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Optische Eigenschaften dentaler monolithischer CAD/CAM - Materialien im Hinblick auf deren Eignung zur adhäsiven Befestigung

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Für meine Familie

Inhaltsverzeichnis:

1. Einleitung:

Der in unserer Gesellschaft gestiegene Anspruch an Ästhetik in der Zahnmedizin sorgte für eine rasante Zunahme an unterschiedlichen zahnfarbenen Materialien zur Herstellung eines natürlich wirkenden, quasi unsichtbaren, Zahnersatzes. Eine genaue Kenntnis über diese modernen Materialen zu besitzen, ist für niedergelassene Zahnärzte eine notwendige Voraussetzung um die hohen Erwartungen ihrer Patienten hinsichtlich des funktionellen aber auch optischen Behandlungsergebnisses erfüllen zu können.

Insbesondere die monolithischen CAD/CAM (computer-aided design / computer-aided manufacturing) – Materialien erfreuten sich zunehmender Beliebtheit in den vergangenen Jahren. Zum einen, weil sie aufgrund ihrer industriellen Fertigung deutlich weniger Materialfehler (z.B. entstandene Defekte beim Sintervorgang einer Keramik, oder bei der Polymerisation von Kunststoff) vorweisen als individuell, manuell hergestellter Zahnersatz. Zum anderen, weil die direkte Produktion in der Praxis eine erhebliche Zeitersparnis zur Folge hat. Doch diese Unabhängigkeit von einem Zahntechniker, legt die Verantwortung für das ästhetische und funktionelle Ergebnis der Arbeit gänzlich in die Hände des Behandlers. Fundierte Kenntnis über die optischen und mechanischen Eigenschaften dieser Materialien ist daher notwendig um sie erfolgreich im Praxisalltag einsetzen zu können.

Die Ästhetik einer Restauration und die Möglichkeit einer adhäsiven Befestigung mit lichthärtenden Materialien wird entscheidend von der Transluzenz der Restauration determiniert. Darunter versteht man im Wesentlichen die Materialeigenschaft die angibt, wieviel Licht des sichtbaren Spektrums ein Material durchlässt, anstelle es zu reflektieren oder zu absorbieren[A11-14]. Somit umfasst der Begriff Transluzenz jede Stufe zwischen kompletter Opazität und völliger Transparenz[A10]. Transluzenz sorgt einerseits für ein lebendiges Aussehen des Zahnersatzes, da der natürliche Zahnschmelz ebenfalls eine gewisse Lichtdurchlässigkeit besitzt[A4-6], und das menschliche Auge, für Unterschiede in der Helligkeit sensibler ist, als für Farbton- und Farbsättigungsdifferenzen.[A18-20] Anderseits ist diese Lichtdurchlässigkeit unverzichtbare Voraussetzung für eine suffiziente Befestigung mittels eines lichthärtenden Befestigungszements und somit für eine erhöhte Langzeitstabilität der Restauration,[B19,20] da die Konversionsrate sowohl lichthärtender als auch dualhärtender[B34] Zemente maßgeblich davon abhängt.[B27,41,42] Im klinischen Alltag kommen konventionelle Befestigungszemente auf Glasionomer- oder Zinkphosphatbasis zwar immer noch häufig zum Einsatz, doch reduzieren diese nicht nur das optische Ergebnis der Restauration aufgrund ihrer Opazität, sondern nachweislich auch die Langzeitstabilität von Restaurationen aus Glaskeramik[B19,20]. Folglich lassen Hersteller ihre Materialien je nach Indikation zwar oftmals großzügig für eine konventionelle Zementierung zu, empfehlen aber durchaus die Befestigung mittels eines dual- oder lichthärtenden Zements. Für den erfolgreichen Einsatz letztgenannter Zemente sind Kenntnisse über die Lichtdurchlässigkeit der CAD/CAM – Materialien unverzichtbar.

Die in dieser Arbeit getesteten neun, klinisch bewährten, Materialien decken ein großes Indikationsgebiet für die Anwendung dentaler CAD/CAM – Materialien in der Praxis ab. Dabei wurde ein breites Spektrum an unterschiedlichen Materialklassen untersucht:

- Leuzit-Glaskeramik **(IPS Empress® CAD)**
- Lithium-Disilikat-Glaskeramik **(IPS e.max® CAD)**

- durch Zirkonbeigabe modifizierte Lithiumsilikat-Keramik **(Celtra® Duo)**
- Feldspatkeramik **(VITABLOCS® Mark II)**
- kunststoffbasiertes Komposit mit Nanopartikel-Füllkörpern **(LAVA™ Ultimate)**
- IPN - Materialien (**I**nter**p**enetrated **n**etwork: durch Polymernetzwerk verstärktes Keramiknetzwerk**, VITA Enamic® und ein experimentelles Material)**
- Langzeitprovisorien auf Polymethylmethacrylat (PMMA)-Basis **(Telio® CAD und VITA CAD-Temp®)**

Das Indikationsspektrum der getesteten Materialien umfasst hauptsächlich Restaurationen im Einzelzahnbereich, von Inlays über Implantat-Abutments bis hin zu Vollkronen. Das breiteste Anwendungsfeld besitzt dabei die Lithium-Disilikat-Glaskeramik IPS e.max® CAD, welche als einzige der getesteten Keramiken nach Restaurationsherstellung zum definitiven Auskristallisieren einen zusätzlichen 25-minütigen Brand bei 840 – 850 °C benötigt, wodurch eine höhere mechanische Biegefestigkeit erreicht wird und somit auch dreigliedrige Brücken für den druckbelasteten Seitenzahnbereich hergestellt werden können (Herstellerangabe Ivoclar Vivadent AG, Schaan/Liechtenstein; 02/2017; *www.ivoclarvivadent.de/zoolu-website/media/document/1167/IPS+e-max+Zahnarzt+?f=1*). Die Leuzit-Glaskeramik IPS Empress® CAD, erreicht ebenfalls hohe Werte für Biegefestigkeit, da durch eine gleichmäßige Verteilung von Leuzit-Kristallen in der Glasmatrix Mikrorisse abgelenkt werden und somit eine Festigkeitssteigerung der Keramik erzielt werden kann[A20]. Zu den neuartigen IPN (Interpenetrated network) - Materialien zählen sowohl das experimentelle Material, als auch VITA Enamic®. Ihre Charakteristik ist die Kombination aus einem Feldspatkeramikanteil, welcher in ein Polymer-Netzwerk integriert ist[A58], mit dem Ziel ein Material zu entwickeln, das zwar die Stabilität von Keramik, aber die reduzierte Abriebfestigkeit von Kunststoff besitzt und somit den natürlichen Zahnschmelz des Antagonisten kaum beschädigt[A59]. Zudem wurden in dieser Studie eine monochromatische Feinstruktur-Feldspatkeramik (VITABLOCS® Mark II), eine durch Zirkonbeigabe modifizierte Lithium-Silikat-Keramik (Celtra® Duo), sowie ein kunststoffbasiertes Komposit mit Nanopartikeln (LAVA™ Ultimate) getestet, aus denen Restaurationen bis hin zu Vollkronen auch für den Seitenzahnbereich hergestellt werden können - eine suffiziente adhäsive Befestigung vorausgesetzt. Unterschiedliche Studien schreiben Provisorien aus den beiden CAD/CAM – Materialien auf PMMA-Basis signifikant bessere mechanische Eigenschaften zu, als konventionell hergestellten Provisorien[B1-5], wodurch sich diese Materialien vor allem bei der Herstellung von Langzeitprovisorien einer zunehmenden Beliebtheit erfreuen und in diese Studien mitaufgenommen wurden[B6].

Die mechanischen Eigenschaften dieser modernen CAD/CAM-Materialien sind häufig Gegenstand wissenschaftlicher Untersuchungen, wohingegen kaum Informationen über die optischen Eigenschaften dieser Materialien verfügbar sind.

Ziel dieser Arbeit - bestehend aus zwei publizierten Fachartikeln - war es, die Auswirkung von Schichtstärke, Materialzusammensetzung, Oberflächenrauigkeit und Polymerisationsbedingungen auf die Transluzenz und Blaulichtdurchlässigkeit moderner, im klinischen Alltag häufig eingesetzter CAD/CAM – Materialien zu untersuchen. Hierbei beschäftigte sich die erste Studie mit der absoluten Transluzenz der CAD/CAM – Materialien in Abhängigkeit von ihrer Schichtstärke und Oberflächenrauigkeit, also hinsichtlich der optischen Eigenschaften der Keramiken und zwar nicht nur im hochglanzpolierten Zustand, sondern auch im Zustand einer angerauten Oberfläche, wie man sie nach einer gewissen Tragezeit erwartet. In der zweiten Studie hingegen, wurde die Auswirkung der Polymerisationsbedingungen, wie Abstand der Lampe zur Materialoberfläche und verschiedene Irradianzen ausschließlich auf die Durchlässigkeit für Blaulicht derselben Materialien gleicher Schichtstärke untersucht, um Rückschlüsse auf das Ausmaß an Polymerisationslicht, welches bei der Befestigung der Restauration den Zement erreicht, ziehen zu können. Dabei wurden ausschließlich LT (low-translucency) CAD/CAM – Blöcke der Farbe A2 der VITA Farbskala (oder entsprechende Nomenklatur) getestet, die im Gegensatz zu den HT (high-translucency) Blöcken aus einer erhöhten Anzahl kleinerer Kristalle bestehen[A32,46]. Da zudem von Seiten des Herstellers auf die unproblematische Individualisierung und Ausbesserung der CAD/CAM – Restaurationen mittels zugehörigem Komposit-Füllungsmaterial (Filtek Supreme™ XTE für LAVA™ Ultimate und Tetric EvoCeram® für Telio® CAD[A20,21]) ausdrücklich hingewiesen wird, wurden diese methacrylat-basierten Kunststoffe in der ersten Publikation zusätzlich hinsichtlich ihrer Rauigkeit und optischen Eigenschaften untersucht, nicht allerdings in der zweiten Studie, weil diese Materialien im Kontext dieser Arbeit lediglich als potentielles Reparatur-, respektive Modelliermaterial fungierten.

Informationen über die optischen Eigenschaften der neueren CAD/CAM - Materialien beschränken sich bislang meist auf Herstellerangaben. So soll Celtra® Duo, eine neue vom Fraunhofer-Institut entwickelte Materialart, durch die Zugabe von ca. 10 % Zirconium-Silikat aus ca. 4-fach kleineren Kristallen[A52] bestehen und somit über einen relativ erhöhten Anteil an Glasmatrix verfügen, was eine erhöhte Transparenz zur Folge haben soll[A53].

Auch den neuartigen CAD/CAM – Materialien aus kunststoffbasiertem Komposit (LAVA™ Ultimate) schreibt man erhöhte Transluzenzwerte zu. Diese bestehen laut Hersteller aus Keramikpartikeln in Nanogröße, welche in eine Kunststoffmatrix eingebettet sind[A54] und aufgrund ihrer Größe, die kleiner ist als die Wellenlängen des sichtbaren Lichts, weniger Lichtbrechung und Lichtbeugung zur Folge haben sollen[A42,56].

Ziel dieser experimentellen Arbeiten war es, die oben beschriebenen modernen monolithischen CAD/CAM – Materialien hinsichtlich ihrer Transluzenz und Durchlässigkeit für Polymerisationslicht bei einer klinisch relevanten Schichtstärke von 1 und 2 mm zu untersuchen. Dabei wurde in der ersten Studie folgende Nullhypothese aufgestellt: Schichtstärke, Oberflächenrauigkeit und Materialzusammensetzung haben keinen Einfluss auf die Transluzenz der getesteten Materialien.

Die zweite Studie untersuchte folgende Nullhypothese hinsichtlich ihres Wahrheitsgehalts: Materialzusammensetzung, Schichtstärke, Abstand der Polymerisationslampe von der Probenoberfläche und Polymerisationsmodus (1000 – 3200 mW/cm²) haben keinen Einfluss auf die Durchlässigkeit der Proben für Polymerisationslicht.

