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Light propagation through teeth containing simulated caries lesions

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Abstract. The methods currently utilized in dentistry to detect caries lesions have their limitations and alternatives are being investigated. A promising option is tooth transillumination which is based on an increase of light scattering or light absorption in the affected tissue region. In this study transillumination applied to detect approximal caries lesions was investigated using premolar teeth containing simulated caries lesions. Cavities were drilled at the approximal surface and filled with light absorbing and light scattering fluids in different dye and particle concentrations to model successive stages of lesion progress. For light absorbing cavities the extinction as function of the decadic absorption coefficient measured at the occlusal surface could be approximated by the Lambert-Beer law ($r = 0.98 \pm 0.01$). For light scattering cavities the extinction as a function of the decadic reduced scatter coefficient was fitted to a straight line ($r = 0.98 \pm 0.03$) for $\mu'_s(\lambda = 633 \text{ nm}) < 1.25 \text{ mm}^{-1}$. For higher reduced decadic scatter coefficients the curves levelled off due to multiple scattering. In addition, the contribution of the dentinal cavity part to the radiance change induced by the total cavity was estimated. For light absorbing cavities illuminated with red light the average contribution was 10.5 (SD 4.2)% and for those illuminated with green light it was 1.4 (SD 0.9)% indicating that the radiance change caused by a caries lesion is mainly determined by the enamel lesion part.

1. Introduction

Human teeth consist of the turbid materials enamel and dentine, and soft tissue, the pulp. Enamel is the very hard outer tooth crown layer exposed to the oral environment and dentine is the softer, bone-like material covered by the enamel. Enamel and dentine can be subject to dental decay, a process which ultimately can lead to the total destruction of the tooth. One of the predilection places for dental caries is at the contacting, approximal, surface of the tooth (figure 1). These approximal surfaces are for the greater part inaccessible for direct visual inspection, which seriously hampers an early detection of caries lesions.

The methods currently in use to detect approximal caries lesions at molar and premolar teeth are visual inspection and bitewing radiography. Yet, it is known that during clinical examination a large number of incipient caries lesions are being missed, whereas a great number of sound surfaces are wrongly being diagnosed as carious (Wenzel 1993). Furthermore, being based primarily on qualitative information, the diagnosis is somewhat subjective (Verdonschot et al 1991b). Hence, alternative diagnostic methods are being studied (O’Brien et al 1989, Van de Rijke and ten Bosch 1990, Verdonschot et al 1991b). An additional incentive for investigating alternatives to bitewing radiography is the recent
awareness that the lifetime cancer risks from exposure to low levels of ionizing radiation may be greater than previously estimated (UNSCEAR 1988, ICRP 1990).

As early as 1927 it was recognized that the detection of caries lesions can be facilitated by tooth transillumination (Cameron 1927). Lesion detection by transillumination is based on an increase in light scattering of the affected tissue. At visible tooth surfaces the increased opacity of the enamel is the first visual symptom of coronal caries. Since lesions in the oral environment often gradually discolor, an increase in light absorption can also become a mechanism for lesion detection. When the caries process reaches the dentine, the lesion not only progresses into the dentine, but also spreads laterally along the dentino-enamel junction (DEJ). Hence, the outer edge of affected dentine may be covered by sound enamel. For dentine also the visual symptoms are an increase in light scattering, soon followed by discoloration, i.e., an increase in light absorption (Colby et al. 1961).

When glass fibres became commercially available in the late sixties, and with them cold, high-intensity light sources, a resurgence of interest in tooth transillumination was aroused (Friedman and Marcus 1970). Currently, teeth are transilluminated with white light using a fibre to transport the light from a light bulb to the tooth, and approximal lesions are diagnosed when dark spots or 'shadows' are perceived at the occlusal tooth surface. In this manner qualitative information is obtained, leading to a somewhat subjective diagnosis. This may be a cause of the remaining controversy about the true validity of the method (Verdonschot et al. 1991a). Despite this controversy, the results of clinical studies suggest that dentine involvement might be a prerequisite for lesion detection (Mitropoulos 1985). If true, incipient lesions will remain undetected, though preventive care might have resulted in lesion remineralization.

