in situ* and *in vivo* to monitor mineral changes in lesions. Applications of QLF are found in the testing of products designed to inhibit demineralization and promote remineralization

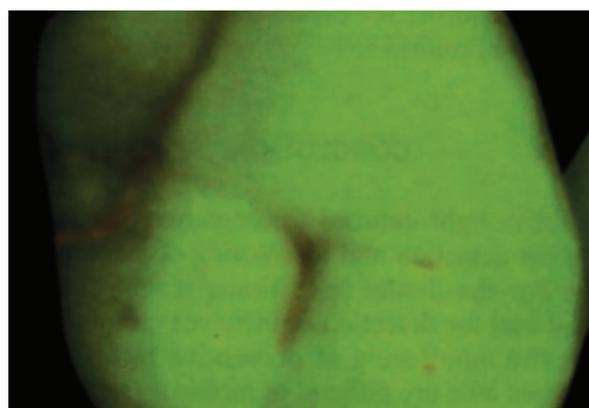
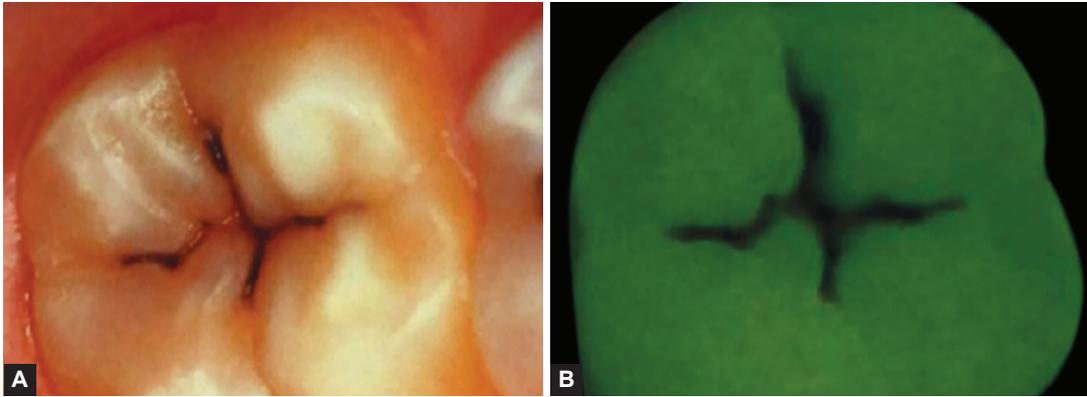
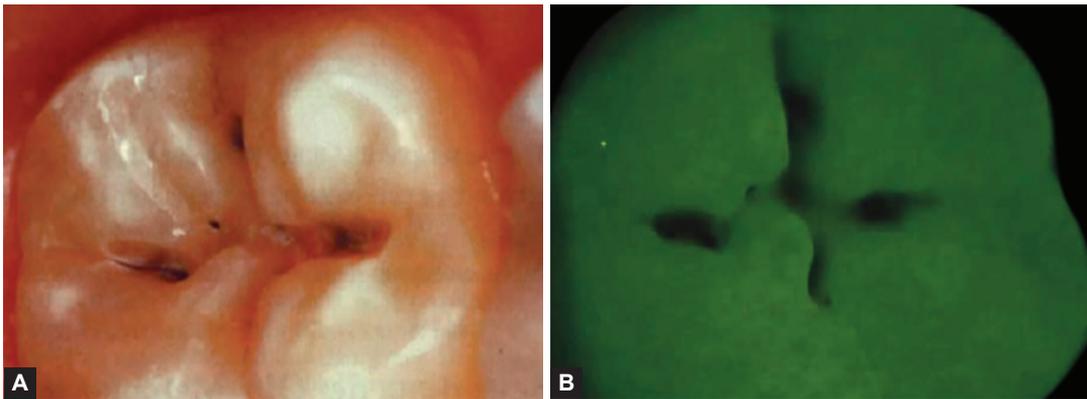


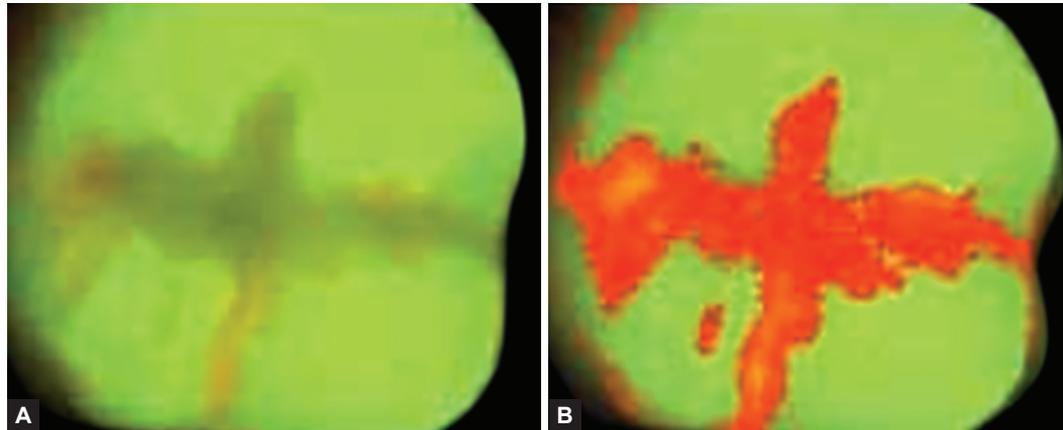
Fig. 9: QLF image revealed residual plaque in occlusal fissure of a maxillary first molar after repeated professional tooth cleaning



