Bio-Emulation: biomimetically emulating nature utilizing a histo-anatomic approach; visual synthesis

Panaghiotis Bazos, DDS
Emulation, Athens, Greece

Pascal Magne, DMD, MSc, PhD
Associate Professor, Don and Sybil Harrington Foundation,
Chair of Esthetic Dentistry, Herman Ostrow School of Dentistry,
University of Southern California, Los Angeles, USA

Correspondence to: Panaghiotis Bazos DDS
33 Vasilissis Sophias Avenue 106 75 Athens, Greece. Tel: +30 210 722 2329; E-mail: p_bazos@mac.com

Abstract

A thorough understanding of the spatial distribution pertaining to the histo-anatomic coronal structures and dynamic light interaction of the natural dentition provides the dental team with the ultimate strategic advantage with regards to optical integration of the final restoration. The second part of this two-part article will attempt to provide insight on the illumination interactivity and the spatial arrangement of the coronal elements of natural teeth through the utilization of this knowledge in the clinical and technical restorative approach.

The main goals for this article are to cognize histo-anatomic visualization by introducing: *(1)* Dynamic light interaction, *(2)* the 9 elements of visual synthesis, *(3)* dynamic infinite optical thickness, and *(4)* amplified visual perception effect of the hard dental tissues. Furthermore, a diversification of photographic illumination techniques will be illustrated in order to juxtapose optical associations between the enamel/dentinoenamel complex/dentin nexus.

(Int J Esthet Dent 2014;9:xxx–xxx)

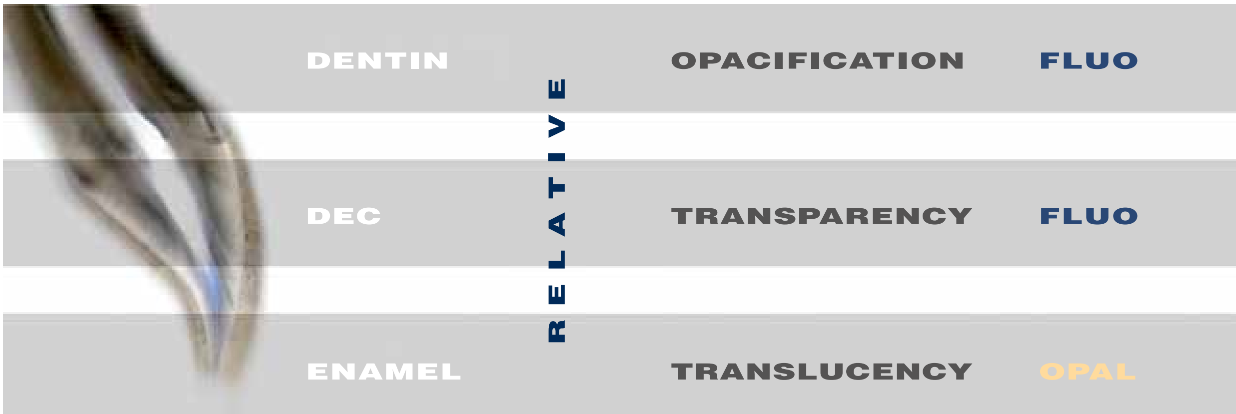


Fig 1 Relative attribution: although translucent by nature, the coronal structural elements can be graded with regards to their relative dynamic light interactivity and unique optical expression.

Introduction

In the modern dental practice, recreating the optical features of the intact tooth presents a formidable task, due to the inherent translucent nature of enamel, the dentinoenamel complex (DEC) and dentin. Translucent materials offer a significant color measurement challenge since they interact with light in a far more complex manner than most other materials.

While being translucent by nature, when coronal structures, such as enamel, the DEC and dentin, are compared among each other, they seem to possess relative translucency, transparency and opacity respectively (Fig 1). Anachronistic traditional visual estimation approaches that solely employ the Munsell color model system based on hue, chroma, and value (H/C/V) dominate the dental market appear to be inadequate when conveying the pertinent information among the dental team members (clinician/technician/patient). Further information regarding the description of surface texture, gloss, and luster (S/G/L) should also be appraised in conjunction with translucency, opalescence and fluorescence (T/O/F) as part of the process of visual assessment (Fig 2).

Dynamic light interaction

Reflection and refraction in enamel and dentin

Incident light ray interactivity with a tooth can be:

- Reflected specularly and/or diffusely from its surface (Fig 3)
- Refracted and either:
  - scattered within it and subsequently reflected, a process largely responsible for color perception (Fig 4)
  - transmitted diffusely through it (relating to the properties of transparency, translucency and opacity) (Fig 5)
  - absorbed within it (the electromagnetic energy is transformed to other forms of energy, eg, heat, photolu-

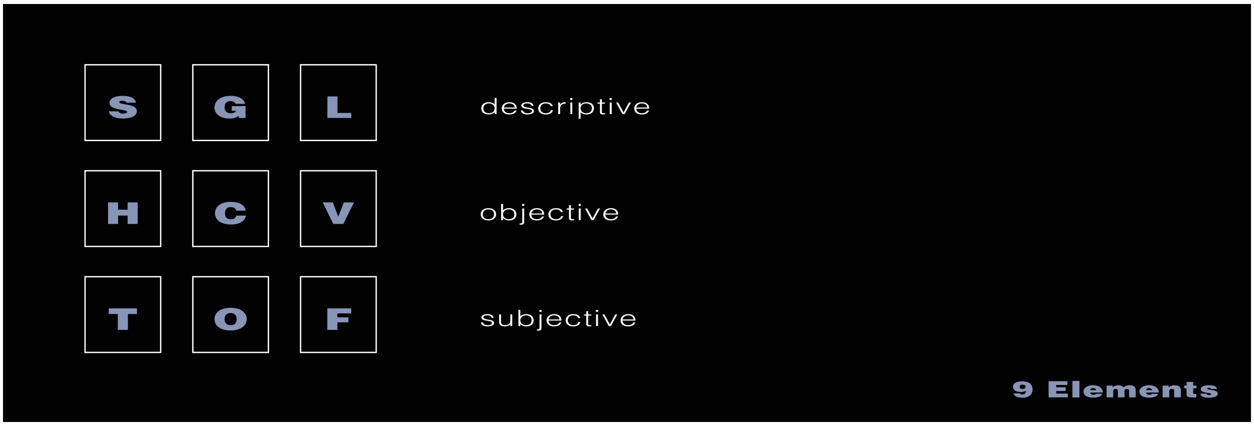


Fig 2 Dynamic light interaction will generate the visual synthesis which is influenced by nine elements: surface texture, gloss and luster (S/G/L); hue, chroma and value (H/C/V) and translucency, opalescence and fluorescence (T/O/F).

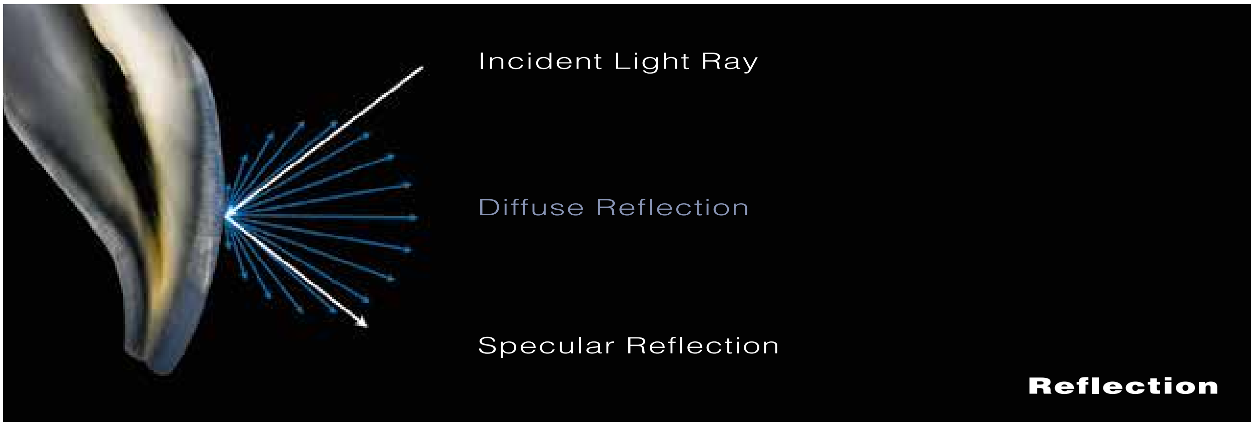


Fig 3 The term reflectance is used to denote the fraction of light energy that is reflected by the surface of a given material. If the surface is not plane but curved, as is the case with enamel above, it may still be considered to be made up of many very small, elementary plane surfaces.

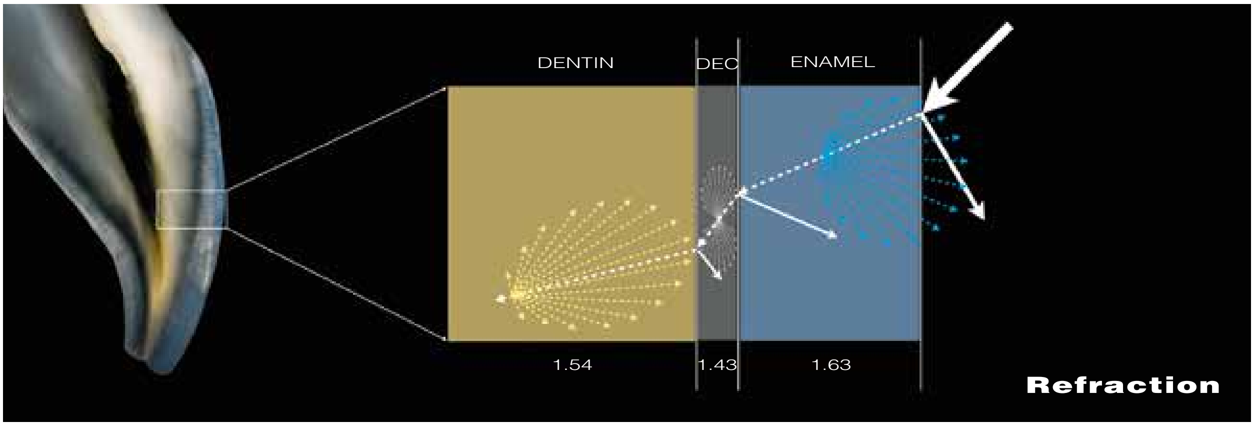


Fig 4 The term refraction is used to denote a change in direction of propagation of light waves as a result of its traveling at different speeds at different points among the wave front between mediums of varying optical densities. Primary subsurface scattering is denoted by the radial arrow depictions.