The main objective of this study was to investigate how lesion characteristics affect the radiance at the occlusal tooth surface when the approximal surface is being transilluminated. Insight into the relation between lesion characteristics and induced signal is required to be able to change the present qualitative transillumination technique for approximal caries detection to a more quantitative method. However, deduction of such relations is seriously hampered by the fact that for a tooth only one stage of lesion progress is available. In addition, though a technique has been developed that gives an impression of the optical properties of the lesion if the lesion surface is available for measurements (Borsboom
and ten Bosch 1982) still a noteworthy uncertainty remains because in principle only information about the outer surface layer is obtained. Finally, also using teeth with artificially demineralized lesions it will be difficult to separate the effects induced by different lesion characteristics, e.g., lesion depth and local mineral loss. Hence, this study was performed with simulated lesions with manipulable and accurately known optical properties.

In this research, after introduction of an optical model of caries lesions and a simplified description of light transport through teeth, the influence of lesion absorption, lesion scattering, and the contribution of the dentinal lesion part to the signal induced by the total lesion were studied, with light wavelength as parameter.

2. Materials and methods

2.1. Simulation of approximal caries lesions

Approximal caries lesions were simulated in freshly extracted sound premolar teeth which were stored in water at room temperature between measurements. The simulated lesions consisted of cavities filled with modelling materials. The cavities were prepared at or below the largest diameter of the tooth crown, either up to the DEJ or up to the pulp chamber, and with diameters of 1.15 ± 0.1 mm. White spot lesions were modelled using Intralipid (20%, Kabi Pharmacia AB, Sweden) and discoloured lesions using coffee as fill material.

To model subsequent stages of lesion progress, 1–32× dilutions of the coffee and Intralipid were used. Sound enamel was modelled using water and, to have an estimate of the maximum possible signal induced by a cavity, a black-pained needle was inserted in the cavity. This black needle was regarded as a total light absorber.

To get an impression of the validity of the model for discoloured lesions, the absorption spectra of coffee and the organic material in discoloured lesions were determined. Three discoloured lesions were separated from the teeth and ground into small fragments. To dissolve the minerals, the fragments were put in a buffered 10% ethylenediaminetetraacetate (EDTA) solution for one week after which the absorption spectra were measured. EDTA was used as reference sample. All spectra were determined with a standard photospectrometer.

The fluid layer in the glass cuvette was 5 mm thick and prior to the measurement the coffee sample was diluted 1000 times in distilled water. The absorption spectrum of undiluted coffee and the average of three curves, each obtained from organic material isolated from a discoloured lesion, are depicted in figure 2.

To investigate the validity of the model for white spot lesions, the transmission spectrum of Intralipid, both measured and obtained from literature (Flock et al. 1992), was compared with the transmission spectra of demineralized bovine enamel as determined in the past by Spitzer (1976). These spectra were also rather similar and contained no sharp peaks. The optical properties of dental hard tissues and fill fluids at $\lambda = 633$ nm are summarized in table 1.

2.2. System analysis and signal definition

The total radiance at tooth surface position $(x, y)$ measured in a certain direction $(\theta, \phi)$ can be written as

$$L_{total}(x, y, \theta, \phi) = L_{through}(x, y, \theta, \phi) + L_{past}(x, y, \theta, \phi).$$

In this equation $L_{through}(x, y, \theta, \phi)$ represents the contribution of light that went through the lesion and hence contains information about the optical properties of the material in the
Figure 2. The absorption spectrum of organic material in discoloured lesions averaged over three samples, and the absorption spectrum of the coffee. Plotted is the extinction $E = c \mu_a l$ of the fluids, with $c$ the dye concentration.

cavity. $L_{\text{past}}(x, y, \theta, \varphi)$ represents the contribution of light that went past the lesion. For ease of notation the $(x, y, \theta, \varphi)$ dependence will be dropped in the following. When the black needle is inserted in the cavity $L_{\text{through}} = 0$ and only $L_{\text{past}}$ is observed. When water is inserted, modelling sound enamel, the highest possible value for $L_{\text{through}}$, denoted as $L_0$, can be determined.