Die Ergebnisse der ersten Studie zeigen deutlich, dass sowohl Materialzusammensetzung als auch Oberflächenrauigkeit und Schichtstärke einen starken Einfluss auf die Transluzenz der getesteten CAD/CAM - Materialien haben. Die erste Nullhypothese musste somit verworfen werden. Eine Verallgemeinerung der optischen Eigenschaften aller Materialien einer bestimmten Substanzklasse ist allerdings nicht möglich, da auch innerhalb einer Substanzklasse signifikante Unterschiede erhoben werden konnten. Die Feinstruktur-Feldspatkeramik VITABLOCS® Mark II erzielte als einziges der getesteten Materialien bei allen Oberflächenbeschaffenheiten gleiche Transluzenzwerte.

Zudem ging aus der zweiten Studie deutlich hervor, dass Materialzusammensetzung, Schichtstärke und die Polymerisationsbedingungen die Blaulichtdurchlässigkeit signifikant beeinflussen, womit auch die zweite Nullhypothese abgelehnt werden musste. Dabei zeichneten sich VITABLOCS® Mark II und LAVA™ Ultimate durch die höchste Lichtdurchlässigkeit aus, wohingegen VITA Enamic® stark reduzierte Werte erzielte, und somit eine Befestigung mit dualhärtendem Zement, vor allem bei dickeren Restaurationen, empfehlenswert zu sein scheint. Die weiteren Ergebnisse der beiden Publikationen werden im Folgenden ausführlicher zusammengefasst.

1.1. Zusammenfassung (deutsch)

Ziel dieser Arbeit war es, moderne monolithische CAD/CAM – Materialien hinsichtlich ihrer Transluzenz und Blaulichtdurchlässigkeit zu untersuchen. In einer ersten Publikation wurde dabei die absolute Transluzenz (T%) in Bezug auf die variierenden Parameter „Materialart“, „Schichtstärke“ und „Oberflächenrauigkeit“ gemessen. Die Blaulichtdurchlässigkeit hingegen wurde in einer weiteren Studie in Bezug auf die Variablen „Materialart“, „Schichtstärke“, „Abstand der Polymerisationslampe von der Probenoberfläche“ und „Polymerisationsmodus“ ermittelt. Alle Werte wurden dabei mittels Spektrophotometrie erhoben (Lambda 35 Perkin Elmer; Perkin Elmer Inc., bzw. USB4000 Spektrometer, MARC System, Bluelight Analytics Inc, Halifax, NS, Canada). Die Oberflächenrauigkeit wurde mittels eines Oberflächenmessgeräts (MarSurf M 400; Mahr GmbH) durch Mittelwertbestimmung nach jeweils 6-maliger Probenmessung in unterschiedlichen Richtungen bestimmt. Die Auswertung der Ergebnisse erfolgte auf Grundlage der Daten, die durch eine ein- und mehrfaktorielle Varianzanalyse (ANOVA), Tuckey´s honest significance post-hoc-Test bzw. post hoc Scheffé – Test ($p<0.05$) gewonnen wurden. Des Weiteren wurde jeweils eine multivariante Analyse (allgemeines lineares Modell mit Eta-Quadrat-Statistiken) zur Evaluation der Größe des Einflusses der variierenden Parameter auf die absolute Transluzenz bzw. Blaulichtdurchlässigkeit durchgeführt.

Zusammenfassend lässt sich sagen, dass alle untersuchten Parameter einen hohen Einfluss auf die absolute Transluzenz sowie die Blaulichtdurchlässigkeit der getesteten Materialien haben. Von den auf dem Markt erhältlichen CAD/CAM – Materialien lieferten in beiden Studien LAVA™ Ultimate und VITABLOCS® Mark II die höchsten Transluzenzwerte. Lediglich für die experimentelle Keramik konnten im hochglanzpolierten Zustand noch höhere Werte gemessen werden, allerdings nur bezogen auf die absolute Transluzenz, nicht auf die Blaulichtdurchlässigkeit. Zudem verlor sich diese Eigenschaft rasant mit zunehmender Oberflächenrauigkeit.

Die in der Literatur öfters beschriebene höhere Transluzenz von Leuzit-Glaskeramik verglichen mit Lithium-Disilikat-Glaskeramik[A3,19,21] zeigte sich auch in diesen beiden Studien. So erzielte, im Falle einer polierten Oberfläche, IPS Empress® CAD höhere Werte als IPS e.max® CAD sowohl hinsichtlich absoluter Transluzenz als auch hinsichtlich Blaulichtdurchlässigkeit.

Bezogen auf die getestete, durch Zirkonbeigabe modifizierte, Lithiumsilikat-Keramik Celtra® Duo lässt sich festhalten, dass sich die vom Hersteller beschriebene erhöhte Transluzenz, in dieser Studie nur verglichen mit der Lithium-Disilikat-Glaskeramik IPS e.max® CAD bestätigte. Alle anderen CAD/CAM – Keramiken erzielten statistisch höhere Transluzenzwerte.

Bezogen auf den Praxisalltag demonstrierte diese Arbeit - trotz limitierter Übertragbarkeit der Ergebnisse einer in vitro-Studie auf die klinische Situation - zum einen erneut die Wichtigkeit einer Hochglanzpolitur der Restaurationen nach Herstellung, da bereits eine leichte Aufrauhung der Oberfläche die Transluzenz signifikant reduziert und das optische Ergebnis beeinflusst. Die Feldspatkeramik VITABLOCS® Mark II, stellte hierbei eine Ausnahme dar und lieferte bei jeder Oberflächenbeschaffenheit nahezu gleiche absolute Transluzenzwerte.

Zum anderen lässt sich für das Befestigen einer Restauration sagen, dass die mit zunehmender Schichtstärke rasant abnehmende Durchlässigkeit für Blaulicht beachtet werden muss. So kam es in dieser Studie bei Zunahme der Materialdicke von 1 auf 2 mm unabhängig vom Polymerisationsmodus zu einer Reduktion der durchgelassenen Lichtmenge von 48,1 bis 71,8 % (0 mm Abstand zwischen Polymerisationslampe und Probe). VITA Enamic® erzielte dabei bei beiden Schichtstärken, die niedrigsten Werte hinsichtlich Durchlässigkeit für Polymerisationslicht unter den getesteten CAD/CAM - Materialien. Somit sollte man bei der Befestigung von Restaurationen dickerer Schichtstärke einen dual-härtenden Zement vorziehen, vor allem bei Restaurationen aus VITA Enamic® der Farbe 3M2 oder dunkler. Zudem zeigte sich erneut die Wichtigkeit, die Polymerisationslampe beim Aushärten bestmöglich nahe an der Restaurationsoberfläche zu positionieren. Zwar reduzierte sich bei allen Materialien, die gemessene Menge an Blaulicht bei einer Abstandszunahme von 0 auf 2 mm nicht, nahm aber bei einer weiteren Zunahme auf 4 mm signifikant ab. Weitere Studien, im Idealfall mit fertig hergestellten Restaurationen aus den getesteten Materialen, sind nötig um weitere Informationen über die Transluzenz und Blaulichtdurchlässigkeit zu gewinnen, und somit genauere Rückschlüsse auf die optischen Eigenschaften und Polymerisationsbedingungen dieser modernen CAD/CAM – Materialien ziehen zu können.

1.2. Zusammenfassung (englisch)

The aim of this study was, to examine modern monolithic CAD/CAM materials regarding translucency and blue-light transmittance. Absolute translucency (T%) was evaluated in respect of varying parameters ‘material’, ‘thickness’ and ‘surface roughness’, whereas blue-light transmittance was analysed in respect of ‘material’, ‘thickness’, ‘curing unit distance to the specimen’ and ‘initial irradiance level (curing modes)’. Thereby, all values were raised by using spectrophotometry (Lambda 35 Perkin Elmer; Perkin Elmer Inc., and USB4000 spektrometer, MARC System, Bluelight Analytics Inc, Halifax, NS, Canada). The surface condition was analysed with a surface roughness measuring instrument (MarSurf M 400; Mahr GmbH) by determining an average roughness profile, after making 6 measurements in different directions.

The results were compared using one and multiple-way ANOVA, Tuckey’s honest significance difference post hoc test and Scheffé’s post hoc test ($p<0.05$), respectively. Furthermore, a multivariate analysis (general linear model with eta squared statistics) was performed, assessing the effect’s strength of the varying parameters on absolute translucency and blue-light transmittance.

In summary, it can be said, that all examined parameters had a high influence on absolute translucency as well as blue-light transmittance of all tested materials. Among the CAD/CAM materials, which are available on the marked, LAVA™ Ultimate and VITABLOCS® Mark II reached the highest values for translucency in both studies. Merely for the experimental IPN-material higher values could be raised, but only for absolute translucency not for blue-light transmittance. Moreover, this property could be attained only for polished specimens, not in case of a rough surface.

The higher translucency of lithium disilicate glass ceramic in comparison to leucite-reinforced glass ceramic, that is most frequently examined in the literature[A3,19,21], could also be confirmed in both studies. Thus, IPS Empress® CAD attained higher values for absolute translucency as well as blue-light transmittance, than IPS e.max® CAD, in case of a polished surface.

As far as the tested zirconia-modified lithium silicate ceramic Celtra® Duo is concerned, it can be noted, that the higher translucency, as stated by the manufacturer, could be confirmed in this study only in comparison to the lithium disilicate glass ceramic IPS e.max® CAD. All other tested CAD/CAM ceramics attained statistically higher values.

Despite the limited transferability of the results of an in vitro study to the clinical situation, this study demonstrated to the clinicians the importance of a sufficient high-gloss polishing of the restoration after milling, because even a slightly roughened surface significantly reduces translucency and therefore the esthetic outcome. Thereby the fine-structure feldspatic ceramic VITABLOCS® Mark II made an exception, attaining almost unchanged values for absolute translucency independent of the surface condition.

Moreover, as far as the cementation of a restoration is concerned, it can be stated, that the rapid decrease of blue-light transmittance, as thickness increases, has to be taken into account.

Thus, in this study, the amount of light that passes the specimen was reduced by 48.1 to 71.8 %, by raising the material thickness from 1 to 2 mm, independent of the initial irradiance level (0 mm exposure distance). VITA Enamic® attained the lowest values for light transmittance of all tested CAD/CAM - materials. Therefore, dual-cure resin cements should be preferred, when a rather thick restoration, especially in case of VITA Enamic® of the color 3M2 or darker, is inserted. Furthermore, once again the

importance of positioning the curing unit as near to the restorations surface as possible could be shown. Though, there was no material, that revealed a reduction of the amount of blue-light, when increasing the distance from 0 to 2 mm, a significant reduction could be determined in case of another increase to 4 mm.
Further studies, ideally examining completed restorations made of the tested materials, are necessary, to get more information about translucency and blue-light transmittance and thus to be able to draw more precise conclusions about the optical properties and curing conditions of these modern monolithic CAD/CAM materials.

1.3. Hinweis zu den Quellenangaben

Es ist zu beachten, dass sämtliche Quellenangaben für die im Text gekennzeichneten Zitate in den Literaturverzeichnissen der beiden Publikationen aufgelistet sind. Dabei wurden alle Quellenangaben, welche im Literaturverzeichnis der ersten Publikation *"Translucency of esthetic dental restorative CAD/CAM materials and composite resins with respect to thickness and surface roughness"* (Kapitel 2.1.) zu finden sind, mit dem Buchstaben A gekennzeichnet. Entsprechend ist eine Quellenangabe, welcher der Buchstabe B vorangeht, im Literaturverzeichnis der zweiten Publikation *"Blue-Light transmittance of esthetic monolithic CAD/CAM materials with respect to their composition, thickness, and curing conditions"* (Kapitel 2.2.) aufgelistet.

