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A Comparative Study of Light Transmission by Various Dental Restorative Materials and the Tooth Structure

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Clinical Relevance

Light transmission through dental materials and tooth structure has direct clinical implication on such factors as selecting an appropriate curing technique during a restorative process.

SUMMARY

Introduction: This study aims to quantify and compare the amount of light that passes through seven different types of direct and indirect restorative materials comprising light-cured resin based composites (regular and bulk-fill), computer-aided design/computer-aided manufacturing (CAD/CAM) restoratives such as resin based composites, poly(-methyl methacrylate) (PMMA) resin, leucite glass-ceramic, lithium silicate glass-ceramic, feldspar ceramic, and the natural tooth structure.

Methods and Materials: Individual sets (n=6) of plane-parallel test specimens (2 mm) of 32 restorative materials belonging to the aforementioned seven material types and the tooth structure were prepared. Within the analyzed materials, one leucite glass-ceramic and one lithium disilicate glass-ceramic were considered in two different translucencies. In addition, two light-cured resin composites, one CAD/CAM resin composite, and one lithium disilicate glass-ceramic were considered in two different shades. Optical properties (transmittance, *T*; absorbance, *A*; and opacity, *O*) of each material were calculated from the relationship between incident and transmitted irradiance [*I*(*d*)] using a violet-blue light-curing unit. Incident and transmitted irradiance were assessed in real time on a spectrophotometer. A multivariate analysis (general linear model) assessed the effects of various parameters on the optical properties.

Results: A very strong influence of the parameter *material* was identified on *I*(*d*) ($p<0.001$; partial eta squared, $\eta_P^2=0.953$), *T* ($p<0.001$; $\eta_P^2=0.951$), *A* ($p<0.001$; $\eta_P^2=0.925$), and *O* ($p<0.001$; $\eta_P^2=0.886$), while the effect of the parameter *material type* was not significant

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(p=0.079, p=0.05, p=0.05, and p=0.051, respectively). Light attenuation differed significantly by material within each shade category and by shade category within the analyzed material.

Conclusions: Attenuation of light through restorative materials and tooth structure is high (59.9% to 94.9%); thus, deficits in polymerization are difficult to compensate for by additional light exposure at the end of the restorative process.

INTRODUCTION

A prerequisite that esthetic dental restorative materials need to fulfill in order to accurately duplicate the tooth structure is the ability to be translucent. When the translucency of a restorative material misses an appropriate range, it is often the main factor responsible for failures in matching the shade of restorative materials to the natural teeth.[1,2] A similar effect was observed when repairing a resin composite restoration with a direct resin composite of the same shade[3,4] or when mixing different types of direct resin composites.[2] Equally important for esthetics is the impact of translucency on various material properties, such as the depth of cure in direct light-cured resin composite restoratives[5] and the sufficiency of curing in underlying, light-curing or dual-curing luting resin composites, when involving indirect restoratives.[6]

The light of a curing unit striking the surface of a dental restoration during polymerization may be reflected, absorbed, scattered, or transmitted. Based on these interactions with light, translucency is described as the relative amount of light transmission or the diffuse reflectance from a substrate surface through a turbid medium.[7] By contrast, opacity is a measure of impenetrability to light and is a consequence of extensive absorption and/or scattering of light in a specific medium. Attenuating the effects of light when passing through matter, such as scattering or reflection, are summarized in optics together with the absorption under the terms *extinction* or *absorbance*. Note that light attenuation increases exponentially with material thickness, as described by Lambert-Beer's law.[8]

Light absorption in dental restoratives occurs when the frequency of the light matches certain quantized frequencies within the constituent atoms and molecules of the material, such as resin components,[9] filler particles,[10,11] photoinitiator molecules,[12] dyes, pigments,[9,13] or structures surrounding the restoration. In contrast, light scattering is due to the deviation of light from its initial trajectory because of localized nonuniformities with a different index of refraction through which the light passes, such as reinforcing particles, porosity voids,[10] or surface roughness. In resin composites, for instance, absorption takes place within photoinitiators, color pigments, and the organic matrix,[9,14] whereas scattering is mainly attributed to filler particles.[10,11] For the tooth structure, a negligible absorption and a weak scattering (scattering coefficient ranging from 15 to 105 cm^{-1}) has been identified in enamel. In comparison, in dentin, scattering is strong (scattering coefficient 260 cm^{-1}), and the absorption low.[15]

It should be noted that the absorption of light on surfaces or when passing through matter depends on the material and the frequency (wavelength) of the incident light. If, for example, a yellow-appearing surface is irradiated with white light, the green light and red light are reflected/transmitted and the blue light is absorbed. When absorbing light, the absorbed energy is usually transformed into thermal energy, though other mechanisms are possible in both dental materials and natural teeth, such as the delayed release of light in the form of fluorescence.[16,17]

The aim of the present study was to compare and quantify the amount of light that would pass through 2-mm-thick increments of a large diversity of restorative materials: 1) regular light-cured resin-based composites (RBCs), 2) bulk-fill light-cured RBCs, 3) computer-aided design/computer-aided manufacturing (CAD/CAM) restoratives based on resin composites, 4) poly(methyl methacrylate) (PMMA), 5) lithium disilicate ceramic, 6) leucite glass-ceramic; and 7) feldspar ceramic, as well as the tooth structure, when irradiated with a contemporary violet-blue light-emitting diode (LED) light-curing unit (LCU). Moreover, optical properties calculated from the relationship between incident and transmitted irradiance, such as transmittance, opacity, and absorbance, are considered.