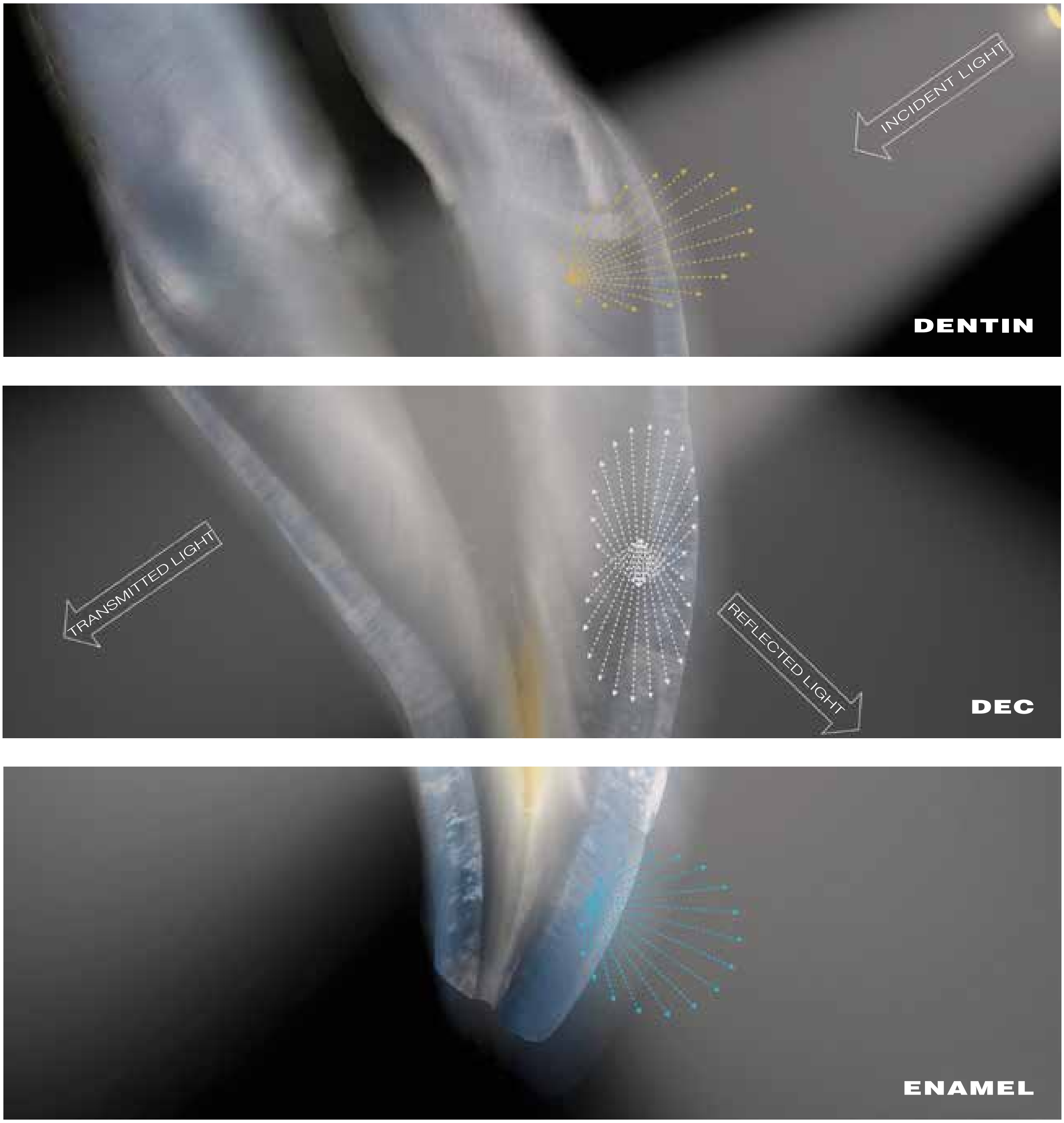


Fig 5 Light interactivity model. From the cervical to the incisal regions, the dominance of the dentin core gradually gives way to that of the enamel shell respectively, achieving a brief equilibrium in the middle region. Multi-directional forms of scattering (colored arrows) and refractive index variations between the enamel/dentinoenamel complex/dentin substrates create infinite photonic pathways, collectively rendering a unique visual synthesis depending upon the incident light direction and intensity.

minescence, photoelectric effect etc)
– re-radiated with a lower energy state (eg, fluorescence)

Relative refractive index

Due to the fact that enamel and dentin are heterogeneous hydrated substrates of variable inorganic and organic composition, one must consider collectively the volume fraction of their individual elemental component's refractive index (RI), resulting in their respective relative refractive index (RRI). Moreover, depending on the localized mineral content of these substrates, minor fluctuations in the RI may ensue, with the highest values always occurring within the more mineralized locations.[1,2]

The structural orientation and the arrangement of the enamel prisms do not seem to have a significant effect on light attenuation, resulting in an RRI value of 1.63.[3,4] Unlike enamel, the structural orientation and arrangement of the dentin tubules seem to play a significant role with regards to the RRI of dentin. Traditionally, dentin has been cited with a generalized RRI value of 1.54.[3] Contemporary localized RRI values for dentin subadjacent to the dentinoenamel complex (DEC) include 1.60 (cervical), 1.56 (middle), and 1.49 (incisal).[4]

The DEC, being an organic proteinaceous continuum[5] that is dominated primarily by Type I collagen, has an RRI value of 1.43.[6,7]

Light guiding by scattering in enamel and dentin

The heterogenous composition and asymmetric directional distribution of the hard dental tissue structural components add to the level of complexity with regards to microscopic light interactivity.

Natural waveguides,[8] such as enamel and dentin, are differentiated from conventional optical fibers by being nonuniform and containing scattering particles. Nonetheless, they have the ability to collect light and transport it purposely towards the pulp chamber (Fig 5).[9-12]

Scattering generally implies a forced deviation of light from a straight trajectory by localized non-uniformities (scatterers), found upon or within the medium through which it interacts, without the loss of energy. Reflection, refraction and diffraction represent various forms of scattering. With regards to enamel and dentin, multiple scattering pathways are prevalent. In the quantum picture, when the wavelength (frequency) of the scattered light is the same as the incident light, elastic scattering occurs. Conversely, when the emitted radiation has a wavelength different from that of the incident radiation, inelastic scattering occurs.

The inorganic component of the dental hard tissues is responsible for elastic scattering; via Rayleigh scattering (rather isotropic, only depending on the polarization of the wavelength) in the case of enamel and via Mie scattering (rather anisotropic, forward scattering is predominant) in the case of dentin,[13] while the organic component of the dental hard tissues is responsible for inelastic scattering; via fluorescence.