When the cavity is filled with (diluted) coffee, light paths are not affected since coffee only absorbs and does not scatter. However, the transmission along all light paths through the cavity is decreased by absorption. For each separate light path the absorption in the cavity is determined by the Lambert–Beer law. As there are many light paths contributing to $L_{\text{through}}$, the influence of absorption on $L_{\text{through}}$ cannot be simply expressed. However, for very small absorption coefficients $\mu_{a,c}$ the radiance $L_{\text{through}}$ decreases linearly with $\mu_{a,c}$. For small, but not very small absorptions, the insertion of an effective path length in the cavity, $l_e$, and the use of the Lambert–Beer law

$$L_{\text{through}} = L_0 10^{-\mu_{a,c} l_e}$$

is a reasonable approximation. In this equation $\mu_{a,c}$ is the decadic absorption coefficient in the cavity.

In other work on tissue optics the concept of substituting some average path length for the collection of path lengths through a medium that is not only light absorbing but also light scattering has been used (Delpy et al 1988). After substitution of this average path length, called the differential path length, the attenuation by the medium is again approximated by the Lambert–Beer law (Matcher et al 1993). However, the differential path length accounts for the fact that the geometrical path length through the medium is prolonged due to scattering in the medium itself, which implies that the paths through the medium are dependent on the scattering and absorption coefficient of this medium. In the case of the light absorbing cavity the existence of a collection of path lengths in the medium is caused outside this medium and differences in absorption coefficient in the cavity only
Table 1. Optical properties at $\lambda = 633$ nm of dental hard tissues and materials to simulate caries lesions, i.e., the decadic absorption coefficient, $\mu_a$, the decadic scatter coefficient, $\mu_s$, the asymmetry parameter, $g$, the decadic reduced scatter coefficient, $\mu'_s$, and the refractive index, $n$. The numbers between parentheses are standard deviations.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\mu_a$ (mm$^{-1}$)</th>
<th>$\mu_s$ (mm$^{-1}$)</th>
<th>$g$</th>
<th>$\mu'_s$ (mm$^{-1}$)</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enamel (sound)</td>
<td>0.04$^a$</td>
<td>1$^a$</td>
<td>0.68$^b$</td>
<td>0.3$^b$</td>
<td>1.62$^a$</td>
</tr>
<tr>
<td>Enamel (carious)</td>
<td>0.042$^{ab}$</td>
<td>24$^c/32^d$</td>
<td>0.3$^b$</td>
<td>1.45$^a$</td>
<td></td>
</tr>
<tr>
<td>Dentine</td>
<td>0.26$^f$</td>
<td>52$^f$</td>
<td>0.44$^f$</td>
<td>29$^f$</td>
<td>1.33</td>
</tr>
<tr>
<td>Water</td>
<td>(—)</td>
<td>(—)</td>
<td>(—)</td>
<td>(—)</td>
<td>1.33</td>
</tr>
<tr>
<td>Coffee</td>
<td>1.0$^b$</td>
<td>(—)</td>
<td>(—)</td>
<td>(—)</td>
<td>1.33$^i$</td>
</tr>
<tr>
<td>Intralipid</td>
<td>0.0054$^i$</td>
<td>32$^h$</td>
<td>0.75$^h$</td>
<td>8.0$^{hk}$</td>
<td>1.33$^i$</td>
</tr>
<tr>
<td></td>
<td>(0.0308)</td>
<td>(—)</td>
<td>(0.18)</td>
<td>(—)</td>
<td>(—)</td>
</tr>
</tbody>
</table>

$^a$ Spitzer and ten Bosch (1975).
$^c$ Values obtained from model calculations and artificial demineralization measurements.
$^d$ From Spitzer and ten Bosch (1975).
$^e$ From Goenhuis (1980).
$^g$ From ten Bosch and Zijp (1987).
$^h$ Experimentally determined, using a standard photospectrometer.
$^i$ Refractive index of water.
$^{hk}$ Data from Flock et al (1992) multiplied by a factor of two, to account for the concentration difference between Intralipid (10%) and (20%).