The results of the present study should allow clinicians to critically judge some customary routines in light polymerization during a restorative process, such as 1) pre-curing for a few seconds at the lowest increment when incrementally reconstructing a deep cavity with light curing RBCs, while assuming that sufficient light passes through the upper layers to complete the polymerization; 2) curing a light-cured or dual-cured luting material through various indirect restoratives (encompassing the novel high translucent CAD/CAM RBCs), assuming sufficient light transmittance through all indirect restoratives to properly cure the luting material; and 3) curing through the tooth structure at the end of the restorative process to compensate for insufficient polymerization. Since all specimens were prepared and analyzed under identical conditions, the presented data allowed for a direct comparison among different material types.

The null hypotheses assume similar transmitted irradiance and optical properties through 1) all material types and tooth structure, 2) materials belonging to one material type, 3) materials belonging to one shade, and 4) materials belonging to one translucency.

METHODS AND MATERIALS

The light transmission through 32 restorative materials representing seven different material types (light-cured RBCs (regular and bulk-fill), CAD/CAM restoratives based on resin composites, PMMAs, lithium disilicate ceramics, leucite glass-ceramics, and feldspar ceramic) (Table 1) and in different shades and opacities was analyzed at a specimen thickness of 2 mm. Optical properties such as transmittance, absorbance, and opacity of each material, were calculated from the relationship between incident and transmitted irradiance using a violet-blue LED LCU (VALO, serial number VO 7710, Ultradent, South Jordan, UT, USA) in the standard exposure mode with an exposure time of 20 seconds. The light transmission through the tooth structure was also considered. For direct comparison of the optical properties among analyzed restorative materials and tooth structure, specimens of 2-mm thickness were considered. Various tooth structure specimen thicknesses (1.7 mm to 3 mm) have also been considered to simulate light transmittance through a tooth cavity wall, as this may occur in a clinical situation.

Specimen Preparation

Individual sets (n=6) of plane-parallel test specimens (2 mm) of 32 materials were prepared. Tooth specimens (n=50) were manufactured in a thickness range of 1.7 mm to 3 mm.

Light-cured RBC pastes were condensed in white cylindrical Teflon molds (6-mm diameter, 2-mm height) and applied on the sensor of a spectrophotometer device (MARC (Managing Accurate Resin Curing) System, Blue light Analytics Inc, Halifax, NS, Canada) while being separated from the sensor by a thin Mylar foil (Frasaco GmbH, Tettnang, Germany).

CAD/CAM blocks were cut using a low-speed diamond saw (Isomet low-speed saw, Buehler, Esslingen, Germany) under water-cooling, then ground with 4000-grit SiC paper and polished with a diamond suspension (mean grain size: 1 μm). The thickness of each specimen was determined at two points using a digital micrometer screw gauge (Mitutoyo, Kawasaki, Japan). Thickness tolerance was set at 0.05 mm.

Tooth specimens 1.7 mm to 3 mm thick were obtained from 25 caries-free human molars. For this purpose, one slice from the buccal and one from the lingual side of each tooth were cut perpendicular to the long axis of the tooth, thus providing specimens with one flat side, while leaving the tooth anatomy intact on the opposite side. This simulated the tooth wall in a Class II cavity through which a light-curing RBC restoration may be additionally irradiated at the end of a restorative procedure. The flat side of the tooth specimen was ground and polished similar to the CAD/CAM specimens and positioned in contact to the sensor of the spectrophotometer. The opposite, intact tooth side was irradiated with the LCU as described previously. Light transmittance was accordingly measured through a natural tooth wall of 1.7 to 3 mm thickness, thus simulating a clinically relevant polymerization condition.

