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Abstract. Tooth color is determined by the paths of light inside the tooth and absorption along these paths. This paper tests the hypothesis that, since the paths are determined by scattering, a relation between color and scattering coefficients exists. One hundred and two extracted incisors were fixed in formalin, mounted in a standardized position in brass holders, and pumiced. A facet was prepared near the incisal edge on the labial plane to allow for Knoop hardness measurements with a 500-gram load. Light scattering by the enamel was measured in a 45°/0° geometry; light scattering by both enamel and dentin was measured in a 0°/0° geometry. The reflection spectrum of the tooth was measured from the labial plane with a spectroradiometer in a 45°/0° geometry, with standard illuminant A and standard illuminant D65. To include all volume-reflected light, we used entire-tooth illumination and small-area measurement. CIELAB color coordinates were calculated from the spectra. Neither spectra nor coordinates showed evidence of a contribution of fluorescence to tooth color. Averaged values and standard deviations for L*,a*,b* were 69.9 (4.1), 1.22 (1.4), and 17.9 (2.9), respectively. Both scattering coefficients averaged to 0.6 (0.4) mm^{-1}; Knoop hardness number was, on average, 271 (39) kg/mm^2. L* correlated with a* ($r = -0.51$), with the enamel scattering coefficient ($r = 0.60$), and slightly with hardness ($r = 0.17$, $p = 0.03$). The colors of 28 teeth from which the enamel was removed correlated strongly with the colors of the complete tooth. This study quantitatively confirms that tooth color is determined mainly by dentin, with enamel playing only a minor role through scattering at wavelengths in the blue range.

Key words: dental enamel, tooth color, light scattering.

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Introduction

Tooth color is important for the esthetics of teeth and prosthetic restorations. Color results from volume scattering of light, *i.e.*, illuminating light follows highly irregular light paths through the tooth before it emerges at the surface of incidence and reaches the eye of the observer (see, *e.g.*, O'Brien *et al.*, 1985, and Van der Burgt *et al.*, 1990). Non-white color is predominantly a result of absorption along these paths, the degree of absorption being determined by the path lengths and the absorption coefficient of the tooth tissues. Wavelength-dependent scattering may also play a role. Light paths are determined by multiple light scattering inside the tooth and have lengths on the order of a few mm. Therefore, this paper investigates a possible relation between the scattering coefficients of the tissues and the color.

The color range of teeth has been measured by several authors (MacEntee and Lakowski, 1981; Ishiwata, 1986; Goodkind and Schwabacher, 1987; Kobayashi, 1988; Solheim, 1988; Rosenstiel *et al.*, 1991). Color can be described by color coordinates. The internationally defined CIELAB system (*e.g.*, Billmeyer and Saltzman, 1981) is also receiving attention for dental applications (Ishiwata, 1986; Kobayashi, 1988; O'Brien *et al.*, 1990; Rosenstiel *et al.*, 1991). Coordinates in whatever system are most reliably determined from a reflection spectrum, which must be determined in a standardized geometry of illumination and measurement. The length of the light path in the tooth indicates that incident light travels from one to a few mm sideward inside the tooth before it emerges. Thus, when color is measured with an instrument that has a small window (a few mm) for both illumination and collection of light, a considerable fraction of the light entering the tooth is probably lost, because it emerges at the surface outside the window of measurement and thus is excluded from the measurement (Van der Burgt *et al.*, 1990). For measurement of the true (visual) color, such edge losses should be avoided, and a spectroradiometer should be used, since it

measures the reflection with a camera located at a certain distance so that the measurement does not interfere with the illumination (McEntee and Lakowski, 1981; Ishiwata, 1986; Kobayashi, 1988).

Scattering and absorption coefficients of tooth enamel and dentin have been determined earlier on tooth sections (Spitzer and ten Bosch, 1975; ten Bosch and Zijp, 1987; Zijp and ten Bosch, 1991). Non-destructive methods to determine light scattering in carious teeth (ten Bosch *et al.*, 1984; Brinkman *et al.*, 1988) have not been applied to non-carious teeth, although sound enamel was included in their calibration (Borsboom and ten Bosch, 1983).

This paper attempts to identify the quantitative and optically correct measurement of the color of a rather large sample of extracted teeth and to relate the results to the scattering coefficients of enamel. Because scattering might be related to enamel porosity and thus to enamel microhardness, this property was included in the study.

