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Wavelength-Dependent Fibre-Optic Transillumination of Small Approximal Caries Lesions: The Use of a Dye, and a Comparison to Bitewing Radiography

Key Words

Bitewing radiography
Caries diagnosis
Dye
Fibre-optic transillumination

Abstract

The mere detection of caries lesions is insufficient for optimal treatment decision-making. Hence, the aim of this study was to investigate whether quantitative information about approximal lesion depth can be obtained from a technique based on the wavelength dependency of light propagation and additional use of a dye. Another aim was to compare the diagnostic performance of the optical technique and bitewing radiography. Measurements were performed on 33 extracted premolar teeth. Twelve proximal surfaces had white-spot, and 17 had discoloured small lesions. Four surfaces were sound. The teeth were transilluminated with a single glass fibre at the approximal surface before and after dye application. The occlusal surface was imaged with a CCD camera. Light in the blue and red part of the electromagnetic spectrum was selected using Schott glass filters. Average decadic optical thickness differences, $\Delta_{bl-rd} \bar{\tau}_{eff}$, were estimated and plotted as a function of normalised lesion depth, d_{hist} , established from histological validation by two observers. The Spearman rank correlation was $\hat{r}_s(\Delta_{bl-rd} \bar{\tau}_{eff}, d_{hist}) = 0.87$ (95% confidence interval, CI: 0.74–0.94). A marked increase in average decadic optical thickness in the blue part of the electromagnetic spectrum, $\Delta_{dye} \bar{\tau}_{eff}$, was observed for those lesions that, upon direct visual inspection of the approximal surface, clearly showed dye uptake. Bitewing radiographic depth ratings of two observers were plotted as a function of d_{hist} . The correlations were $\hat{r}_s(d_{RA,1}, d_{hist}) = 0.62$ (95% CI: 0.34–0.80), $\hat{r}_s(d_{RA,2}, d_{hist}) = 0.75$ (95% CI: 0.54–0.87), and between the observers $\hat{r}_s(d_{RA,1}, d_{RA,2}) = 0.44$ (95% CI: 0.10–0.69). The p values of $r_s(\Delta_{bl-rd} \bar{\tau}_{eff}, d_{hist}) - r_s(d_{RA,1}, d_{hist})$ and $r_s(\Delta_{bl-rd} \bar{\tau}_{eff}, d_{hist}) - r_s(d_{RA,2}, d_{hist})$ were $p_1 = 0.01$ and $p_2 = 0.08$, respectively. It was concluded that quantitative information about lesion depth can be obtained optically. The dye penetrates into only a limited number of caries lesions, in which cases dye uptake is detectable in transillumination geometry. Under laboratory circumstances the optical technique performs as well as bitewing radiography in the diagnosis of small approximal caries lesions.

Caries has become a slow process, and when the oral conditions change incipient lesions may fully remineralise [Pine and ten Bosch, 1996]. Therefore, early and quantitative detection of caries lesions may lead to a shift from restorative interventions to 'curative' and preventive treatments [Angmar-Månsson and ten Bosch, 1993]. To monitor the result of preventive treatment a very sensitive quantitative method is required. Furthermore, to decide for restorative intervention at 'lesion progress into the dentine' [Verdonschot et al., 1991], lesion depth must be established. Consequently, for optimal treatment decision-making the mere detection of lesions is insufficient, and a sensitive quantitative method to monitor lesion progress would be valuable.

Although the diagnostic sensitivity of fibre-optic transillumination for lesions progressed into the dentine is significantly lower than that of bitewing radiography [Vaarkamp et al., 1996a], in previous research it was shown that quantitative information about an approximal lesion is transferred to the occlusal surface when transilluminating teeth [Vaarkamp et al., 1995]. In addition, where the diagnostic performance of bitewing radiography for incipient lesions is known to be low [Russel and Pitts, 1993; Svenson et al., 1994], small lesions could be detected using wavelength-dependent fibre-optic transillumination [Vaarkamp et al., 1996b]. Though no distinction could be made between white-spot and discoloured lesions, it remains to be investigated whether wavelength-dependent fibre-optic transillumination has a better diagnostic performance than bitewing radiography.

