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Propagation of Light through Human Dental Enamel and Dentine — [Source link](#)

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Key Words

Caries diagnosis
Dentine
Enamel
Light absorption
Light scattering

Abstract

Techniques based on transillumination of teeth with visible light will be a valuable aid in caries diagnosis, if a higher sensitivity than that of the present Foti method is achieved. Therefore, a better understanding of light propagation through teeth is required, and hence it is useful to investigate the propagation of light through sound dental material. In this study the intensities emanating from the surfaces of enamel and dentine bars were measured when these bars were illuminated using a fibre rod transporting the light from a HeNe laser ($\lambda = 633 \text{ nm}$) as a light source. From the measured intensities, the radiant fluxes emanating from the surfaces were calculated. To account for a directional dependence of these fluxes, optical anisotropy in dental material was investigated by comparing the transmitted light intensity in a direction perpendicular and parallel to the approximal surface of the tooth from which the sample was cut. The mean ratio of the transmitted intensities in perpendicular and parallel direction was 0.86 ± 0.06 for enamel and 2.88 ± 0.43 for dentine. In addition, for enamel the asymmetry parameter, g , was estimated. The averaged value was $g = 0.68 \pm 0.09$. It was concluded that for dentine the optical anisotropy as measured supports the idea that tubules are the predominant cause of scattering in dentine. For enamel the results indicate that the hydroxyapatite crystals contribute significantly to scattering and that the influence of the prism structure on the light propagation is small.

For many years X-rays have been used for qualitative approximal caries diagnosis and restorative decision making. If carious lesions could be detected and quantified at an early stage, it would be possible to take preventive rather than restorative actions. If, in addition, non-ionizing radiation is used, it will be possible to monitor the caries process without any health hazard. Therefore, several researchers have investigated optical alternatives to bite-wing radiography, and results indicating that quantitative methods are achievable have been reported [O'Brien et al., 1989; van de

Rijke and ten Bosch, 1990; Verdonshot et al., 1991]. Yet, to exploit the full potential of these quantitative optical methods, it is necessary to obtain a thorough understanding of light transport through human teeth.

The optical properties of bulk dental material are an important factor in the propagation of light through teeth. Some optical properties of dental material have already been studied. Spitzer and ten Bosch [1975] measured the scattering and absorption coefficients of human and bovine enamel as a function of wavelength. Brodbelt et al. [1981]

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measured the translucency of human dental enamel as a function of both wavelength and degree of dehydration. O'Brien [1988] observed Fraunhofer diffraction patterns when illuminating human enamel slabs. His observations indicate that the prism structure in enamel might influence light propagation, possibly resulting in optical anisotropy. Finally, Zijp and ten Bosch [1991] investigated the angular dependence of HeNe laser light scattering by bovine and human dentine. The optical properties of dentine have been summarized [ten Bosch and Zijp, 1987], and the mechanism of light scattering in dentine has been described [Zijp and ten Bosch, 1993]. From this research, it is known that the tubules are the most important scattering particles in dentine, and as the tubules are oriented from pulp towards the dentino-enamel junction, the anisotropic structure of dentine may result in a directionally dependent light propagation.

Since a carious lesion can be regarded as a deformation of the internal structure in a diffusing object, the detection of approximal carious lesions in teeth might be achieved using the procedure for reconstructing images of the internal structure of objects that diffuse radiation as described by Singer et al. [1990]. In the present study, the relative radiant fluxes emanating from small cubic volumes of dental hard tissue, which constitute the parameters in the above-mentioned model, were estimated from measurements.

Materials and Methods

Samples

Approximately square 0.85 ± 0.03 mm thick enamel and dentine bars with heights varying between 2.5 and 5.0 mm were cut from the approximal sites of human premolar teeth using a saw microtome (Leitz 1600, Hamburg, Germany; sawblade hardness D46, grain size $45 \mu\text{m}$). The samples were checked under a light microscope, and those with cracks or other irregularities were discarded. A total of 15 enamel and 15 dentine samples were cut and stored in a physiological salt solution.