Materials and methods

Teeth

Upper front teeth were obtained from dental practitioners in a fluoridated area in the USA. Immediately after extraction, the teeth were fixed in formalin and visually inspected. Teeth with missing corners, etched-on composite, and/or lateral fillings (all if larger than 1.5 mm), teeth that had undergone endodontic treatment, and teeth with fillings in the center of the crown were discarded. The sample thus obtained was composed of 73 central incisors, 27 lateral incisors, and two canines. During the entire investigation, the teeth were stored in a humid anti-bacterial atmosphere at 4°C.

The apical end of each tooth was removed, and the roots were mounted with transparent polymethylmethacrylate in cubic brass-holders, with the labial tooth surface standardized in angle and position. The teeth were pumiced for one minute with a low-speed dental handpiece (KAVO blue stripe), rubber cup, and a slurry paste of fine flour pumice and water, then rinsed for 30 sec with tap water. We created a facet of about 1 by 2 mm on the labial-incisal region of each tooth by using a grinding wheel with 1200-grit paper and water, followed by polishing on the same wheel with polishing paper and water. A dedicated gadget was used to ensure that facets on all teeth had the same angle with respect to the brass-holder.

In an additional series of experiments to determine the influence of the enamel layer on the color, a randomly selected subset of 28 of these teeth was used again. Since the original measurements, these teeth had been exposed to an etching treatment (37% phosphoric acid for 20 s) and four cycles of a simulated oral environment (Coops and ten Bosch, 1993) in the course of another study. The teeth were pumiced, the spectra measured, and the color calculated. The enamel was then ground away with a special gadget to ensure parallelism with the anatomical surface, and the spectra were measured again.

Measurements. Dedicated devices were used to ensure that color measurements and scattering measurements were done at the same (within 0.5 mm) central position of the crown and at the same angle, and to ensure that the hardness diamond was perpendicular to the facet.

Color

The entire tooth was illuminated under 45° from the cervical side with a standard illuminant. The light emerging under 0° from a 2 x 0.5 mm^2 area (mesio-distal and cervical-incisal) was measured with a spectroradiometer (Photoresearch, PR-703A/M) (Fig. 1a). Spectra were measured for $390 \leq \lambda \leq 730$ nm with 2-nm intervals. Standard white $BaSO_4$ pills (CIE, 1977) were measured before and after each series of measurements for calibration of the spectroradiometer. Two series of measurements were done: one with a source strongly resembling the standard illuminant D65 (≈ daylight), and one with standard illuminant A (= incandescent lamp). The D65-resembling source consisted of a Xenon arc (Osram XBO 450W) and a blue filter (Schott, FG6, 1 mm thick). A spectrum is given by Wijszecki (1970) in his Fig. 4. For every tooth, we checked whether glossy speckles were present in the area of measurement. This occurred rarely, but when it did, the tooth holder was moved slightly (a few tenths of a mm) in the socket attached to the optical bench.

The teeth were kept moist until placed in the socket. The measurement of a single tooth took < 1 min. Within a series with one illuminant, the error due to instrument errors and variations in tooth repositioning was below 1%, and between the two series with the two illuminants, the error was about 2%, probably due to inadequately equal angles of illumination.

From each spectrum, color coordinates in the CIE L*a*b* color system (*e.g.*, Hunter, 1975; Billmeyer and Saltzman, 1981) were calculated for a 2° Standard Observer.

Scattering

We used two scattering instruments. The scattering meter for bulk materials (ten Bosch *et al.*, 1984) has a 45°/0° geometry (Fig. 1b), *i.e.*, two small light beams illuminate the sample under 45°. Light returned from the illuminated area (≈ 0.3 mm diam.) is collected perpendicularly to the surface. Thus, light that penetrates for more than, say, 0.5 mm and then is multiply scattered to emerge at the surface will do so outside the area and aperture of collection of the collection fiber and will not be measured. As a result, for any material, the depth of measurement is about 0.5 mm. White light is used. The measured scattering coefficient for fluxes is written S_A and is in mm^{-1}. The optical caries meter (Brinkman *et al.*, 1988; Angmar-Månsson and ten Bosch, 1987) uses parallel fibers for illumination and measurement (0°/0° geometry) (Fig. 1c). Because of this parallelism, light that is superficially unscattered, but reflected by a deep layer, is also collected. Thus, the depth of measurement is dependent upon the material investigated. For a tooth, this implies that dentin scattering contributes much to S_C, the measured scattering coefficient. Monochromatic light is used ($\lambda = 560$ nm).