At visible surfaces the visual appearance of lesions provides some information about the lesion process and activity, as of 'older', discoloured lesions it is assumed that the surface porosity decreases [Bibby, 1971]. This may prohibit dye penetration. On the other hand, it has been shown that artificially demineralised white-spot lesions can be stained, thereby increasing the colour contrast [O'Brien et al., 1989]. Moreover, in transillumination geometry and measured on whole teeth with both natural and artificial white-spot lesions, the correlation between fluorescent dye signal and average mineral loss was $\hat{r} = 0.86$ (95% confidence interval, CI: 0.70–0.94) [van de Rijke et al., 1991]. Hence, to distinguish white-spot from discoloured lesions at surfaces that cannot be inspected visually, dye application may be a fruitful approach.

The aims of the present research were to investigate, firstly, whether it is possible to obtain quantitative information about approximal caries lesion depth using tooth transillumination at different wavelengths, secondly, whether it is possible to differentiate between approximal white-spot

Fig. 1. Schematic outline of the experimental set-up.

and discoloured caries lesions, and, thirdly, whether there is a difference in diagnostic performance between bitewing radiography and wavelength-dependent tooth transillumination.

Materials and Methods

Tooth Material

In this study freshly extracted premolar teeth with naturally developed small approximal caries lesions were used. A total of 33 approximal surfaces were investigated. Four surfaces were clinically sound, 12 had a white-spot and 17 had a discoloured lesion. A lesion was classified as discoloured when part of the lesion had a yellow-brownish or darker appearance. The teeth were stored in water at room temperature between measurement.

Optical Measurements

Optical measurements were performed before and after dye application. The approximal surfaces of the premolar teeth were illuminated using a single fibre ($\varnothing 300 \mu\text{m}$). On the other end of the fibre the incandescent wire of a 20-watt halogen light bulb was projected with an objective ($\times 20$). A water film was used to improve optical coupling between enamel and fibre. The occlusal surface was imaged using a CCD camera. Light in the blue and red part of the electromagnetic spectrum was selected by putting the Schott glass filters BG23 and RG610, respectively, between detector and occlusal tooth surface. The experimental set-up for the optical measurements is depicted in figure 1. In the area with a well-defined change above the lesion position, the average effective optical thickness difference, $\Delta_{\text{bl-rd}} \bar{\tau}_{\text{eff}}$, was determined for every approximal surface. A more detailed description of these optical transillumination measurements and the definition of $\Delta_{\text{bl-rd}} \bar{\tau}_{\text{eff}}$ have been given elsewhere [Vaarkamp et al., 1996b].

After measurement of $\Delta_{\text{bl-rd}} \bar{\tau}_{\text{eff}}$ the optical coupling fluid was removed with a tissue. The tooth was dried with warm air for 1 min using a hair-drier. Subsequently, a drop of water saturated with the red dye E124 was put on the approximal surface for 5 min. The excess dye was removed using water and a tissue. Subsequently, the increase in decadic optical thickness at the blue part of the electromagnetic spectrum due to dye imbibition, $\Delta_{\text{dye}} \bar{\tau}_{\text{dye}}$, was measured.

Bitewing Radiography

After performing the optical measurements the premolar teeth were mounted in rubber blocks in which a C, M₁ and M₂ were also fixed. Bitewing radiographs of these artificial jaws were made (70 kV; 15 mA; E-speed film), using a 1.5-cm-thick acrylic layer to simulate the soft tissues. The bitewing radiographs were developed under standardised conditions and scored by two dentists on a four-point ordinal scale: 0 = no signs of demineralisation; 1 = demineralisation confined to the outer half of the enamel layer; 2 = demineralisation into the inner half of the enamel layer, and 3 = demineralisation progressed into the dentine.

Histological Validation and Dye Penetration Depth

After performing the measurements, the teeth were stored in water for 2 weeks. From the visual appearance of the outer approximal surface it was judged whether the dye had diffused out of the lesions. After these 2 weeks, the teeth were dyed once again. Subsequently, approximately 0.75-mm-thick sagittal slices were cut from the teeth with a water-cooled diamond coated saw (blade thickness 0.5 mm). Based on the clinical appearance, cuts were made such that the slice contained the central part of the lesion. It was verified how deep the dye had penetrated the lesion. The maximum lesion depth and, dependent on lesion progress, the local enamel or dentine layer thickness were assessed independently by two observers on a continuous scale by direct visual inspection under a stereo microscope ($\times 2.5$). The samples were placed on a diffuse light source. Similar to the bitewing radiographic rating scale, the normalised lesion depth, d_{hist} , was obtained by division of the maximum lesion depth by the local enamel or dentine layer thickness established by the dentist.