Experimental Arrangement

The samples were illuminated using a 5.0-mW HeNe laser light source ($\lambda = 633$ nm), the beam of which was projected on a 50/125- μm graded-index glass fibre to transport the light to the sample. The numerical aperture of the fibre was 0.2. The enamel samples were illuminated parallel to the approximal tooth surface, whereas the dentine samples were illuminated in a direction perpendicular to the approximal tooth surface. The light radiated from a sample surface was measured with a photodiode, mounted in a holder with a lens placed approximately 5 mm before the photodiode. A green filter (standard Schott minus infrared filter) in front of the lens was used to reduce the sensitivity of the photodiode to red and infra-red wavelengths. The detector was rotated around the sample for measurements at different angles to the sample surface. The distance between sample surface and lens of the

detector was 18 ± 0.5 mm. The width of the square-shaped diaphragm of the lens was 1.0 ± 0.05 mm, and the field of view of the detector system was approximately 3.2° . To measure the intensity emanating from only one sample surface at a time, surfaces not used to illuminate or measure the intensity were covered with black light-absorbing plastic material. The experimental set-up for measurements in forward (F) and sideward (S) direction are depicted in figure 1. The set-up for measurements in backward (B) direction is obtained from the set-up in forward direction by shifting the detector so that it faces the back surface of the sample.

Before a measurement was carried out, the surfaces of a sample was blotted dry with a tissue. To avoid dehydration of the sample [Spitzer and ten Bosch, 1975; Brodbelt et al., 1981], the surface of the sample holder was covered with a thin water film, and a drop of water was put on top of the sample. The intensity distribution of every surface was determined five times with intervals of at least 4 h.

Part of the light intensity measured in backward direction is due to reflection at the sample surface and is not caused by scattering in backward direction. To separate the effects of scattering and surface reflection, an additional measurement was performed on a glass bar, and the reflected light measured for glass was subtracted from the enamel and dentine results in backward direction.

To account for a directional dependence of the radiant fluxes, the optical anisotropy of enamel and dentine was investigated by measuring the intensity $I_{F,per}(0)$ and $I_{F,par}(0)$ of 15 enamel and 15 dentine samples. $I_{F,per}(0)$ is the intensity measured in forward direction at $\Theta = 0^\circ$ with the light source perpendicular to the approximal surface of the sample. Likewise, $I_{F,par}(0)$ is the intensity measured when source and detector are parallel to the approximal surface of the sample (fig. 1). As a measure for anisotropy, the ratio $I_{F,per}(0)/I_{F,par}(0)$ was adopted.

For the anisotropy measurements the same equipment was used as for the measurements of the intensity distribution. However, to increase the power received by the detector, the distance between sample surface and the lens of the detector was reduced to 5 ± 0.5 mm. Consequently, the interval of Θ over which radiation was received from the sample surface ($\Delta\Theta$) became approximately 11° . Samples were removed from the storage liquid, and their surfaces were blotted dry. The bottom of a sample was fixed in a holder of sticky wax, and the transmitted light was measured to obtain $I_{F,per}(0)$ 1 min after the sample had been removed from the liquid. The hole in the wax was partly filled with water to reduce dehydration of the sample. Then the sample was submerged in the storage liquid for 1.5 min, after which the same procedure was repeated to measure the transmitted light in the other direction to obtain $I_{F,par}(0)$. The entire procedure was repeated seven times for every sample, alternating the order in which $I_{F,per}(0)$ and $I_{F,par}(0)$ were measured, with at least a 4-hour interval between measurements.

Calculations

From a measured intensity distribution of the surfaces F, S, and B, the total light emission by a particular surface, the radiant flux, Φ [W], was calculated, using the following expressions:

$$\Phi_{F,B} \approx 2\pi \sum_0^{\frac{1}{2}\pi} I_{F,B}(\Theta,0) \sin(\Theta) \Delta\Theta \quad (1)$$

$$\Phi_S \approx \pi \sum_0^\pi I_S(\Theta,0) \sin(\Theta) \Delta\Theta \quad (2)$$