2. Publikationen:

2.1. Translucency of esthetic dental restorative CAD/CAM materials and composite resins with respect to thickness and surface roughness.

(J Prosthet Dent. 2015 Jun;113(6):534-40. doi: 10.1016/j.prosdent.2014.12.003.)

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CLINICAL IMPLICATIONS

Absolute translucency seems to be material specific, and no generalization relating to the different material classes can be made. Except for the ceramic VITA Mark II, all CAD/CAM ceramics demonstrated a greater decrease in translucency after roughening than did the resin-based materials, making sufficient polishing of the restoration essential.

ABSTRACT

Statement of problem. Little information is available about the translucency of monolithic CAD/CAM materials.

Purpose. The purpose of this study was to evaluate the translucency of restorative CAD/CAM materials and direct composite resins with respect to thickness and surface roughness.

Materials and methods. In total, 240 disk-shaped specimens (12 × 14 × 1 mm and 12 × 14 × 2 mm) of 3 different CAD/CAM glass ceramics (CELTRA Duo, IPS e.max CAD, IPS Empress CAD), a fine-structure feldspathic ceramic (VITA Mark II), a hybrid ceramic (VITA Enamic), a resin nanoceramic composite resin (LAVA Ultimate), an experimental (CAD/CAM nanohybrid composite resin), 2 interim materials (Telio CAD; VITA CAD-Temp), and 3 direct composite resins (Tetric EvoCeram; Filtek Supreme XTE; Tetric EvoCeram Bulk Fill) were fabricated (n=10). After 3 different surface pretreatments (polished, rough SiC P1200, or SiC P500), absolute translucency and surface roughness were measured using spectrophotometry and tactile profilometry. The influence of material type, thickness, and roughness on absolute translucency was analyzed using a multivariate analysis, 1-way ANOVA, and the Tukey HSD post hoc test (P<.05). Pearson correlations and statistical hypothesis tests were used to assess the results (P<.05).

Results. The effect of all tested parameters was significant among the materials (P<.05). The greatest influence on the measured translucency was thickness (partial eta squared ηP^2=.988), closely followed by material (.982), and the pretreatment method (.835). The surface roughness was strongly influenced by the pretreatment method (.975) and type of material (.941).

Conclusion. Thickness and surface roughness are major factors affecting the absolute translucency of adhesively luted restorations.

INTRODUCTION

Increased demand for esthetics in dentistry has led to an increase in the use of ceramic and tooth-colored composite resin restorations.[1] In particular, the CAD/CAM ceramics have enjoyed growing popularity.[2,3] Because more dentists work independently of a technician, they need to better understand the optical characteristics of dental materials in order to closely match them with those of the natural tooth.[4-6]

Translucency has been emphasized as one of the primary factors in controlling the esthetic outcome[7] because it makes ceramic and resin-based restorations appear more natural.[8,9] As translucency permits the passage of light and also disperses light, it could be described as a state between complete opacity and transparency,[10] the light being diffused rather than reflected or absorbed.[11-14] Errors in brightness among teeth are considered the most noticeable esthetic error[15-17] because the human eye is more sensitive to the differences in value (brightness) than hue or chroma.[18-20] In addition, the translucency of ceramics is closely related to the light transmission and polymerization efficiency of underlying resin-based luting agents.[21-23] However, little information is available about the translucent characteristics of contemporary CAD/CAM materials. Moreover, all current studies have analyzed the translucency of dental materials in a high-gloss polished condition, but not with a roughened surface such as would occur after a period of wear, or in the case of insufficient polishing after milling or occlusal adjustment.[24-28] Accurate knowledge of the relationship between translucency and thickness and surface roughness is fundamental to improving the esthetic outcome of dental restorations.[22,29,30]

The null hypotheses tested were that material thickness would not affect translucency; that the pre-treatment method (roughening) would not affect translucency; and that the material type would not affect translucency.

MATERIAL AND METHODS

The dental materials evaluated in the present study are listed in Table 1. A total of 240 disk-shaped, rectangular specimens (12 mm width × 14 mm length) were fabricated and analyzed with a spectrophotometer and a tactile profilometer, both popular methods of measuring translucency and surface roughness.[31-35] For all tested materials, color A2 blocks were chosen. The CAD/CAM blocks were cut (Secotom-50; Struers) under water cooling to produce 10 disks with a thickness of 1 or 2 mm. The specimens were fixed to a plate index and polished sequentially by using a series of diamond grinding sheets (up to SiC P2000) on a grinding machine (Abramin; Struers). The grinding and polishing procedures were performed on both sides of the specimens. The definitive thickness was determined with a digital micrometer (Mitutoyo IP65; Mitutoyo) with an accuracy of ± 0.05 mm.

After production, all specimens were ultrasonically cleaned in distilled water (Sonorex RK102H; Bandelin electronic) and additionally cleaned with isopropanol to remove grease residue. Subsequently, the specimen surface was roughened on one side by using grinding sheets with a grain size of SiC P1200 or P500 and measured again. A silicone mold (12 × 14 × 1 or 2 mm) was used to produce disk-shaped specimens of the light-polymerizing composite resins. Each specimen was polymerized 4 times for 20 seconds on each side with an LED polymerization unit (Freelight 2; 3M ESPE, 1226 mW/cm^2) to ensure complete polymerization and subjected to the same surface treatment procedure. Altogether, 3 different CAD/CAM glass ceramics, a fine-structure feldspathic ceramic, a hybrid ceramic, a nano-ceramic composite resin, an experimental CAD/CAM nanohybrid composite, and 2 interim materials (PMMA) were analyzed.[36] Furthermore, because the manufacturer recommends characterization of the CAD/CAM restoration with the recommended composite resin (Filtek Supreme

XTE for LAVA Ultimate and Tetric EvoCeram for Telio CAD),[37,38] materials that should ensure color matching to the surrounding restoration, were also tested. One bulk-fill composite resin was added to the study to broaden the spectrum with add a substance with a relatively high translucency.[39]

Translucency measurements

A quantitative measurement of absolute translucency was made by measuring the total transmission of light through the specimen. A spectrophotometer (Lambda 35 Perkin Elmer; Perkin Elmer Inc) with a dual beam system was used, whereby a sensor records the light transmission in comparison to the light intensity from a split beam. The light source provided a wavelength varying between 400 and 700 nm. At first, the light quantity was measured with no specimen in the optical path ($Luminance_{source}$) before each measurement and served as the baseline value. Then the luminance ($Luminance_{specimen}$) was recorded and calculated for each specimen (UV Win LabTM 2.8; Perkin Elmer Inc): $T\% = (L_{specimen} / L_{source}) \times 100$.

A value T% = 100 indicates the specimen is transparent and T% = 0 that the material is opaque.

Roughness measurements

The specimens were analyzed with a surface roughness measuring instrument (MarSurf M 400; Mahr GmbH). The probe of the inductive skidless tracing system was placed in the middle of the specimen surface, and 6 measurements were made in different directions with a traversing length of 5.6 mm and a constant measuring speed of 1 mm/second to determine an average roughness profile.

Statistical analysis

A multivariate analysis (general linear model) assessed the effect of the parameters material, thickness (1 and 2 mm), and pretreatment method (polished, roughened with P1200 or P500) on the translucency and roughness. The results were statistically compared by using 1-way ANOVA and the Tukey HSD post hoc test. The relationship between translucency and surface roughness was analyzed for each material with the Pearson correlation test and statistical hypothesis tests were used to check the null hypotheses ($\alpha = .05$) (SPSS v22.0; IBM SPSS Inc).

RESULTS

Figure 1 shows the values for all tested materials at a thickness of 1 mm in ascending order (24.49% to 49.09%). In the case of polished specimens, the experimental material reached the statistically significant highest value, closely followed by Tetric EvoCeram BulkFill and LAVA Ultimate. Filtek Supreme XTE, VITA Enamic, IPS e.max CAD, and Celtra Duo reached the lowest values and differed significantly from each other (24.49% to 37.98%), whereas no difference was revealed among VITA CAD-Temp, IPS Empress CAD, VITA Mark II, Telio CAD, and Tetric EvoCeram A2 (40.35% to 41.18%). For the rough specimens, a similar trend, but with a little lower and statistically finer graduated values, was observed. Thereby, differences among the substance classes could be identified. Except for VITA Mark II, all CAD/CAM ceramics demonstrated a greater decrease in translucency than the PMMA-based materials and the resin-based composites (Table 2).

Regarding the 2-mm-thick specimens, a decrease in translucency (average about 14.59 percentage points) concerning all materials was noticed (Fig. 2). These values varied from 11.91% to 30.38%. The materials ranked in the same order, but with a statistically wider graduation independent of the pretreatment method, with the lowest values at P500 (11.28% to 29.46%).

Pretreatment with P1200 reduced the translucency by an average of 1.72 percentage points; in the case of P500, even by 4.31 percentage points. The collected values for surface roughness are listed in Table 3. Altogether, values from 0.026 to 0.140 µm were reached. The ascending order of roughness profiles is based on a stringent classification in different types of material (glass / feldspathic / hybrid ceramics / resin based composites / PMMA). After roughening, the order of the other materials remained almost unchanged. Figure 3 illustrates the aforementioned material properties.

The greatest influence on the measured translucency was exerted by thickness (partial eta squared η_P^2 = .988), closely followed by material (.982), and the pretreatment method (.835). The surface roughness was strongly influenced by the parameters pretreatment method (.975) and material (.941). How far the translucency correlated with the surface roughness depended greatly on the kind of material (Table 4), even though no statistically significant correlation between the parameters could be ascertained in general (P = .056). For the resin-based materials Filtek Supreme XTE and Tetric EvoCeram BulkFill, no correlation could be found between translucency and surface roughness; however, a strong inverse correlation was found for the CAD/CAM ceramics (Table 5).

DISCUSSION

Spectrophotometry is a commonly used method to quantitatively measure color and translucency in dentistry[12,24] but is gradually being replaced by spectroradiometry, which is considered more accurate.[14] Different parameters are used to describe translucency, such as the contrast ratio or the translucency parameter, making it difficult for clinicians to compare studies.[22,25,28] Moreover, these parameters are not applicable to the direct measurement of translucency and cannot be used below 50% transmission.[3,34,35] That is why in this study the absolute translucency was determined to obtain meaningful and comparable values. For the same reason, each specimen was first measured with both sides polished to obtain translucency values that depend only on the material composition. This standardization prevented misinterpretations of low T% values due to the milling unit, even though the restoration is always rough on 1 side in vivo.

