Journal of
Biomedical Optics

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Journal of Biomedical Optics 20(4), 045002 (April 2015)

Translucency of human teeth and dental restorative materials and its clinical relevance

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Abstract. The purpose was to review the translucency of human teeth and related dental materials that should be considered for the development of esthetic restorative materials. Translucency is the relative amount of light transmission or diffuse reflection from a substrate surface through a turbid medium. Translucency influences the masking ability, color blending effect, and the degree of light curing through these materials. Regarding the translucency indices, transmission coefficient, translucency parameter, and contrast ratio have been used, and correlations among these indices were confirmed. Translucency of human enamel and dentine increases in direct proportion to the wavelength of incident light in the visible light range. As for the translucency changes by aging, limited differences were reported in human dentine, while those for enamel proved to increase. There have been studies for the adjustment of translucency in dental esthetic restorative materials; the size and amount of filler and the kind of resin matrix were modified in resin composites, and the kind of ingredient and the degree of crystallization were modified in ceramics. Based on the translucency properties of human enamel and dentine, those of replacing restorative materials should be optimized for successful esthetic rehabilitation. Biomimetic simulation of the natural tooth microstructure might be a promising method. [DOI: 10.1117/1.JBO.20.4.045002]

Keywords: translucency; tooth; esthetic restorative material; scattering; tooth microstructure.

Paper 150079RR received Feb. 9, 2015; accepted for publication Mar. 24, 2015; published online Apr. 15, 2015.

1 Introduction

The following subjects related to the translucency of human teeth and substituting restorative materials were considered based on peer-reviewed papers: (1) clinical relevance and significance of translucency in teeth and dental restorative materials, (2) varied measurement methods for translucency, (3) influence of tooth microstructure on translucency, (4) normal and age-dependent translucency of human teeth, and (5) control of translucency in restorative materials. The purpose was to review the translucency of human teeth and related materials that should be considered for the development of biomimetic esthetic restorative materials.

2 Clinical Relevance of Translucency in Dentistry

2.1 *Significance and Definition of Translucency*

The clinical significance of the translucency of human teeth and dental esthetic restorative materials was reconsidered. A successful dental prosthesis or restoration should fulfill esthetic, masticatory, and phonetic requirements.[1] When selecting esthetic restorative materials, there are several major factors to consider such as color, translucency, and strength.[2] With respect to the color and translucency, a number of optical properties have been investigated to understand the appearance of dental tissues and substituting restorations, and clinical application of these results improved the esthetic performance of dental restorations.[3]

The color and appearance of a tooth is a complex phenomenon, with many factors such as lighting conditions, translucency, opacity, light scattering, gloss, and the human eye and brain influencing the overall perception of tooth color.[1] The color of tooth and dental restorations is determined by the effect of underlying substances, which indicates that the apparent color is the result of diffuse reflectance from the inner dentine or opaque material layer through the outer translucent layer.[4] In addition to three primary color attributes such as lightness, hue, and chroma, many other optical properties of tooth, such as translucency, opacity, opalescence, surface gloss and fluorescence, should be considered. Translucency has been reported to be the most important following the primary color attributes[5] and is also one of the fundamental factors influencing the esthetic performance of dental restorations.[6,7] Translucency was used to describe the optical properties of dental resin composites, ceramics, prosthetic elastomers, fiber posts, orthodontic brackets, natural tooth dentine and enamel, and combinations of materials.[8]

Translucency is the relative amount of light transmission or diffuse reflection from a substrate surface through a turbid medium.[9] While the term translucency is used to describe the optical property, the corresponding word transmission is a physical term which represents the ability of a medium to permit light to pass through it.[6] For a successful esthetic restoration of discolored tooth or "through and through" class III and IV tooth cavities with resin composites, the translucency should be

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considered.[10] It was also reported that one of the main objectives in the contemporary development of dental resin composites was improving their optical properties to reproduce the original shape, color, and translucency of tooth.[11] The esthetic performances of glass ionomer, resin-modified glass ionomer, and compomer seriously deteriorated during clinical service, mainly because of changes in translucency and opacity.[12] Even the color difference detection performance of an intraoral colorimeter varied depending on the translucency of the materials.[13]