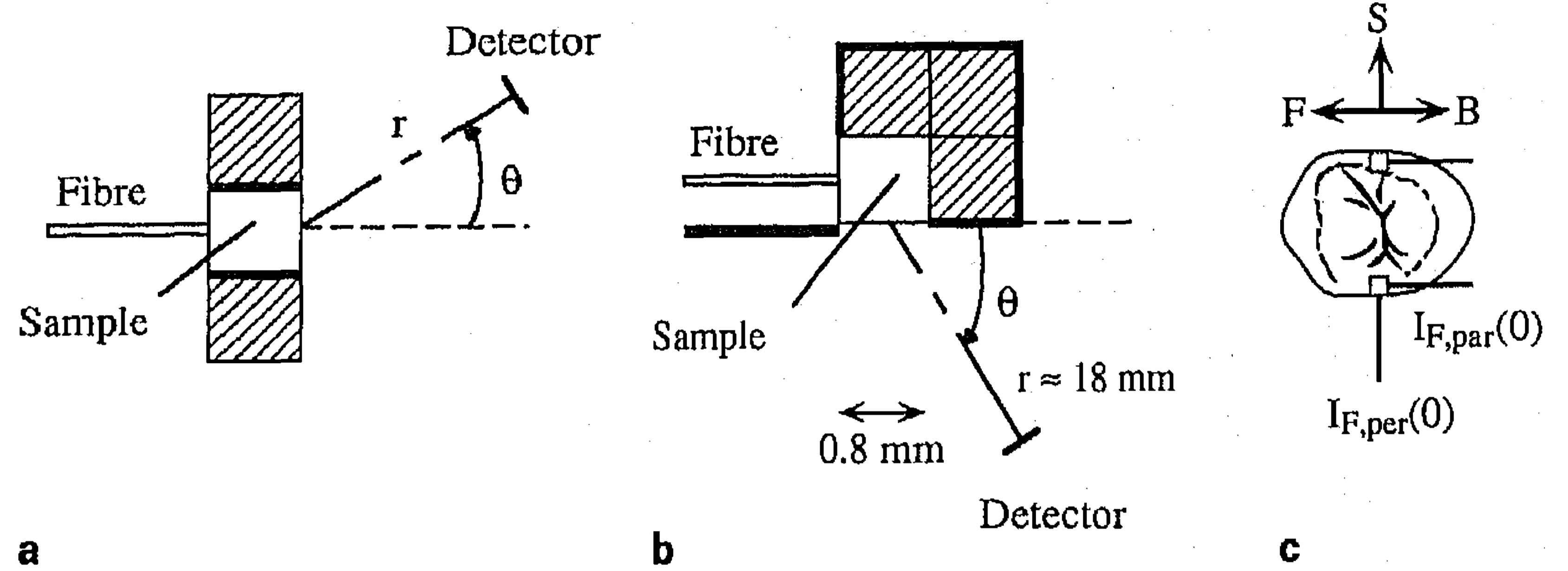


Fig. 1. Experimental set-up to measure the intensity distribution in forward (a) and in sideward direction (b). The set-up for measurement in backward direction is obtained from the set-up in forward direction by shifting the detector so that it faces the back surface of the sample. The thick black lines indicate a light-absorbing black cover, and the shaded squares indicate glass bars. The glass bars in b were glued together. c Projection of the enamel samples on the occlusal surface. Indicated are the sample surfaces F, S, and B, and the intensities measured in forward direction for the glass fibre positions, indicated by the straight lines, parallel and perpendicular to the approximal surface.

Table 1. Relative radiant fluxes perpendicular and parallel to the approximal tooth surface in forward, sideward, and backward direction for dentine and enamel

	F_{per}	F_{par}	S_{per}	S_{par}	B_{per}	B_{par}
Dentine	0.20 ± 0.01^a	0.07 ± 0.03^b	0.15 ± 0.02^a	0.19 ± 0.10^b	0.19 ± 0.01^a	0.19 ± 0.01^b
Enamel	0.48 ± 0.12^b	0.56 ± 0.02^a	0.13 ± 0.07^b	0.11 ± 0.01^a		

^a Values derived from intensity measurements.