For Intralipid, used to model white spot lesions, the situation is more complicated because now light paths through the cavity are not terminated by absorption, but changed in direction by scattering. This scattering elongates light paths, both inside and outside the cavity. For small scattering coefficients, however, an equation similar to the Lambert–Beer law will hold:

$$L_{\text{through}} = L_0 10^{-\mu'_s \bar{l}_c}. \quad (3)$$

In this equation $\mu'_s$ is the decadic reduced scatter coefficient, which is defined as $\mu'_s = \mu_s (1 - g_c)$, with $\mu_s$ the decadic scatter coefficient and $g_c$ the asymmetry parameter in the cavity. The decadic reduced scatter coefficient, rather than the decadic scatter coefficient is used, because due to the experimental geometry some of the forward-scattered light is still detected. For higher scatter coefficients, the extinction is reduced due to multiple scattering.

From the above it follows that by definition of the extinction $E$

$$E = - \log_{10} \left( \frac{L_{\text{total}} - L_{\text{past}}}{L_0 - L_{\text{past}}} \right) \approx (\mu_a + \mu'_s) \bar{l}_c. \quad (4)$$

the average path length in a cavity, $\bar{l}_c$, can be determined from measured radiances, since $\mu_a$ and $\mu'_s$ are known for coffee and Intralipid, respectively. When the optical properties of the material in the cavity would be position dependent, as is the case for naturally
developed lesions, \((\mu_{a,c} + \mu'_{s,c})\ell_c\) should be replaced by the more general reduced optical thickness, here defined as \(\tau'_c = \int (\mu_{a,c} + \mu'_{s,c})\,dl_c\).

The slope \(dE/d\mu_{a,c}\) of the linear regression line fitted through the determined points \(E\) as a function of \(\mu_{a,c}\) served as an estimate of \(\ell_c\) in a light absorbing cavity. For the light scattering cavities the linear regression line was fitted through the four points \(E\) with the lowest decadic reduced scatter coefficients.

The average path length in a cavity in its turn is related to the cavity diameter. However, the exact relation between path length and cavity diameter is dependent on, e.g., the intensity distribution of the light source and the optical properties of the material between light source and cavity. As a first estimate of the magnitude of the average path length given the cavity diameter, the light source was modelled as a homogeneous parallel beam directed at a light absorbing cylinder perpendicularly at its axis. The average path length follows from integration of the paths through the cylinder circle.

In the above the role of dentine was neglected. For this, one has to assume that light having reached the dentine will not reach the occlusal surface or will only contribute to a homogeneous background. Either assumption is conflicting with the findings of Mitropoulos (1985) who inferred that dentine involvement may be a prerequisite for lesion detection. Therefore, these assumptions will be tested in this paper.

### 2.3. The experimental set-up

The light source consisted of a 20 W halogen light bulb (black-body radiator at 3000 K) projected on one end of a glass fibre (diameter 300 \(\mu\)m) with an objective (20\(\times\)). The free fibre tip served as the point light source for the teeth. The position of the light source with respect to the cavity introduced in the premolar tooth is outlined in figure 3. Optical coupling between enamel and fibre tip was improved using water.

The occlusal surface of the premolar teeth (\(\approx 6 \times 6\) mm\(^2\)) was imaged with a CCD camera (eight bits; 512 \(\times\) 512 pixels; lens \(f = 135\) mm). Though for displaying purposes the radiances were measured over the entire surface, for data analysis a region of interest (ROI) with approximately the size of the cavity was defined above the cavity (figure 3(b)). To determine the cavity position and dimensions a protruding needle was inserted into the cavity (figure 3(c)) and a reflected light image of the tooth was made, using an ordinary desk lamp as light source. In the ROI thus obtained the average radiances, \(\bar{L}\), was calculated.