The teeth were under water; the measured area was the same as for the reflection spectrum. The back-scattered light flux was recorded on paper and later converted to S_A or S_C, respectively. Both meters were calibrated to black (zero) and four shades of ABS white plastic (Borsboom and ten Bosch, 1983).

Knoop Hardness Number

For each facet on each tooth, four indentations were made with a Knoop diamond in a Leitz hardness measurement apparatus (type 301.252.001) and a load of 500 g. The indentations were made parallel to the tooth axis and photographed under an Olympus light

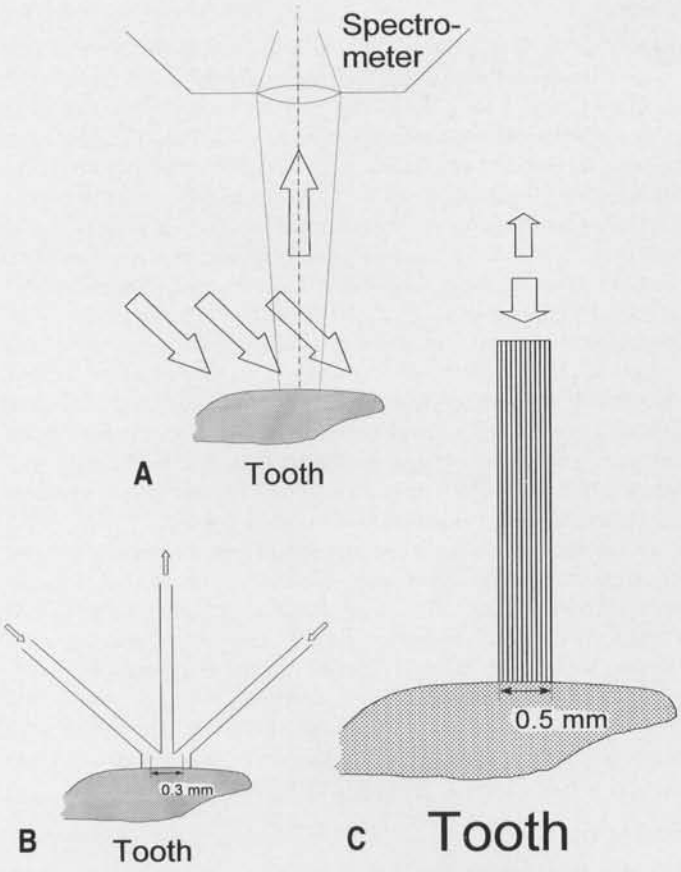

Figure 1. Optical geometries for the three measurements. (a) Spectral measurement with the spectroradiometer: illumination of the entire tooth under 45° from the cervical side and measurement from a 2 x 0.5 mm² area under 0°. (b) Measurement of the scattering coefficient S_A with the scattering meter for bulk materials: fiber-optic illumination of a 0.3-mm-diameter area from two sides under 45° and measurement from the same area under 0°. (c) Measurement of the scattering coefficient S_C with the optical caries meter: illumination of a 0.5-mm-diameter area under 0° with a bundle of optical fibers, measurement of light back-scattered from the same area under 0° with other fibers in the same bundle.

microscope with an Olympus camera with an M plan 10 N objective on Kodak Tmax 100 film. After being developed, the negatives were magnified (1 cm = 50 µm) with a Leitz Focomat, projected on millimeter paper, and measured. Calibration was done by means of the micrometer of the hardness tester. The average indentation length was used to calculate KHN in kg/mm² from the formula:

$$KHN = \frac{14230 \bullet (\text{load in g})}{(\text{indent. length in } \mu m)^2}$$

Statistical evaluation. Spectra were subtracted, averaged, etc., with dedicated Turbo Pascal programs. Numerical data were evaluated with the package BioMedical Data Processing (BMPD, 1985). Modules 3D, 6D, 7D, and 3R were used.