Spectrophotometry: Measurement of the Incident and Transmitted Irradiance

Incident and transmitted irradiance through the described specimens were assessed on a laboratory-grade National Institute of Standards and Technology (NIST)–referenced USB4000 Spectrometer while using the aforementioned LCU. The incident irradiance (the irradiance reaching the specimen's surface) was determined on six occasions by applying the LCU directly to the sensor. The transmitted irradiance was measured by positioning the specimens between the LCU and the sensor. The Teflon molds containing the light-cured RBC, as well as the CAD/CAM and tooth structure specimens, were aligned and centered on the round detector of the spectrometer, which had a diameter of 3.9 mm. Consequently, the irradiance and radiant exposure reaching this area was considered. The miniature fiber optic USB4000 Spectrometer uses a 3648-element Toshiba linear Charge-coupled Device array detector and high-speed electronics (Ocean Optic, Largo, FL, USA). The spectrometer was calibrated using an Ocean Optics' NIST-traceable light source (300–1050 nm). The system uses a CC3-UV Cosine Corrector (Ocean Optic) to collect radiation over a

Table 1: *Materials, Manufacturer, Shade, and Lot Number for Light-cured RBCs and CAD/CAM Restoratives*

Type	Material	Manufacturer	Shade	Lot
Light-cured RBCs				
Regular (nanohybrid)	Filtek Supreme XTE	3M, Seefeld, Germany	A3 Dentin	N229448
	Filtek Supreme XTE flow	3M	A3	N236527
	Synergy D6 Dentin	Coltene, Altstätten, Switzerland	A3/D3	F88495
Regular (microhybrid)	G-eanial	GC, Leuven, Belgium	A3	140919A
			A2	160208A
	Gradia Direct	GC	A3 Anterior	140709A
			A2 Anterior	151221A
	Charisma	Heraeus, Hanau, Germany	A3	010700A
	XRV Herculite Enamel	Kerr, Orange, USA	A3	5223302
	Filtek Z250	3M	A2	N768186
Bulk-fill (low viscosity)	SDR	Dentsply Sirona, Charlotte, USA	Universal	1309183
	Venus	Heraeus	Universal	010100
Bulk-fill (high viscosity)	Admira Fusion X-tra	Voco, Cuxhaven, Germany	Universal	1537600
	Sonic Fill 2 Composite	Kerr	A3	5767358
	Filtek One	3M	A3	N782223
CAD/CAM restoratives				
RBC	VITA ENAMIC	VITA Zahnfabrik, Bad Säckingen, Germany	3M2	33000
	Luxacam Composite	DMG, Hamburg, Germany	A3	769515
	Grandio Blocs	Voco	A3 HT	1709591
	Lava Ultimate	3M	A3 HT	N933658
			A2 HT	N372985
	Brilliant Crios	Coltene	A3 HT	I35186
	Cerasmart	GC	A3 HT	1702011
	Tetric CAD	Ivoclar Vivadent, Schaan, Liechtenstein	A3 HT	W93631
PMMA	VITA CAD-Temp	VITA Zahnfabrik	2M2	CE 0124
	Telio CAD	Ivoclar Vivadent	A2 LT	N73354
Leucite glass-ceramic	IPS Empress CAD		A2 LT	R39335
			A2 HT	K24309
Lithium silicate glass-ceramic	IPS e.max CAD		A2 LT	R37085
			A3 LT	N73805
			A2 HT	T1888
	CELTRA Duo	Dentsply Sirona	A2 LT	18015733
Feldspar ceramic	VITA Mark II	VITA Zahnfabrik	A2	N502353

Abbreviations: CAD/CAM, computer-aided design/computer-aided manufacturing; PMMA, poly(methyl methacrylate; RBC, resin-based composite.
[a] A total of seven material types were considered: 1) regular light-cured RBCs, 2) bulk-fill light-cured RBCs, 3) CAD/CAM restoratives based on resin composites, 4) PMMA, 5) lithium silicate ceramics, 6) leucite glass-ceramics, and 7) feldspar ceramic.

180° field of view, thus mitigating the effects of optical interference associated with light collection sampling geometry. Irradiance at a wavelength range of 360–540 nm was individually collected at a rate of 16 records/second. The sensor was triggered at 20 mW.

Transmittance, Opacity and Absorbance

Transmittance (T) is defined as the ratio of transmitted irradiance (radiant power) to incident irradiance: $T = I(d)/I_0$, where $I(d)$ is the irradiance after the beam of light passes through the specimen of thickness d, and I_0 is the irradiance of the incident light. The inverse of transmittance is called *opacity* (O) ($T^{-1}=I_0/I(d)$). The negative decadic logarithm of the transmittance, that is, the decadic logarithm of the opacity, is the absorbance (A) ($-\log(T)=-\log(I(d)/I_o)$), where absorbance stands for the number of photons absorbed. Being defined as ratios of irradiance values, T, O, and A are dimensionless.

Statistical Analysis

A Shapiro-Wilk test verified the normal distribution of the data. A multivariate analysis (general linear model) assessed the effects of various parameters as well as their interaction terms on the transmitted irradiance and optical parameters. The partial eta-squared statistic reports the practical significance of each term based on the ratio of the variation accounted for by the effect. Larger values of partial eta-squared indicate a greater amount of variation accounted for by the model effect, to a maximum of one. In all statistical tests, p-values < 0.05 were considered statistically significant when using SPSS software (Version 24.0, SPSSS Inc, Chicago, IL, USA).