Light with a limited bandwidth in the blue, green and red part of the electromagnetic spectrum was obtained by introducing a red absorbing blue (BG23), a green (VG5) and a red sharp cut-off (RG610) Schott glass filter, respectively, between detector and tooth. IR radiation was blocked by a heat reflecting mirror. Images for tooth transillumination with IR radiation were obtained by subtraction of the image obtained using the red sharp cut-off filter and heat reflecting mirror from the image obtained using only the red sharp cut-off filter.

From the wavelength characteristics of the components that constitute the optical system the relative contribution of a specific wavelength to the measured signal for a specific glass filter was calculated as follows:

\[
C_f(\lambda) = \frac{S_{\text{source}}(\lambda)T_{\text{filter}}(\lambda)R_{\text{det}}(\lambda)}{\int_0^\infty S_{\text{source}}(\lambda)T_{\text{filter}}(\lambda)R_{\text{det}}(\lambda)\,d\lambda}
\]

with \(S_{\text{source}}(\lambda)\) the spectral dependence of the light source, \(T_{\text{filter}}(\lambda)\) the transmission of the applied filters, and \(R_{\text{det}}(\lambda)\) the spectral response of the detector. The curves obtained for the different filters are depicted in figure 4. To plot the extinction as a function of
the extinction coefficient of the fill fluid the extinction coefficient was taken at the $\lambda_f$ that solves the equation
\[ \int_0^{\lambda_f} C_f(\lambda) \, d\lambda - \int_{\lambda_f}^{\infty} C_f(\lambda) \, d\lambda = 0 \]  
for light in the blue, green, red and IR parts of the electromagnetic spectrum, respectively.

2.4. Investigated lesion parameters and experimental procedure

Cavities were filled with the black-painted needle, Intralipid (20%) and coffee in 0, 1, 2, 4, 8, 16 and 32x diluted particle and dye concentrations, and water, respectively. Five premolar teeth were used with cavities prepared up to the DEJ. Prior to a measurement the tooth was blotted dry and during measurement of a series with all fillings the teeth were not removed from the set-up. Three teeth were used for the transillumination measurements with IR radiation. For these measurements only undiluted Intralipid and coffee were used.

Four premolar teeth were used to study the contribution of the dentinal lesion part to the radiance change induced by the total lesion. First cavities were prepared up to the DEJ. The cavities were filled with water, and undiluted coffee and Intralipid (20%), respectively. The radiance at the occlusal surface was determined nine times for red light (all four teeth) and green light (for the last two teeth). Subsequently, the cavities were deepened up to the pulp chamber, and filled with coffee and Intralipid, respectively. To measure the contribution of the dentinal cavity part to the total radiance change, the quantity
\[ D = \left( \frac{\langle \hat{L}_{\text{enamel}, \mu_{\text{ext}}} - \hat{L}_{\text{enamel+dentine}, \mu_{\text{ext}}} \rangle}{\langle \hat{L}_{\text{enamel}, 0} - \hat{L}_{\text{enamel}, \infty} \rangle} \right) \times 100\% \]
was used. \( \tilde{L}_{\text{enamel}, \mu_{\text{ext}}} \) is the averaged radiance for a cavity restricted to the enamel and with extinction coefficient, \( \mu_{\text{ext}} \), of the fill fluid. Similarly, \( \tilde{L}_{\text{enamel+dentine}, \mu_{\text{ext}}} \) is the radiance for a cavity in both enamel and dentine. By categorizing the light paths into through sound material, through the enamel cavity volume and through the dentinal cavity volume, it can be verified that the numerator of expression (7) represents the radiance contribution to the total signal induced by a cavity of the light paths through the dentinal cavity volume. Similar to expression (4) the denominator represents the maximum radiance change induced by a cavity restricted to the enamel.