Statistics

CI (95%) of the correlation coefficients $\hat{r}$ were calculated and the difference between two correlation coefficients was tested using the methodology described by Ferguson [1976]. To calculate 95% CI values of $\hat{r}$ were transformed to $\hat{z}_r$ values using the transformation

$$Z_r = \frac{1}{2} \ln \left(\frac{1+r}{1-r} \right). \quad (1)$$

The standard error of $\hat{z}_r$ is given by

$$\hat{e}_{z_r} = \frac{1}{\sqrt{n-3}}, \quad (2)$$

in which n is the number of surfaces. The 95% CI of $\hat{z}_r$ is given by

$$[\hat{z}_r - t\hat{e}_{z_r} - \hat{z}_r + t\hat{e}_{z_r}], \quad (3)$$

in which t is the critical value of the t distribution at the 5% significance level and at $n-1$ degrees of freedom. After converting back to $\hat{r}$ values, the 95% CI of $\hat{r}$ is obtained.

Assuming independence between the data obtained to calculate the correlation coefficient for wavelength-dependent transillumination and bitewing radiography, the statistical significance of the difference is tested by calculating the normal deviate

$$\hat{z}_i = \frac{\hat{z}_{\text{ropt}} - \hat{z}_{\text{rRA},i}}{\sqrt{(1/n_{\text{ropt}} - 3) + (1/n_{\text{rRA},i} - 3)}} \quad (4)$$

and estimating the p value p_i .

Results

In figure 2 the average decadic optical thickness difference, $\Delta_{\text{bl-rd}} \bar{\tau}_{\text{eff}}$, is plotted as a function of normalised lesion depth established from histological validation, d_{hist} . The Spearman rank correlation between $\Delta_{\text{bl-rd}} \bar{\tau}_{\text{eff}}$ and d_{hist} was $\hat{r}_s(\Delta_{\text{bl-rd}} \bar{\tau}_{\text{eff}}, d_{\text{hist}}) = 0.87$ (95% CI: 0.74–0.94). The correlation between $\Delta_{\text{bl-rd}} \bar{\tau}_{\text{eff}}$ and d_{hist} for white-spot and discoloured lesions separately was $\hat{r}_s(\Delta_{\text{bl-rd}} \bar{\tau}_{\text{eff, wh}}, d_{\text{hist}}) = 0.77$ (95% CI: 0.40–0.92) and $\hat{r}_s(\Delta_{\text{bl-rd}} \bar{\tau}_{\text{eff, dis}}, d_{\text{hist}}) = 0.84$ (95% CI: 0.62–0.94), respectively. The Pearson correlation between the normalised lesion depths assessed by the two observers was $\hat{r}(d_{\text{hist},1}, d_{\text{hist},2}) = 0.97$ (95% CI: 0.94–0.99).

In figure 3 the increase in average optical thickness at the blue part of the electromagnetic spectrum due to dye imbibition, $\Delta_{\text{dye}} \bar{\tau}_{\text{eff}}$, is plotted as a function of d_{hist} . Except for a distinct reddish glow at the surface of two white-spot lesions which remained throughout 2 weeks of storage in water, after 3 days no visual evidence of the dye was present at the tooth surface. After staining the lesions again, it was observed in the sections that if a dye penetrated through the lesion surface the whole lesion body was impregnated.

In figure 4 bitewing radiographic scorings of two observers are plotted as a function of d_{hist} . The correlations were $\hat{r}_s(d_{\text{RA},1}, d_{\text{hist}}) = 0.62$ (95% CI: 0.34–0.80) and $\hat{r}_s(d_{\text{RA},2}, d_{\text{hist}}) = 0.75$ (95% CI: 0.54–0.87), respectively. The correlation between the two observers was $\hat{r}_s(d_{\text{RA},1}, d_{\text{RA},2}) = 0.44$ (95% CI: 0.10–0.69). $\hat{z}_1 = 2.36$ and $\hat{z}_2 = 1.39$, corresponding to a statistically significant difference between wavelength-dependent transillumination and bitewing radiography at the $p_1 = 0.01$ and $p_2 = 0.08$ levels, respectively.