RESULTS

The incident irradiance at the applied curing conditions amounted to 1174.1 (12.4) mW/cm^2. The transmitted irradiance through 2-mm-thick specimens varied between 471.0 ± 0.4 mW/cm^2 (flowable bulk-fill resin composite, Venus, universal) and 60.4 ± 0.1 mW/cm^2 (CAD/CAM resin composite, VITA Enamic). This denotes a drop in irradiance of 59.9% to 94.9% when light is passing through diverse restorative materials. In comparison, the attenuation of light through the tooth structure of the same thickness was 89.4% (transmitted irradiance = 124.6±36.7 mW/cm^2).

In the material range described earlier (Venus to VITA Enamic), the absorbance varied between 0.40 ± 0.02 and 1.29 ± 0.03, and the opacity between 2.52 ± 0.11 and 19.56 ± 1.13 (Table 2). The related optical properties of the tooth structure of the same thickness were 1.0 ± 0.03 and 10.5 ± 3.3, respectively.

A very strong influence of the parameter *material* was identified on the transmitted irradiance $I(d)$ ($p<0.001$; partial eta squared, $\eta_P^2=0.953$), T ($p<0.001$; $\eta_P^2=0.951$), A ($p<0.001$; $\eta_P^2=0.925$), and O ($p<0.001$; $\eta_P^2=0.886$), while the effect of the parameter *material type* was not significant ($p=0.079$, $p=0.05$, $p=0.05$, $p=$and 0.051, respectively).

Individual shades (A2, A3, 2M2, and U), irrespective of the chemical composition and structure of the analyzed materials, have been identified as having a highly significant influence on all determined optical parameters ($p<0.001$; $\eta_P^2=0.461$ for $I(d)$; 0.479 for T; 0.393 for A; and 0.361 for O).

The singular effect of shade (A2 and A3) on the transmitted irradiance for a given chemical composition and structure of a material can be directly observed in the light-cured RBCs G-eanial and Gradia Direct Anterior, the CAD/CAM RBC Lava Ultimate, and the lithium disilicate glass-ceramic IPS e.max CAD. Accordingly, light was attenuated significantly stronger in specimens of shade A3 compared with A2, in all aforementioned material types. Note, however, that difference in light attenuation owing to a difference in shade was higher in the glass-ceramic (relative change=29.9%) compared with the RBCs (15.6% Lava Ultimate, 13.2% G-eanial and 11.9% Gradia Direct Anterior).

The individual effect of translucency on the transmitted irradiance for a given shade (A2) was gathered in the leucite glass-ceramic IPS Empress CAD and the lithium disilicate glass-ceramic IPS e.max CAD (Table 2). The comparison indicates a strong attenuation of light in low translucent (LT) compared to the high translucent (HT) specimens. While the transmitted irradiance was higher through the leucite glass-ceramic, the difference in transmitted irradiance between HT and LT formulations was higher in the lithium disilicate glass-ceramic (49.72% vs 39.25% in the leucite glass-ceramic).

Figure 1 illustrates the exponential decrease of the transmitted irradiance through the tooth structure as a function of specimen thickness.

The direct comparison of 2-mm-thick tooth specimens with the analyzed restorative ceramics and glass-ceramics (Figure 2) emphasizes statistically similar transmitted irradiances through the tooth structure and the materials IPS e.max CAD, LT, A2 and CELTRA Duo, LT, A2. Compared with the tooth structure, significantly lower light transmittance was identified in IPS e.max CAD, LT, A3, while significantly higher light transmittance was found in all other materials. In the same material group presented in Figure 2, the opacity was significantly highest in the lithium disilicate glass-ceramic IPS e.max CAD, LT, A3, and the tooth structure.

Figure 3 illustrates graphically, in descending order, the transmitted irradiance through all analyzed RBC materials, both light-cured and CAD/CAM, in comparison to 2-mm-thick tooth structure specimens. A large range of RBC materials, comprising the material interval Charisma A3 (mean transmitted irradiance=92.33 mW/cm^2) to Telio CAD, A2 (170.6 mW/cm^2), showed a statistically similar transmitted irradiance to the tooth structure.

DISCUSSION

The present study quantifies the attenuation of light when traveling through different types of restorative materials of a predetermined thickness of 2 mm.

Table 2: *Transmittance, Absorbance, and Opacity as a Function of Material and Material Type (Mean and Standard Deviation)*[a]