The tested materials were chosen because of their popularity among clinicians; however, little information can be found about their optical properties. As is clearly shown in Figure 1, for polished specimens, the affiliation to a certain material category does not allow conclusions to be drawn regarding the translucency qualities of a material. Within the different material classes, every tested material obtained statistically different values, except IPS Empress CAD and VITA Mark II. In general, the translucency of dental ceramics is influenced by factors such as crystalline structure, grain size, pigments, as well as number, size, and distribution of defects, and porosity.[13,21] If the crystals are smaller than the wavelength of visible light (400 to 700 nm) the glass will appear transparent; however, in the case of light scattering and a diffuse reflection, the material will appear opaque.[20] All manufacturers offer a high-translucency (HT) and a low-translucency (LT) version of the CAD/CAM blocks. A small number of large lithium meta-silicate crystals are present in the precrystallized state of the HT material, whereas the LT material contains a large number of smaller crystals.[34] Lithium disilicate glass ceramics ($LiSi_2$-GC) and leucite-reinforced glass ceramics (LR-GC) have been most commonly examined.[19,21,23,34] In this study, the $LiSi_2$-GC IPS e.max CAD attained significantly lower T% values than the LR-GC IPS Empress CAD in the case of polished specimens. In another study, IPS Empress CAD revealed higher translucency values than a $LiSi_2$-GC when 1-mm-thick specimens were analyzed. Especially at low wavelengths, the $LiSi_2$-GC appeared almost opaque.[23] The authors explained this by the different microstructures, with less dense crystals in the LR-GC than in the $LiSi_2$-GC. $LiSi_2$ and $Li_2Si_2O_5$ crystals are needle-shaped and randomly orientated, representing about two thirds of the glass ceramic volume.[34]

In contrast, the microstructure of the LR-GC is said to be less dense and characterized by the single crystal formation of leucite ($KAlSi_2O_6$) with no interlocking among crystals.[21,26] Niu et al[15] stated that the higher strength ceramic system tends to be more opaque because of the required increased crystalline content. Moreover, the aluminosilicate glass in the $LiSi_2$-GC can result in lower translucency values because aluminum compounds cause the ceramic to appear dull and opaque.[20] In a further study, IPS e.max CAD and IPS Empress CAD showed comparable T% values for a thickness of 1 mm (26% to 36%).[3] In this study,[3] a coupling medium was added, which could explain the slightly lower T% values (33.86% to 40.35%). These characteristics were less pronounced after moderate surface roughening (P1200), and the situation was even reversed in the case of a rough surface (P500). This is confirmed by the strong inverse correlation between roughness and translucency for IPS Empress CAD (r = -.955) (Table 5). The tested monochromatic fine-structure feldspathic ceramic VITA Mark II obtained T% values statistically equal to those of IPS Empress CAD in a polished condition. Similar results were reported in a previous study.[3] Furthermore, both materials showed comparable roughness values (Fig. 3), but differed strongly as far as the effect of roughness on translucency was concerned. The translucency of

VITA Mark II showed hardly any change after roughening, which was unlike the other tested ceramics.

Celtra Duo is a new class of ceramic, which is called zirconia-reinforced lithium silicate. The inclusion of 10% zirconia dissolved into the lithium silicate glass matrix results in 4 times smaller silicate crystals, implying a high glass content and higher translucency than conventional $LiSi_2$ ceramics (Celtra Duo; DeguDent GmbH). In fact, Celtra Duo attained higher T% values than IPS e.max CAD, but only in the case of a polished surface. Figure 1 demonstrates that the so-called resin nano-ceramic (RNC) LAVA Ultimate reached the highest T% values of all commercially available CAD/CAM ceramics at all 3 surface conditions. RNC blocks are new CAD/CAM materials made of nanoceramic particles embedded in a highly polymerized resin matrix.[37] Approximately 80 wt% can be attributed to the nanoceramic particles, whereby the nanotechnology and proprietary heat treatment result in a composition that is different from light-polymerized or autopolymerized composite resins, but that can easily be characterized with those materials (3M ESPE recommendation: Filtek Supreme XTE).[37] The nanofiller particle sizes could explain the higher translucency, because particles with a diameter smaller than the wavelength of visible light cause less light scattering and absorbance.[20]

The experimental material belongs to a new substance class, advertised as "hybrid-ceramic." It consists of a hybrid structure with 2 interpenetrating networks of ceramic and polymer, a so-called double network hybrid.[36] The manufacturer states that the fine-structure feldspathic ceramic network (approximately 86 wt%) is strengthened by a fully integrated polymer network.[36] The principal idea behind this was to create a substance offering high strength and low antagonist wear suitable for patients with bruxism. In this study the experimental ceramic revealed 2 remarkable characteristics:

In the case of a polished surface, it obtained statistically the highest T% values. Secondly, this material recorded the greatest loss of translucency after roughening. Conceivably, the weaker polymer matrix is easily separated from the ceramic-network, resulting in the highest roughness values of all the tested hybrid materials. This characteristic may be an advantage with respect to antagonist wear, but it could impair the optical properties of the restoration after long service.

VITA Enamic achieved the lowest T% values, which may be due to the relatively high amount of Al_2O_3 (approximately 23 wt%) (VITA Zahnfabrik H). However, the color 3M2-T cannot be seen as an absolute equivalent to the color A2 from the VITA classic color scale and may appear a little darker.

Regarding the translucency of the resins, great differences were revealed. As with the ceramics, numerous parameters affected the light transmission in composite resin restorations, for example, thickness, filler particles, resin matrix composition, polymerization, and aging.[17,27] Moreover, the translucency seemed to be material specific, because no clear correlation among the mentioned parameters could be found in the latest studies. Especially, the filler size is well discussed: Almost all authors stated that smaller filler size results in higher translucency,[5,6,17] although occasionally the opposite was stated.[4] The tested universal nanofiller composite Filtek Supreme XTE (particle size: 4 to 20 nm) achieved the lowest T% values of all the tested materials. Remarkably, Filtek Supreme XTE showed no decrease in T% after roughening and the lowest roughness profiles of the tested resins. The nanometer-sized particles could explain why this material retained its polished surface. The matrix is infiltrated by clusters of nanoparticles that shear at a rate similar to that of the wear of the surrounding resin network during abrasion, allowing the restoration to maintain a smoother surface for long-term polish retention.[38] In contrast, other nanofiller materials such as the nanohybrid composite Tetric EvoCeram (particle size: 40 to 3000 nm) incorporate larger particles and filler complexes. These materials are made by pre-polymerization methods and require residual monomers to link with the matrix, which could weaken the bond. Larger particles could explain the higher roughness values if they pluck out from the material. Still, Tetric EvoCeram obtained higher T% values than the PMMA-based materials, although lower than the bulk-fill material. The high T% values of Tetric EvoCeram BulkFill were expected, because a high transmission of light is necessary for the greater depth of polymerization.[39] Nevertheless, this material has a range of indications unlike those of the other materials and was added to this study to serve as a reference level for high translucency.

In general, together with the color and composition of a material, the surface condition affects the optical appearance of a restoration, which should not be underestimated. High-gloss polishing modifies the appearance of a dental ceramic or composite resin restoration. The reflection of light on a flat surface is called specular, or regular, because the angle of light breakup is equal to the angle of reflection. On rough surfaces, the reaction of the light is termed diffuse because the surface behaves as an infinity of tiny surfaces reflecting the rays in several directions. This applied above all to the CAD/CAM ceramics, although the slowest increase in surface roughness was recorded for this substance class. Thus, the classification of ceramics and resins by their roughness profiles (Fig. 3) is remarkable, but no conclusion can be drawn as to how this affects translucency. Conversely, the loss of translucency seems to be greatly material specific and does not necessarily correlate with the absolute roughness profiles.

Regarding the influence of the parameter "thickness", doubling the thickness resulted in a large decrease in translucency (on average 14.59 percentage points), but no substance class seemed to be more strongly affected than others. Whether a linear or exponential relation exists within a clinical relevant thickness of 1 to 2 mm is unclear.[22,29,30] Moreover, the total refractive index is directly related to the thickness of the material. The loss of translucency in the case of increased thickness is of clinical relevance. A recent study revealed, that at thicknesses above 1.5 mm, the esthetic outcome of a ceramic restoration is rather independent of the color of the underlying foundation or cement.[15] However, care has to be taken to ensure sufficient polymerization, either by extending the polymerization time or by using a dual-polymerized resin luting agent.

The translucency results cannot automatically be related to the clinical situation, because the effect of the underlying structure was not taken into consideration and the abrasion caused by a grinding sheet does not perfectly reflect the loss of polish in function. Furthermore, no a priori power analysis was performed to determine sample size. These are limitations of this study.

CONCLUSION

In summary, the findings indicate that surface roughness and thickness are only 2 among many parameters that strongly influence translucency; therefore, the first and second hypothesis were rejected. Translucency seems to be material specific, and no generalization relating to the different substance classes can be made; therefore, the third hypothesis was rejected. Sufficient polishing after milling or occlusal adjustment is necessary to guarantee optimal translucency.

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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TABLES

Table I. Materials, manufacturer, LOT, color of all tested materials.

Material	Manufacturer	LOT	Color
CELTRA Duo	DENTSPLY DeguDent GmbH	18015733	LT A2/C14
IPS e.max CAD	Ivoclar Vivadent AG	R37085	LT A2/C14
IPS Empress CAD	Ivoclar Vivadent AG	R39335	LT A2/C14
LAVA Ultimate	3M ESPE AG	N372985	A2 - LT/14L
Telio CAD	Ivoclar Vivadent AG	N73354	LT A2/B55
Experimental nano-hybrid composite	Ivoclar Vivadent AG	b. 28923	HAT A2/C14
VITA CAD-Temp	VITA Zahnfabrik H. Rauter GmbH und Co. KG	CE 0124	2 M2T/CT-40
VITA Enamic	VITA Zahnfabrik H. Rauter GmbH und Co. KG	33000	3M2-T EM-14
VITA Mark II	VITA Zahnfabrik H. Rauter GmbH und Co. KG	19511	2M2C I14
Tetric EvoCeram Bulk Fill	Ivoclar Vivadent AG	P48872	Bulk IV A
Tetric EvoCeram	Ivoclar Vivadent AG	S12963	A2
Filtek Supreme XTE	3M ESPE AG	N502353	Dentin A2

Table II. Mean and standard deviation of translucency as function of material, surface pretreatment, and specimen thickness.

Material	Surface pretreatment					
	Polished		P1200		P500	
	1 mm	2 mm	1 mm	2 mm	1 mm	2 mm
CELTRA Duo	37.98 (0.68)^{d}	24.37 (0.61)^{e}	34.58 (0.32)^{c}	21.28 (0.53)^{c}	27.59 (0.31)^{b}	16.43 (0.37)^{b}
IPS e.max	33.86 (0.50)^{c}	20.35 (0.50)^{c}	31.87 (1.40)^{b}	19.43 (0.40)^{b}	30.34 (1.06)^{c}	18.15 (0.36)^{c}
IPS Empress	40.35 (0.75)^{ef}	25.84 (0.49)^{f}	37.20 (0.58)^{d}	23.30 (0.57)^{d}	28.55 (0.41)^{b}	16.85 (0.56)^{b}
LAVA Ultimate	46.72 (0.58)^{g}	28.06 (0.25)^{g}	44.19 (0.89)^{h}	26.49 (0.96)^{e}	42.10 (1.29)^{g}	24.96 (0.80)^{f}
Telio CAD	41.18 (1.33)^{f}	26.10 (0.29)^{f}	37.85 (1.23)^{de}	23.12 (0.24)^{d}	34.67 (1.41)^{d}	21.36 (0.31)^{d}
Experimental	49.09 (0.42)^{h}	29.20 (0.42)^{h}	45.40 (0.53)^{hi}	26.51 (0.36)^{e}	31.85 (1.92)^{c}	25.62 (0.25)^{fg}
VITA CAD Temp	39.63 (0.59)^{e}	23.13 (0.68)^{d}	38.92 (0.80)^{ef}	22.14 (0.91)^{c}	37.71 (0.84)^{e}	20.57 (0.57)^{d}
VITA Enamic	27.92 (0.22)^{b}	13.98 (0.50)^{b}	26.01 (0.40)^{a}	12.79 (0.52)^{a}	23.92 (0.41)^{a}	11.28 (0.25)^{a}
VITA Mark II	41.04 (0.57)^{f}	27.53 (0.81)^{g}	40.80 (0.47)^{g}	27.30 (0.71)^{e}	40.28 (0.48)^{f}	26.41 (0.57)^{g}
TEC BulkFill	46.94 (1.70)^{g}	30.38 (1.40)^{i}	46.01 (1.23)^{i}	29.62 (0.69)^{f}	46.17 (1.34)^{h}	29.46 (0.97)^{h}
TEC A2	41.18 (1.45)^{f}	24.51 (0.85)^{e}	39.26 (1.40)^{f}	23.74 (0.67)^{d}	38.54 (1.29)^{e}	22.88 (0.87)^{e}
Filtek Supreme XTE	24.49 (1.13)^{a}	11.91 (0.50)^{a}	24.74 (1.08)^{a}	11.99 (0.55)^{a}	24.87 (0.96)^{a}	11.64 (0.50)^{a}

^{abc} All values are presented as percent (standard deviation). Different superscript letters present significant differences among 1 surface condition, for 1- or 2-mm-thick specimens.