^b Values calculated from values in the other sample direction and the anisotropy ratio $I_{F,per}(0)/I_{F,par}(0)$.

in which the indices indicate the surfaces from which the light emanates, and $I(\Theta, 0)$ [$W \cdot \Omega^{-1}$] is the intensity measured in the direction Θ at $\Phi = 0^\circ$. In figure 2, the co-ordinate system and the symmetries that have to be assumed to apply these equations are visualized. Due to the symmetries, the definition of the angles Θ and Φ for surface S differs from the definition for the surfaces F and B. However, in both cases it is assumed that the intensity is independent of the angle Φ .

For every sample a radiant flux, averaged over the five measurements, and a standard error of the mean were calculated for the three surfaces measured. Assuming no absorption of light, the total radiant flux, Φ_{tot} , was calculated as: $\Phi_{tot} = \Phi_F + 4\Phi_S + \Phi_B$. Finally, for this particular intensity distribution of the applied light source, the relative radiant fluxes were calculated as follows: $F = \Phi_F / \Phi_{tot}$, $S = \Phi_S / \Phi_{tot}$ and $B = \Phi_B / \Phi_{tot}$.

To obtain the radiant fluxes for illumination in both perpendicular and parallel direction to the approximal tooth surface, the following equations were used:

$$F_{per} = F_{par} \cdot I_{F,per}(0) / I_{F,par}(0) \quad (3)$$

$$S_{per} = 4S_{par} / [I_{F,per}(0) / I_{F,par}(0)] \quad (4)$$

assuming no change in backward direction.

For calculating the fluxes for arbitrary source distributions, the asymmetry parameter, g , is needed. The asymmetry parameter of den-