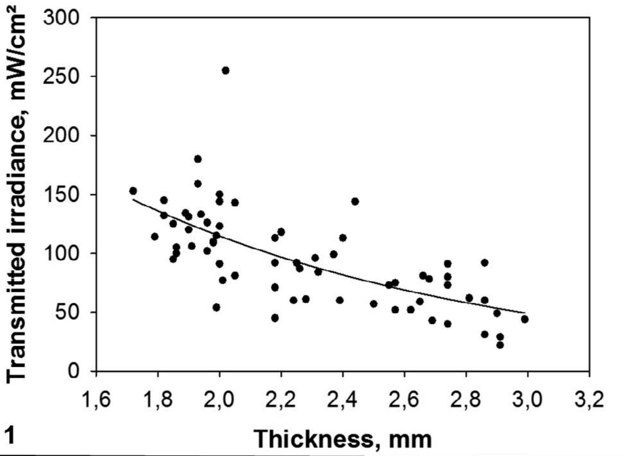
Material	Type	Transmittance		Absorbance		Opacity	
FiltekTM Supreme XTE, A3	Resin composite (LC)	0.02 A	0.001	1.61	0.01	40.46	1.79
VITA Enamic, 3M2	Resin composite (CAD/CAM)	0.05 A	0.004	1.29	0.03	19.56	1.13
IPS e.max CAD, LT, A3	Lithium silicate glass-ceramic	0.08 AB	0.004	1.12	0.01	13.09	0.37
Charisma A3	Resin composite (LC)	0.08 AB	0.001	1.11	0.02	12.86	0.44
Sonic Fill 2 A3	Resin composite (LC)	0.08 AB	0.001	1.09	0.01	12.24	0.25
FiltekTM Supreme XTE flow	Resin composite (LC)	0.08 AB	0.024	1.10	0.01	12.48	0.39
XR V Herculite A3	Resin composite (LC)	0.08 AB	0.01	1.07	0.01	11.80	0.33
G-aenial A3	Resin composite (LC)	0.09 BC	0.001	1.06	0.01	11.52	0.20
Synergy D6 A3/D3	Resin composite (LC)	0.09 BC	0.001	1.04	0.01	10.92	0.21
Gradia Direct A3	Resin composite (LC)	0.09 BC	0.01	1.03	0.02	10.77	0.55
G-aenial A2	Resin composite (LC)	0.10 BC	0.001	1.00	0.01	10.00	0.17
Enamel+Dentin	Enamel+Dentin	0.10 BC	0.03	1.00	0.12	10.51	3.27
Gradia Direct A2	Resin composite (LC)	0.11 BC	0.01	0.98	0.02	9.48	0.38
Filtek Z250 A2	Resin composite (LC)	0.11 BC	0.01	0.96	0.02	9.25	0.29
IPS e.max CAD, LT, A2	Lithium silicate glass-ceramic	0.11 BCD	0.001	0.96	0.01	9.16	0.30
Luxacam Composite, HT, A3	Resin composite (CAD/CAM)	0.11 BCDE	0.001	0.95	0.01	8.92	0.18
CELTRA Duo, LT, A2	Lithium silicate glass-ceramic	0.12 CDEF	0.01	0.92	0.04	8.32	0.75
Grandio Blocs, LT, A3	Resin composite (CAD/CAM)	0.13 CDEF	0.01	0.90	0.04	7.95	0.71
VITA CAD-Temp, 2M2	Resin composite (CAD/CAM)	0.14 DEF	0.01	0.85	0.02	7.06	0.36
IPS Empress CAD, LT, A2	Leucite glass-ceramic	0.15 DEFG	0.01	0.84	0.03	6.89	0.51
Lava Ultimate, HT, A3	Resin composite (CAD/CAM)	0.15 DEFG	0.01	0.84	0.02	6.84	0.26
Telio CAD	Resin composite (CAD/CAM)	0.15 DEFGH	0.01	0.84	0.01	6.91	0.13
Filtek One A3	Resin composite (LC)	0.15 EFGH	0.01	0.83	0.02	6.83	0.35
Brilliant Crios, HT, A3	Resin composite (CAD/CAM)	0.16 FGH	0.01	0.81	0.01	6.42	0.12
Cerasmart, HT, A3	Resin composite (CAD/CAM)	0.18 GHI	0.01	0.75	0.02	5.62	0.24
Lava Ultimate, HT, A2	Resin composite (CAD/CAM)	0.18 HI	0.01	0.74	0.03	5.54	0.36
Vita Mark II, A2	Feldspar ceramic	0.20 I	0.01	0.71	0.02	5.18	0.21
Tetric CAD, HT, A3	Resin composite (CAD/CAM)	0.20 I	0.00	0.70	0.01	5.02	0.07
ADMIRA Fusion X-tra, U	Resin composite (LC)	0.2 IJ	0.01	0.68	0.02	4.76	0.13
IPS e.max CAD, HT A2	Lithium silicate glass-ceramic	0.21 IJ	0.01	0.67	0.01	4.66	0.09
IPS Empress CAD, HT, A2	Leucite glass-ceramic	0.24 J	0.001	0.63	0.01	4.21	0.04
SDR U	Resin composite (LC)	0.29 K	0.01	0.53	0.02	3.42	0.13
Venus U	Resin composite (LC)	0.40 L	0.02	0.40	0.02	2.52	0.11