Results

Fig. 2 shows seven randomly chosen reflection spectra, and Fig. 3 the averaged spectrum. Averaging of the subtraction spectra of

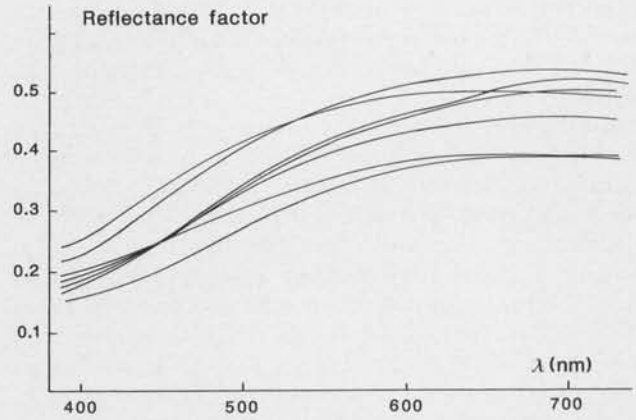

Figure 2. Spectra of seven randomly chosen teeth.

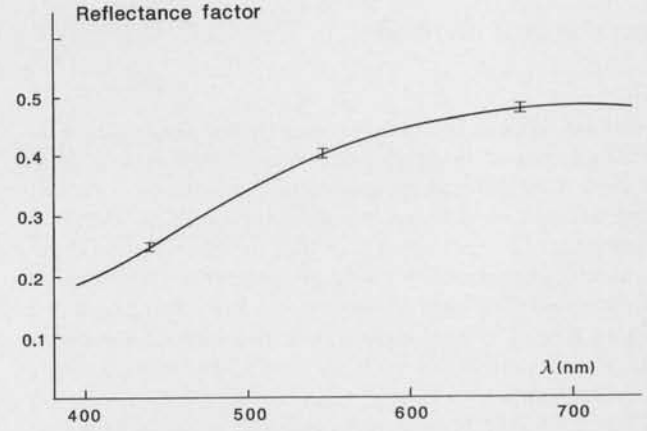

Figure 3. The average reflection spectrum of all 102 teeth. Bars indicate standard error at a few wavelengths.

each tooth (*i.e.*, the spectrum obtained with Illuminant A subtracted at each wavelength from the spectrum obtained with Illuminant D65) revealed no illuminant influence, *i.e.*, this influence was less than 1% reflectance. When the color difference, $\triangle E$, between the two illuminants was calculated and averaged for each tooth, $\triangle E = 0.93$, s.d. = 0.68 was found.

Table 1 gives the numerical data obtained. Since linear dependence seemed adequate, all correlation coefficients are product-moment correlations.

Fig. 4 shows the scatter plot of lightness L* against the enamel-scattering coefficient S_A. Since a non-linear dependence might decrease residual variation, a few such dependencies were tried, but the residue did not decrease. Therefore, in this case, a linear regression is also shown. All other pairs of quantities were also checked for non-linear dependencies, but none was apparent.

The most important results from the additional series of experiments are shown in Figs. 5-7. Since the abscissa and the ordinate are both independent coordinates, the regression lines are the bisectors of the regression of x *vs.* y and of y *vs.* x.

Discussion

This study used teeth extracted either because of decay in

Table 1. Average values, SD, and correlations

Quantity	Scattering Coefficients		CIELAB Color Coordinates			Hardness
	45°/0° geom. (S_A)(mm^{-1})	0°/0° geom. (S_C)(mm^{-1})	(L*)	(a*)	(b*)	(KHN)(kg/mm^2)
Average	0.60	0.59	69.9	-0.22	17.9	271
SD	0.43	0.48	4.1	1.4	2.9	39
Correlations						
S_C(mm^{-1})	0.60 (0.46-0.71)					
L*	0.46 (0.29-0.60)	0.23 (0.04-0.43)				
a*	-0.08	0.00	-0.51 (-0.37-0.76)			
b*	0.12	-0.15	0.15	0.25 (0.06-0.43)		
KHN(kg/mm^2)	0.10	0.07	0.17	-0.14	-0.05	

In parentheses are the 95% confidence intervals of those correlation coefficients that are significant at the 5% level.

the dentition or for periodontal reasons. Vital teeth may have different colors, but differences will not be large (Goodkind and Schwabacher, 1987). A comparison of the spectra found in this study with the spectra of vital teeth as found in a similar illumination-measurement geometry (MacEntee and Lakowski, 1981) shows good agreement. The average reflection spectrum in this study (Fig. 3) is in the red, somewhat lower than the average spectrum shown by MacEntee and Lakowski (1981). We ascribe this to a role of the gingiva, as did Goodkind and Schwabacher (1987), who reported that vital teeth were more red than extracted teeth and that the cervical part was more red than the central part. The latter observation was also reported by Ishiwata (1986) and Kobayashi (1988).