3. Results

The results of the transillumination measurements with IR radiation showed no measurable differences between cavities filled with water and with coffee. The difference in IR measurements between cavities filled with Intralipid and water was approximately the same as with red light.

In figure 5(a) the extinction defined in expression (4) for light absorbing cavities is plotted as a function of the decadic absorption coefficient for blue, green and red light. The estimated average path lengths in the cavity, i.e., the slopes \( dE/d\mu_{\alpha,c} \) of the linear regression lines fitted through the measured points, are summarized in table 2. The extinction for light scattering cavities is plotted as function of the decadic reduced scatter coefficient in figure 5(b). The slopes of the linear regression lines fitted through the four points with the lowest decadic reduced scatter coefficient are also summarized in table 2.
Figure 5. A typical example of the extinction for a cavity at the approximal surface illuminated with red, green and blue light as a function (a) of the decadic absorption coefficient and (b) of the decadic reduced scatter coefficient for a cavity filled with coffee and Intralipid, respectively.

Table 2. Estimated average path length in cavities, $l_c$, of five teeth filled with light absorbing and light scattering fluids, for light in the blue, green and red parts of the electromagnetic spectrum.

<table>
<thead>
<tr>
<th>Tooth No</th>
<th>$\mu_a$</th>
<th>$\mu_s'$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\bar{l}_c(\lambda_B)$ (mm)</td>
<td>$\bar{l}<em>c(\lambda</em>{GR})$ (mm)</td>
</tr>
<tr>
<td>1</td>
<td>1.5</td>
<td>1.13</td>
</tr>
<tr>
<td>2</td>
<td>0.97</td>
<td>0.98</td>
</tr>
<tr>
<td>3</td>
<td>1.1</td>
<td>1.04</td>
</tr>
<tr>
<td>4</td>
<td>1.31</td>
<td>0.99</td>
</tr>
<tr>
<td>5</td>
<td>1.15</td>
<td>1.13</td>
</tr>
<tr>
<td>Mean</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>SD</td>
<td>0.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The estimates of the quantity $D$, to determine the contribution of the dentinal cavity part to the total radiance change, are given in table 3 for red and green light.
Table 3. The contribution of the dentinal cavity part, $D_0$, to the change in radiance measured at the occlusal surface for light absorbing and light scattering cavities in four teeth, for light in the green and red parts of the electromagnetic spectrum.

<table>
<thead>
<tr>
<th>Tooth No</th>
<th>$D(\lambda_{gr})$ (%$\mu_a$)</th>
<th>$D(\lambda_{rd})$ (%$\mu_a$)</th>
<th>$D(\lambda_{gr})$ (%$\mu_s$)</th>
<th>$D(\lambda_{rd})$ (%$\mu_s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.7</td>
<td>4.8</td>
<td>-2.4</td>
<td>4.1</td>
</tr>
<tr>
<td>2</td>
<td>13.7</td>
<td>-3.2</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>13.5</td>
<td>5.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2.0</td>
<td>10.0</td>
<td>1.1</td>
<td>5.7</td>
</tr>
<tr>
<td>Mean</td>
<td>1.4</td>
<td>10.5</td>
<td>-0.7</td>
<td>2.9</td>
</tr>
<tr>
<td>SD</td>
<td>0.9</td>
<td>4.2</td>
<td>2.5</td>
<td>4.1</td>
</tr>
</tbody>
</table>

4. Discussion

4.1. Validation of the model

In the model light is reflected and refracted at the cavity surface. Because water-based fluids were used, the influence of reflection and refraction is reduced. Using water to model sound enamel has the advantage that both scatter and absorption coefficient are effectively zero, so that a well defined reference is used. However, the use of water as a reference results in a small, but systematic, overestimation of the radiance change induced by lesions.