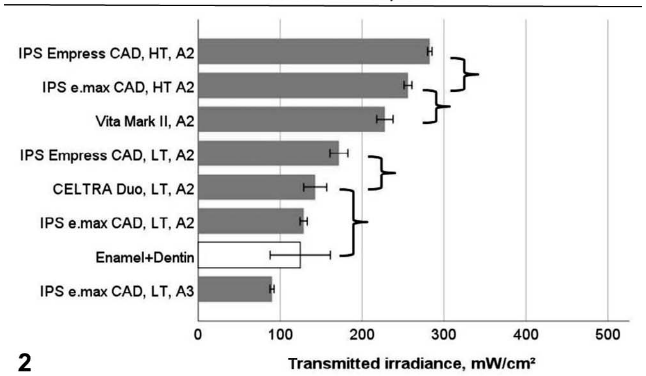
Abbreviations: CAD/CAM, computer-aided design/computer-aided manufacturing; HT, high translucency; LT, low translucency; LC, light cured.
[a] *Material description followed in the sequence brand, followed by translucency (LT or HT, if applicable) and shade. Data are arranged in ascending order of transmittance, descending order of absorbance, and opacity. Letters indicate statistically homogeneous subgroups for transmittance (Tukey honestly significant difference test, α=0.05).*

This thickness was chosen to allow for a direct comparison among a large variety of direct and indirect restoratives that might be involved in light curing during the restorative procedure and is due to the need for curing regular RBCs in increments that should not exceed 2 mm. The comparison of the optical properties among tooth and material specimens refers only to this thickness.

The light transmission through light-cured RBCs and the tooth structure has direct clinical implications, such as selecting an appropriate curing technique. While there is no experimental evidence, clinicians are often taught to only pre-cure the lowest increment when incrementally reconstructing a deep cavity, based on the estimate that the lowest increment will receive enough light when curing the upper increments or when curing through the tooth structure. The latter is recommended when completing the restoration.

The present study gives a comparison of the light transmittance through some representative regular micro- and nanohybrid light-cured RBCs (Table 2) in the clinically most commonly used shades (A2, A3), thus identifying light transmitted irradiances rang-





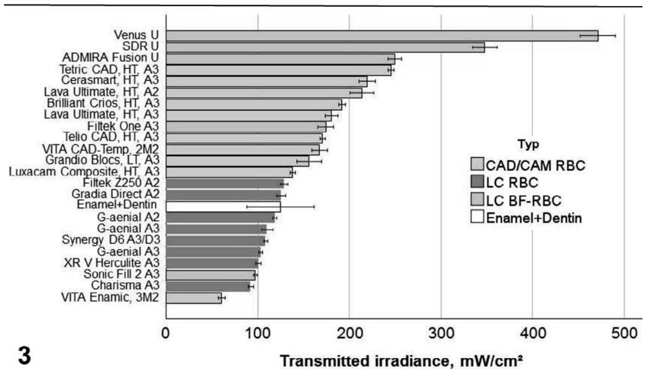


Figure 1. *Transmitted irradiance through the tooth structure (enamel + dentin) as a function of specimen thickness.*

Figure 2. *Transmitted irradiance through diverse ceramics and the tooth structure for 2-mm-thick specimens.*

Figure 3. *Transmitted irradiance through diverse resin composites (light-cured regular, light-cured bulk-fill and CAD/CAM) and tooth structure for 2-mm-thick specimens.*

ing from 92.32 ± 3.21 mW/cm^2 (Charisma, A3) to 128.33 ± 4.04 mW/cm^2 (Filtek Z250, A2). The indicated values represent the maximal irradiance recorded at the bottom of 2-mm-thick specimens during curing for 20 seconds. Converted to radiant exposure (incident irradiance × exposure time), the allocated values to underlying increments are 1.8 to 2.5 J/cm^2. Corroborated with the radiant exposure values indicated in the literature for sufficient polymerization in regular RBCs (21-24 J/cm^2),[18,19] the light transmitted through the upper increment may not be sufficient to compensate for a short pre-curing of the underlying increment. Thicker RBC layers, as may occasionally occur in a clinical situation during restoring a cavity, are even completely impermeable to light.[20] Note that the majority of RBCs,[20,21] including all light-cured materials analyzed in the present study, become progressively more translucent during polymerization, thus allowing more light to be transmitted through the 2-mm-thick specimens toward the end of the exposure time. Changes in translucency during polymerization are related in large part to the monomer reactivity and particularly to the filler/resin refractive index mismatch and their interface.[5,22,23] The measured transmitted irradiances through RBCs are similar to values measured through the tooth structure (enamel and dentin) of the same thickness (124.55±36.73 mW/cm^2). The high standard deviation is ultimately related to the diversity of the tooth structure as well as to the different fraction of enamel and dentin in the selected specimen, as it represents the real anatomy of the tooth. This enables quantification of light transmission as it will occur in a clinical situation. It is noteworthy that the transmitted irradiance through 3-mm-thick tooth specimens is lowered to insignificant values (25 mW/cm^2) while following an exponential decrease with the thickness. It should be emphasized that the incident irradiance within the curing conditions of the present study amounted to 1174.1 ± 12.4 mW/cm^2. The indicated transmitted irradiances will be even lower when using LCUs of lower irradiance, enhancing the exposure distance or changing the angulation of the LCU, as might occur in a clinical situation. All of these aspects raise questions about the benefit of additional polymerization through the tooth structure and limit it to a thermal effect.