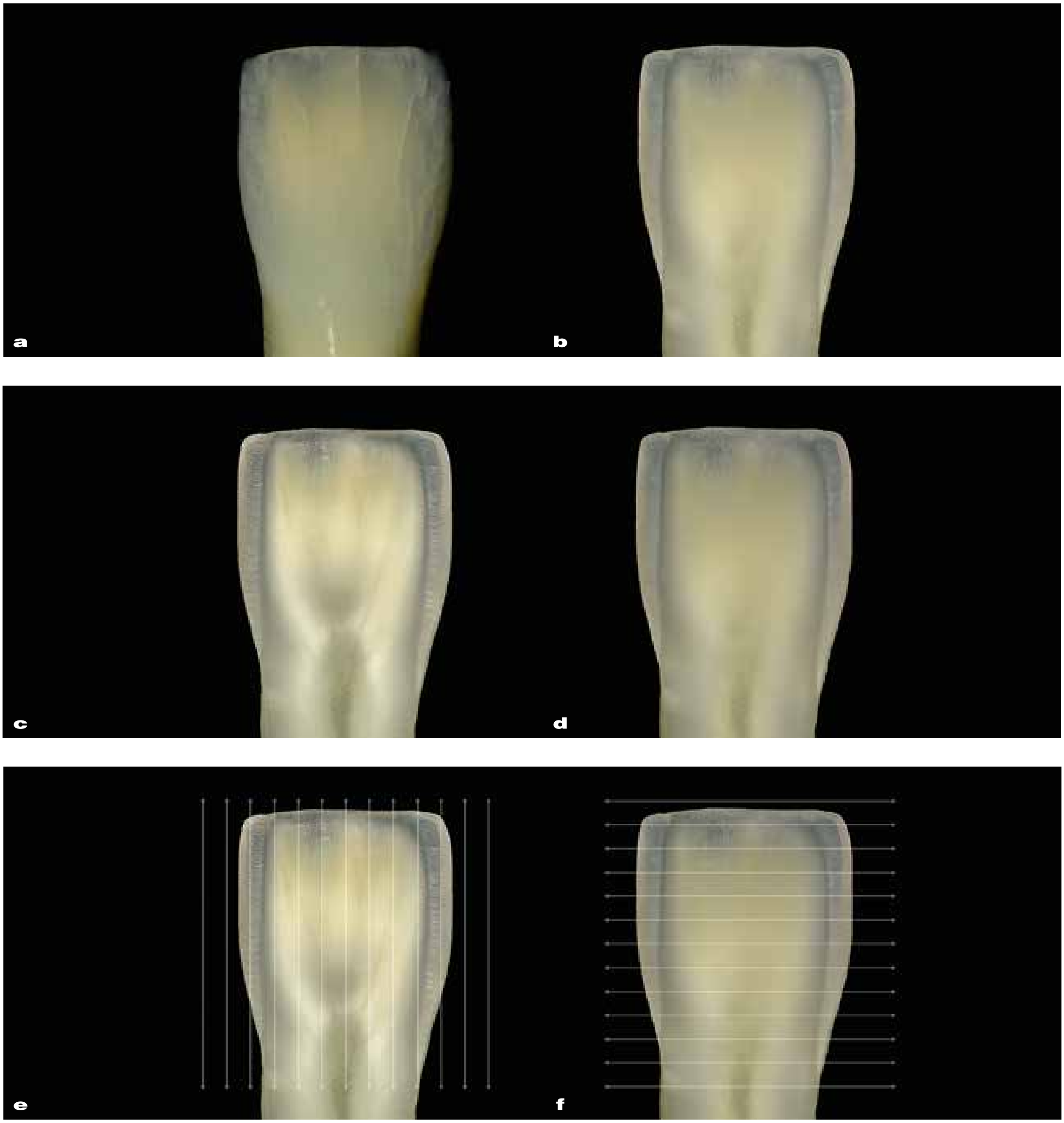


Fig 6 The frontal longitudinal tooth section was submerged in distilled water and photographed on a black background. Despite using the same amount of direct reflective illumination per exposure, a directional change of 90 degrees reveals stunning and complex light transmissive and reflective pathways, emphasizing the optical anisotropy of dentin. Sharp details and remarkable contrast within the dentin shade is seen **(c)**. Pronounced backscattering across the enamel prisms and the dentin tubules render a diffuse appearance obscuring critical details as evident in depiction **(d)**, based on incident light direction. Parallel illumination with respect to the long axis of the tooth present on the left and perpendicular on the right.

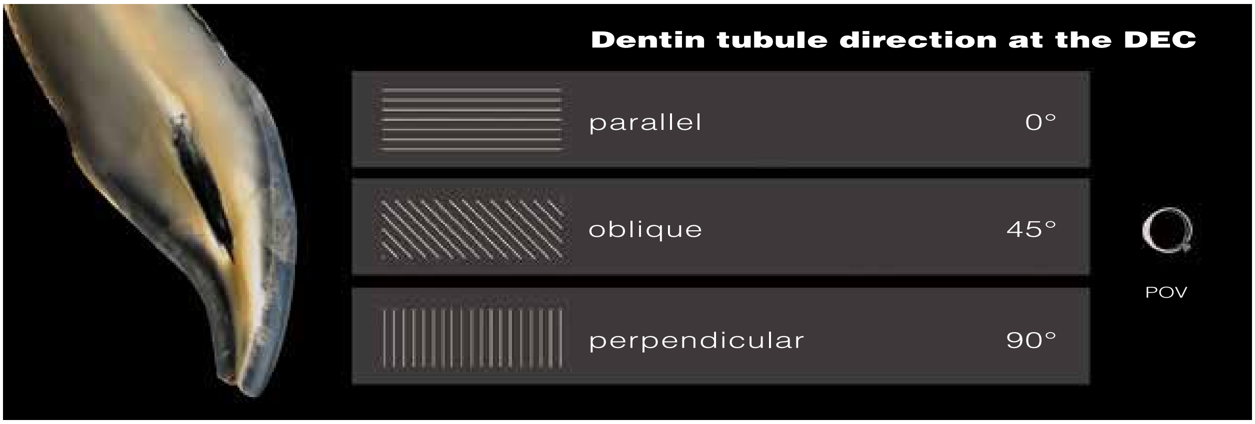


Fig 7 Dentin subadjacent to the DEC exhibits a transitional orthogonal rotational orientation from cervical to incisal with regards to the dentin tubules. Hence, despite the fact that cervical dentin is thicker, due to the parallel orientation of of the tubules, it is rendered more translucent. The opposite happens with respect to incisal dentin, despite the fact that it is thinner, due to the perpendicular orientation of the tubules, it is rendered more opacious.

In the case of enamel, major random scattering occurs on the ultrastructural level from the hydroxyapatite (HAp) crystal subunits, whereas minor random scattering occurs on the microstructural level due to the prism sheaths/interprismatic material orientation in conjunction with the sinuous paths of Hunter-Schreger bands.[14,15] The scattering coefficient appears to increase with shorter wavelengths,[16] while thin enamel sections also exhibit a Fraunhofer diffraction pattern in the plane perpendicular to the enamel prisms,[17] acting as a diffraction grating which in turn may be responsible for generating iridescent reflections (Fig 6).

In the case of dentin, multiple directional scattering occurs on the microstructural level due to the presence and spatial arrangement of the dentin tubules and the collagen fiber mesh.[14,18,19] In contrast with enamel, the scattering coefficient does not change significantly with wavelength.[20] Directly below the DEC, scattering is decreased due to low tubule density with small tubule size, compared to the dentin directly adjacent to or above the pulp due to high tubule density with large tubule size.[21] Thus there exists a significant translucency gradient, that of superficial dentin which is more translucent and that of deep dentin, which is three times more opacious.[22] Additionally, the regional variation of dentin tubule orientation is of particular relevance with regards to light transmission, rendering cervical dentin as highly transmissive, middle dentin as moderate, and incisal dentin as low (Fig 7).

Conversely, the DEC lacks significant scatterers. The elevated lateral light diffusion that occurs at the DEC has been described as the “glass layer” or “high diffusion layer” or “brilliance zone.”[23,24] Factors that may be considered for this enhanced light diffusion is that the inner aprismatic enamel presents a more uniform HAp crystal orientation, con-

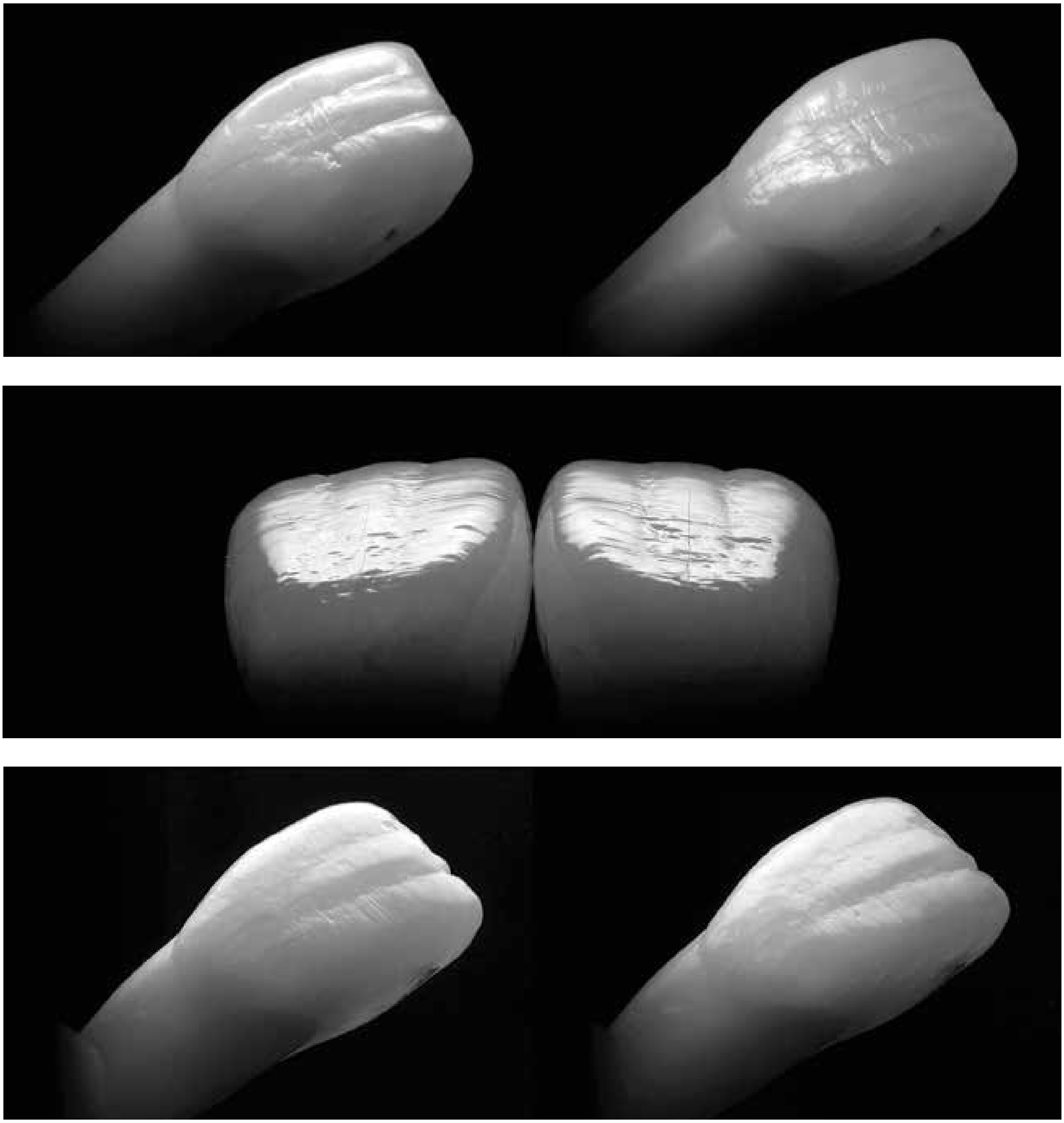


Fig 8 Direct illumination is used to enhance the sensation of surface topography of the maxillary central incisors. Moderate wear is viewed on the vertical developmental lobular heights of contour whereas the concave depressions have retained parts of their original horizontal structural anatomy; diffuse light was utilized via indirect illumination to enhance the sensation of gloss and luster.

sequently producing an elevated light-flux density concentration at this junction,[25,26] while the underlying mantle dentin exhibits low tubule density and small tubular size, providing minimal scattering. Furthermore, the change in the RRI between dentin and enamel results in partial reflections of light at this junction and theoretically, when conditions are favorable for short distances, localized total internal reflections may be attained.