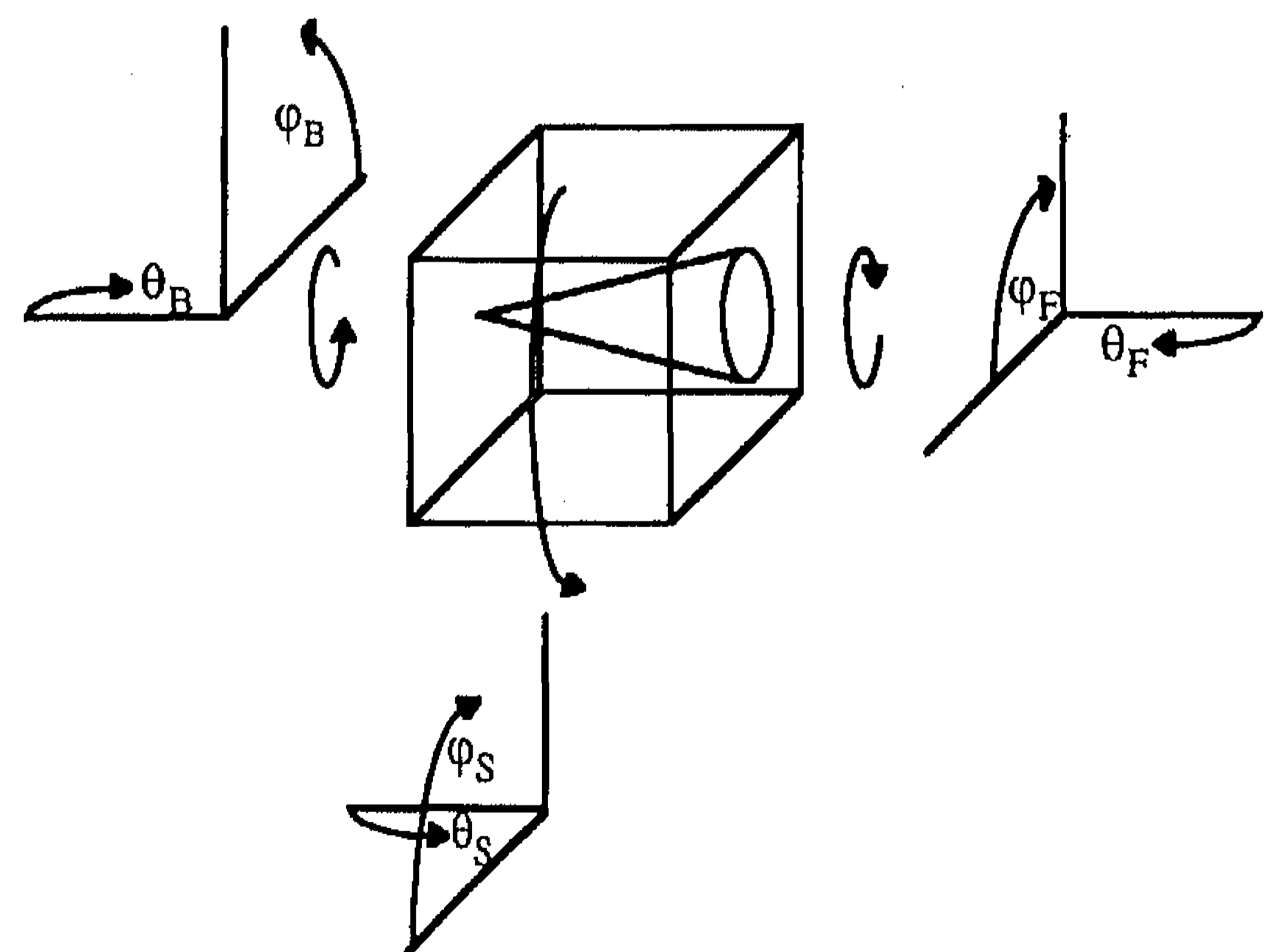


Fig. 2. Symmetry of the intensity distribution at the sample surfaces and definition of the co-ordinate system used for calculation of the emitted radiant fluxes. The subscripts F, S, and B at the angles Θ and φ denote the forward, sideward, and backward direction, respectively.

tine is known [Zijp and ten Bosch, 1991], and the asymmetry parameter of enamel was estimated from the measurements, assuming single scattering in the bar and no absorption. A least-squares fit of a measured intensity distribution in forward direction was optimized with a calculated intensity distribution using g as parameter. The calculated distribution was obtained by convolution of a function describing the intensity distribution of the light source with the Henyey-Greenstein phase function [Henyey and Greenstein, 1941] which accounted for the single scattering events. The intensity distribution of the light source, the fibre rod, was Gaussian with $\sigma = 11^\circ$. The extinction coefficient, μ_{ext} , was set to the value 0.11 mm^{-1} [Spitzer and ten Bosch, 1975]. To correct for intensity losses due to diffuse surface reflection, the source distribution was multiplied by the factor 0.52. This factor was obtained from a transmission measurement through a glass bar that was cut with the saw microtome used to prepare the dentine and enamel samples. A 95% confidence interval of the estimated optimum value of the asymmetry parameter was calculated using chi-square boundaries as outlined by Press et al. [1988].

Results

In figure 3 a typical example of the angular intensity distribution measured at the surfaces F and S for enamel is shown. The difference between the intensity emanated from surface B of enamel and the intensity emanated from surface B of glass was not statistically significant. This implies that surface reflection can account fully for the measured signal. A typical example of the angular intensity distribution measured at the surfaces F, S, and B for dentine is shown in figure 4.

For enamel and dentine the ratio $I_{\text{F,per}}(0)/I_{\text{F,par}}(0)$ averaged over 15 samples was 0.86 ± 0.06 and 2.88 ± 0.43 , respectively. Since the 95% confidence interval of the ratios for enamel and dentine do not contain the null value, i.e., 1, the results are statistically significant. The relative radiant fluxes cal-

culated from the intensity distributions and the anisotropy ratios, averaged over the 15 dentine and enamel samples, are given in table 1. For the asymmetry parameter, g , of enamel a value 0.68 ± 0.09 was found.

Discussion

Measurements on a glass bar were performed to correct the measured intensities in backward direction for surface reflection when light enters a sample. The error which is introduced because the refractive indices of dentine ($n = 1.45$) [ten Bosch and Zijp, 1987] and enamel ($n = 1.62$) [Spitzer and ten Bosch, 1975] are unequal to the refractive