Table III. Roughness as function of material and surface pretreatment.

Material	Surface pretreatment		
	Polished (µm)	P 1200 (µm)	P 500 (µm)
CELTRA Duo	0.028 (0.005)[a]	0.077 (0.005)[a]	0.162 (0.012)[a]
IPS e.max	0.026 (0.003)[a]	0.084 (0.009)[a]	0.150 (0.010)[a]
IPS Empress	0.027 (0.004)[a]	0.126 (0.020)[b]	0.217 (0.013)[b]
LAVA Ultimate	0.053 (0.009)[bc]	0.219 (0.024)[d]	0.484 (0.025)[e]
Telio CAD	0.067 (0.016)[cd]	0.364 (0.027)[f]	0.784 (0.063)[h]
Experimental	0.053 (0.005)[bc]	0.221 (0.020)[d]	0.487 (0.036)[e]
VITA CAD Temp	0.038 (0.005)[ab]	0.287 (0.028)[e]	0.706 (0.067)[g]
VITA Enamic	0.058 (0.010)[bc]	0.212 (0.011)[d]	0.391 (0.015)[d]
VITA Mark II	0.068 (0.035)[cd]	0.181 (0.030)[c]	0.261 (0.046)[c]
TEC BulkFill	0.058 (0.007)[bc]	0.339 (0.030)[f]	0.616 (0.046)[f]
TEC A2	0.140 (0.033)[e]	0.281 (0.024)[e]	0.582 (0.037)[f]
Filtek Supreme XTE	0.085 (0.040)[d]	0.297 (0.050)[e]	0.581 (0.047)[f]

[abc] All values are presented as percent (standard deviation). Different superscript letters present significant differences among 1 surface condition.

Table IV. Influence of parameters material, thickness and surface pretreatment on translucency and surface roughness.

Parameters	**T%**		**Ra**	
	ηP^2	P	ηP^2	P
Material	.982	<.001	.941	<.001
Thickness	.988	<.001	.008	.026
Surface pretreatment	.835	<.001	.975	<.001

$P < .05$ indicates significant influence. Higher partial eta-Sq values (ηP^2) stand for stronger influence.

Table V. Pearson correlation coefficients (*R*) between translucency and roughness.

Material	Thickness			
	1 mm		2 mm	
	R	*P*	*R*	*P*
CELTRA Duo	-0.986	<.001	-0.987	<.001
VITA Enamic	-0.974	<.001	-0.932	<.001
experimental	-0.963	<.001	-0.882	<.001
IPS Empress	-0.955	<.001	-0.930	<.001
Telio CAD	-0.902	<.001	-0.959	<.001
LAVA Ultimate	-0.870	<.001	-0.882	<.001
IPS e.max CAD	-0.820	<.001	-0.900	<.001
VITA CAD Temp	-0.722	<.001	-0.834	<.001
VITA Mark II	-0.617	<.001	-0.472	.008
TEC A2	-0.597	<.001	-0.653	<.001
TEC BulkFill	-0.241 not significant	.200	-0.353 not significant	.056
Filtek Supreme XTE	0.145 not significant	.446	-0.281 not significant	.133

P < .05 indicates significant correlation.

LEGENDS

Fig. 1. Variation of translucency as function of pretreatment method and material for 1 mm thick specimens.

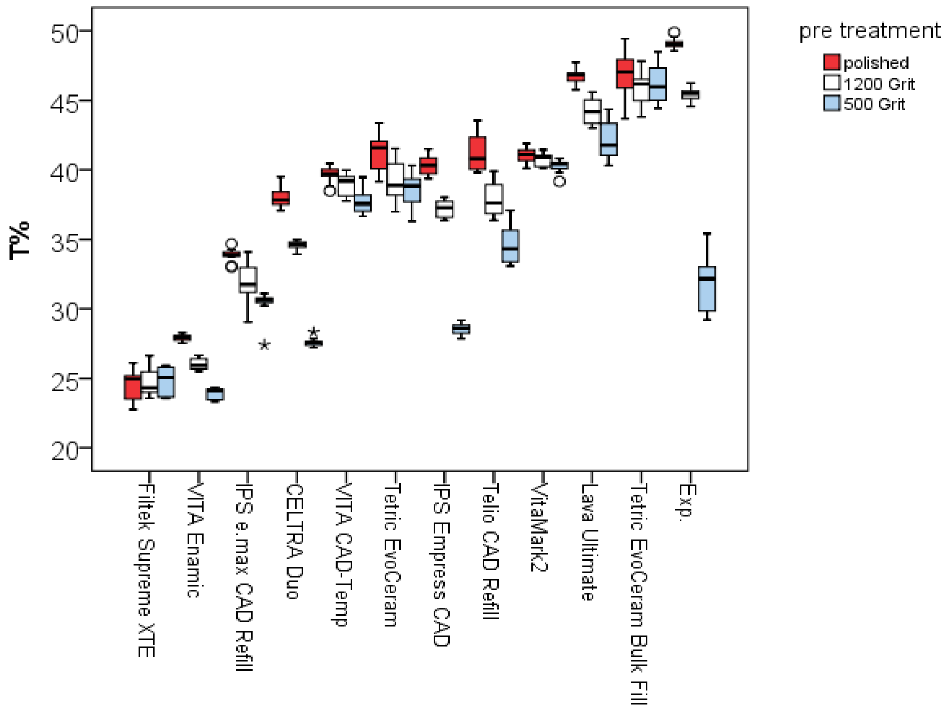


Fig. 2. Variation of translucency as function of material and specimen thickness (polished specimens).

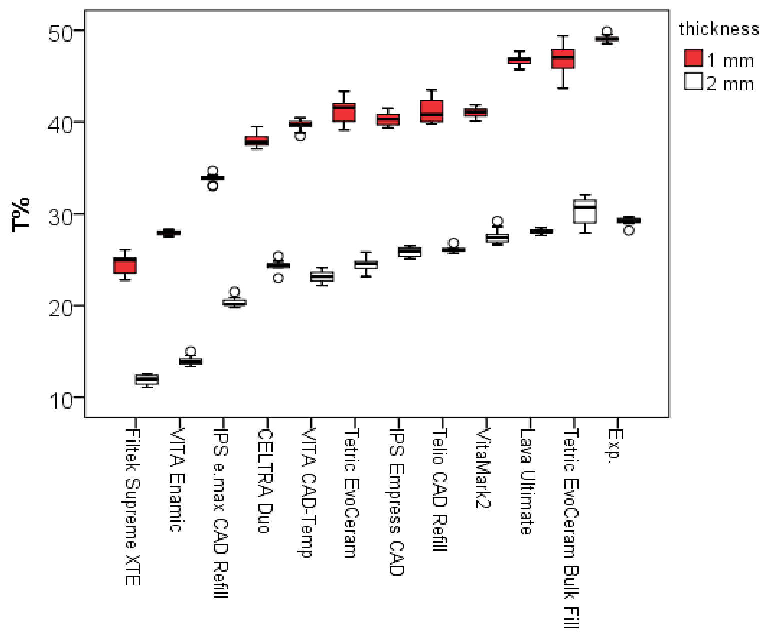
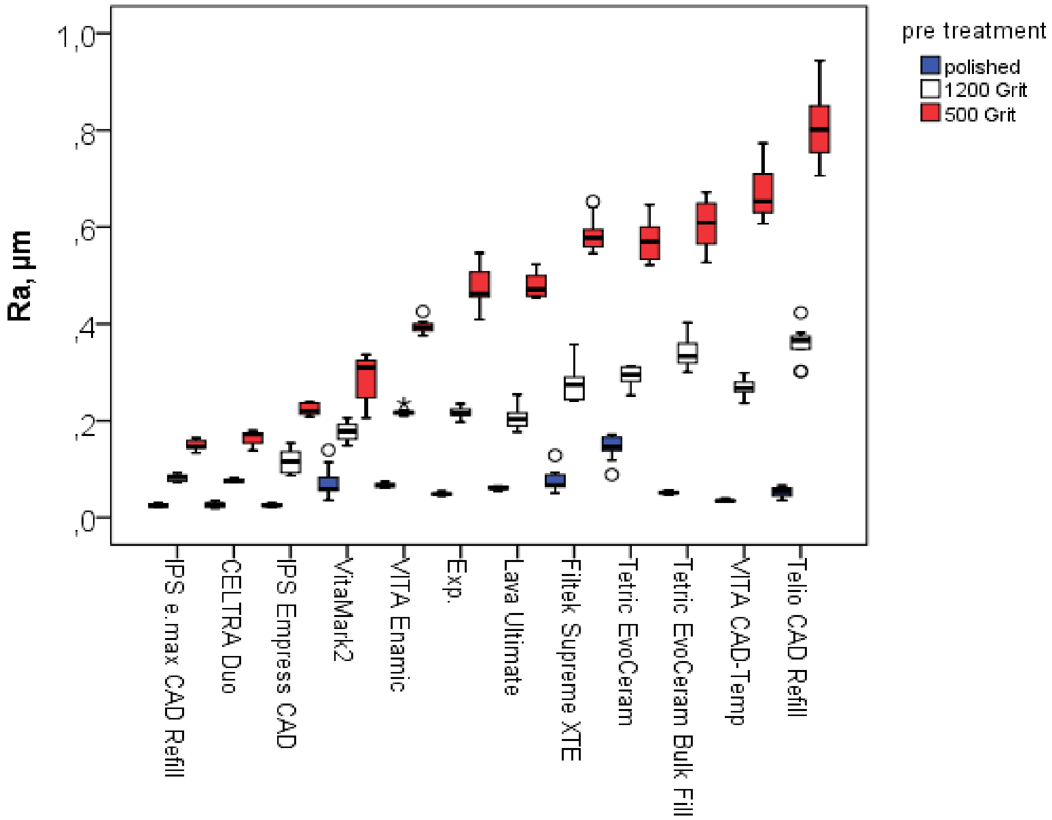


Fig. 3. Variation of roughness as function of pretreatment method and material for 1 mm thick specimens.



2.2 Blue-Light transmittance of esthetic monolithic CAD/CAM materials with respect to their composition, thickness, and curing conditions.

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CLINICAL IMPLICATIONS

The amount of light passing through VITA ENAMIC restorations is reduced and less light-sensitive dual-curing cements should be used for cementation.

SUMMARY

Determining the amount of blue light (360 – 540 nm) passing through nine monolithic computer-aided design / computer-aided manufacturing (CAD/CAM) materials depends on material thickness, initial irradiance, and the distance between the curing unit and the specimen's surface. A total of 180 specimens of two thicknesses (1 mm and 2 mm, n=10/subgroup) were fabricated from Telio CAD, VITA CAD-Temp (VCT), experimental nano-composite, LAVA Ultimate (LU), VITA ENAMIC (VE), VITA Mark II (VM), IPS Empress CAD (IEC), IPS e.max CAD (IEM), and CELTRA DUO (CD). The irradiance passing through the CAD/CAM materials and thicknesses was measured using a light-emitting-diode curing unit with standard-power, high-power, and plasma modes by means of a USB4000 spectrometer. The curing unit was placed directly on the specimen's surface at 2- and 4-mm distances from the specimen's surface. Data were analyzed using a multivariate analysis and one-way analysis of

variance with the *post hoc* Scheffé test ($p<0.05$). The highest transmitted irradiance was measured for VM and LU, followed by VCT and IEC, while the lowest values showed VE, followed by IEM and CD. The highest transmitted irradiance was recorded by exposing the material to the plasma mode, followed by the high- and standard-power modes. The measured irradiance was decreased by increasing the specimen's thickness from 1 to 2 mm. Fewer differences were measured when the curing unit was placed at 0 or 2 mm from the specimen's surface, and the irradiance passing through the specimens was lower at a distance of 4 mm.