The nine elements of visual synthesis

Descriptive surface elements

Surface texture
Surface texture describes the physical characteristics of the enamel surface, being directional (vertical developmental lobes/horizontal cervical ridges) and structural (perikymata). Perpetual surface texture adaptation is a function of the inherent microstructure at eruption and the subsequent physical and chemical processes that modify it: attrition, abrasion, and erosion (Fig 8).

Gloss
Gloss describes the visual perception based on the interaction of light with the physical characteristics of the enamel surface, relating to the ability to reflect light in a specular ("glossy appearance" observed on polished convex contours) or diffuse ("matte appearance" observed within concave depressions) manner. Like color, it exhibits physical, physiologic, and psychological aspects (Fig 8).

Luster
Luster describes the qualitative correlation of the visual appearance produced by the reflection of light with the enamel surface. Also known as contrast gloss, luster can be somewhat subjective, expressed in relative terms such as satin-like, pearly, metallic, glass-like (Fig 8).

Objective color elements

Hue
Hue Is defined as the name that distinguishes one family of colors from another. Hue is specified as the dominant range of wavelengths in the visible spectrum that yields the perceived color.[27] The base shade of dentin primarily determines the hue of a tooth.[28,29] Hue can be considered the quality of pigment (Figs 9 and 10).

Chroma
Chroma is defined as the saturation, intensity, or strength of the hue. Unlike value, which occurs independently of hue, chroma is only present when there is hue.[30] Chromaticity is an objective specification of the quality of a color regardless of its value, that is, as determined by its hue and chroma, and is readily visualized via cross-polarized reflective photography (Figs 9 and 10).

Value
Value is defined as the relative whiteness or blackness of a color and is determined by comparing it to a gray of similar brightness. Value is also called lightness, brightness or luminance (Figs 9 and 10).

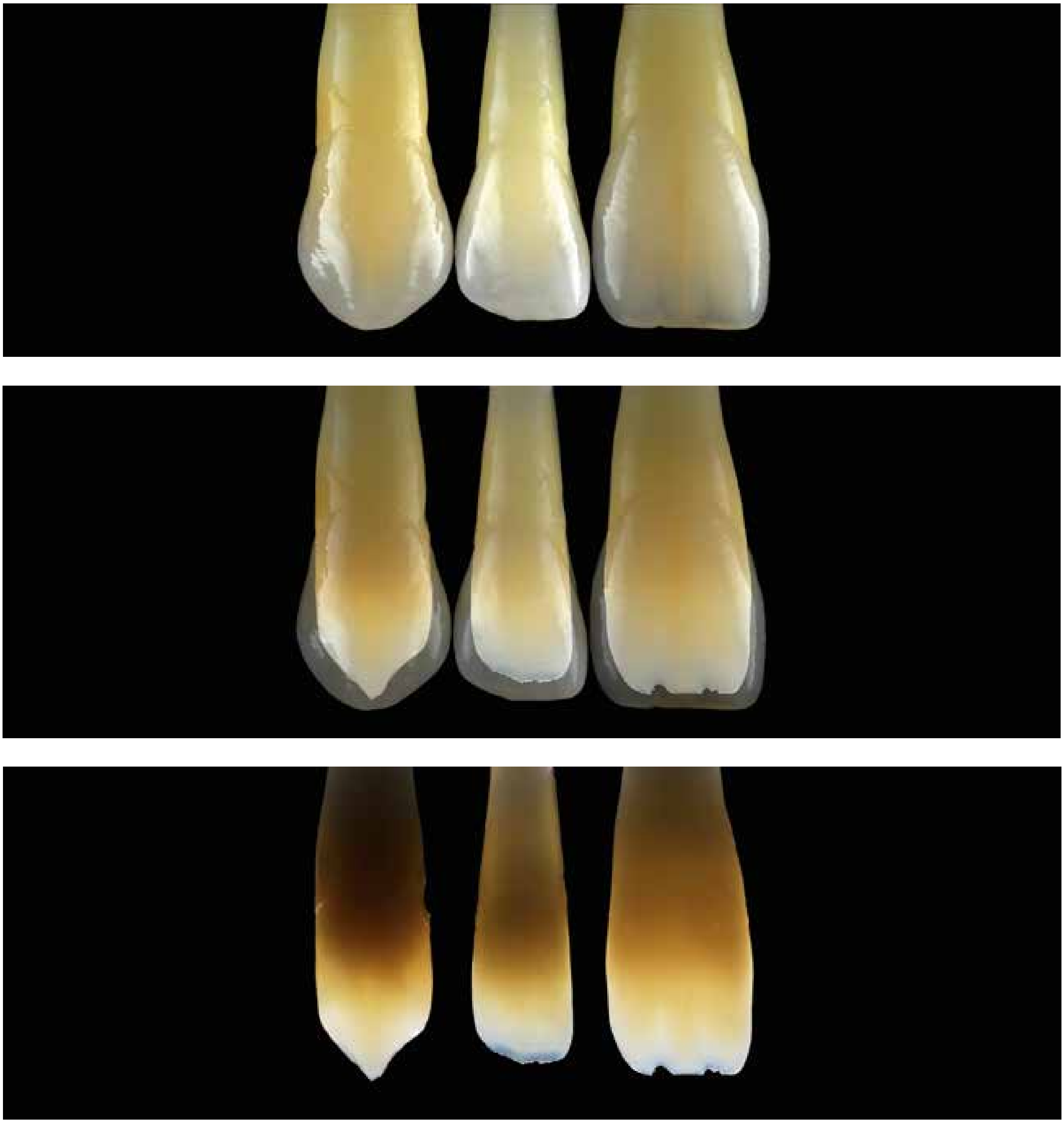


Fig 9 The intact teeth comprising the maxillary triad were extracted concurrently due to periodontal reasons and deemed as exemplary dental specimens for exploring interdental structural and optical inter-relationships. Aggressive acidulation led to the selective enamel dissolution and revealed the dentin substructure. Lobular coalescence is particularly prevalent in the central incisor.

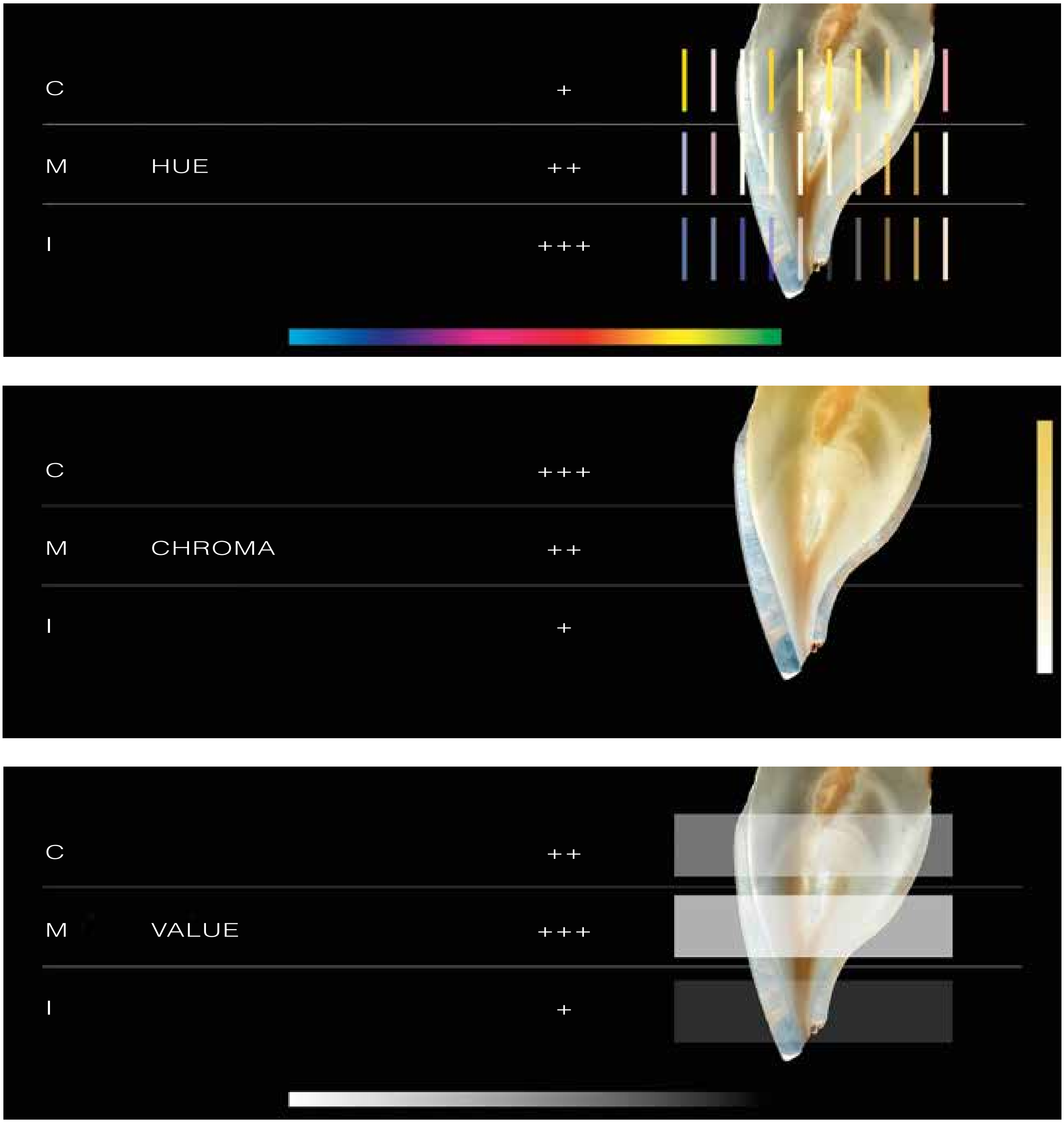


Fig 10 The objective color elements as viewed and estimated; general congruency is observed among the cervical (C), middle (M) and incisal (I) thirds amongst the maxillary triad. A multitude of hues is found at the incisal third due to the phenomena of opalescence and counter-opalescence. Chroma is more pronounced at the cervical third due to the thickness of dentin.[31] In all instances Value is highest at the middle third, due to the fact that the enamel and dentin present an equilibrium in terms of thickness ratios.[32]