A second property of the model is the absence of a transition region from sound to heavily affected material, as is present for caries lesions. This omission will affect details in the radiance distribution but the magnitude of the dominant effects will primarily be determined by the increase in optical thickness due to the lesion presence. This optical thickness increase is determined by the physical dimensions and material properties of the cavities and lesions, respectively. Dimensions and material properties of the cavities filled with Intralipid and white spot lesions have the same order of magnitude.

The transmission spectra of Intralipid and demineralized ‘white spot’ enamel resemble each other. The asymmetry parameters $g(\lambda)$ of carious enamel are unknown. To a first approximation at $\lambda = 633$ nm the asymmetry parameter of sound enamel can be used. At other wavelengths the spectral behaviour of $g(\lambda)$ has to be assumed. Note that the asymmetry parameters $g(\lambda)$ of Intralipid (20%) are the values determined for Intralipid (10%) by Flock et al (1992). Due to differences in preparation there may be more differences than just the concentration (Van Staveren et al 1991). Furthermore, intersample variations and variations between brands also exist (Flock et al 1992).

No quantitative data are available on the absorption or scatter coefficient of discoloured lesions. Since the signal measured for a total absorber and for coffee in the highest dye concentration were of the same order, it was assumed that measurements were performed over the entire range of discoloration.

The absorption spectra determined for the organic material in discoloured lesions showed no absorption peaks and were continuously increasing with decreasing wavelengths. These spectra were similar to the spectrum of the coffee used to model the discoloured lesions. The scatter coefficient of coffee was considered to be negligible compared to the absorption coefficient because the coffee was a coloured but transparent fluid when viewed through it.

In this study the effect of absorption and scattering were measured separately. Yet, it
Optical model of approximal caries

is likely that during lesion discoloration the enhanced scatter coefficient initially remains unchanged. Hence, to describe the behaviour of discoloured caries lesions the effect of absorption and scattering should be combined.

4.2. Extinction

For light absorbing cavities the extinction as function of the decadic absorption coefficient was well approximated by the regression line \( r = 0.98 \pm 0.01 \). Therefore, light propagation is fairly well described by the Lambert–Beer law. The slopes \( \frac{dE}{d\alpha} \) of the regression lines increased with decreasing wavelength. Note that the extinction is plotted as function of the decadic absorption coefficient and not as a function of the dye concentration. Therefore, the curves should have had approximately the same slopes. This deviation can be explained from wavelength-dependent scattering in the sound enamel (Spitzer and ten Bosch 1975) when light propagates from the light source to the cavity. Due to scattering the vector describing the propagation direction, which was initially perpendicular to the cavity cylinder axis, acquires an increasing component parallel to the cavity axis (see figure 3(c)), thus prolonging the average path length in the cavity. Hence, the estimated path length will increase with decreasing wavelength because the scatter coefficient of sound enamel increases with decreasing wavelength. This implies that the slope of the curve obtained for the red light can be considered as the most accurate approximation for the cavity diameter. For a parallel homogeneous beam oriented perpendicular to the cylinder axis of a light absorbing medium the ratio between average path length and cylinder diameter has the value 0.785. The estimated slopes are in acceptable agreement with the average cavity diameter of 1.15 mm (subsection 2.1) multiplied with this correction factor.

For light scattering cavities the extinction as a function of the decadic reduced scatter coefficient was fitted to a straight line \( r = 0.98 \pm 0.03 \) for \( \mu'_d (\lambda = 633 \text{ nm}) < 1.25 \text{ mm}^{-1} \). For higher decadic reduced scatter coefficients the curves levelled off due to multiple scattering. Also for the scattering fluid the slopes \( \frac{dE}{d\mu'_c} \) of the regression lines increased with decreasing wavelength. This observation can partly be explained in the same way as for the absorber. However, since there is a difference in magnitude of the effect for the absorbing and scattering fluids, an additional factor may be involved. This may concern an inaccurate estimation of \( \mu'_d (\lambda) \), since a wavelength dependence of the slopes \( \frac{dE}{d\mu'_c} \) can also be induced by a wavelength-dependent underestimation or overestimation of \( \mu'_s (\lambda) \). To determine \( \mu'_s (\lambda) \), experimentally determined values \( \mu'_s (\lambda) \) and asymmetry parameters \( g(\lambda) \) derived from Flock et al (1992) were used. The intersample variations or variations between brands which also exist for the curve \( g(\lambda) \) (compare the curves \( g(\lambda) \) of Van Staveren et al (1991) and Flock et al (1992)) may have caused a wavelength-dependent underestimation or overestimation of \( \mu'_d (\lambda) \) for the light scattering cavities.