Figs 10A and B: Clinical and QLF image of dark brown discolored fissure



Figs 11A and B: Clinical image of tooth after minimal invasive opening of fissure and QLF image of tooth shows remaining caries at bottom of fissure that can easily recognize due to reduced fluorescence



Figs 12A and B: Sealant with a significant amount of red fluorescence along the margins and the same sealant as the one on the left after RF analysis. The entire sealant and margins have a higher red fluorescence than the surrounding tooth tissue

of caries. The method has been successfully applied to smooth surfaces as well as occlusal surfaces, but application on approximal lesions is not yet possible.¹⁹

VISUALIZATION AND MONITORING OF CARIES UNDER SEALANTS

Assessment of the integrity of sealants is a big problem in front of practicing clinicians. While sealants have been shown to be effective in preventing occlusal caries, detection of caries underneath sealants is difficult to determine with current visual examination. To date, QLF

is the only method able to visualize and monitor caries under sealants.

Significant amounts of red fluorescence are viewed along the edges of the sealant and along the fissures. (Figs 12A and B). Since, the molar was professionally cleaned prior to producing the image, the red fluorescence originates from under the sealant. The results of red fluorescence (RF) analysis are displayed in pseudocolors to enhance the difference between areas with and without red fluorescence. RF analysis confirms that significant red fluorescence is emanating from under the sealant and in

the fissures. QLF is the most promising method available to detect faulty sealants at an early stage because of the ease and speed by which an image can be made.⁹

LIMITATIONS OF QLF

Majority of carious lesions are found on occlusal and approximal surface of teeth. The QLF method has hitherto been developed and tested for quantification of caries lesion restricted to smooth surfaces, which is a substantial limitation in the application of method.²⁰ QLF can image all tooth surfaces except interproximal.²¹

Commercial Name, Cost, Manufacturers

Inspektor™ Pro (Inspektor Dental Care, www.inspektordentalcare.com), a QLF method available in several countries, can detect lesions to a depth of approximately 500 µm on smooth enamel surfaces. QLF uses a 370 nm excitation wavelength, resulting in a green autofluorescence of the tooth. The Inspektor™ Pro consists of a trolley that contains a computer and the Inspektor™ Pro System Box. The trolley makes the system easily transportable between operatories. The Inspektor™ Pro System Box contains the QLF™ light-source and the necessary hardware for the live video and the patient isolation. Connected to the system box is the Inspektor™ Pro handpiece which is used to make the images in the oral cavity.

The inspektor™ Pro is compliant with the European Medical Device Directory and approved by UL and the FDA.²²

Now a days, Q-Ray™ is also available and is specifically developed for use in the daily dental practice. Q-Ray™ presents the clinician with a complete and integrated diagnostic imaging system.

High quality white light and QLF™-images are created, stored and retrieved, together with their analysis data, for each patient and can be reviewed on any workstation on the network.

The simplest Q-Ray™ system consists of the following items:

- QLF-D Biluminator™ 2+
- Q-Ray™ clinical software license
- QLF-D Biluminator™ backpack and can be extended with the following options:
- Q-Ray™ high performance laptop
- Q-Ray™ high quality touch screen (various sizes)
- Q-Ray™ EndoZoom mechanical arm (mobile)
- Q-Ray™ EndoZoom mechanical arm (fixed)

When a QLF-D Biluminator™ system is connected to the computer the Take Picture button and the 4 icons representing the state of the QLF-D Biluminator (Biluminator, Camera, SD-card and Battery) will be

active. Clicking the Take Picture button or pressing the shoot-button on the camera will start the image capture sequence. Q-Ray™ will normally take a set of 2 pictures: a normal white-light image and a QLF™ image. The images taken are stored in pairs in a temporary list on the right side of the acquisition screen. When ready, all sets taken can be assigned a view-type using the view-type selector on the right. All assigned pictures can then be saved using the Save button and will then appear in the image overview on the bottom-left of the main Q-Ray™ screen. In the image overview all the images of a patient are shown vertically ordered by time (most recent on top) and horizontally by view-type. Double clicking on an image set brings up the 'cross-view'. The Cross Views provide a concise overview of the state of the oral cavity at a certain point in time. White-light and QLF™ images can both be easily selected and reviewed and compared to pictures made earlier or later in time. Information regarding the system is available through the link: <http://www.inspektor.nl/index.php/products/23>.