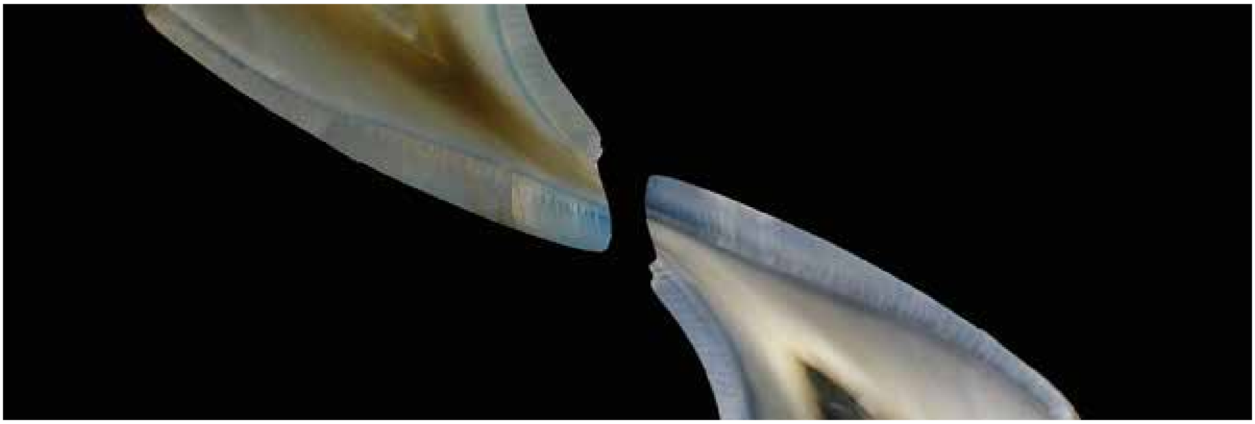


Fig 11 The longitudinal histological tooth section of a maxillary central incisor, 1 mm in thickness, was submerged in distilled water and photographed via transmissive illumination (upper) and reflective illumination (lower) to epitomize the opalescent nature of enamel.

Subjective optical elements

Translucency

Translucency is defined as a gradient between transparency (complete transmission of light) and opacification (complete reflection of light). The light transmission of enamel has been shown to be wavelength specific, age related and is influenced by its state of hydration. A decrease in translucency during dehydration is explained as a result of an increased difference in refractive indices between the enamel prisms and the surrounding medium when water is replaced by air.[33]

Opalescence

Known as the Rayleigh scattering effect; enamel demonstrates this dichroic effect, which is caused by scattering particles with typical dimensions much smaller than the wavelength of illumination used. The mineral crystals present in the enamel prism (measuring 4 μm wide to 8 μm high) meet this property because the HAp subunit crystals exhibit thicknesses of 25 to 40 nm, and widths of 40 to 90 nm. For that reason the short blue wavelengths reflect preferentially from the enamel, while the longer amber wavelengths transmit accordingly through it (Fig 11).

Fluorescence

An example of photoluminescence is a phenomenon in which invisible UV light is absorbed and then re-emitted almost immediately[34] (10^{-8} s) at a less energetic wavelength in the visible spectrum. Enamel and dentin both possess fluorescent properties, with dentin generally exhibiting three times the intensity than that of enamel[35] upon longitudinal section, emitting a white-blue luminescence after excitation, imparting additional vitality and brightness to the natural tooth appearance predominantly in UV rich environments only. The DEC also exhibits its elevated fluorescence due to the col-

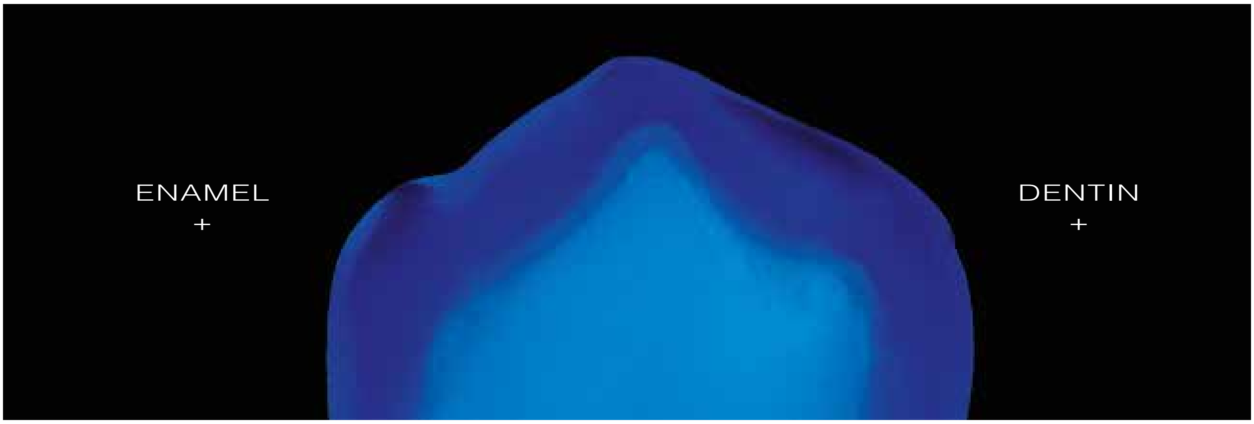


Fig 12 A submerged maxillary premolar was photographed with reflected long wavelength UV illumination (365 nm), enabling the visualization of dentin exhibiting three times the fluorescence intensity than that of enamel. Note that the DEC also exhibits pronounced fluorescence.[39-41]

lagen-rich, highly cross-linked composition, with primary intrinsic (endogenous) fluorophores being the aromatic amino acid tryptophan[36,37] and the collagen cross-linking agent hydroxypyridium (Fig 12).[38]

Dynamic infinite optical thickness

Perceived color can be considered a combination of the reflected color of the translucent enamel layer plus the color reflected from the underlying relatively opacified dentin layer. As the enamel and dentin layers vary inversely in relative thickness from cervical to incisal, the amount of color contribution from the two tissues will be reciprocal (vice versa) (Figs 13 and 14).[44–46]

The thickness of a given translucent material at which any further material addition does not alter the transmission of light, nor the perceived reflected color of that material either on a white or black background, defines its infinite optical thickness (IOT).

Although light transmission in enamel at 1 mm has been tentatively measured to be 66% ± 11%, while that of dentin at 1 mm is 44% ± 12%,[47] one must consider the significance of sample location, the relative thickness distribution of both tissues as well as stage of tissue maturation.[48]

With regards to dynamic aging on the macrostructural level, enamel inadvertently goes through a volumetric reduction via functional wear, mechanical abrasion and chemical erosion, resulting externally in a hyperpolished surface. Conversely, internally the dentin volume increases via secondary and tertiary dentin deposition.

On a microstructural level, a significant reduction in the porosity of the enamel is due to posteruptive maturation via hypermineralization[49–51] and homogenization leading to HAp crys-

