Optical integration of CAD/CAM materials

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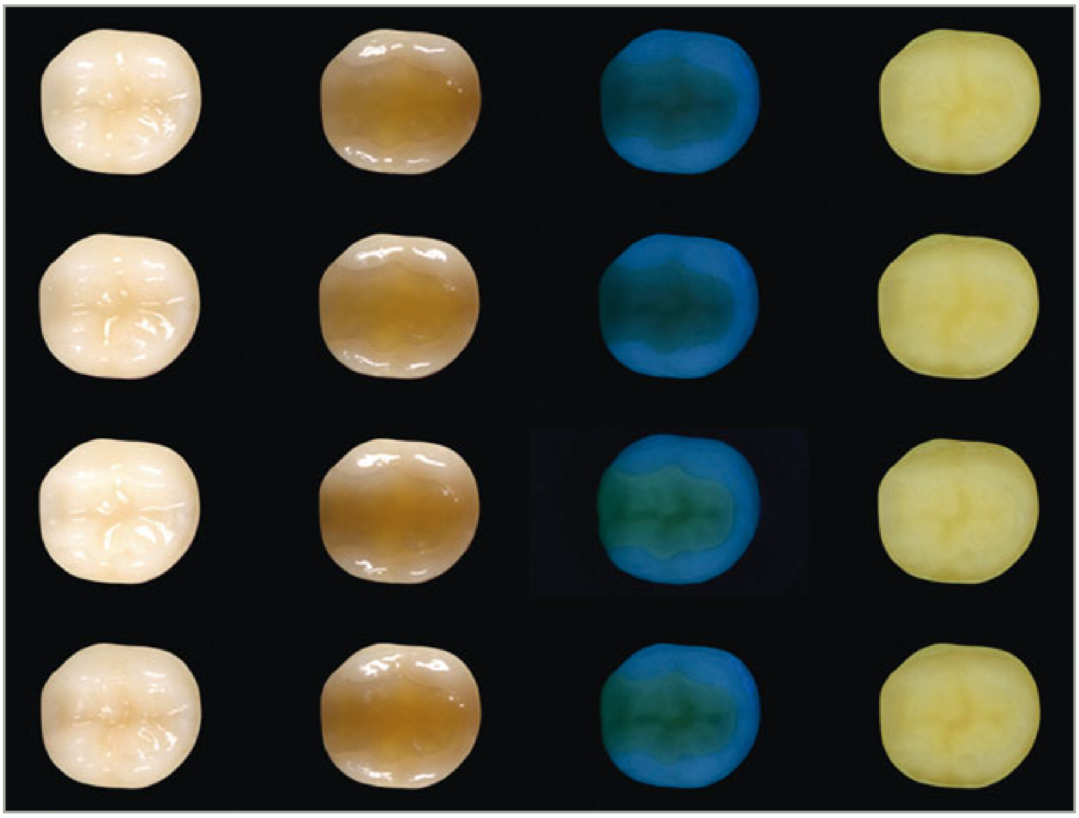

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Abstract

Objective: The optical integration (OI) of monolithic CAD/CAM materials under 4 illuminations was evaluated using a standardized and clinically relevant method.

Materials and methods: Eighteen inlays were manufactured and placed (glycerin gel). Standardized photos were taken under 4 illuminations (neutral white light direct and indirect illumination, cross-polarized light, fluorescent light). Six evaluators defined the optical integration score (OIS) as the "visibility" of the restoration (0 = worst OI, 4 = optimal OI). The intact tooth served as control. The null hypothesis was that different illuminations did not influence the OI of CAD/CAM inlays. One-way ANOVA, followed by Scheffe's post hoc, was applied ($P = 0.05$).

Results: Neutral light direct illumination: OIS between 2.67 (IPS e.max CAD LT A1, ENAMIC A1) and 3.83 (IPS e.max CAD HT A1) with a mean of 3.28 (± 0.339). Indirect illumination: OIS from 1.00 (Paradigm MZ100 A1) to 2.41 (ENAMIC A1) with a mean of 1.88 (± 0.598). Fluorescent light: OIS between 0.75 and 3.25 with a mean of 1.67 (± 1.025). ENAMIC and VITABLOCS Mark II showed the best optical integration in fluorescence. IPS e.max CAD, Paradigm MZ 100 demonstrated low fluorescence; Lava Ultimate high fluorescence. OI was influenced by different illumination.