2.2 *Impacts of Translucency in Restorative Materials*

There are several clinical impacts of the translucency in esthetic restorative materials, such as the influences on the masking ability, the color blending effect of restorations, and the influence on the degree of light curing through these materials. Regarding the influence on the masking ability, the final esthetic outcome of an all-ceramic restoration was affected by the abutment color if the thickness of a restoration was <1.5 mm, but was not affected when the thickness was >2.0 mm.[14] Therefore, it was advised to take the substrate aspects into consideration when the ceramic thickness decreased to 1.5 mm. The effect of the translucency of resin composites and ceramics and the abutment color on the final appearance of crowns was also determined.[15] The results indicated that some materials could not reproduce the target color satisfactorily when the abutment color was darker than the target color. The optical influence of core build-up resin composites on the final color of ceramic-composite combinations was evaluated.[16] For this, the color difference ($\Delta E*_{ab}$) of ceramic-composite combinations to the referenced shade guide tabs was analyzed. As a result, color difference values were significantly associated with the translucency. The Commission Internationale de l'Eclairage (CIE) color difference was calculated with the equation: $\Delta E*_{ab} = (\Delta L*^2 + \Delta a*^2 + \Delta b*^2)^{1/2}$.[17]

Color differences between teeth and adjacent esthetic restorations are perceived as smaller than those viewed in isolation.[18] This phenomenon is frequently described as the chameleon effect, and the related color science terms are color induction, color assimilation, and color blending.[19] The color blending effect of dental esthetic materials refers to the inter-relation of these materials or materials and hard dental tissues, manifested by a smaller color difference when they were observed together than when viewed in isolation, thus improving esthetics.[20] With respect to the influence of translucency on the color blending effect, color blending using resin composite translucency to show through the underlying and surrounding tooth structure achieved improved color matching and color transition from tooth structure to a restoration.[18,19] Discovering and quantifying the mechanism for the color change in dental materials toward the color of surrounding teeth (=color shift) might improve the esthetics of restorations and simplify the shade matching procedure.[19] Therefore, the influence of translucency on the blending effect of resin composites was evaluated,[20] which concluded that the blending effect increased with an increase of the translucency, and was dependent on the kind of composite and shade. The color adjustment potential of resin composites originating from the physical translucency of these materials was explored and the existence of the physical component of color adjustment of translucent dental materials was proved.[21] Color adjustment potential is an equation for quantification of the color shift toward the surrounding shade, in which the physical component of blending can be quantified as the ratio of color difference values between two objects observed under two conditions: one surrounded with another and compared in isolation. Color adjustment potential was dependent on the kind of composite and shade.[21]

With respect to the influence of translucency in dental restorative materials on the degree of light curing through these materials, the amount of light passing through ceramics is an important aspect for an adhesive cementation, since many dual-cured luting materials reveal a high sensitivity to the additional occurrence of blue light. The amount of light passing through zirconia was evaluated with respect to material thickness, exposure distance, and different curing modes.[22] The results advised that the use of dual-cured cements with less light sensitivity was recommended for restorations thicker than 1.5 mm in light shaded zirconia and 0.5 mm in darker shaded zirconia. The degree of monomer conversion in varied resin cement shades was evaluated when light cured through varied feldspathic ceramic shades.[23] As a result, the transmission percentages of ceramics, based on the shade, were 12.4%, 5.8%, and 1.1%, respectively.

3 Measurement of Translucency

3.1 *Indices for Translucency*

A method for the specification of the translucency of teeth and esthetic materials may be based on clinical appearance requirements of the patient, on technical demands for optimizing the curing of the underlying material through these materials, or on both.[8] Indices for the quantification of the translucency vary by viewpoint and/or measurement method. Varied indices have been used in literature to describe the translucency, making it difficult for researchers and clinicians to find universal and definite information on the translucency.[24] There are several methods to measure the translucency based on various basic colorimetric concepts. However, there are currently no guidelines regarding which method to use to describe the translucency in dentistry.[8] As the indices for the translucency, total or direct transmission coefficient (t_c), translucency parameter (TP), and contrast ratio (CR) have been generally used. The transmission coefficient and CR indices each have the possibility of being either luminous or spectral.[8] Measurements using the instruments spectrophotometer,[9,25] colorimeter,[26] spectroradiometer,[27] and digital camera and software[28] were reported. Concerning the influence of thickness on the translucency, the use of more-developed models that relate the thickness of the materials to the translucency index was encouraged.[8]