Discussion

In this study the maximum normalised lesion depth was considered the main characteristic of caries lesions. The high correlation between normalised lesion depths assessed by the two observers suggests that normalised lesion depth can be reproducibly estimated. However, an important problem of sagittal tooth sections is that the slice may not contain the maximum extent of the lesion. Hence, not all sources of variation show up in reassessing the normalised lesion depth by a second observer. Nevertheless, it is as-

Fig. 2. Average decadic optical thickness difference, $\Delta_{bl-rd} \bar{\tau}_{eff}$, as a function of normalised lesion depth established from histological validation, d_{hist} . Discoloured and white-spot lesions that showed a marked increase in average optical thickness due to dye uptake, as visualised in figure 3, are indicated with filled squares and circles, respectively. DEJ = Dentine-enamel junction.

Fig. 3. Increase in average decadic optical thickness in the blue part of the electromagnetic spectrum due to dye imbibition, $\Delta_{dye} \bar{\tau}_{eff}$, as a function of normalised lesion depth established from histological validation, d_{hist} . To identify the corresponding lesions in figure 2 discoloured and white-spot lesions that show a marked increase in $\Delta_{dye} \bar{\tau}_{eff}$ are marked by filled squares and circles, respectively. DEJ = Dentine-enamel junction.

Fig. 4. Bitewing radiographic scorings of two observers as a function of normalised lesion depth established from histological validation, d_{hist} . DEJ = Dentine-enamel junction.

sumed that due to the relatively thick samples this risk is low. To account for biological variation in enamel or dentine layer thickness the maximum lesion depth was divided by this local layer thickness. Since additional variation is introduced, the interobserver correlation decreases somewhat.

Average mineral loss is also frequently used as the main characteristic of lesions. Since lesion depth and average mineral loss, $\Delta\bar{C}$, are only moderately correlated, one particular lesion parameter may not suffice to define lesion severity fully [Vaarkamp, 1996]. Hence, the choice of a lesion parameter may influence a comparison with the outcomes of a diagnostic technique. Since the signal in wavelength-dependent transillumination is determined by the combination of affected volume and the severity of mineral loss, it is to be expected that the correlation coefficients

$\hat{r}_s(\Delta_{bl-rd} \bar{\tau}_{eff}, d_{hist})$ [0.87 (95% CI: 0.74–0.94)] and $\hat{r}(\Delta_{bl-rd} \bar{\tau}_{eff}, \Delta\bar{C})$ [0.79 (95% CI: 0.47–0.93); Vaarkamp et al., 1996b], are comparable to the correlation coefficient $\hat{r}(d_{hist}, \Delta\bar{C})$ [0.71 (95% CI: 0.67–0.74; Vaarkamp, 1996)].

The data in figure 2 indicate a non-linear relation between $\Delta_{bl-rd} \bar{\tau}_{eff}$ and normalised lesion depth. Hence, the Spearman rank correlation coefficient $\hat{r}_s(\Delta_{bl-rd} \bar{\tau}_{eff}, d_{hist})$ was used. At any specific lesion depth the $\Delta_{bl-rd} \bar{\tau}_{eff}$ of a discoloured lesion seems somewhat larger than the $\Delta_{bl-rd} \bar{\tau}_{eff}$ of a white-spot lesion. Nonetheless, in view of the large variations, the correlation between $\Delta_{bl-rd} \bar{\tau}_{eff}$ and d_{hist} was based on discoloured and white-spot lesions together.

From figure 3 it can be concluded that with additional use of a dye an increased number of small lesions can be diagnosed correctly. However, no relation between the measure for lesion severity, lesion depth, and the measure

for dye uptake, $\Delta_{\text{dye}} \bar{\tau}_{\text{eff}}$, was observed. In addition, no evidence of dye penetration was visible on the surfaces for which no marked increase in $\Delta_{\text{dye}} \bar{\tau}_{\text{eff}}$ occurred. Why the dye did not penetrate into some of the lesions requires further investigation. Consequently, though using this particular dye no additional information about the 'lesion progress into the dentine' point is obtained, if with a clinically feasible dye, indeed, only the active lesions with a high surface porosity absorb the dye, measuring the increase in average optical thickness due to dye imbibition may still be a valuable tool, in particular because information about surface porosity cannot be obtained by tooth separation.