Table 2 gives the L*a*b* data found by others and in this work. Several points are noteworthy. The radiospec-

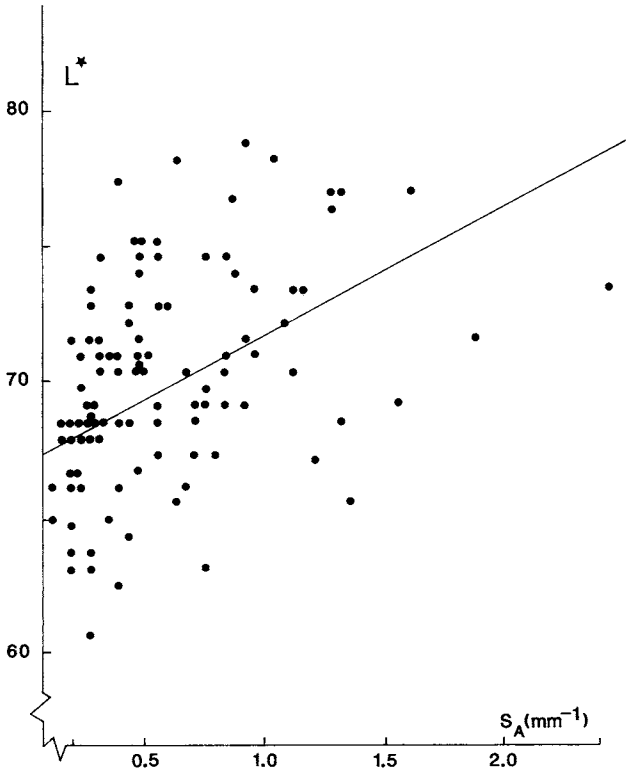

Figure 4. Scatter plot of lightness L* *vs.* the scattering coefficient of enamel, S_A.

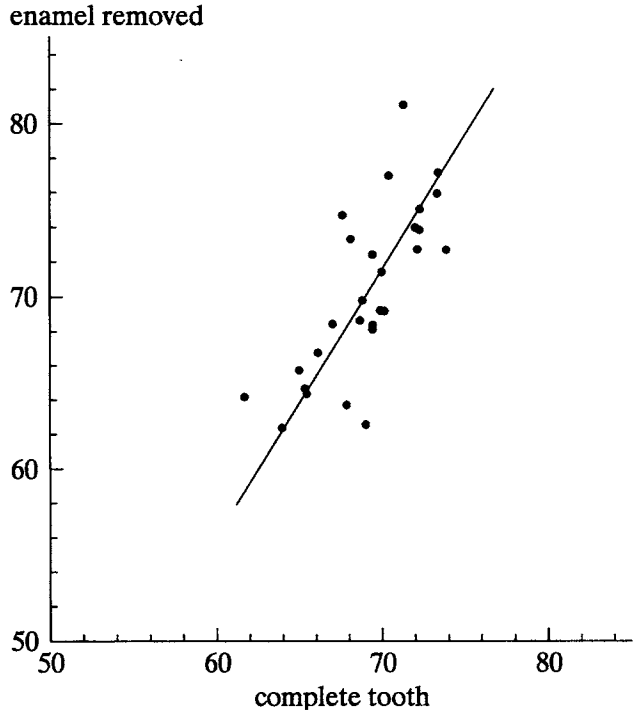

Figure 5. Scatter plot of lightness L* of 28 complete teeth with the lightness L* of these teeth after removal of the labial enamel. The regression line is the average between the regression lines of x *vs.* y and y *vs.* x, r = 0.75.