INTRODUCTION

There is a range of polymer-, composite-, or ceramic-based esthetic monolithic computer-aided design / computer-aided manufacturing (CAD/CAM) materials presently available on the market. Dentists can process these materials using CAD/CAM technology in minutes while the patient is seated in the chair. Industrially prefabricated CAD/CAM materials appear to be more structurally reliable for dental applications than materials that are manually processed under dental laboratory conditions. Polymeric-based CAD/CAM materials showed significantly higher mechanical properties compared to conventional temporaries[1-5] and can be used for long-term restorations.[6] Standard monolithic CAD/CAM materials for permanent restorations contain lithium disilicate glass ceramics,[7-9] feldspathic silicate ceramics,[10] and feldspar-based leucite-reinforced glass ceramics[11,12] but also newly developed materials, such as a resin-based block nanocomposite,[13] an experimental isofiller resin-based composite with "nano additives",[14] and a novel interpenetrating network ceramic (VITA ENAMIC).[15-18] Similarly, a zirconia-reinforced lithium silicate ceramic

(CELTRA DUO) offers the opportunity for a permanent restoration. Since the latter materials are quite new, there is little scientific knowledge about them.

In addition to the particular restorative material, the esthetics of a CAD/CAM restoration also depends on the chosen luting cement. Traditional cements, such as glass ionomer and zinc phosphate, are usually very opaque and can therefore distort the color of the esthetic restoration. Esthetic glass-ceramic restorations also demonstrated better longterm clinical stability when cemented with resin composite cements rather than traditional cements.[19,20] An *in vitro* study also reported on the increase of fracture resistance of adhesive-luted crowns compared to traditionally cemented ones.[21] Esthetic restorative materials with lower mechanical properties require reinforcement by adhesive cementation.[21-23] Dual-cure resin adhesive composite cements are often used for these indications. An advantage of these resin composite cements is that they can cure both chemically (autocuring) and via visible-light activation. Such resin composite cements include a catalyst paste with a chemical activator (benzoyl peroxide) and a base paste containing blue-light-cured resin cement as well as an amine responsible for the beginning of the autocuring reaction.[24,25] After mixing both pastes and with a supply of light, the polymerization takes place through physical (photo) and chemical (redox) activation.[24] The working time is controlled by inhibitors of the autocure reaction or by the amount of activators in the polymerization.[26] Nevertheless, when not properly photoactivated, dual-cure resin cements may present reduced degrees of conversion.[27-29] This in turn leads to lower mechanical properties, such as hardness[25] and flexural and compressive strength,[25,30] and higher solubility.[31] Studies have also shown that the absence of light negatively influences the long-term bond strength.[32,33] The impact of light on the polymerization process of dual-cure luting resin composite cements is material dependent.[34] Light-cured resin cements and, in particular, resin composites have thus become an important part of modern, minimally invasive treatment.[35] These resin composites consist of a single paste with a visible-light activation of a photosensitive component (eg. camphorquinone) and an amine. The visible light activates the photosensitive initiator to generate a short-lived excited-state species that complexes with the tertiary amine to promote a sequential electron and proton transfer that creates the active initiating radicalable to start the polymerization.[24]

Direct resin composites are densely filled with inorganic particles and therefore provide high mechanical properties. However, increasing filler parts in resin composites also enhances viscosity, which could reduce the ease of clinical application. Options to improve the rheological behavior by using ultrasonics[36] or preheating[37-39] are of primary interest to the clinician.

Along with improvements of the mechanical properties, cementation using light-luting resin composites has several benefits in clinical applications. Light-cured resin composites have long working times, with the polymerization beginning immediately after the exposure of the material to light.[33]

Many resin composites indicate a high sensitivity to the additional occurrence of blue light, which significantly affects their mechanical properties.[34] The amount of light passing through restoration materials and the translucency of the materials are thus essential elements of cementation with dual-curing resin composite cements. A previous study investigated the amount of blue light passing through differently colored zirconia ceramics and recommended the use of less light-sensitive dual-cured cements for restorations thicker than 1.5 mm in light-shaded zirconia and 0.5 mm in darker-shaded zirconia.[40]

This study investigated the amount of blue light passing through nine CAD/CAM monolithic materials. Four hypotheses were tested: 1) different CAD/CAM materials, 2) material thickness, 3) curing unit distance to the specimen, and 4) initial irradiance level (curing modes) show no impact on the transmitted irradiance through the CAD/CAM materials.

MATERIAL AND METHODS

Nine different CAD/CAM monolithic materials were selected: Telio CAD (TC; PMMA based; Ivoclar Vivadent, Schaan, Liechtenstein), VITA CAD-Temp (VCT; PMMA based and 10% filled with prepolymers; VITA Zahnfabrik, Bad Säckingen, Germany), experimental nanocomposite (TEC; filled composite; Ivoclar Vivadent) LAVA Ultimate (LU; filled composite; 3M ESPE, Seefeld, Germany), VITA ENAMIC (VE; interpenetrating network ceramic; VITA Zahnfabrik), VITA Mark II (VM; feldspar ceramic; VITA Zahnfabrik), IPS Empress CAD (IEC; leucite glass ceramic; Ivoclar Vivadent), IPS e.max CAD (IEM; lithium disilicate glass ceramic; Ivoclar Vivadent), and CELTRA DUO (CD; zirconia-reinforced lithium silicate ZLS; DeguDent, Hanau, Germany) (Table 1). CAD/CAM blocks were cut using a low-speed diamond saw in 1- and 2-mm-thick slices (n=10) (Well 3241, Well Diamantdrahtsägen, Mannheim, Germany) under water cooling.

All specimens were polished up to 1 µm with a diamond suspension (Struers, Ballerup, Denmark) and then ultrasonically cleaned for 5 minutes in distilled water. The final dimensions of all specimens were 10×10×1 mm ± 0.05 and 10×10×2 mm ± 0.05 mm.

The analysis of the irradiance passing through the CAD/CAM materials was performed using the blue-violet light-emitting-diode polymerizing unit (VALO, Ultradent, South Jordan, UT, USA) on a laboratory-grade National Institute of Standards and

Technology–referenced USB4000 Spectrometer (MARC System, Bluelight Analytics Inc, Halifax, NS, Canada) (n=10). The miniature fiber-optic USB4000 spectrometer uses a 3648-element Toshiba linear charge-coupled-device array detector and high-speed electronics. The spectrometer was spectroradiometrically calibrated using Ocean Optics' NIST-traceable light source (300-1050 nm) (Figure 1). The system uses a CC3-UV Cosine Corrector to collect radiation over a 180-degree field of view, thus mitigating the effects of optical interference associated with light collection sampling geometry.

The irradiance (wavelength ranged from 360 to 540 nm) passing through the nine different CAD/CAM materials and material thicknesses (1 and 2 mm) was measured at the bottom of the specimens at a velocity of 16 records per second. The sensor was triggered at 20 mW. The curing unit was placed directly on the specimen's surface as well as 2 and 4 mm away from the specimen's surface. Three curing modes were examined (standard-power, high-power, and plasma modes), resulting in 180 measurements (2 material thicknesses × 3 exposure modes × 3 distances × 10 specimens) for each ceramic.

Additionally, one randomly selected specimen for each material was analyzed in a scanning electron microscope (SEM; Supra 55 VP, Zeiss, Jena, Germany). For this, the VM and IEC were etched for 60 seconds and IEM and CD for 30 seconds with 9% hydrofluoric acid (Ultradent, lot B6X7B). The specimens were then ultrasonically cleaned and subsequently gold sputtered for 20 seconds. Surface topography analyses were performed using an inLens detector at 10 kV with a working distance of 4.5 - 6.0 mm.

A multivariate analysis (general linear model) assessed the effect of the material, material thickness (1 and 2 mm), distance from the surface (0, 2, and 4 mm), and curing mode (standard-power, high-power, and plasma modes) on the irradiance passing through the CAD/CAM materials. The statistical comparisons between the groups were performed using one-way analysis of variance followed by the *post hoc* Scheffé test; *p*-values smaller than 5% were considered statistically significant (SPSS, version 22.0, SPSS Inc, Chicago, IL, USA).

RESULTS

The greatest influence on the transmitted irradiance was exerted by the curing mode (η_P^2 = 0.991), closely followed by specimen thickness (η_P^2 = 0.989), CAD/CAM material (η_P^2 = 0.966), and distance from the specimen's surface (η_P^2 = 0.904). All binary combinations of these parameters were also significant ($p<0.05$). The highest significant values for transmitted irradiance were measured for the materials VM and LU, followed by VCT and IEC, while the lowest significant values were for VE, followed by IEM and CD (Figures 2 through 4). Detailed information about the significant differences between the tested CAD/CAM materials is presented in Table 2.

Among the three tested curing regimens, the highest significant irradiance was recorded by exposing the CAD/CAM material to the plasma mode, followed by the high- and standard-power modes ($p<0.05$). The irradiance measured at 0-mm distance was 3416 ± 8.3 mW/cm^2 for the plasma mode, 1766 ± 0.1 mW/cm^2 for the high-power mode, and 1178 ± 0.5 mW/cm^2 for the standard-power mode. Following the same sequence, an increase in irradiance was identified at 2-mm distance (3797 ± 87.6 mW/cm^2, 1939 ± 3.2 mW/cm^2, and 1272 ± 24.5 mW/cm^2, respectively), and the lowest irradiances were measured at 4-mm distance from the specimen surface (2606 ± 6.6 mW/cm^2, 1346 ± 3.7 mW/cm^2, and 1002 ± 18.0 mW/cm^2).

The transmitted irradiance decreased significantly by increasing the specimen's thickness from 1 to 2 mm ($p<0.05$). Fewer differences were measured when the curing unit was placed at 0 or 2 mm from the specimen's surface, and the irradiance passing through the specimens was lower at a distance of 4 mm ($p<0.05$). SEM pictures of the microstructure of all tested CAD/CAM materials are presented in Figure 5.

DISCUSSION

Tooth-colored monolithic CAD/CAM materials seem to be suitable materials for dental applications; however, a cementation method using resin composite cements remains a key factor in ensuring long-lasting survival and success rates. Previous investigations have shown that the mechanical properties of dual-cure luting cements,[34] as well as the bond strength to dental ceramics, are positively influenced by the amount of light reaching the cements.[41,42]

In general, the highest transmitted irradiance was measured at the bottom of the feldspathic ceramic VM and the resin composite LU in the present study. The lowest values were measured for a hybrid ceramic VE followed by both lithium disilicate ceramics IEM and CD. The first null hypothesis, that the different CAD/CAM materials show no impact on the irradiance through the material, is rejected. It is worth noting that 60.8% - 84.0% of the initial irradiance reaching the material surface is lost in passing 1-mm-thick increments of the analyzed materials, and this range changes to 80.6% - 95.5% for 2-mm-thick specimens. Within one material, this value is influenced in only a minor way by the level of the initial irradiance. The analyzed materials might be grouped into four categories with respect to this behavior in descending order of their translucency: 1) LU and VM (60.8% - 62.7% initial irradiance loss when passing 1-mm-thick increments and 80.6% - 81.9% when passing 2-mm-thick increments); 2)

VCT, IED, TEC, and TC (67.1% - 68.3% and 85.8% - 86.8%, respectively); 3) CD and IEM (73.3 - 78.8% and 87.9% - 89%); and 4) VE (82.5% and 94.9%).