Conclusion: A simple method accessible to clinicians for additional evaluation of CAD/CAM materials in daily practice is presented. All materials showed excellent OI under direct illumination with neutral white light. The most pronounced differences in optical integration between tooth and evaluated materials were observed under fluorescent light.

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Introduction

Over the past decade, computer-aided design/computer-aided manufacturing (CAD/CAM)-generated indirect or semi-/indirect restorations have gained increasing importance. Especially for the restoration of single teeth, semi-/indirect chairside-fabricated inlays, overlays, and partial crowns represent an attractive alternative to laboratory fabricated restorations or direct composite fillings.[1] To date, these restorations are most often milled from industrially fabricated ceramic blocks. Such restorations, fabricated with the Cerec system, have proven their clinical reliability over more than 1 decade, even when compared to cast gold restorations.[2-5]

Besides ceramic materials, practitioners have recently started to have access to blocks/blanks made from polymer materials. These materials have been called high-performance polymers (HPPs) due to the superior mechanical stability of CAD/CAM-fabricated polymer restorations milled from resin blocks, compared to those fabricated by conventional methods.[6-8] These enhanced mechanical properties are due to the polymerization of the CAD/CAM blanks under controlled and standardized industrial conditions, with optimized pressure and temperature parameters. Additionally, milled restorations from composite blocks seem to minimize the risk of cuspal fracture below the cementoenamel junction (CEJ) when compared to porcelain onlays.[9,10] Nevertheless, regardless of whether blocks from ceramic or HPPs are used, little is known about their optical properties and individual color integration.

The esthetic appearance of a restoration and a natural tooth is dependent on the optical properties of the hard tissue, the restorative material, and the interaction between them. The restoration material should closely resemble the natural tooth structure to achieve an esthetically pleasing result. Although matching the color of a restoration to a natural tooth has been widely debated and researched, it remains a challenging task for the restorative team.[11-13] The versatility of layered porcelains and composites permits the knowledgeable clinician and dental technician to mimic the chroma, shade, hue, translucency, and surface of a natural tooth.[14] However, in contrast to layered indirect and direct restorations, the color scheme of CAD/CAM-fabricated restorations is very limited. The challenge of matching the correct color becomes even more difficult when restorations are milled from monolithic/monochromatic blanks. Despite the fact that multicolored blanks are available on the market, in most cases the restorations are still fabricated out of single-colored blocks. Therefore, the morphology and optical properties of CAD/CAM restorative materials become even more important in order to obtain perfectly integrated dental restorations.

Since patients are seen under various illuminations, the ability to assess appearance-matching characteristics under diverse lights helps to assure an optimum match for the patient.[15] Besides direct illumination, Kelly et al identified translucency as one of the primary factors controlling the esthetics of a restoration, and therefore a critical consideration in the selection of materials.[16,17] Also, illumination under polarized light helps clinicians to understand the inner histo-anatomical structure of a natural tooth, which essentially influences its optical appearance, and that of dental restorations, respectively.[18] A further parameter that impacts the optical appearance of a restoration in the oral cavity is the fluorescence. Fluorescence describes the phenomenon when radiation of shorter wavelength is absorbed, and a reemission of visible light occurs. Modern esthetic restorative materials should exhibit fluorescent properties. Under black light that emits ultraviolet light in the range of wavelength below 390 nm, the fluorescence of a material can be easily made visible. By the use of current filter and flash systems such as, for example, fluor_eyes (Emulation), clinicians can visualize and evaluate the fluorescent properties of teeth and restorative materials, even *in vivo*.

The optical behavior of a dental restoration material and its match or optical integration (OI) to the natural tooth is a multifactorial phenomenon that is difficult to evaluate using technical/physical parameters. Therefore, Magne and So introduced the optical integration score (OIS) that evaluates the "visibility" of a dental restoration with the unaided human eye.[19] Knowledge about the OI of CAD/CAM materials under different illuminations compared to a natural tooth would enable clinicians to improve the optical adjustment of a monolithic restoration in an individual clinical situation. To the authors' best knowledge, there is currently no study that evaluates the OI of CAD/CAM materials using all aforementioned illumination sources.

The aim of this study was to evaluate the OI of six CAD/CAM materials, including different degrees of translucency and different colors. Emphasis was given to a standardized, simple, and clinically relevant evaluation method that would take into account various lighting conditions (direct and indirect illumination, neutral white light, fluorescent light, and cross-polarized light), and allow direct comparison with a substantial amount of intact, remaining hard tissue (enamel/dentin).