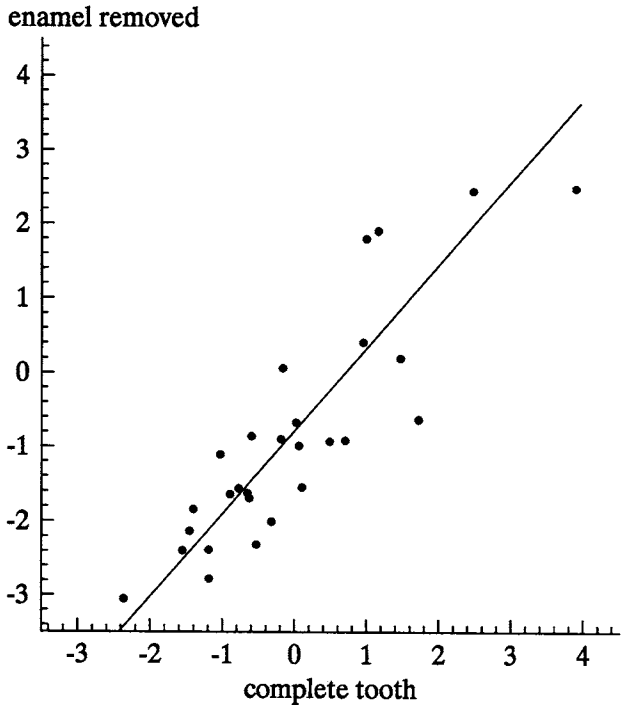

Figure 6. As in Fig. 4 except for the red-green color coordinate a*, r = 0.87.

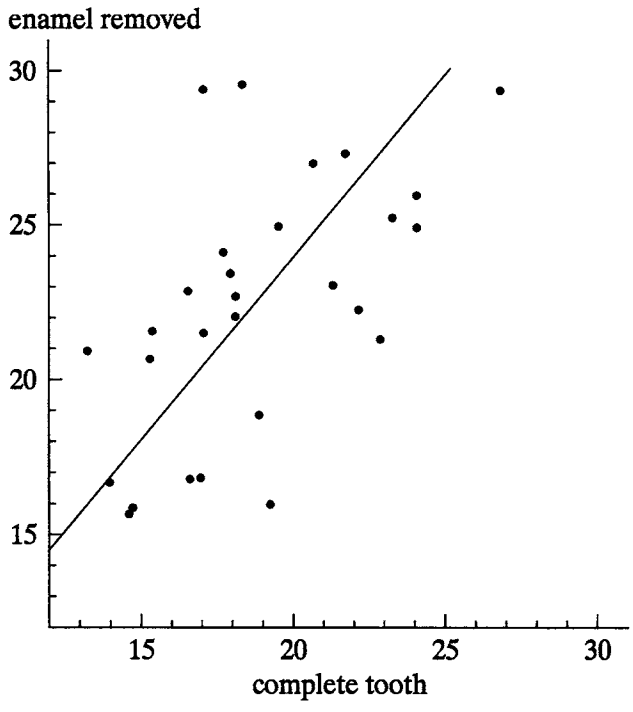

Figure 7. As in Fig. 4, except for the yellow-blue color coordinate b*, r = 0.57.

troscopically obtained L*- and b*-values reported by Ishiwata (1986) correspond very well with our data. In contrast, the L*- and b*-values obtained by Rosenstiel *et al.* (1991) with a small-area spectrophotometer are significantly lower. The difference in L*-values is due to edge-loss of light that diffuses through the tooth and emerges at the surface outside the area of measurement. The difference in b*-values is probably due to a wavelength-dependence of this edge-loss. Further, our a*-values are about the same as those of Rosenstiel *et al.* (1991). Both are much lower than those of Ishiwata (1986), which we ascribe to the use of extracted teeth. This is also in agreement with the report by Goodkind and Schwabacher (1987) cited above.

Illuminant D65 contains a rather strong emission in the near-ultraviolet; Ill. A does not (Billmeyer and Saltzman, 1981). A substantial contribution of tooth fluorescence is excited in the blue and near-ultraviolet (Spitzer and ten Bosch, 1976; Sundström *et al.*, 1985), and would therefore appear in our subtraction spectrum as a color difference. Since $\triangle E \approx 1$, it is concluded that, under everyday lighting conditions, fluorescence does not contribute measurably to visually observed tooth color (Johnston and Kao, 1989).