The translucency of ceramic materials and thus the transmitted irradiance are dependent on the crystalline structure, grain size, and pigments as well as the number, size, and distribution of defects and porosity.[43,44] In this study, lithium disilicate glass-ceramic IEM and lithium silicate glass-ceramic CD showed significantly lower transmitted irradiance values than the leucite-reinforced ceramic Empress CAD or feldspathic ceramic VM. A previous study reported higher translucency values for leucite-reinforced IEC than for lithium disilicate glass ceramics and explained this as a result of the different microstructures, with less dense crystals in the leucite-reinforced ceramic than in the lithium disilicate ceramic.[45] These results were confirmed in this study. Lithium disilicate crystals are needle shaped and randomly oriented, representing about two-thirds of the glass-ceramic volume.[46] The microstructure of the leucite-reinforced ceramic is less dense and characterized by the single crystal formation of leucite ($KAlSi_2O_6$) without interlocking of the crystals.[44,47] Higher-strength ceramics also tend to be less translucent due to the necessary increased crystalline content.[48] Aluminosilicate glass in the lithium disilicate ceramic can result in lower transmitted irradiance values because aluminum compounds cause the ceramic to appear dull and opaque.[49] Feldspathic ceramic (VM) and composites based on tetraethyleneglycol dimethacrylate (TEGDMA) and urethane dimethacrylate (UDMA) (LU) showed the highest transmitted irradiance. In agreement with previous studies,[50,51] VE showed the lowest transmitted irradiance values. VE is a polymer-infiltrated feldspathic ceramic-network material with an 86 wt% ceramic part. The polymer part contains TEGDMA and UDMA monomers. It can thus be assumed that the low transmitted irradiance is related to the density and grain size of the ceramic matrix.

In accordance with previous studies[40,52,53] that investigated the translucency of ceramic materials, this investigation confirmed that material thickness significantly influences the transmitted irradiance. The second null hypothesis was therefore also rejected. In previous studies,[40,52] the glass-ceramic specimens showed a greater decrease in transmitted irradiance compared to zirconia, still in accordance with material thickness, when using standard-power and extra-power curing modes. A lower impact of material thickness on irradiance was observed in exposures to the high-power curing mode. Dental restorations involve various thicknesses, depending on the different conditions of the tooth, and therefore, for use of light-curing cementation, an accurate knowledge of the relationship between irradiance and thickness, depending on the shades, is fundamental to improving the long-term stability of ceramic restorations. The present study confirmed this.

Within one type of CAD/CAM material, thickness, or curing mode, no significant difference in transmitted irradiance was recorded until an exposure distance of 2 mm, and this decreased significantly for larger distances (4 mm). This was the result of the particular curing unit used in this study since the variation in irradiance with increasing exposure distance in all three modes showed a slight increase, up to an exposure distance of 2 mm, then decreased exponentially with the distance.[40] For this, the irradiance levels at 0 and 2 mm were comparable. This means that the third null hypothesis is rejected. The special concave glass lens at the tip of the curing unit can explain the impact of the distance between the curing light unit and specimens on the irradiance, where the emitted light is focused to a collimated beam with maximum irradiance at 2 mm. The highest significantly transmitted irradiance was recorded while using the extra-power mode, followed by the high- and standard-power modes. Thus, the fourth hypothesis is also rejected.

In general, it was found that the more translucent a CAD/CAM material, the greater the change in transmitted irradiance as a result of varying thickness. If the microstructure crystals are smaller than the wavelength of visible light (400-700 nm), the glass will look transparent.[49] The material will appear opaque in the case of light scattering and a diffuse reflection.[49] The monolithic CAD/CAM blocks are available in high-translucency (HT) and low-translucency (LT) versions. The LT materials contain a high number of smaller lithium metasilicate crystals, whereas a small number of crystals are present in the precrystallized state of the HT materials.[46] To the best knowledge of the authors, all materials were ordered in similar A2 colors for the group comparisons; however, materials are offered in different tooth color systems, namely, VITA classic A1 - D4 shade guide (classical method) and VITA 3D Master. For this study, the VITA 3D Master colors were translated into the classical colors using VCT and VE. In this study, VE was present in only one tooth color 3M2. Another limitation of this study was that TEC was analyzed in a HT shade, and no information was available for VCT, VE, and VM. It can be assumed that TEC in LT showed comparable transmitted irradiance values to those of the composite LU, but it must be emphasized here that the values obtained provide tendencies for the orientation of the irradiance values.

The transmitted irradiance was evaluated in this study using flat specimens of a standardized thickness. Future investigations should be performed directly on a dental restoration for greater clinical relevance. The influence of the fabrication process of CAD/CAM restorations, such as milling and finishing, could be integrated into these investigations.

CONCLUSIONS

Within the limitations of this laboratory investigation, the following conclusions can be drawn:

(1) VITA Mark II and Lava Ultimate showed the highest transmitted irradiance.
(2) The novel interpenetrating network ceramic, followed by the lithium (di)silicate ceramics, showed the lowest transmitted irradiance.
(3) The highest transmitted irradiance was recorded by exposing the material to the plasma mode, followed by the high- and standard-power modes.

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 Prosthodontics, Dental School, Ludwig-Maximilians University, Munich, Germany.

CONFLICT OF INTEREST

The authors of this article 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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TABLES

Table 1: Product name, abbreviation, material type, Lot number, and color of CAD/CAM materials evaluated

Material (Abbreviation)	Manufacturer	Material Type	Lot Number	Color
Telio CAD (TC)	Ivoclar Vivadent, Schaan, Liechtenstein	PMMA	N73354	LT A2
VITA CAD-Temp (VCT)	VITA Zahnfabrik, Bad Säckingen, Germany	PMMA	CE 0124	2M2
Experimental nanocomposite (TEC)	Ivoclar Vivadent	Resin composite	28923	HT A2
LAVA Ultimate (LU)	3M ESPE, Seefeld, Germany	Resin composite	N372985	HT A2
VITA ENAMIC (VE)	VITA Zahnfabrik	Hybrid ceramic	33000	3M2
VITA Mark II (VM)	VITA Zahnfabrik	Feldspar ceramic	N502353	A2
IPS Empress CAD (IEC)	Ivoclar Vivadent	Leucite glass ceramic	R39335	LT A2
IPS e.max CAD (IEM)	Ivoclar Vivadent	Lithium disilicate glass ceramic	R37085	LT A2
CELTRA Duo (CD)	DeguDent, Hanau, Germany	Zirconia-reinforced lithium silicate	18015733	LT A2

Table 2: Descriptive statistics for all tested CAD/CAM materials with respect to material thickness, curing modus, and distance between specimens and light unit

CAD/CAM Material	**Distance between specimens and light unit**					
	0 mm		**2 mm**		**4 mm**	
	Material thickness		Material thickness		Material thickness	
	1 mm Mean (SD)	2 mm Mean (SD)	1 mm Mean (SD)	2 mm Mean (SD)	1 mm Mean (SD)	2 mm Mean (SD)
Standard-power mode						
TC	373 (18.3)^{C}	171 (3.1)^{D}	371 (16.1)^{C}	168 (3.9)^{C}	275 (9.9)^{C}	129 (2.1)^{DE}
VCT	388 (11.4)^{C}	167 (8.5)^{D}	395 (10.3)^{D}	163 (7.0)^{C}	285 (6.8)^{C}	126 (4.4)^{*DE}
TEC	377 (7.7)^{C}	156 (2.9)^{CD}	372 (5.9)^{C}	155 (4.5)^{*C}	276 (4.8)^{C}	120 (2.6)^{CD}
LU	462 (14.3)^{E}	213 (13.1)^{E}	455 (11.9)^{F}	204 (10.7)^{D}	333 (8.6)^{D}	157 (8.4)^{F}
VE	206 (7.3)^{A}	60 (3.5)^{A}	212 (5.9)^{A}	62 (5.0)^{A}	162 (3.5)^{A}	50 (2.0)^{A}
VM	439 (10.6)^{D}	228 (10.0)^{E}	429 (9.1)^{E}	219 (7.6)^{*E}	322 (6.3)^{D}	178 (4.3)^{G}
IEC	381 (8.1)^{C}	172 (10.9)^{D}	378 (7.9)^{CD}	167 (11.8)^{C}	285 (4.6)^{C}	132 (7.4)^{*E}
IEM	308 (9.1)^{B}	129 (4.4)^{B}	310 (9.7)^{B}	127 (4.9)^{B}	232 (8.3)^{*B}	102 (3.7)^{B}
CD	314 (5.7)^{B}	143(14.1)^{BC}	323 (7.3)^{B}	139 (10.2)^{B}	245 (17.7)^{B}	111 (7.1)^{BC}
High-power mode						
TC	542 (26.3)^{C}	243 (3.2)^{DE}	537 (23.8) ^{C}	236 (3.5)^{C}	397 (13.8)^{C}	183 (3.3)^{CD}
VCT	567 (15.7)^{C}	241(11.5)^{DE}	575 (15.0)^{CD}	237 (9.4)^{C}	414 (11.0)^{C}	181 (7.4)^{CD}
TEC	546 (13.9)^{*C}	221 (5.8)^{CD}	540 (6.2)^{C}	220 (6.4)^{C}	399 (6.1)^{C}	171 (4.3)^{C}
LU	676 (20.2)^{E}	307 (20.1)^{F}	666 (11.1)^{E}	294 (15.4)^{D}	486 (10.3)^{D}	226 (12.2)^{E}
VE	297 (8.5)^{A}	84 (4.0)^{A}	307 (8.0)^{A}	86 (5.1)^{A}	233 (5.9)^{A}	69 (2.3)^{A}
VM	641 (14.5)^{D}	330 (13.2)^{F}	609 (60.9)^{D}	317 (12.6)^{*F}	473 (9.8)^{E}	257 (6.9)^{F}
IEC	558 (12.5)^{C}	246 (17.7)^{E}	554 (11.7)^{C}	241 (17.7)^{*C}	417 (7.2)^{C}	190 (13.4)^{D}
IEM	448 (11.7)^{B}	183 (5.4)^{B}	450 (14.7)^{B}	181 (5.5)^{B}	338 (12.4)^{B}	140 (5.0)^{B}
CD	451 (10.0)^{B}	200(18.4)^{BC}	466 (7.7)^{B}	199 (15.0)^{B}	355 (27.9)^{B}	155 (11.1)^{B}
Plasma mode						
TC	1014 (48.7)^{C}	441 (8.3)^{DE}	1007 (44.3)^{C}	431 (8.4)^{DE}	744 (30.2)^{C}	333 (5.9)^{DE}
VCT	1078 (28.3)^{D}	452 (21.4)^{E}	1100 (29.2)^{E}	441(20.1)^{DE}	793 (20.4)^{D}	340(13.8)^{DE}
TEC	1025(26.3)^{CD}	406 (9.9)^{CD}	1017(13.6)^{CD}	405(13.3)^{CD}	753 (9.4)^{CD}	315 (7.5)^{CD}
LU	1283 (40.0)^{E}	564 (39.6)^{F}	1261 (38.7)^{G}	543 (33.5)^{G}	922 (19.6)^{E}	418 (22.4)^{G}
VE	546 (16.3)^{A}	155 (7.7)^{A}	582 (14.2)^{A}	158 (10.5)^{A}	443 (9.7)^{A}	125 (5.6)^{A}
VM	1239 (30.2)^{E}	625 (26.5)^{G}	1204 (24.0)^{F}	605 (22.5)^{G}	909 (19.1)^{E}	485 (14.9)^{G}
IEC	1067(23.6)^{CD}	466 (35.9)^{E}	1064(22.4)^{DE}	455 (37.2)^{E}	797 (12.7)^{D}	359 (29.7)^{E}
IEM	844 (22.6)^{B}	339 (10.3)^{B}	850 (27.7)^{*B}	336 (10.0)^{B}	636(21.7)^{*B}	263 (8.5)^{B}
CD	852 (24.4)^{B}	371(35.3)^{BC}	879 (27.1)^{B}	370(30.1)^{BC}	672(59.4)^{*B}	291(20.7)^{BC}

* Significant differences between the different CAD/CAM materials within one material thickness, cutting modus, and distance between specimens and light unit are marked with different letters.

LEGENDS

Figure 1. Testing apparatus.