With respect to the total transmission coefficient, this is measured using a spectrophotometer with an integrating sphere that includes the scattered light. Translucency can be expressed as the relative amount of light passing through the unit thickness of a material.[29] TP is obtained by calculating the color difference between the specimen over a white standard and the specimen over a black standard: $\mathrm{TP} = [(L_W* - L_B*)^2 + (a_W* - a_B*)^2 + (b_W* - b_B*)^2]^{1/2}$, where the subscript W refers to the CIE color coordinates over a white background and the subscript B refers to those over a black background.[30] CR is the ratio between the daylight apparent reflectance (Y) of a specimen (typically 1-mm thick) when backed by a black standard (Y_b) and its reflectance when backed by a white standard (Y_w). The equation for CR is defined as $\mathrm{CR} = Y_b/Y_w$. The CR value of a perfectly transparent material is 0, while the value of a completely opaque material is 1.[3,31]

3.2 *Correlations Between Translucency Indices*

With respect to the correlations among the translucency indices, the CR and TP values of resin composites and an all-ceramic material were compared.[32] As a result, CR increased in inverse proportion to TP (correlation coefficient: $r = -0.93$). Mean CR values of human and bovine enamel and dentine were negatively correlated with TP values ($r = -0.93$ to -0.78).[33] The correlation between CR and TP was assessed when the translucency of different types of ceramic systems was compared, and a significant correlation between CR and TP was found ($r = -0.99$).[24]

Translucency of different types and shade categories of resin composites was compared using TP and light transmittance ($\%T$), and the correlation was also determined.[34] As a result, TP and $\%T$ were positively correlated ($r = 0.63$). Translucency of dental ceramics was determined by direct transmission and total transmission methods at a wavelength range of 400 to 700 nm.[9] For 1 mm of ceramics, the values for direct transmission averaged 0.13%, whereas the values for total transmission averaged 26.8%. Light transmission increased with increasing incident wavelength, which indicated a high degree of light scattering.

3.3 *Factors Influencing Translucency Values*

With respect to the factors that influence the translucency values, the significance of surface condition and water content of specimens and of the illumination was reported.[29,35–37] Since surface finishing procedures have a mechanical impact on ceramic surfaces, these procedures could eventually affect surface topography and light scattering. The effects of different surface finishing procedures on the translucency of ceramic restorations were determined.[36] As a result, surface finishing significantly affected the translucency. The effect of prophylactic polishing pastes on the translucency of lithium disilicate ceramic was evaluated,[37] and it was concluded that prophylactic pastes produced a reduction in translucency. In addition to the influence of the surface condition, underlying layer materials influenced the translucency of esthetic restorations.[4] Resin composites placed in layers reduced the straight-line light transmission compared with a bulk-filled resin composite.[38]

With respect to the influence of the water content of specimens on the translucency of teeth, conflicting reports were found.[29,35] Between 5 min and 48 h after human enamel specimens were taken out of the water, there was no influence of water content on the total reflectance and transmission.[29] However, it was reported that the transmission coefficient decreased after dehydration and was reversed on rehydration, which was due to the result of the replacement of water around the enamel prisms by air during dehydration.[35] Further research is recommended.

With respect to the influence of illumination, it was reported that the translucency changes of tooth enamel due to illumination altered the overall color of teeth.[4] Differences in TP values by the illuminants (CIE standard illuminant D65, A, and F2) and the correlations between the differences in TP (ΔTP) and color ($\Delta E*_{ab}$) by the illuminants in porcelain and porcelain repairing resin composites were determined.[39] As a result, TP values were influenced by the illuminant, and TP values relative to the illuminants A and F2 were higher than those relative to the D65. The correlation between CR and three TP values relative to the three illuminants was high ($r = -0.95$). Color changes by illuminant were positively correlated with the difference in translucency in resin composites ($r = 0.47$ to 0.65) but were negatively correlated in porcelain ($r = -0.69$ to -0.37). Therefore, changes in translucency by illumination should be considered when matching shades of different materials.