Scattering coefficients, determined with either instrument (Table 1), are somewhat lower than S_A-values ≈ 1 mm^{-1} which were reported by Borsboom and ten Bosch (1983) for bovine teeth and about equal to S_C-values ≈ 0.7 mm^{-1} for human teeth, reported by Brinkman *et al.* (1988). Since 1/S is of the order of the mean length of a photon path needed for a 90° change in direction, these values imply that the average length of light path in the tooth will be on the order of 3 mm, and that the average distance between point of entrance of light and point of exit, measured along the tooth surface, will be of the order of 1 to 2 mm, confirmed by observation (ten Bosch *et al.*, 1993). Such distances are not short compared with tooth size and certainly not compared with a measuring window or an optical fiber with a diameter of only a few mm, as are used in color measuring instruments that might otherwise be suitable for determination of tooth color.

The Knoop Hardness Number found in this study, 271 kg/m^2 (S.E. 4 kg/m^2), is significantly lower than that found previously for slightly abraded and polished premolars (Purdell-Lewis *et al.*, 1976), KHN = 345 kg/mm^2, and by Arends *et al.* (1980), KHN = 316 kg/mm^2. Our lower value might be due to differences in type and age of teeth. Since KHN correlated only very weakly with any optical quantity, these discrepancies were not further investigated. These weak correlations, the highest one having a significance of $p = 0.03$, were unexpected. In particular, we anticipated a significant correlation with scattering: The less porous the enamel, the higher the hardness and the lower the scattering may be expected to be. This expectation was not confirmed, $p = 0.14$. Previously, the Vickers hardness number (VHN) of translucent (low scattering) enamel of three macropod species was shown to be about 25% higher than the VHN of opaque (strongly scattering) enamel in the same tooth (Palarama *et al.*, 1984). Further examination of the correlation (Table 1) shows that the L*-value is weakly but significantly ($p < 0.001$) correlated with the a*-value: The lighter the tooth, the more greenish.

Finally, the measurements of the two scattering instruments correlate far from ideally—r = 0.6—implying

Table 2. Comparison of CIELAB color data with those of other workers (D_{65} illumination, central part of central upper incisor)

	Number of Teeth	CIELAB Coordinates with SD					
Radiospectrophotometry	(N)	(L*)	SD	(a*)	SD	(b*)	SD
This work (extracted)	102	69.9	4.1	-0.22	1.4	17.9	2.9
Ishiwata (1986)							
(19-28 yr) (*in vivo*)[a]	40	74.3	4.9	2.5	1.1	16.6	3.0
(30-49 yr) (*in vivo*)	23	67.5	4.6	4.1	2.3	18.4	3.4
(> 50 yr) (*in vivo*)	20	65.0	3.0	6.3	2.8	20.1	3.6
Fixed-window color meter (3 mm)	N	L*	SD	a[a]	SD	b[a]	SD
Rosenstiel *et al.* (1991) (extracted)	24	52.5	3.8	-0.7	2.0	5.2	2.3

[a] As reported by Kobayashi (1988).

that they determine different although related quantities. This can be ascribed to the different light-beam geometries and corresponding depths of measurement: S_A relates to the enamel only; S_C relates to the dentin as well. The relation S_A to the lightness L* is weakly positive: The more the enamel scatters, the lighter the tooth. This correlation indicates that enamel scattering does play a role in determining lightness. The regression is not very steep, however: $S_A = 0$ gives L* = 67.2, while $S_A = 2$ mm^{-1}, about the maximum, would give L* = 76.1. Thus, enamel scattering does not contribute much to lightness, as confirmed by additional experiments with 28 teeth. The colors of the teeth before and after removal of the labial enamel correlate surprisingly well: 0.79 for L*, and 0.82 for a*. For b*, r = 0.56, indicating that, on the yellow-blue axis, the influence of enamel is most important. Also, enamel removal causes a decrease of a*, *i.e.*, a green shift, and an increase of b*, *i.e.*, a yellow shift. The predominant cause for this will be the scattering in the enamel, which is much stronger at wavelengths in the blue range than at higher wavelengths (Spitzer and ten Bosch, 1975). Since enamel absorption is small (Spitzer and ten Bosch, 1975), these data indicate that tooth color is almost entirely determined by the dentin properties.

In conclusion, this study indicates that tooth color is predominantly determined by the properties of the dentin. Enamel contributes through scattering at wavelengths in the blue range. A weak correlation exists between tooth greenness and lightness, and only a very slight correlation of color with microhardness of enamel. Fluorescence plays no role in tooth color.

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