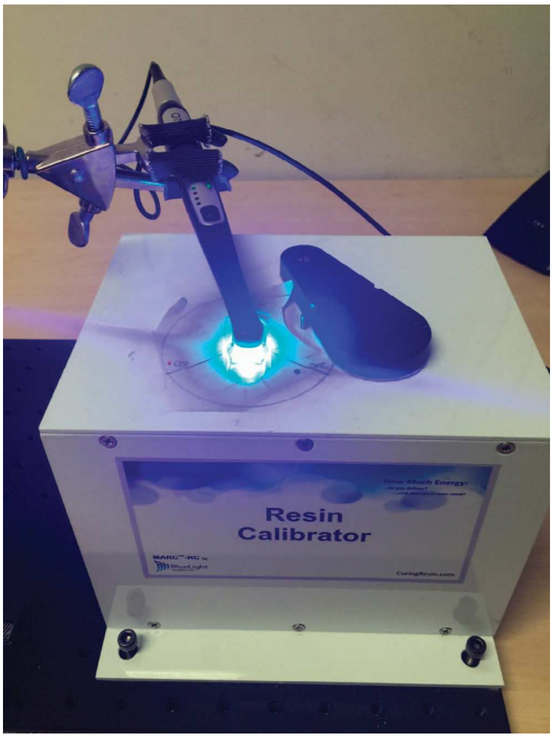


Figure 2. Transmitted irradiance as a function of material and initial irradiance in 1-mm-thick specimens. Curing unit was positioned directly on the specimen surface.

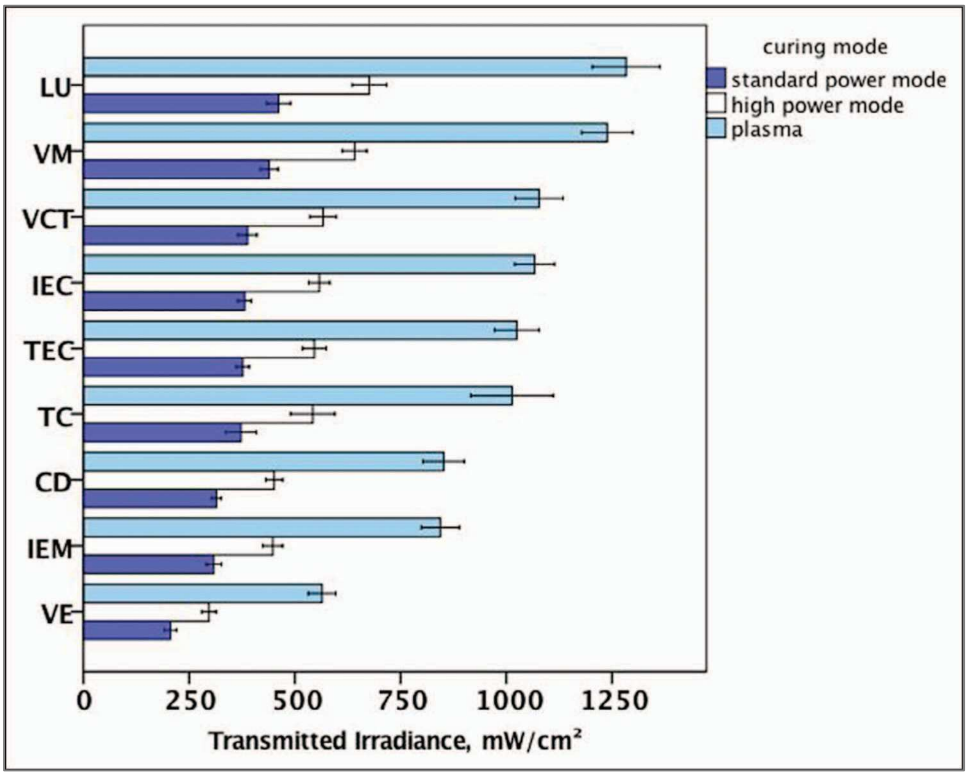


Figure 3. Effect of distance between light curing and material surface (standard curing mode, 1-mm-thick specimens).

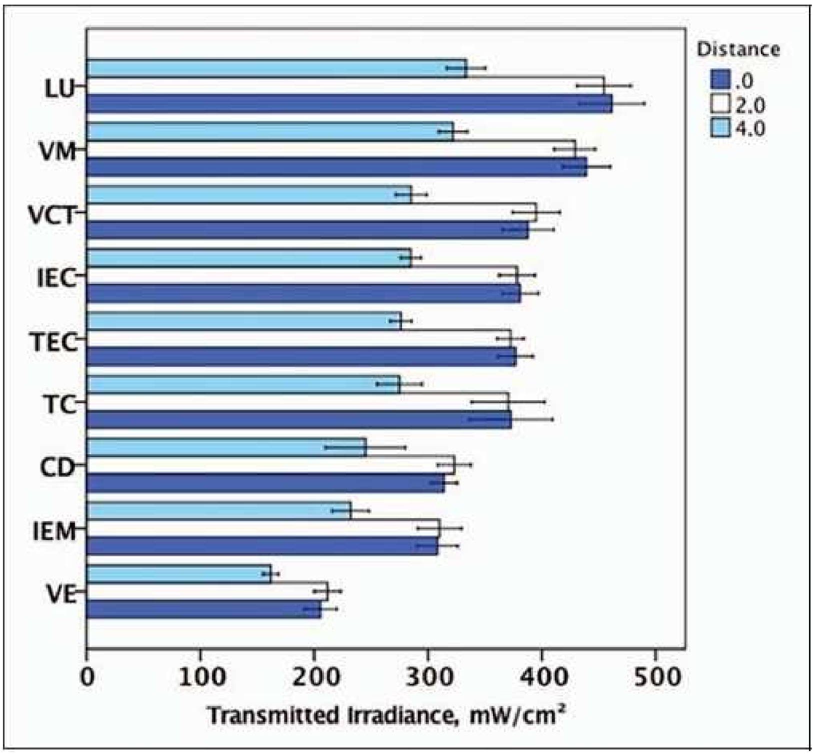


Figure 4. Transmitted irradiance as a function of material type and thickness. The curing unit (standard curing mode) was positioned directly on the specimen surface.

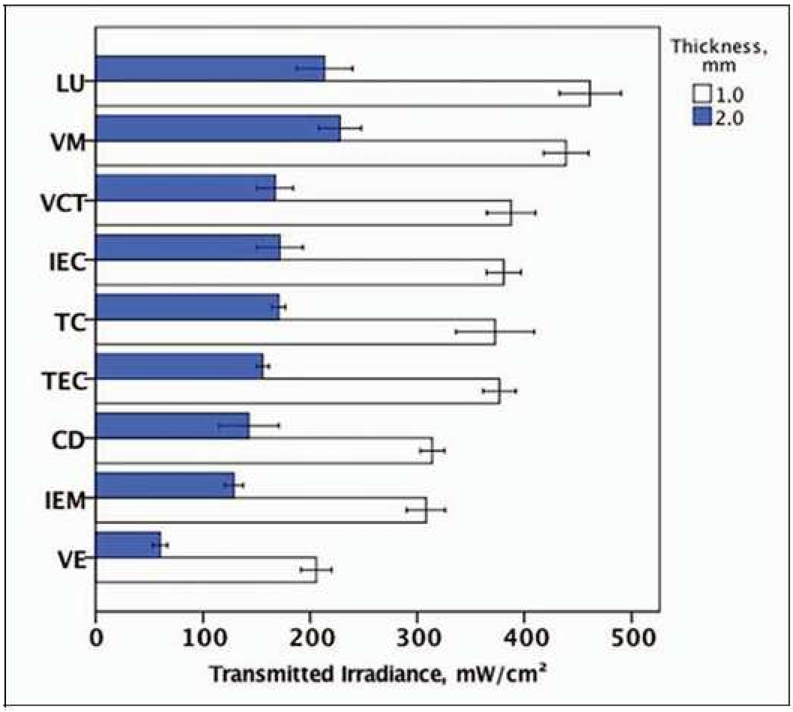
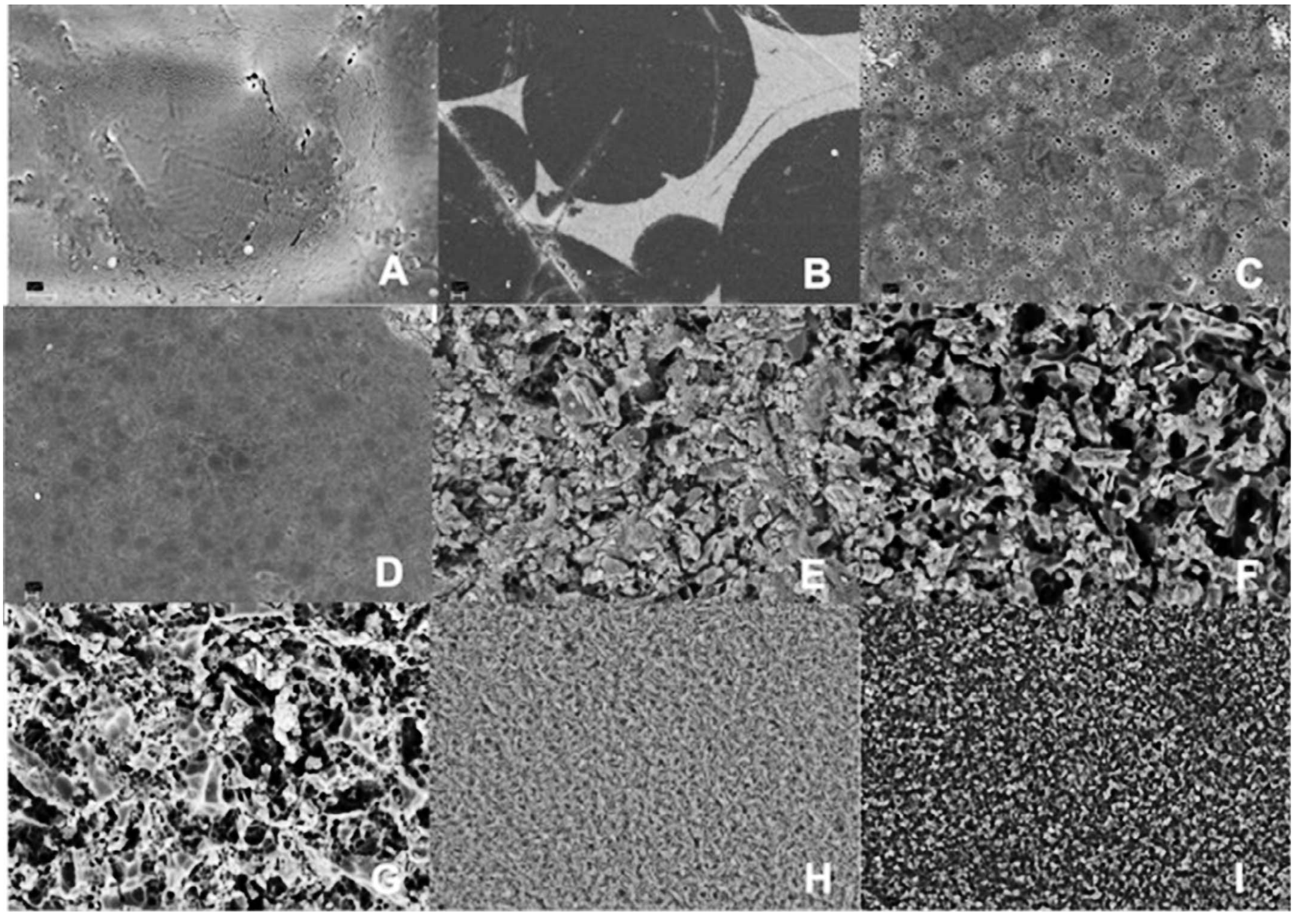


Figure 5. Scanning electron microscope images of the microstructure of all tested materials: A: TC; B: VCT; C: TEC; D: LU; E: VE; F: VM; G: IEC; H: IEM; I: CD.



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