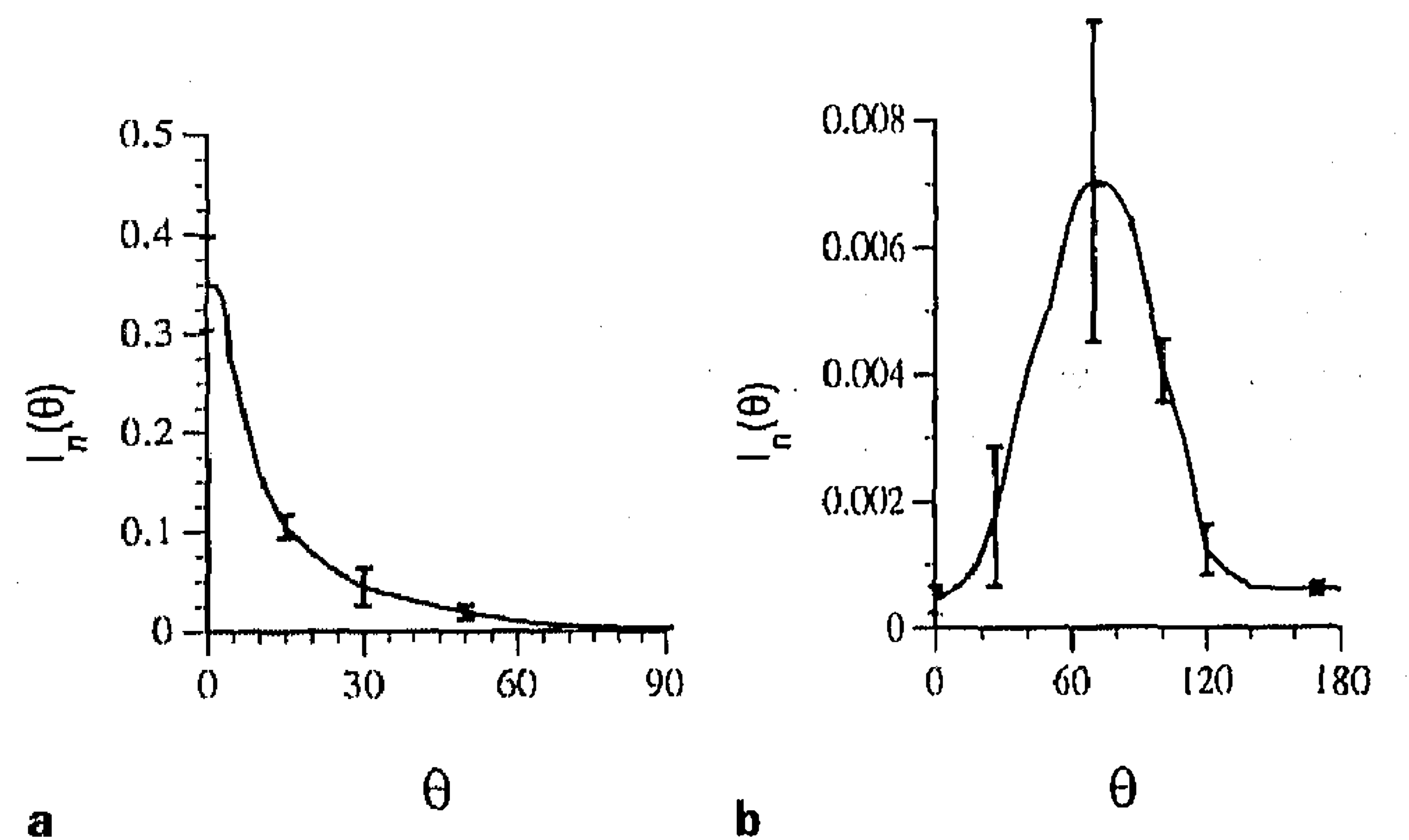


Fig. 3. A typical example of the angular intensity distribution of an enamel sample in forward (a) and in sideward (b) direction. The results are divided by the intensity measured for air in direction $\Theta = 0^\circ$.