3.4 *Physical Meaning of Translucency*

The physical meaning of translucency indices and perception of translucency has been studied to provide visual assessment criteria which are essential for the clinical application of this property. The relationship between instrumental measurements and subjective visual assessment of differences in dental ceramic translucency (translucency perception threshold, TPT) was determined using the difference in contrast ratio (ΔCR) value.[31] The overall mean TPT was 0.07 ΔCR. ΔCR greater than 0.06 might be perceived by 50% of the participants. Neither viewing condition nor ceramic opacity affected the perceived translucency threshold. As for the perception of translucency, although translucent materials involve complex optics such as subsurface scattering and refraction, humans can easily distinguish them from opaque materials. The spatial and contrast relationship between specular highlights and nonspecular shading patterns is a robust cue for the perceived translucency.[40] Humans are able to estimate translucency in a consistent way across different shapes and lighting conditions to some extent, i.e., to exhibit translucency constancy. However, humans show significant failures of translucency constancy across changes in lighting direction.[7]

4 Influence of Tooth Microstructure on Translucency

4.1 *Whole Tooth and Enamel*

The optical properties of human tooth are basically determined by the microstructure. Knowledge of the optical properties of tooth and an understanding of the origin of these properties are necessary for the development of new optical methods for the measurement of tooth color and caries diagnosis[41] and also for the development of biomimetic restorative materials. Human tooth color is determined by the paths of lights inside the tooth and absorption along these paths. Light scattering by both enamel and dentine of extracted whole incisors was measured.[42] As a result, scattering coefficients [μ(s)] averaged to 0.6 (± 0.4) mm^{-1}, and the lightness of tooth (CIE $L*$) correlated with the enamel scattering coefficient. A model containing scattering by crystals and by prisms of enamel was presented in which the prisms were the most important scatterers, but the crystals were responsible for the back scattering.[41] Angularly resolved scattering distributions of enamel and dentine were measured from 0 to 180 deg using a rotating goniometer.[43] As a result, enamel weakly scattered lights with the scattering coefficient ranging from 15 to 105 cm^{-1}, while the absorption was negligible in enamel. Dentine scattered strongly in the visible and near-IR light [$\mu(\mathrm{s}) = 260$ cm^{-1}] and absorbed weakly.

4.2 *Dentine*

Human dentine is a hierarchical mineralized tissue with a two-level composite structure, with dentinal tubules being the prominent structural feature at a microlevel, and collagen fibers decorated with hydroxyapatite crystallite platelets dominating the nanoscale.[44] Therefore, light propagation and scattering in dentine is affected not only by the tubule volume fraction but also by the shape and orientation distribution of mineral crystallites. Properties of dentine are largely determined by the intertubular dentin matrix, which is a complex composite of type I collagen fibers and a carbonate-rich apatite mineral phase. These mineralized fibers were perpendicular to the dentinal tubules and parallel with the mineralization growth front.[45] Dentine contains mineral platelets that are embedded in a collagen fiber mesh. Most of the mineral particles are randomly orientated with about 20% having a preferred orientation that is parallel to the plane of the dentinoenamel junction.[46]

A theoretical model for the scattering of light by dentine was presented.[47] The model was a superposition of several scattering contributions, i.e., scattering by mineral crystals, collagen fibrils, and dentinal tubules. The tubules were oriented so that they cause an asymmetrical scattering process. Dependence of light propagation in dentine on its microstructure was investigated.[48] As a result, the main scatterers in dentine were the tubules, the shape of which can be approximated as long cylinders. Optical properties of enamel and dentine in relationship to the structural orientation of enamel prisms and dentinal tubules were investigated by optical coherence tomography (OCT).[49] Discs of 300- to 400-μm thickness including enamel with cross-cut or long-cut prisms and mid-coronal dentine with cross-cut, long-cut or oblique-cut tubules were investigated. As a result, in dentine, there was a significant difference among different regions. Unlike enamel, refractive index and OCT signal patterns in dentine varied according to structural orientation, with dentinal tubules responsible for the variations.