When disregarding the one exception for which the dye had penetrated into the white area surrounding the discoloured lesion, $\Delta_{\text{dye}} \bar{\tau}_{\text{eff}}$ increased more for the white-spot than for the discoloured lesions, i.e., when actual staining occurred. This may be caused by a greater amount of dye uptake, but may also be due to the fact that an increase in absorption coefficient in a scattering object causes a greater increase in extinction than the same amount of absorption coefficient increase in a non-scattering light-absorbing object. The increase of $\Delta_{\text{dye}} \bar{\tau}_{\text{eff}}$ for the sound surfaces may be due to dehydration of the enamel. This increases the scattering in the enamel [Brodelt et al., 1981] and thus reduces the amount of transmitted light. The effect on the measured $\Delta_{\text{dye}} \bar{\tau}_{\text{eff}}$ for surfaces with caries lesions is unknown.

In a previous study, in which a fluorescent dye was used, a substantial correlation with average mineral loss was obtained and all lesions showed dye penetration [van de Rijke et al., 1991]. This may be explained by two factors. First of all, in that study small artificial lesions and smaller, and hence possibly still active, natural lesions were used. In larger older lesions periods of remineralisation may have occurred, degenerating the relation between lesion porosity and both average mineral loss and lesion depth. Secondly, the lesion characteristic mineral loss is probably a more direct measure of lesion porosity than the characteristic lesion depth.

In accordance with other studies [Arnold, 1983; Mileman, 1985; Verdonschot et al., 1993], the data in figure 4 demonstrate that there is a considerable interobserver variation in the interpretation of approximal caries from radiographs, which was quantified by the Spearman rank correlation. Consequently, such an assessment of lesion depth using bitewing radiography is not very reliable.

The data in figures 2 and 4 indicate the wavelength-dependent transillumination performs as well as bitewing radiography in the diagnosis of small approximal caries lesions. To test the difference in diagnostic performance between wavelength-dependent transillumination and bite-

wing radiography, statistical independence between the data obtained in figures 2 and 4 was assumed because wavelength-dependent transillumination and bitewing radiography are two entirely different methods. If the independence assumption is not completely valid, because the same teeth were used, in this approximation the actual significance level is somewhat overestimated. In addition, as is common practice in dentistry, an ordinal scale was used to score the bitewing radiographs. However, in this process information is lost. Consequently, when the aim is to compare the performance of two diagnostic techniques the power of the study design is somewhat reduced.

Figures 3–4 contain all information obtained about the diagnostic techniques. From figure 2 the relation between $\Delta_{\text{bl-rd}} \bar{\tau}_{\text{eff}}$ and d_{hist} can be derived. If using only wavelength-dependent transillumination for operative-intervention decision-making, i.e., to determine the 'lesion progress into the dentine' point, the optimal cut-off level must be determined. Future research should establish how well this technique performs in terms of proportions of correctly identified diseased and sound surfaces using that cut-off level. Note however, that previous research showed that the outcomes of these calculations are strongly dependent on the distribution of lesion characteristics in the sample [Vaarkamp et al. 1996a]. To obtain valid sensitivity and specificity values only a randomly selected population can be used. In this research e.g., this condition would be severely violated. Finally, it has been shown that when the correlation coefficient between measured and 'true' quantity of a certain diagnostic technique is highest, for any population not only will the performance in terms of sensitivity and specificity be highest, but if the population characteristics are known sensitivity and specificity can also be calculated [Vaarkamp, 1996].

Optical techniques have an important clinical advantage over bitewing radiography, as they are repeatable without risk to the patient. Hence, wavelength-dependent transillumination can be applied for monitoring purposes. However, the measurement system described in this study must be miniaturised before the technique, with or without additional use of a dye, can be applied in vivo.

In summary, quantitative information about lesion depth can be obtained with wavelength-dependent transillumination. The dye penetrated into only a limited number of caries lesions, in which cases dye uptake was detectable in transillumination geometry. Results indicate that under laboratory circumstances the optical technique performs as well as bitewing radiography in the diagnosis of small approximal caries lesions.

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