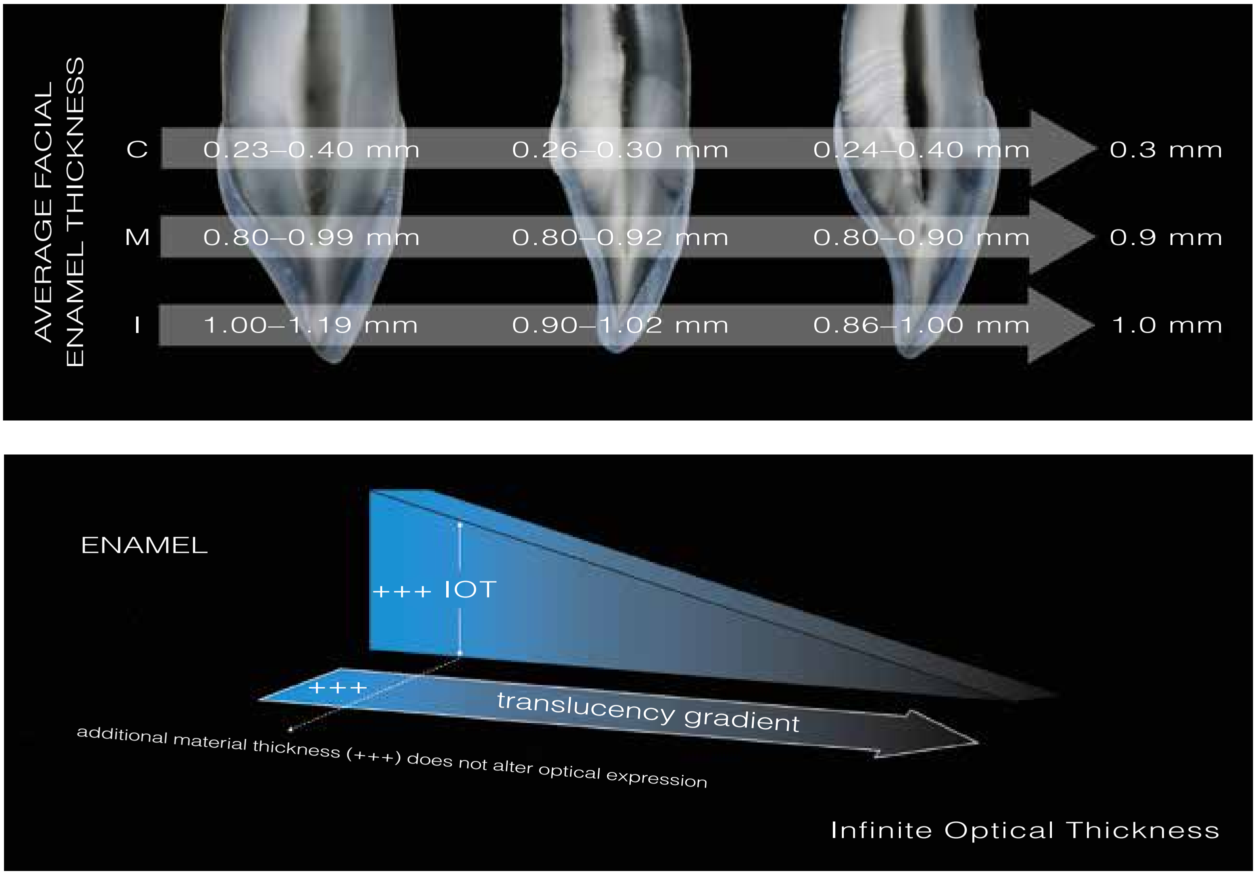
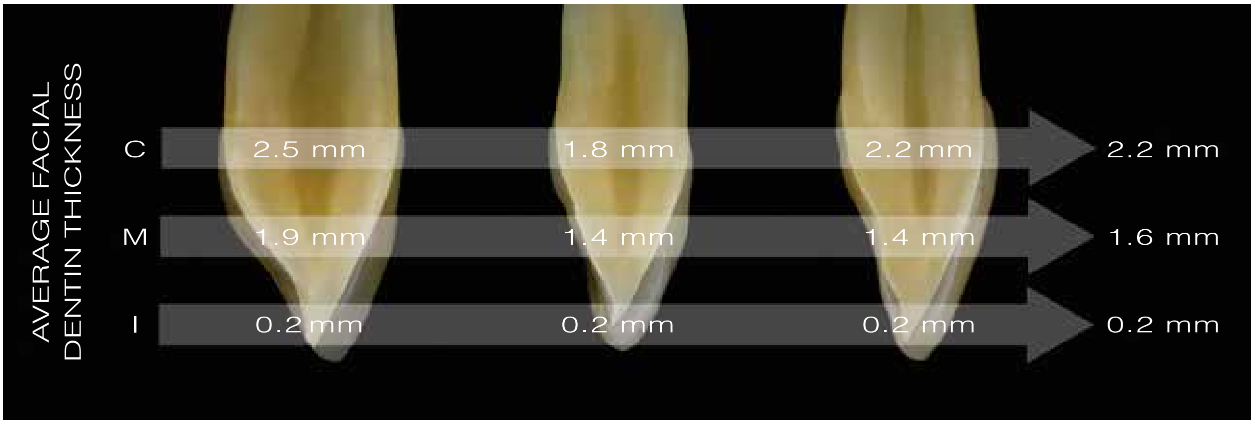


Fig 13 Individual and pooled averages with regards to labial enamel thickness for the maxillary triad at the cervical (C), middle (M) and incisal (I) thirds.[44-46]

tal elongation,[52] while in a homologous manner, hypermineralization of dentin ensues via natural tubular obliteration, rendering dentin more translucent over time.

Due to this dynamic cycle of events, juvenile enamel, which is thicker, possesses a texturized surface and is composed of small HAp crystals, appearing to be translucent white (higher value) due to more light scattering, while adult (and senior) enamel, which is thinner, is characterized by a polished surface and composed of large HAp crystals, thus appearing more transparent grey (lower value) due to less light scattering.

Further research is desired in order to estimate the dynamic IOT values for enamel and dentin at different stages of tissue maturation, thus establishing universal industry standards for composite resins and etchable ceramics. Possessing knowledge of the dynamic IOT and the degree of translucency and opacity of dental resins[53,54] and etchable ceramics at given thicknesses will automatically enable clinicians and technicians to strategize accordingly in order



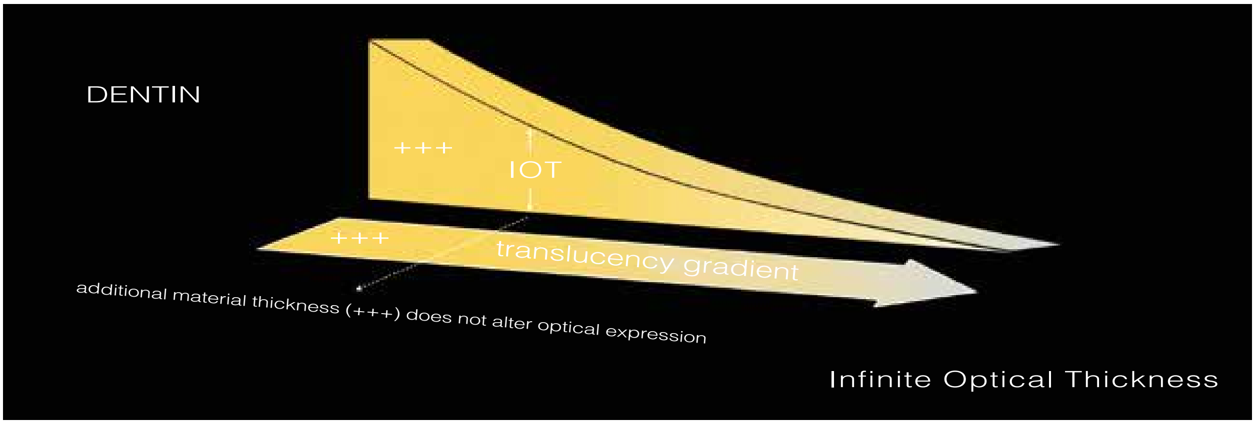


Fig 14 Pooled averages with regards to labial dentin thickness for the maxillary triad at the cervical (C), middle (M) and incisal (I) thirds.[44]

to provide adequate tooth reduction to meet the specific objectives that are required.

Amplified visual perception effect

Due to the convex lens-like shape of enamel in conjunction with possessing an RRI of 1.63, optical distortion occurs. Thus, light being refracted within enamel, the DEC and subsequently internally reflected from dentin produces a stunning effect; an optical illusion of magnification[55] and spatial proximity is perceived with regards to the underlying dentin mamelons. This apparent magnification manifests in an incisobuccal direction, creating an optical illusion with regards to the position and dimension of dentin mamelons. This optical illusion is subdued in part by the birefringent nature of enamel, obscuring details rendering a hazy net appearance (Fig 15). Concurrently, dentin also exhibits magnification properties[56,57] due to the divergent radial fanning of the dentin tu-

Fig 15 Enamel is responsible for creating an optical illusion of the apparent versus the actual position with regards to the visualization of the underlying incisal dentin.

bules when light is reflected internally from the deeper strata.

Diversification of photographic illumination techniques

Intact dental specimens provide the ultimate reference for the perpetual devotion of time and attention to acquire the needed knowledge with regards to visual interpretation.[58,59]

Over the last decade, there has been profound interest in alternative photographic techniques aimed at increasing the accuracy and objectivity of dental shade evaluation and laboratory communication. In order to minimize the user-dependent error in future clinical practice, it is necessary to develop standardized, reproducible imaging modalities and objective image analysis methods (Figs 16 and 17).

Reflective Illumination

Direct reflective illumination utilizing a macro twin flash, via manual standardization of power output, remains the pho-

Fig 16 Facial illumination techniques from top to bottom: reflective, reflective cross-polarized, reflective UV and transillumination.

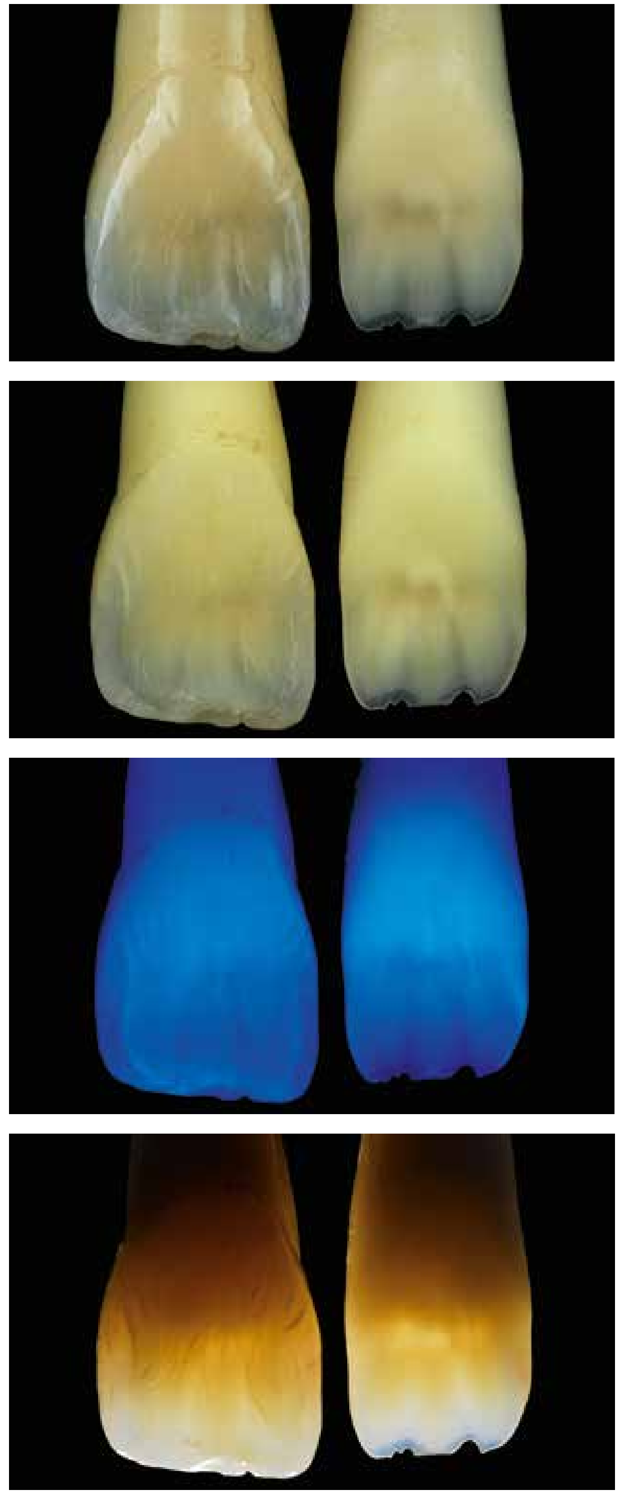


Fig 17 Palatal illumination techniques from top to bottom: reflective, reflective cross-polarized, reflective UV and transillumintion.