4.3 *Tooth Microstructure and Caries Diagnosis*

Techniques based on transillumination of tooth with visible light would be a valuable aid in caries diagnosis. The intensities emanating from the surfaces of enamel and dentine bars were measured when these bars were illuminated ($\lambda = 633$ nm). It was concluded that the optical anisotropy supported the idea that dentinal tubules were the predominant cause of scattering in dentine, and hydroxyapatite crystals contributed significantly to scattering in enamel.[50] Near-IR imaging methods do not require ionizing radiation and have great potential for detecting caries lesions.[51] An understanding of how near-IR light propagates through sound and carious dental hard tissues is essential for the development of optical diagnostic systems, since image contrast is based on changes in the optical properties of these tissues on demineralization. The scattering coefficient increased exponentially with increasing mineral loss.[52] It was determined that near-IR wavelengths between 1200 and 1600 nm provided the highest contrast of demineralization or caries lesions in tooth. As a result, a significantly higher contrast was attained for reflectance measurements at wavelengths that have higher water absorption.[51] The reflectance from tooth occlusal surfaces with demineralization and transmitted light through tooth thin sections with caries lesions were investigated. This study suggested that polarization resolved optical imaging could be exploited to obtain higher contrast images of dental caries.[53]

5 Translucency of Human Teeth and Age-Dependent Changes

Ranges for the human teeth translucency and age-dependent translucency changes in enamel and dentine were put together in this section. Translucency changes by tooth bleaching were also reviewed.

5.1 *Translucency Ranges of Teeth*

Translucency of teeth should be the referenced standard in the assessment of the translucency of dental restorative materials and appliances. However, care must be taken when comparing previously generated translucency indices with any other values because technical details of the thickness and the backings used in previous studies must be matched or adjustments must be made to make any newly generated values comparable with previous indices.[8]

Due to difficulties in the measurement of the clinically relevant translucency of human teeth, limited reports are available.[6] Translucency of human central incisors was measured each 1.0 mm in diameter at five sites, and the differences between teeth and commercial shade guide tabs were clarified.[27] Translucency decreased from the incisal to cervical, and the TP value of incisal site was around 15, which decreased to around 5 at the cervical site. Translucency of human and bovine enamel and dentine was determined using spectrophotometers.[33] In this study, TP and CR values of tooth enamel and dentine were determined using plasticine as backing because the specimens were not flat (Fig. 1). Mean TP values of 1-mm thick bovine enamel and dentine and human enamel and human dentine were 14.7, 15.2, 18.7, and 16.4, respectively. The translucency of enamel and dentine increased in proportion to the wavelength in the visible range (CR values decreased; correlation coefficient: $r = 0.87$ to 0.91, Fig. 2). These data should be used as references in the development of esthetic restorative materials and clinical shade matching.

The total transmission of enamel increased as the incident light wavelength increased from 400 to 700 nm; therefore, it was confirmed that human tooth enamel was more translucent at higher wavelengths,[35] which was similar to the result based on the spectral CR.[33] Light transmission of maxillary central incisors was measured at nine locations, and the relationship between translucency and anatomic locations was analyzed.[6] As a result, the transmission ranged from 0.13% to 0.65%, and decreased from incisal to cervical. To account for a directional dependence of light fluxes in sound teeth, optical anisotropy was investigated by comparing the transmitted light intensity in directions perpendicular and parallel to the approximal surface of teeth with the light from a HeNe