The null hypothesis was that the different illuminations do not influence the visible OI of CAD/CAM inlays from ceramic and HPPs.

Materials and methods

Approval was obtained from the University of Southern California Institutional Review Board. A freshly extracted, sound third maxillary molar, stored in a Thymol-saturated solution, was used for the study. The color of the molar was rated A2 using the Vita Classic shade guide (Vita). The color assessment was done independently by two examiners in the same laboratory under the same controlled light environment as that of the following evaluations of specimens.

Subsequently, standardized photographs were taken of the intact tooth under four different illuminations. They were taken with a digital camera (Nikon D800E, Nikon), a 105 mm macro photography lens (Micro NIKKOR AF 105mm 1:2.8G with Close-up no. 4T, Nikon), and a twin flash (Nikon Close-up speedlight Remote Kit R1) at a magnification of 1.5X. The camera was attached to a reproduction stand, and the sensor was positioned perpendicular to

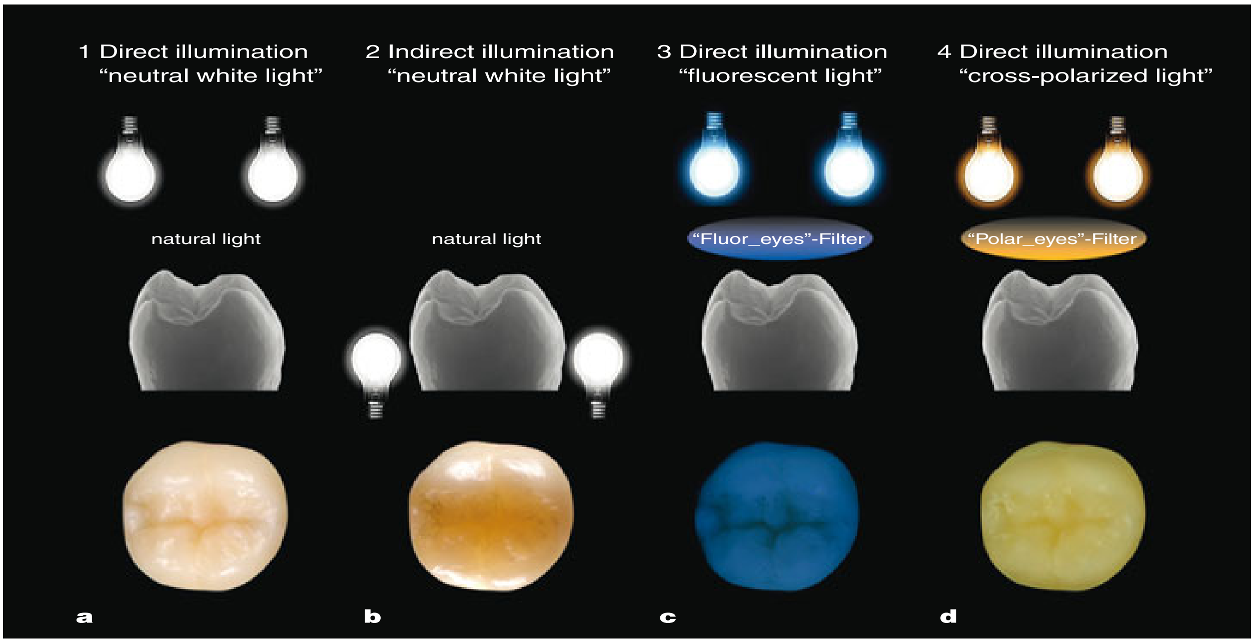

Fig 1a to d Standardized photographs (occlusal view) under different light conditions. The resulting photographs (below: a to d) served as a control group for the later evaluation of optical integration (OI).

the long axis of the tooth. Precise framing was possible by the use of a grid in the camera viewfinder. The four photographs taken under four different light conditions are shown in Figure 1:

- Photo 1: direct illumination "neutral white light" with the flashes mounted on the lens. The room was illuminated by a daylight-imitating lamp with a color temperature over 5500 Kelvin and a color spectrum close to daylight (ISO 400; shutter 1/60, Aperture 57) (Fig 1a).
- Photo 2: indirect illumination "neutral white light" with the flashes positioned 1 inch beside the vestibular and oral surface of the tooth to simulate translucency. The room was illuminated by a daylight-imitating lamp with a color temperature over 5500 Kelvin and a color spectrum close to daylight (ISO 400; shutter 1/60, Aperture 57) (Fig 1b).
- Photo 3: direct illumination "fluorescent light" with the fluor_eyes flashes and filter mounted on the lens. The room was dark (ISO 400; shutter 1/60, Aperture 36) (Fig 1c).
- Photo 4: direct illumination "cross-polarized light" with the polar_eyes flashes and filter mounted on the lens. The room was illuminated by a daylight-imitating lamp with a color temperature over 5500 Kelvin and a color spectrum close to daylight (ISO 400; shutter 1/60, Aperture 57) (Fig 1d).