tographic standard for providing predictable and repeatable levels of light for shade estimation. Indirect reflective illumination (Lumiquest, Pocket Bouncers,) on the other hand, aids in revealing fine surface texture details.

Reflective cross-polarized illumination

This photography technique significantly mitigates unwanted specular reflections which obscure the fine details of dental structures[23,60], while providing a high contrast/hypersaturated dental image to be objectively analyzed via a calibrated RAW workflow utilizing a generic software program (Adobe Photoshop) in the CIE L*a*b color space. To obtain such a photographic image intraorally, a cross-polarization filter is utilized (polar_eyes, Emulation).

UV Illumination

Ultraviolet Illumination is utilized in order to induce fluorescence and aid in the selection of the restorative material (etchable ceramics and resins) with a similar fluorescence intensity,[61-63] providing the restoration with optimal integration primarily in the event of exposure to a UV dominant lighting environment, such as a dancehall or a nightclub. To obtain such an image intraorally, a custom modified xenon flash tube is utilized (fluor_eyes, Emulation).

Transillumination

Transillumination reveals histo-anatomic relative opacity levels (transparent dentin vs opaque) and visual quantitative estimation of incisal enamel distribution. Opalescence may also be visually assessed and gauged via this type of photography. To obtain such an image intraorally, a fiber optic transilluminator is utilized (Micro-Lux, AdDent).

Discussion

The restorative task is elaborated along four levels of integration: biological, functional, mechanical, and optical. To meet contemporary challenges, the dental team must enhance its capacity in all four levels equally.

From an optical standpoint in ambient light, enamel can be considered isotropic, with the visual gradient being expressed in the vertical direction (cervical/incisal) due to thickness variation, whereas dentin can be considered anisotropic, with the visual gradient being expressed: *a)* in a radial direction due to the dentin tubule attributes of diameter and density (qualitiative), and *b)* in a horizontal zonal direction (cervical/middle/incisal) due to thickness variation and differing RRI indexes (quantitative).

Hue and chroma are predominately determined by the properties of dentin, dynamically changing over time as secondary deposition occurs. In some instances, as in the cases of severe incisal wear, dentin can be breached to such an extent that external chromophores become readily absorbed, resulting in infiltration staining (Fig 10).

While the opacity of dentin provides and establishes a baseline for value, the luminosity is predominately regulated by the properties of enamel. The surface texture influences the primary interac-

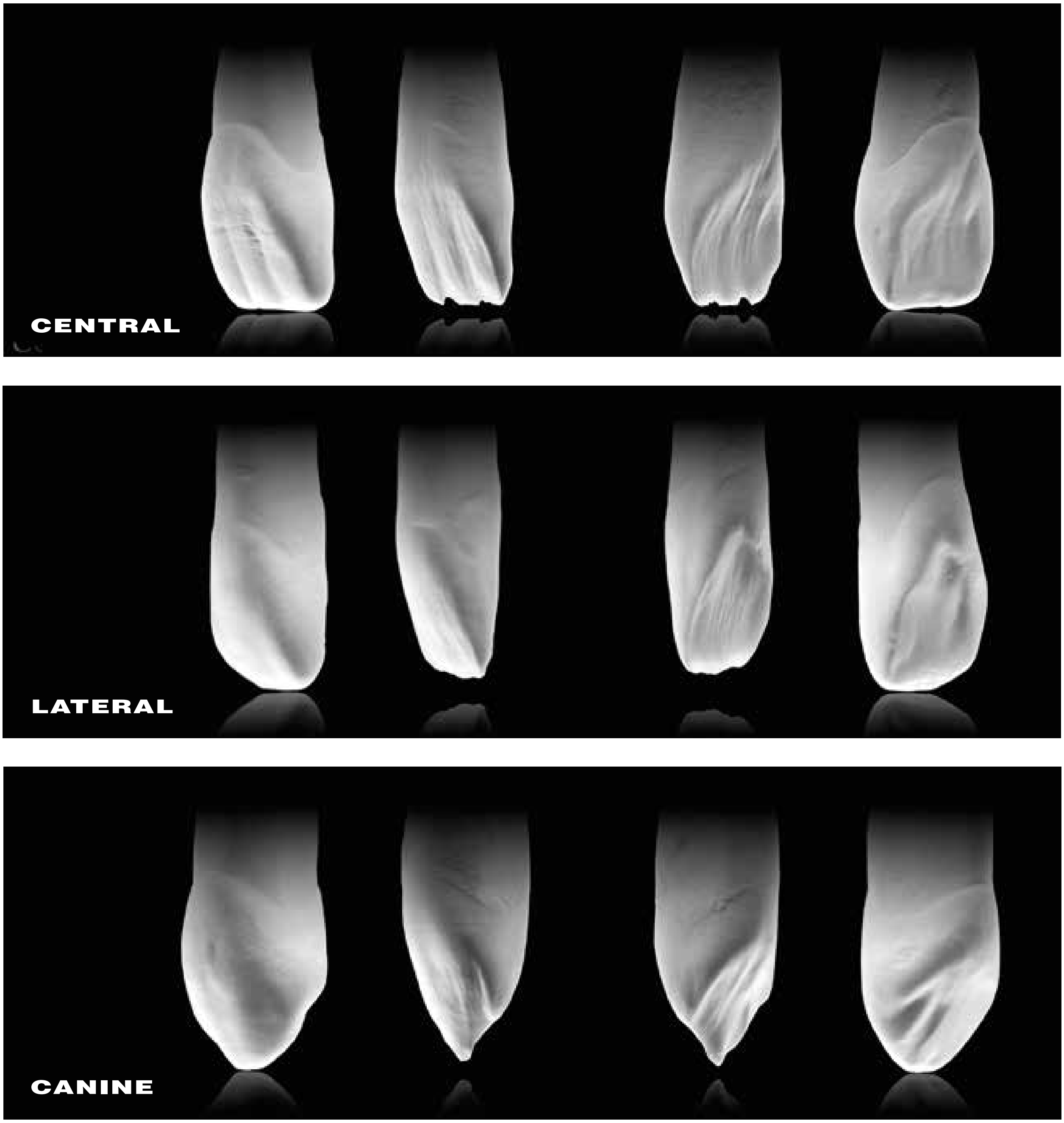


Fig 18 Stone replicas facilitate visual assessment and rumination of the variability between enamel and dentin surface topography. Mesiobccal **(left)** and Mesiopalatal **(right)** oblique views of central incisor, lateral incisor and canine (top to bottom). Generalized external enamel macromorphological congruency is seen upon the dentin counterpart, with amplified vertical corrugations, providing added roughness and waviness that is critical to be emulated during restorative stratification techniques.[64]

tion of the incident light. A highly textured surface renders higher amounts of diffuse surface scattering, thus elevating the perceived value, appearing to be more translucent. This is in contrast to a smooth surface, which would exhibit lesser amounts of diffuse surface scattering, thus demoting the perceived value, and appearing to be more transparent. The relative thickness of enamel dictates the proportional amount of diffuse subsurface scattering (quantitative), while the degree and postmaturation stage of the HAp crystals affects the type of photonic interaction (qualitative).

Transparency, translucency and opacification are all visual representations of the amount of light that is scattered and subsequently reflected to the observer by the microstructural features of a given substrate. Embracing the paradigm shift of thinking in terms of dynamic light interactivity via the principle of scattering enables the clinician and technician to choose the level of sophistication within the stratification protocol they opt to employ; a trilaminar technique (enamel/DEC/dentin) for a simplex interpretation or a pentalaminar technique (Exo enamel/eso enamel/DEC/exo dentin/eso dentin) for a complex one. The utilization of this knowledge in the clinical and technical restorative approach is to be described thoroughly in articles that will be published in future issues of this journal.

Conclusion

This article presented fundamental yet simplified photonic interactions with regards to the histoanatomic elements, rendering the final visual synthesis. It should be emphasized that a thorough understanding of the light propagation within the coronal structures is a prerequisite in order to elucidate color and shade, however mastery of spatial distribution of the three-dimensional histoanatomic relationships is paramount in the quest for restorative dental emulation (Fig 18).