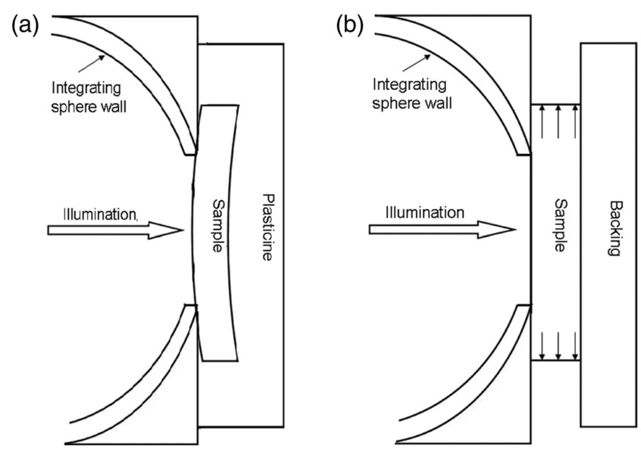

Fig. 1 Diagrams of color measurement of a sample over the aperture of an integrating sphere in different configurations: (a) the sample was embedded in the plasticine; (b) the backing was placed conventionally over the sample, the arrows show possible paths of edge loss.[33]

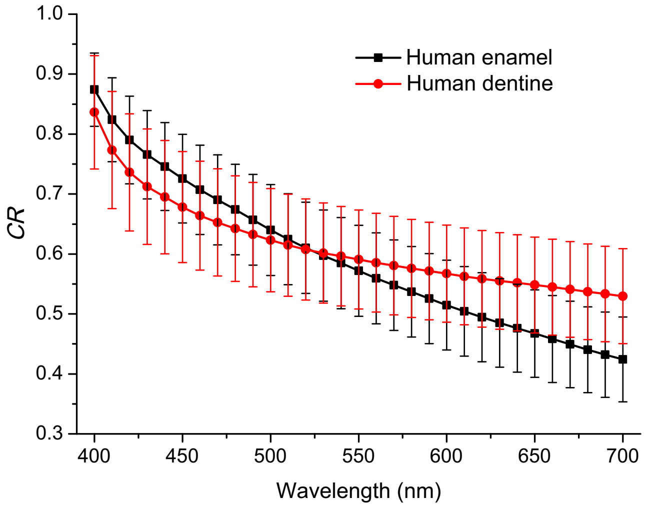

Fig. 2 Wavelength-dependent contrast ratio (CR) of human enamel and human dentine.[33]

laser.[50] The result indicated that the mean ratio of the transmitted intensities in perpendicular and parallel directions was 0.86 for enamel and 2.88 for dentine.

Although direct clinical relevance of the following transmission or absorption values of teeth is limited, these optical properties of teeth at specific wavelengths were determined for analytical purposes. The reflectance and transmission of thin slabs of human enamel were measured between 220 and 700 nm, and an absorption peak at 270 nm was common.[29] Hence, it was concluded that an organic component, presumably aromatic amino acids, was responsible for most or all of the observed optical absorption. The transmission coefficient of human enamel at 525 nm was $0.481\ \text{mm}^{-1}$,[35] and the absorption coefficient of human dentine at 400 to 500 nm was $0.141\ \text{mm}^{-1}$.[54]

5.2 *Translucency Changes by Aging or Bleaching*

The translucency of tooth changes by aging. The primary changes in tooth by aging are the shrinkage of pulp, reduction of blood supply, increase in thickness of dentine and cementum, and reduction of enamel due to abrasion.[55] It has been confirmed that tooth structure changes by aging based on the studies of the changes in hardness and Young's modulus of the transparent layer of dentine.[56] As for the human dentine translucency changes, limited differences were reported, while enamel proved to increase by aging.[57] Aging also affected light transmission in certain locations of tooth crown; older teeth demonstrated higher transmission.[6]

By aging, normal dentine is altered to form what is known as transparent or sclerotic dentine. Dentinal tubules gradually fill up with a mineral phase over time, beginning at the apical end of root and often extending into coronal dentine. Therefore, the transparency of tooth root is caused by the deposit within dentinal tubules of hydroxyapatite crystals.[58] Assessment of age from the dentition constitutes an important step in constructing an identity profile of the decedent. Dentinal translucency is one of the morphohistologic parameters considered best for dental age estimation, not only in terms of accuracy but also for its simplicity.[59]

With respect to the influence of tooth bleaching, changes in enamel translucency during the tooth bleaching procedure were evaluated, and it was observed that the bleaching procedure significantly changed the enamel translucency, making it more opaque.[60] Change in translucency of enamel following treatment with carbamide peroxide was investigated and the translucency of bleached enamel slabs was significantly lower than that of controls.[61]

6 Control of Translucency in Esthetic Materials

There has been research that investigated the adjustments of translucency of esthetic dental restorative materials. In resin composites, the size and amount of fillers and the type of resin matrix were modified. In ceramics, the kind of ingredient and the degree of crystallization were modified. Several of these reports are summarized here.