The photographs of the intact tooth were saved in JPEG format and served as a control group for the evaluation of OI.

Fabrication of inlays

A Class II defect was simulated by preparing for an inlay with a mesial box

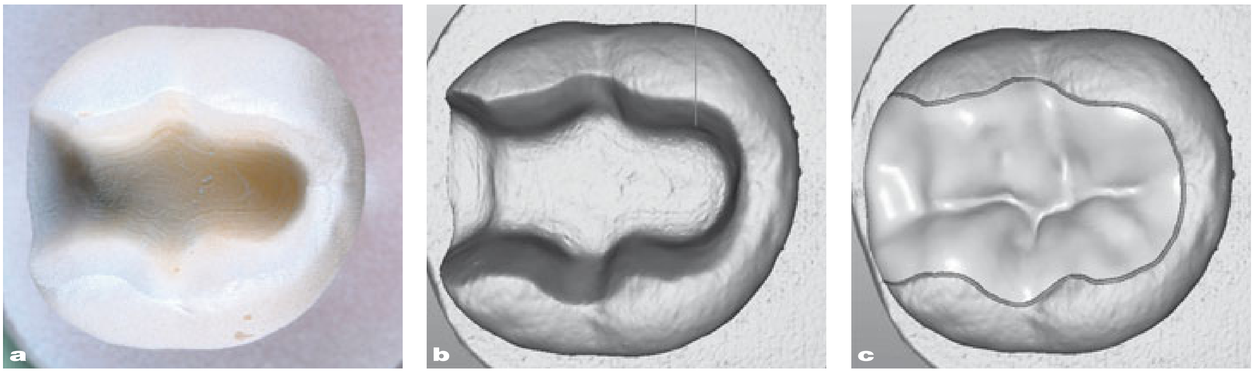

Fig 2a to c Fabrication of the inlay: **(a)** Powder layer (Cerec Spray) on the prepared MO inlay, **(b)** dataset of the scaned natural tooth preparation, **(c)** virtually designed inlay using Cerec Software 3.60.

Table 1 Tested materials

Material name	Color	Material class	Manufacturer	Address
VITABLOCS Mark II	A1	glass-ceramic	Vita Zahnfabrik	Bad Säckingen, Germany
VITABLOCS Mark II	A2	glass-ceramic	Vita Zahnfabrik	Bad Säckingen, Germany
IPS Empress CAD HT	A1	glass-ceramic	Ivoclar Vivadent	Schaan, FL-Liechtenstein
IPS Empress CAD HT	A2	glass-ceramic	Ivoclar Vivadent	Schaan, FL-Liechtenstein
IPS Empress CAD LT	A1	glass-ceramic	Ivoclar Vivadent	Schaan, FL-Liechtenstein
IPS Empress CAD LT	A2	glass-ceramic	Ivoclar Vivadent	Schaan, FL-Liechtenstein
IPS e.max CAD HT	A1	lithium disilicate-ceramic	Ivoclar Vivadent	Schaan, FL-Liechtenstein
IPS e.max CAD HT	A2	lithium disilicate-ceramic	Ivoclar Vivadent	Schaan, FL-Liechtenstein
IPS e.max CAD LT	A1	lithium disilicate-ceramic	Ivoclar Vivadent	Schaan, FL-Liechtenstein
IPS e.max CAD LT	A2	lithium disilicate-ceramic	Ivoclar Vivadent	Schaan, FL-Liechtenstein
Lava Ultimate HT	A1	resin nano-ceramic	3M ESPE	Seefeld, Germany
Lava Ultimate HT	A2	resin nano-ceramic	3M ESPE	Seefeld, Germany
Lava Ultimate LT	A1	resin nano-ceramic	3M ESPE	Seefeld, Germany
Lava Ultimate LT	A2	resin nano-ceramic	3M ESPE	Seefeld, Germany
Paradigm MZ100	A1	high-performance polymer (HPP)	3M ESPE	Seefeld, Germany
Paradigm MZ100	A2	high-performance polymer (HPP)	3M ESPE	Seefeld, Germany
ENAMIC	A1	dental hybrid-ceramic	VITA Zahnfabrik	Bad Säckingen, Germany
ENAMIC	A2	dental hybrid-ceramic	VITA Zahnfabrik	Bad Säckingen, Germany