To simulate clinical treatment, measurements were done on a dehydrated tooth structure. This procedure encompassed a 10-second exposure to the air stream followed by a period of 5 minutes in air, which was used to standardize the position of sample and LCU previous to measurement. Dehydration was identified to reduce the translucency of the tooth structure as a result of an increased difference in refractive indexes between the enamel prisms and the surrounding medium when water is replaced by air.[24] The reduction in translucency was quantified for enamel at 82% of the value measured in wet

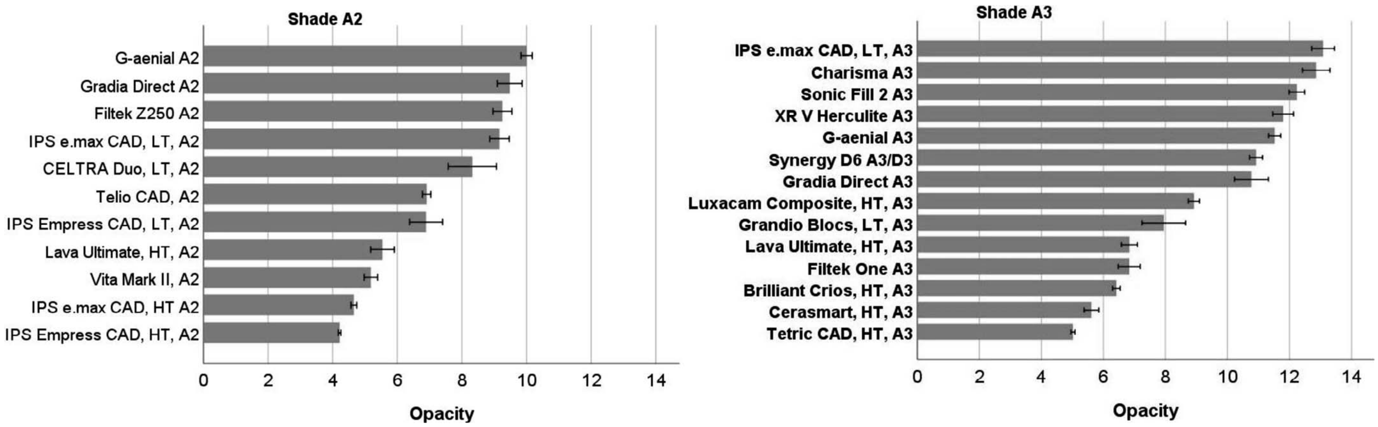


Figure 4. *Opacity of the analyzed materials grouped for the shades A2 (left) and A3 (right).*

enamel,[24] an aspect that needs to be considered when translucency is measured, other than in the present study, for esthetic purposes. Moreover, the chosen period of 5 minutes for drying the specimens before measurement was based on the fact that the assumptive water content change during drying of human enamel samples does not alter optical measurements above 5 minutes and up to 48 hours after specimens were taken out of the water.[25]

As for the analyzed bulk-fill RBCs, significantly higher light transmittance has been identified through 2-mm increments, except for Sonic Fill 2 A3, which performed similarly to regular RBCs and the tooth structure. It has already been shown that bulk-fill RBCs permit light transmission even in 4-mm-thick increments that may amount to up to 24% of the incident blue light,[26] which explains the good polymerization in depth of such materials. The reasons for enhanced light transmission in bulk-fill RBCs is mostly attributed to a reduced amount of pigments and enhanced filler sizes that lower the total interfacial area between the filler and matrix, reducing scatter.[5]