The transmission spectra of the different materials, measured from the IR to the blue part of the electromagnetic spectrum, show the highest extinction at the lowest wavelengths. Hence the biggest change induced by lesions will be observed when using these lower wavelengths, and hence lower wavelengths will be more sensitive. However, for quantification purposes it may be more suitable to choose a higher wavelength since for that higher wavelength the induced change may be distributed more evenly over the occurring demineralization and discoloration range. Hence, higher wavelengths might be more suitable for lesion monitoring purposes.

From the relatively high correlation values \( r \) it can be inferred that the random variations in the average radiances, e.g., due to cavity refilling, are small. Since the standard deviation
of the estimated path lengths in the cavity is of the same order as the standard deviation of the cavity diameter, the influence of repositioning on the estimated path lengths seems to be small.

4.3. The contribution of the dentinal part of the lesion

The results shown in table 3 indicate that the dentinal contribution to the total change in radiance at the occlusal surface induced by a lesion is small. This inference is not necessarily in disagreement with the observation reported in literature that lesions diagnosed with transillumination have regularly progressed into the dentine (Mitropoulos 1985), since it seems a fair assumption that for these lesions the enamel will be more demineralized and discoloured, with the affection expanding over a bigger volume, than for lesions not yet progressed into the dentine.

Note that the contribution of the dentinal cavity part was measured with the total dentinal cavity covered by the enamel cavity. Naturally developed lesions reaching the DEJ start to expand on the DEJ itself. Moreover, the outer edge of the affected DEJ may not be covered by carious enamel. This effect may increase the 'dentinal' contribution somewhat for naturally developed lesions.

The quantity $D$, defined to estimate the contribution of the dentinal cavity part to the total decrease in radiance, was larger when illuminated with red light than when illuminated with green light. A possible explanation for this phenomenon is that more of the red light that arrived in the dentine arrives at the occlusal surface. Note that this statement indicates that the assumptions to justify neglecting the dentinal cavity part are only a first approximation and that light propagating through the dentine does arrive at the occlusal surface. That more of the red than of the green light arrives at the occlusal surface may be due to the fact that both absorption and scattering are lower for the red than for the green light for sound and simulated carious material. So, these can be interpreted as an illustration of the fact that light with higher wavelengths penetrates deeper into turbid materials. In itself this is an interesting observation since it is a mechanism to extract information from the deeper dentine volume. Unfortunately, because the contribution itself is small, the effect may not be applicable for lesion quantification purposes.

5. Conclusion

For transilluminated premolar teeth with simulated caries lesions at the approximal surface the radiance at the occlusal surface as function of the decadic absorption coefficient of the light absorbing fill fluid in the cavity was fairly approximated by the Lambert–Beer law. For light scattering cavities, with $\mu_s^2 (\lambda = 633 \text{ nm}) < 1.25 \text{ mm}^{-1}$, the radiance as a function of the decadic reduced scatter coefficient was fairly approximated by an equation similar to the Lambert–Beer law. For higher decadic reduced scatter coefficients the curves levelled off due to multiple scattering.

The small contribution to the signal of the dentinal cavity part strongly indicates that the supposed prerequisite of dentinal involvement for lesion detection using transillumination is not caused by the dentinal lesion part itself, but more probably by the processes accompanying lesion progress into the dentine, i.e., an increased demineralization and discoloration expanding over a larger volume in the enamel itself.
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