Current Applications

QLF has been repeatedly tested for monitoring different carious lesions' remineralization and demineralization. The following are some of these applications which are done mostly in the lab situation:

Root lesions: Lesions were artificially produced on extracted teeth then reversed. QLF readings correlated with these lesions changes measured using radiographic analysis.²⁴

Secondary caries: Detection of early secondary carious lesions was the core of recent laboratory studies. Early secondary caries and different stages of early demineralization were produced artificially or by cariogenic bacteria. Glass ionomer was the best material tested for remineralizing secondary lesions and followed by fluoride releasing resin fillings. Nonfluoride releasing composite allowed for the development of larger lesions. QLF was able to measure these as well as compare between different materials effects in remineralizing them.^{25,26}

Assessment of early lesions in primary teeth.^{19,21,27,28}

Lesions related to orthodontic cleats and brackets.²⁹⁻³¹

Detection of demineralized and remineralized incipient lesions.³²

Quantitative assessment of the gradual change in shade of discolored teeth by tooth whitening products.^{33,34}

SENSITIVITY AND SPECIFICITY

It is very clear that QLF can assess the ability of caries-preventive measures to arrest or remineralize carious lesions.¹⁹ Several investigations have reported the validity

of this technology and its related ability to detect dental caries expressed in terms of sensitivity and specificity. As noted in recent reviews, the results of laboratory studies as well as *in vivo* studies have demonstrated the significant potential for this technology to be used in both clinical research and clinical practice.^{6,35-41}

Further, tests of the *in vivo* repeatability and reproducibility of both stages of the method (image capture and image analysis) showed excellent results, with intraclass correlation coefficients between 0.95 and 0.98 for image capture, and between 0.93 and 0.99 for image analysis.⁶

Comparison of QLF with Other Caries Detection Methods

A 1 year pilot clinical trial was performed on children, 9 to 12-year-old to assess the value of QLF as a caries detection method compared to the conventional clinical examination. Based upon preliminary data from the study, authors concluded that QLF was able to monitor changes in the lesions, even small changes over time and these changes were in agreement with the clinical findings. Exfoliated, deciduous teeth were collected from study subjects participating in the clinical trial and examined in the multisite laboratory study to validate the ability of QLF to accurately detect lesion area. Sections of the teeth were examined by transverse microradiography, histology and polarized light microscopy. The authors concluded that the QLF analysis under clinical conditions for the buccal-lingual specimen showed a sensitivity 79% and specificity of 75%.^{42,43}

Shi XQ et al compared QLF *in vitro* with another laser based method, DIAGNOdent for quantification of natural caries for smooth surfaces.⁴⁴ Seventy one noncavitated approximal surfaces were assessed with QLF and DIAGNOdent. To provide a gold standard for verification the teeth were then sectioned and lesion depth, stratified on a five point scale, was determined by histopathology and microradiography. For lesion depth, the Spearman's rank correlation with gold standard was similar for QLF and DIAGNOdent about 0.85. The correlation coefficient for enamel mineral loss and QLF and DIAGNOdent respectively were 0.76 and 0.67. It was concluded that for quantification of smooth surface caries, the methods are of equal merit but for scientific purposes, QLF offers the advantage of closer correlation with changes in mineral content.⁴⁰

QLF is a more versatile system than either DIAGNOdent or DIFOTI and can measure absolute mineral loss along with a number of other applications. Research suggests that the correlation between QLF and absolute mineral loss (as measured by a radiographic gold standard) may be as high as $r = 0.92.63$. The ability

to visualize bacterial products, which appear as red fluorescence, may be used to determine the activity of lesions. QLF can be considered a diagnostic system, rather than simply a detection device. The feasibility of using QLF to detect root caries and early orthodontic demineralization will be of interest to specialists treating patients with these kinds of lesions.¹³

FUTURE APPLICATION OF QLF

QLF may have the greatest impact on nonsurgical preventive interventions and the ability to monitor the success of dental caries. This is a promising area for use of the instrument and should be validated in additional research. QLF is unparalleled as a tool to evaluate the efficacy of remineralization on smooth surface lesions. The QLF system can save and document the state of demineralization/remineralization of any tooth surface exclusive of proximal tooth surfaces at intervals in time. In addition, QLF can demonstrate disclosure of caries at a very early stage and assess the success or failure of a chosen prevention regime with objective, rather than subjective, criteria. A benefit using QLF may be in its ability to motivate patient behavior. Showing patients the bacterial activity with red fluorescence before-and-after pictures may be particularly useful in motivating patients in their self-care regimens. While additional behavioral research is needed to demonstrate the long-term benefits, showing patients the impact of their prescribed homecare regimens (e.g. proper brushing and use of home fluorides) may have a long-term benefit in adherence to recommended treatment of demineralized tooth surfaces.⁹

CONCLUSION

Diagnosis of caries activity proves to be more important than caries severity. QLF is a dental diagnostic tool for *in vivo* and *in vitro* quantitative assessment of dental caries lesions, dental plaque, bacteria activity, calculus, staining and tooth whitening.

Although there is a wide application potential for QLF, more studies are needed to apply these principles in the clinical situation, for complex occlusal caries and deep dentinal lesions.

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