For comparative purposes, a series of modern CAD/CAM RBCs as well as two temporary, PMMA-based materials were studied. The transmitted irradiance through CAD/CAM RBCs and PMMA-based materials (p=0.90) as well as through each material category and the tooth structure (p=0.16 and p=0.149, respectively) were similar. Compared with light cured RBCs, transmitted irradiance was higher through CAD/CAM RBCs and PMMA-based materials (p<0.001, 0.024). Within the CAD/CAM RBCs material category, however, the variation in light transmission was high (60.4 to 245.2 mW/cm^2) and was due to differences in microstructure, pigments, chemical composition of the resin and filler, and filler morphology. It followed the sequence VITA Enamic < Luxacam Composite < Grandio Blocs < Lava Ultimate A3 and Brilliant Crios < Lava Ultimate A2 and Cerasmart < Tetric CAD. Note that all materials, except for VITA Enamic and Luxacam Composite, were analyzed in the HT version, thus explaining the ranking. The latter material category comprises a polymer infiltrated ceramic network material (VITA Enamic) with a three-dimensional interconnected dual network structure[27] that differs from the structure of the other analyzed CAD/CAM RBCs, in which only the polymer matrix phase is continuous, while fillers of different sizes and morphology are dispersed in the matrix.[28] The organic phase in all CAD/CAM RBCs is composed of dimethacrylates, which consist of either a mixture of urethane dimethacrylate (UDMA) and triethylene glycol dimethacrylate (TEGDMA) in VITA Enamic[27] or variations of UDMA, TEGDMA, bisphenol a glycol dimethacrylate (Bis-GMA), and ethoxylated bisphenol a dimethacrylate (Bis-EMA) in the other materials. The inorganic phase amount is highest in VITA Enamic (86 wt% or 75 vol%) and Grandio Blocks (86 wt%), being followed by Lava Ultimate (86 wt%) while varying between 61 wt% to 71.1 wt% in the other materials. This variation is mostly reflected in the light transmittance ranking of the materials. Significant variations are also identified in the chemical composition of the fillers, which is specified as a feldspar ceramic (predominant element silicon, followed by aluminum, potassium, sodium, and inclusions of yttrium) in VITA Enamic,[27] silicon and zirconium oxide in Lava Ultimate, and silicon oxide and barium glass in the other materials. An increased scattering, and thus a lower light transmittance, must be attributed to fillers containing elements of a higher atomic number. In addition, radiopaque agents,[29-31] which are introduced to improve the radiopacity of dental RBCs, also include elements with a high atomic number and may thus contribute to an increased scattering as well.

As for both analyzed temporary PMMA materials, their optical parameters were statistically similar (p=0.99) and lined up well in the sequence of the CAD/CAM RBCs. Similar light transmittances have been identified in VITA CAD-Temp and Grandio Blocs (p=0.161) as well as in Telio CAD and Lava Ultimate A3 (p=0.373).

In the analyzed CAD/CAM ceramics and glass-ceramics, the variation in translucency (HT or LT) showed a higher impact on light transmission than the shade (A2 or A3) or the ceramic systems (feldspar ceramic, leucite and lithium disilicate glass-ceramic). In ceramic systems, translucency in general decreases with increasing crystalline content.[32] Apart from the fact that the optical properties of each constituent of a system must be considered individually, it can be stated that the crystalline content in the analyzed ceramic systems increases in the sequence feldspar ceramic (30 vol%[32]), leucite glass–ceramics (35 vol%[32]), and lithium disilicate glass-ceramic (70 vol%[33]). At a given translucency (HT or LT) and shade, this sequence is also reflected in the range of transmitted irradiances (Figure 2). Within one ceramic system, the translucency (HT or LT) seems to be regulated by adjustments in the sintering program as well as by controlling crystal nucleation and growth in glass-ceramics, which allows intervention in the crystal type and size.[32] Interestingly, the present analysis identified larger differences in light transmittance between HT and LT versions in the lithium disilicate glass-ceramic compared with the leucite glass-ceramic.

A large portion of the light attenuation through a material is due to reflection at the incident surface.[34] The surface-reflection ratio (fraction of incident radiance that is reflected at the interface), as calculated by Watts and Cash[34] by considering the shift in absorbance-path length relation from its theoretical origin, amounts to 30% to 90%,[34] while recently, values of 11% to 27% were determined in CAD/CAM RBCs.[28] The reflection of light, when incident on the interface between air and material, varies with the refractive index of optical media (Fresnel equation); however, a large part of the reflection must be related to surface roughness. Since all the specimens in the present study were polished following an identical protocol, the surface-reflection ratio was also related to the material's ability to be polished. Considering that the angle of incidence was constant, since the LCU was placed in a standardized manner, perpendicular to the specimens' surface, by means of a mechanical arm, the transmitted light might be considered a material characteristic, determined not only by the optical properties of constituents and microstructure but also by the inherent surface roughness.

The results of the present study clearly indicate that the light passing through the upper layers of an incrementally restored cavity with light-cured RBCs is insufficient to complete the polymerization of an undercured lowest increment; consequently, each increment should be *ab initio* adequately cured. Moreover, the attenuation of light through various indirect restoratives and the restoration thickness need to be considered clinically when deciding the type of luting RBCs to be used. The outcome of an additional curing through the tooth structure at the end of the restorative process to compensate for insufficient polymerization may be very low and is dependent on the thickness of the tooth structure. In this context, it must be emphasized that transmitted irradiance decreases exponentially with tooth structure thickness and is lowered to insignificant values in 3-mm-thick tooth walls.

CONCLUSIONS

The attenuation of light when passing through diverse 2-mm-thick restorative materials is high and varies between 59.9% to 94.9%; thus, deficits in polymerization are difficult to compensate for by additional light exposure at the end of the restorative process. The values measured for the tooth structure are identified toward the upper end of this range (89.4%). Light attenuation differs significantly by material within each shade category and by shade category within each analyzed material. Light attenuation was determined by shade and translucency rather than by the type of restorative material. Therefore, all null hypotheses are rejected.

Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of the Department of Operative Dentistry and Periodontology, University Hospital, Ludwig-Maximilians-Universität München. The approval code for this study is 19-118 KB.

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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