References

1. Hariri I. Estimation of the enamel and dentin mineral content from the refractive index. Caries Res 2013;47:18–26.
2. Wiemann MRJR, Besic FC, Keller O. Application of dispersion staining to the study of refractive index of dental enamel. J Dent Res 1970;49:174.
3. Meng Z, Yao XS, Yao H, Liang Y, Liu T, Li Y, et al. Measurement of the refractive index of human teeth by optical coherence tomography. J Biomed Opt 2009;14:034010.
4. Hariri I, Sadr A, Shimada Y, Tagami J, Sumi Y. Effects of structural orientation of enamel and dentine on light attenuation and local refractive index: an optical coherence tomography study. J Dent 2012;40:387–396.
5. Bodier-Houllé P, Steuer P, Meyer JM, Bigeard L, Cuisinier FJ. High-resolution electron-microscopic study of the relationship between human enamel and dentin crystals at the dentinoenamel junction. Cell Tissue Res 2000;301:389–395.
6. Wang XJ, Milner TE, Chang MC, Nelson JS. Group refractive index measurement of dry and hydrated type I collagen films using optical low-coherence reflectometry. J Biomed Opt 1996;1:212–216.
7. Bashkatov NA, Genina EA, Kochubey VI, Tuchin VV. Estimation of wavelength dependence of refractive index of collagen fibers of scleral tissue. Proc. SPIE 2000;4162:265–268.
8. Zolotarev VM, Grisimov VN. Architectonics and optical properties of dentin and dental enamel. Optics and Spectroscopy 2001;90:753–759.
9. Altshuler GB, Erofeev AV. Lasers in Dentistry. Chicago: Quintessence Publishing, 1995.
10. Altshuler GB. Optical model of the tissues of the human tooth. J Opt Technol 1995;62:516–520.
11. Altshuler GB, Grisimov VN, Ermolaev VS, Vityaz IV. Human tooth as an optical device. SPIE Proc Holography Interferometry Opt Pattern Recognition Biomed 1991;1429:95–104.
12. Altshuler GB, Grisimov VN. Effect of waveguide light propagation in human tooth. Dokl Acad Sci USSR 1990;3:1245–1248.
13. Raulin C, Karsai S. Laser and IPL Technology In Dermatology and Aesthetic Medicine. London: Springer, 2011.
14. Vaarkamp J, Ten Bosch JJ, Verdonschot EH. Propagation of light through human dental enamel and dentine. Caries Res 1995;29:8–13.
15. Zijp JR, Bosch JJ, Groenhuis RAJ. HeNe-laser light scattering by human dental enamel. J Dent Res 1995;74:1891–1898.
16. Spitzer D, ten Bosch J. The absorption and scattering of light in bovine and human dental enamel. Calcif Tissue Res 197517:129–137.
17. O'Brien WJ. Fraunhofer diffraction of light by human enamel. J Dent Res 1988;2:484–486.
18. Kienle A, Forster FK, Diebolder R, Hibst R. Light propagation in dentin: influence of microstructure on anisotropy. Phys Med Biol 2003;48:N7–N14.
19. Kienle A, Hibst R. Light guiding in biological tissue due to scattering. Phys Rev Lett 2006;97:018104.
20. Fried D, Glena RE, Featherstone JD, Seka W. Nature of light scattering in dental enamel and dentin at visible and near-infrared wavelengths. Appl Opt 1995;34:1278–1285.
21. Garberoglio R, Brännström M. Scanning electron microscopic investigation of human dentinal tubules. Arch Oral Biol 1976;21:355–362.
22. ten Bosch J, Zijp JR.Optical properties of dentin. In: Thylstrup A, Leach SA, Qvist V (eds). Dentine and Dentine Reactions in the Oral Cavity. Oxford: IRL Press, 1987:59–65.
23. Vanini L. Light and color in anterior composite restorations. Pract Periodontics Aesthet Dent 1996;8:673–682.
24. Touati B, Miara P, Nathanson D. Esthetic Dentistry and Ceramic Restorations. London: Martin Dunitz Ltd;1999:61-79.
25. Odor TM, Watson TF, Pitt Ford TR, McDonald F. Pattern of transmission of laser light in teeth. Int Endod J 1996 Jul;29:228–234.
26. Seka W, Fried D, Featherstone JD, Borzillary SF. Light deposition in dental hard tissue and simulated thermal response. J Dent Res 1995;74:1086–1092.
27. Fondriest J. Shade matching in restorative dentistry: The science and strategies. Int J Periodontics Restorative Dent 2003;23:467–479.
28. ten Bosch JJ, Coops JC. Tooth color and reflectance as related to light scattering and enamel hardness. J Dent Res 1995;74:374–380.
29. Dietschi D, Ardu S, Krejci I. A new shading concept based on natural tooth color applied to direct composite restorations. Quintessence Int 2006;37:91–102.
30. Preston JD, Bergen SF. Color Science and Dental Art. St Louis: CV Mosby, 1980.
31. Dozic A, Kleverlaan CJ, Aartman IH, Feilzer AJ. Relations in color among maxillary incisors and canines. Dent Mater 2005 Mar;21:187–191.

32. Hasegawa A, Ikeda I, Kawaguchi S. Color and translucency of in vivo natural central incisors. J Prosthet Dent 2000;83:418–423.
33. Brodbelt RH, O'Brien WJ, Fan PL. Translucency of dental porcelains. J Dent Res 1980;59:70–75.
34. Frazier PD, Engen DW, Scamack SK. X-Ray-induced light emission from enamel, bone, and other calcium phosphate materials. J Dent Res 1967;46:731–735.
35. Monsénégo G, Burdairon G, Clerjaud B. Fluorescence of dental porcelain. J Prosthet Dent 1993 Jan;69:106–113.
36. Hoerman KC, Mancewicz SA. Fluorometric demonstration of tryptophane in dentin and bone protein. J Dent Res 1964;43:276–280.
37. Foreman PC. The excitation and emission spectra of fluorescence components of human dentine. Arch Oral Biol 1980;25:641–647.
38. Walters C, Eyre DR. Collagen crosslinks in human dentin: increasing content of hydroxypyridinium residues with age. Calcif Tissue Int 1983;35:401–405.
39. Villa VG. Dentino-enamel cuticle present in adult human teeth. J Dent Res 1949;28:565–568.
40. Villa VG. Further evidence on the presence of dentino-enamel cuticle in adult human teeth. Oral Surg Oral Med Oral Pathol 1955;8:1315–1317.
41. Villa VG. Further evidence tending to show that enamel tufts are extensions of the dentino-enamel cuticle into the substance of the enamel. Aust Dent J 1958;3:331–333.
44. Shillingburg HT, Grace CS. Thickness of enamel and dentin. J South Calif Dent Assoc 1973;33–52.
45. Crispin B. Expanding the application of facial ceramic veneers. J Calif Dent Assoc 1993;21:43–46, 48–49, 52–54.
46. Ferrari M. Patroni S, Balleri P. Measurement of enamel thickness in relationship for etched laminate veneers. Int J Periodontics Restorative Dent 1992;12:407–413.
47. Cook WD, McAree DC. Optical properties of esthetic restorative materials and natural dentition. J Biomat Mat Res 1985;19:469–488.
48. Dietschi D, Ardu S, Krejci I. A new shading concept based on natural tooth color applied to direct composite restorations. Quintessence Int 2006;37:91–102.
49. Glick PL. Patterns of enamel maturation. J Dent Res 1979;58:883–895.
50. Schulte A, Gente M, Pieper K. Posteruptive changes of electrical resistance values in fissure enamel of premolars. Caries Res 1999;33:242–247.
51. ten Bosch JJ, Fennis-le Y, Verdonschol EH. Time-dependent decrease and seasonal variation of the porosity of recently erupted sound dental enamel in vivo. J Dent Res 2000;79:1556–1559.
52. Eimar H, Marelli B, Nazhat SN, Abi Nader S, Amin WM, Torres J, et al. The role of enamel crystallography on tooth shade. J Dent 2011;39(Suppl 3):e3–10.
53. Villarroel M, Fahl N, De Sousa AM, De Oliveira OB Jr. Direct esthetic restorations based on translucency and opacity of composite resins. J Esthet Restor Dent 2011;23:73–87.
54. Schmeling M, De Andrada MA, Maia HP, De Araújo EM. Translucency of value resin composites used to replace enamel in stratified composite restoration techniques. J Esthet Restor Dent 2012;24:53–58.
55. Hajtó J, Schenk H. Optische Eigenschaften von Verblendkeramiken auf Kronengerüsten aus Zirkoniumdioxid, Quintessenz Zahntech 2006;5:466–483.
56. Walton RE, Outhwaite WC, Pashley DF. Magnification – an interesting optical property of dentin. J Dent Res 1976 55:639–642.
57. Kienle A, Michels R, Hibst R. Magnification—a new look at a long-known optical property of dentin. J Dent Res 2006;85:955–959.
58. Dietschi D. Free-hand bonding in esthetic treatment of anterior teeth: creating the illusion. J Esthet Dent 1997;9:156–164.
59. Dietschi D. Layering concepts in anterior composite restorations. J Adhes Dent 2001;3:71–80.
60. Vanini L, Mangani FM. Determination and communication of color using the five color dimensions of teeth. Pract Proced Aesthet Dent 2001;13:19–26.
61. Rey F, Andrade JS, Duarte S Jr. Fluorescence: clinical evaluation of new composite resins. Quintessence Dent Technol 2012;35:145–156.
62. Schmeling M. Fluorescence of natural teeth and direct composite resin restorations: seeking blue esthetics. Am J Esthet Dent 2013;3:2:100–111.
63. Sensi LG, Marson FC, Roesner TH, Baratieri LN, Monteiro Jr S. Fluorescence of composite resins: clinical considerations. Quintessence J Dent Technol 2006;29:43–53.
64. Wang H, Xiong F, Zhenhua L. Influence of varied surface texture of dentin porcelain on optical properties of porcelain specimens. J Prosthet Dent 2011;105:242–248.


TERMINAL BURCHARDKAI
TERMINAL BURCHARDKAI
TERMINAL BURCHARDKAI