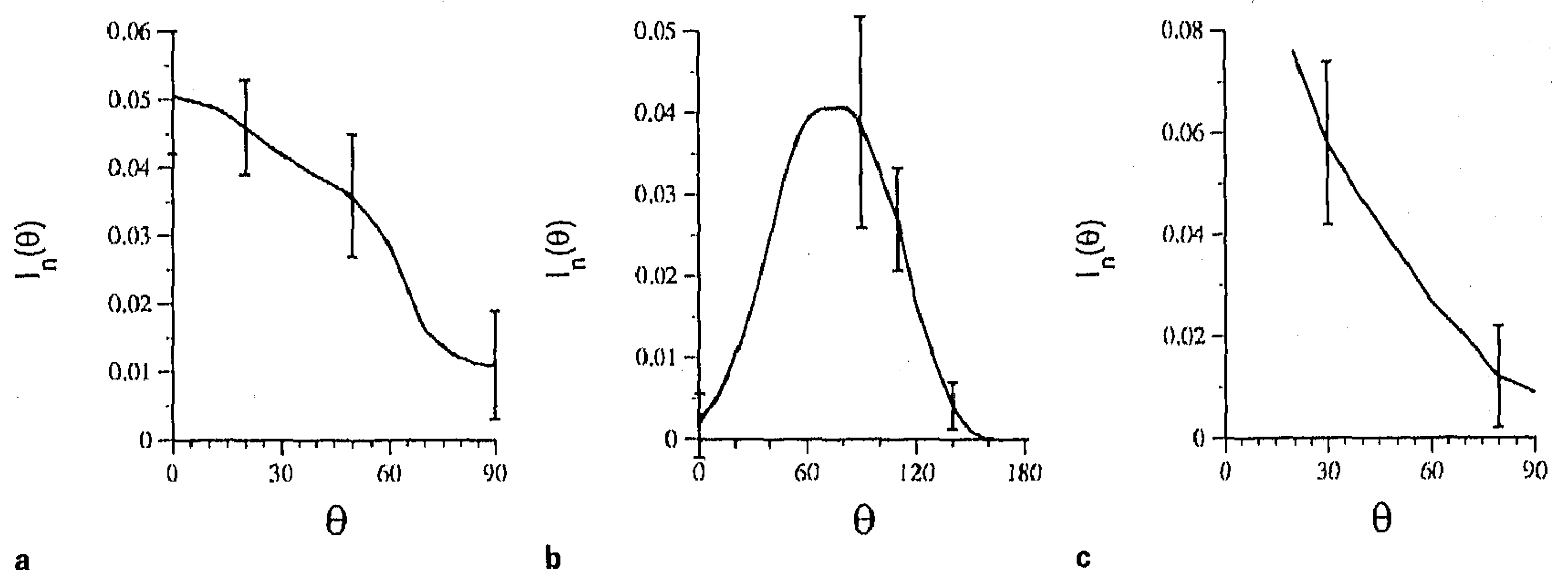


Fig. 4. A typical example of the angular intensity distribution of a dentine sample in forward (a), sideward (b), and backward (c) direction. The results are divided by the intensity measured for air in direction $\Theta = 0^\circ$.

index of the glass bar ($n=1.55$) is much smaller than other error sources and can be neglected.

Intensity distributions were measured with the light source in a direction parallel to the approximal tooth surface for enamel and perpendicular for dentine because the anisotropy measurements showed that the materials had the lowest extinction in these directions. From the measured intensity distributions fluxes were calculated. For the other directions the fluxes were derived from the anisotropy ratio and the intensity distribution in the sample direction that was measured. Due to the intensity distribution of the light source, the anisotropy ratio will be slightly underestimated. However, the same effect would also have occurred if the intensity distribution had been measured instead of calculated. Therefore, the single scattering assumption is a sufficient condition for the calculation of the fluxes to be valid.

For dentine the effect of anisotropy is not only underestimated due to the light source distribution, but also due to multiple scattering. Similar to enamel, both effects would also have occurred when the fluxes had been measured instead of calculated. However, the crucial difference between enamel and dentine is that due to multiple scattering, the anisotropy ratio measured for $\Theta = 0^\circ$ with $\Delta\Theta \approx 11^\circ$ is lower for larger angles Θ . Therefore, it is likely that in particular F_{par} is underestimated.