6.1 *Resin Composite*

Since the translucency property is composed of two parameters (absorption and scattering), this cannot be adequately summarized with one parameter such as transmittance or reflectance.[62] With respect to the direct influence of absorption/scattering coefficients on translucency, since the scattering and absorption characteristics influence the color and translucency of resin composites, the size and volume fraction of fillers should be controlled for the best shade simulation, considering the refractive indices of filler and resin matrix. And also the CIE $L*$, $a*$, and $b*$ values were influenced by TP values.[25]

The influence of filler size and amount on the difference between the transmitted and reflected colors and the translucency of experimental resin composites was determined.[63] LG fillers (median grain size: 0.77 μm) were added by 10 to 70 wt. %, and SG fillers (median grain size: 0.50 μm) were added by 10 to 50 wt. %, and an unfilled resin matrix was used as a reference. The results indicated that TP values decreased as the amount of filler increased when the filler size was the same (Table 1).

With respect to the influence of nanofillers, the translucency of a nanocomposite which contained two types of nanofillers (nanomeric particles and nanoclusters) was measured in comparison with those of conventional resin composites such as hybrid and microfill.[64] As a result, the nanocomposite system showed high translucency similar to those of microfills. Influence of titanium dioxide (TiO_2) nanoparticles (<40 nm) on the translucency of experimental resin composites was also determined.[65] Silane coated glass filler (mean particle size: 1.55 μm) was added in the ratio of 50 wt. %, and TiO_2 nanoparticles were added up to 0.5 wt. %. When the concentration of TiO_2 increased from 0% to 0.5%, the TP value decreased from 35.4 to 13.1 (Fig. 3). The relationship between the photoinitiator system and nanofiller size on the optical properties of experimental resin composites was established.[66] A resin matrix was loaded with 40 wt. % of 7 or 16 nm filler particles and four kinds of photoinitiator systems were used. As a result, the combination of photoinitiator system and filler particle size influenced the CIE color coordinates but did not influence the baseline TP values.

Understanding how the filler orientation in resin composites affects diffuse reflectance of composites would yield insight as to how the orientation of enamel rods affects the diffuse reflectance in teeth by analogy.[62] The translucency of aligned,

Table 1 Translucency parameter (TP) values of experimental resin composites.[63]

Filler (wt. %)	TP
Reference[a]	58.0 (5.3)[b]
LG[c]-10	39.9 (5.3)
LG-20	28.7 (2.7)
LG-30	24.3 (0.9)
LG-40	20.1 (2.6)
LG-50	18.7 (0.8)
LG-70	14.4 (1.7)
PLSD intervals for LG group[d]	1.3
SG[c]-10	45.6 (3.4)
SG-20	39.7 (7.8)
SG-30	27.2 (1.4)
SG-40	20.6 (2.7)
SG-50	23.1 (3.7)
PLSD intervals for SG group	2.1

[a]Reference indicates unfilled resin matrix.
[b]Standard deviations are in parentheses.
[c]LG filler indicates 0.77 μm (d50) and SG filler indicates 0.50 μm (d50).
[d]PLSD interval indicates Fisher's protected least significance difference interval at the level of 0.05.

short-fiber composites was characterized by determining the effects of filler particle orientation on the absorption and scattering coefficients. Composite specimens were filled with very short E-glass fibers, and the fibers were oriented randomly perpendicular and parallel to the surface normal using an alternating electric field.[62] The results indicated that the effects of orientation were different for the absorption and scattering coefficients. Orientation parallel to the average light flux notably decreases the amount of absorption, while perpendicular orientation appreciably increases the amount of scattering.

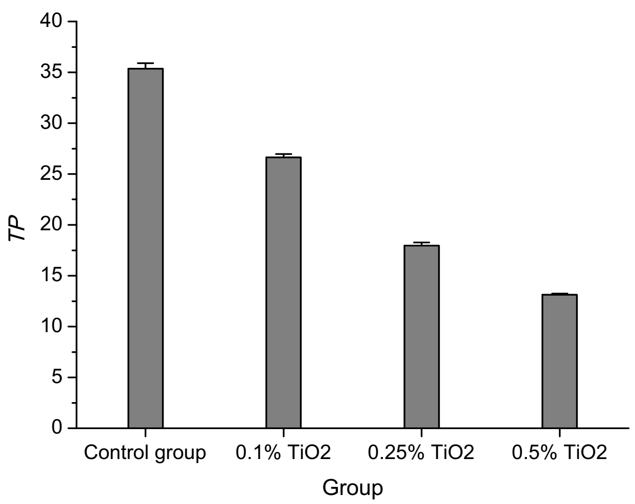

Fig. 3 Translucency parameter (TP) of titanium dioxide nanoparticle (<40 nm)-added resin composites (1-mm thick). Error bars indicate standard deviations.[64]

Light transmission was also related to monomer reactivity and filler/resin refractive index mismatch.[67] With respect to the influence of resin matrix, the influence of the resin matrix composition such as TEGDMA-, UDMA-, and BisGMA-based on the translucency of experimental resin composites with a constant silica filler loading was investigated. Total and diffuse transmission values were measured in the wavelength range of 380 to 700 nm.[68] As a result, there was no statistically significant difference in transmission values between the three unfilled resins. However, with the addition of filler, BisGMA-containing resin composites showed significantly higher transmittance values than the other two resin composites. The amount of BisGMA used in the resin matrix has a significant effect on the translucency of silica filler-containing dental resin composites.

6.2 *Ceramics*

The translucency or opacity of glass ceramics is associated with light scattering at the interfaces between adjacent crystals and between crystals and the glass phase because of differences in refractive indices.[69] The translucency of glass ceramics was highly dependent on the ceramming temperature and/or amount of the crystal phase in the glass matrix. The influence of crystallization on the translucency of castable ceramics containing crystalline apatite and magnesium titanate was measured.[70] As a result, magnesium titanate precipitated during ceramming appeared to be an important factor in decreasing the total transmission. Influence of metals, metal compounds and P_2O_5 as a nucleating agent on the translucency of lithia-based glass ceramic was characterized.[69] The results indicated that, because certain colorants in glass ceramics affect the opacity, development of glass ceramics should be simplified by controlling fixed levels of translucency consistent with mechanical and physical property requirements. In spinel and alumina ceramic veneers, vacuum infiltration with a translucent glass provided increased translucency.[71]

The effect of the number of coloring liquid applications on the translucency of monolithic zirconia was investigated.[72] The results indicated that the translucency was not significantly changed by the coloring procedure. The translucency of six all ceramic materials veneered and glazed at clinically appropriate thicknesses was compared.[73] As a result, the glazing cycle resulted in decreased opacity for all test materials except for the completely opaque ceramic specimens.

7 Conclusions

The translucency of human enamel and dentine increased in direct proportion to the wavelength of light in the visible range. Translucency of human dentine showed limited changes with aging, while enamel proved to increase with aging. Based on the translucency characteristics of human dentine and enamel, those of the replacing esthetic restorative materials for each tissue should be optimized for the best esthetic performance. Since the translucency of esthetic materials influences the masking ability, color blending effect, and the degree of light curing through these materials, optimal translucency ranges that can cover all aspects of the requirements should be decided. As for the indices for translucency, light transmission, TP and CR are generally employed, and the physical meaning of these indices should be further investigated. With respect to the adjustment of translucency of esthetic materials, innovative methods based on biomimetic principles should be tried. Other related subjects such as the range and categorization of translucency of esthetic materials, translucency changes after curing, aging or treatment, and correlation with other physical properties would be reviewed separately.

Acknowledgments

The author declared no conflict of interest.

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