The relative radiant fluxes were experimentally determined for enamel pieces of specific size and with a specific light source distribution. Values for arbitrary but small enamel sizes or arbitrary source distributions can be estimated using part of the algorithm that was used to estimate the asymmetry parameter, i.e., by convolution of the light source distribution with the Henyey-Greenstein phase function assuming single scattering and no absorption and adopting fixed values for the asymmetry parameter and extinction coefficient. Flux values for arbitrary dentine sizes are easiest estimated using a Monte Carlo simulation, since the single scattering assumption is violated for the used dentine samples. All necessary data, i.e., the refractive index, the asymmetry parameter, and the scattering and absorption coefficient, are available. To account for single scattering events in the Monte Carlo algorithm, the Henyey-Greenstein phase function can be adopted [Zijp and ten Bosch, 1991].

The measured anisotropy for dentine is a very strong effect and can be understood by the structure of dentine, thus confirming an earlier suggestion by ten Bosch and Zijp [1987] and Zijp and ten Bosch [1993] that dentinal tubules are the predominant cause of scattering. The anisotropy for enamel was less pronounced and the translucency was larger in the parallel than in the perpendicular direction to

the approximal tooth surface. The experimental design excluded the possibility that the effect was caused by drying of the sample. Furthermore, because the samples were of the same size, and all samples but one – for which the intensity in parallel and perpendicular direction was the same – showed anisotropy, neither variation in size nor surface defects do explain the results. Because transmission in the parallel direction is larger than in the perpendicular direction, it can be concluded that the contribution of the prism structures to light scattering is small as compared with the contribution of the hydroxyapatite crystals. Some additional support that the hydroxyapatite crystals are the dominant cause of scattering is the yellow discolouration of the transmitted beam and the bluish glare of the scattered light, a phenomenon observed for Rayleigh scattering. The anisotropy might be explained by the changing chemical composition of enamel going from the outer surface to the dentino-enamel junction, e.g., a contribution from organic substances.

The shape of the measured angular intensity distributions for enamel indicates that the asymmetry parameter must be high. This was confirmed by estimation of the asymmetry parameter fitting the results in forward direction to a model in the single-scattering approximation. An effect causing a systematically lower asymmetry parameter was scattering at the surface due to surface roughness. Furthermore, an inaccuracy in the extinction coefficient will also produce a systematic effect, since this coefficient determines the ratio between the scattered and directly transmitted component of the propagating light beam.

Usually, estimation of the asymmetry parameter is performed with much thinner samples than the ones used in this study, this to avoid multiple scattering effects. However, it was suggested by Wist et al. [1993] that a possible advantage of the relatively large sample sizes might be that relatively more of the structure of the material stays intact. This is an important consideration when it is not clear what the predominant cause of scattering is in a material, i.e., for enamel the prism structure or the crystals themselves. Now that there are signs that the crystals are the most important scattering particles do the multiple scattering effects, caused by the relatively high thickness of the samples, result in a systematically lower estimation of the asymmetry parameter.

The asymmetry parameter, the average cosine of the scattering angle, has a relatively high value. Hence, scattering events result in only a small deviation from the original direction of light propagation. The high asymmetry parameter, together with the low extinction coefficient of enamel, indicates that light propagation through the enamel layer of teeth cannot accurately be approximated with the light dif-

fusion model. Although no restrictions are imposed on the parameter values in the formulation of the model proposed by Singer et al. [1990], somewhat unrealistic light distributions at the volume surface will be obtained if one of the relative fluxes through a surface of the small cubic volumes, in which the total volume is divided, is much bigger than the relative fluxes through the other surfaces of these small volumes. The measurements showed that the relative flux in forward direction of enamel is much bigger than the relative flux in sideward and backward direction. Since the outer enamel layer will be such an important factor, the model proposed by Singer et al. [1990] might not be the most suitable to model light propagation through teeth.

In summary, from measurements of the angular intensity distribution at the enamel and dentine sample surface, radiant fluxes were estimated. Optical anisotropy was shown for both enamel and dentine. For dentine the results support an earlier suggestion that dentinal tubules are the predominant

cause of scattering, whereas for enamel the results indicate that the crystals contribute significantly to scattering. The asymmetry parameter, g , for enamel was estimated by fitting the angular intensity distribution of enamel measured in the forward direction to a model describing the experimental system. In future research an optical model will be developed to gain more insight in light propagation through teeth when using Foti.

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