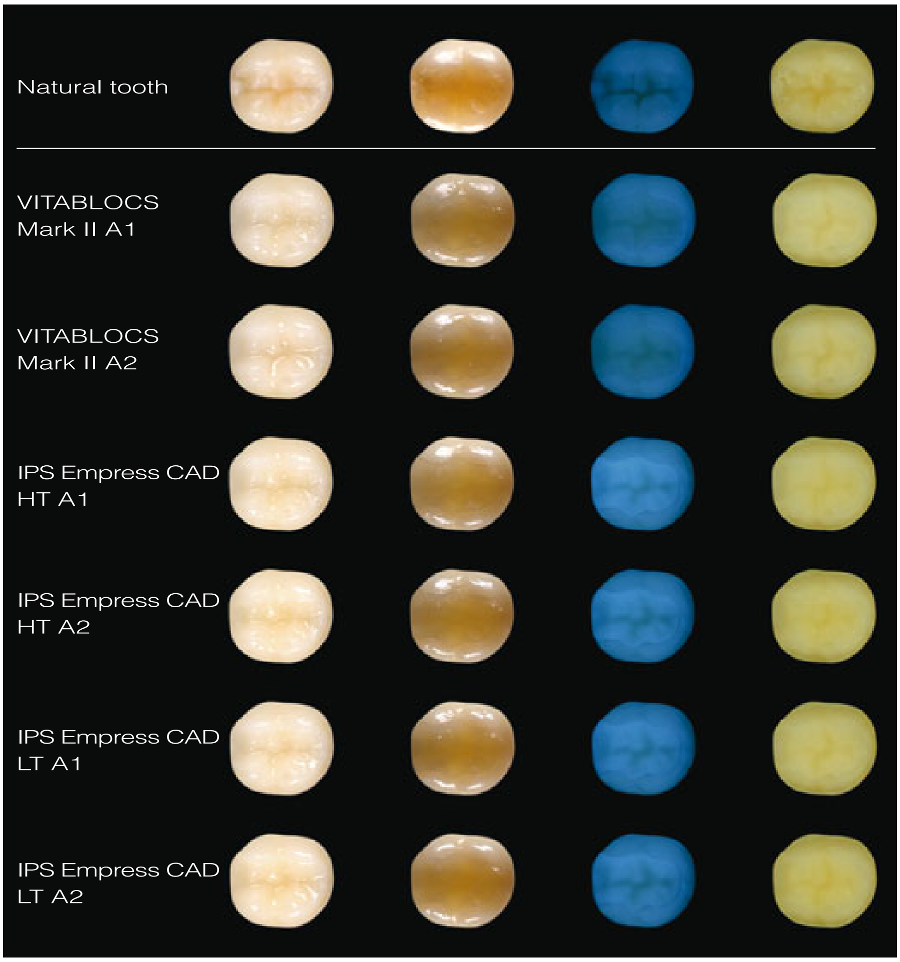

Fig 3a Six evaluators determined the optical integration score (OIS) from 0 ("worst OI") to 4 ("indistinguishable restoration"). The original natural tooth was used as the reference.

and isthmus (isthmus width: 2.5 mm). A thin powder layer (Cerec Spray, Sirona) was applied, the cavity was digitized by Cerec AC Bluecam (Sirona), and an inlay was designed (Cerec Software 3.60, Sirona) (Fig 2a to c). All 18 inlays made from different materials (Table 1) were milled on the basis of one dataset, resulting in standardized inlays with similar geometry and size. During inlay fabrication, the tooth was permanently stored in distilled water at room temperature to allow for enamel/dentin rehydration.

Following the inlay fabrication, each inlay was placed into the preparation using transparent glycerin gel (K-Y Jelly, Johnson & Johnson),[20] and standardized photographs were taken under similar light conditions. After each inlay had been placed, the tooth was stored again in distilled water to avoid dehydration. As glycerin gel was used, the restorations could be easily removed without loss of remaining hard tissue.

All the photographs were saved in JPEG format. For evaluation purposes, all the photographs of the same specimen were arranged in a table and imported into a presentation program (Keynote 2009, Apple). The photo-

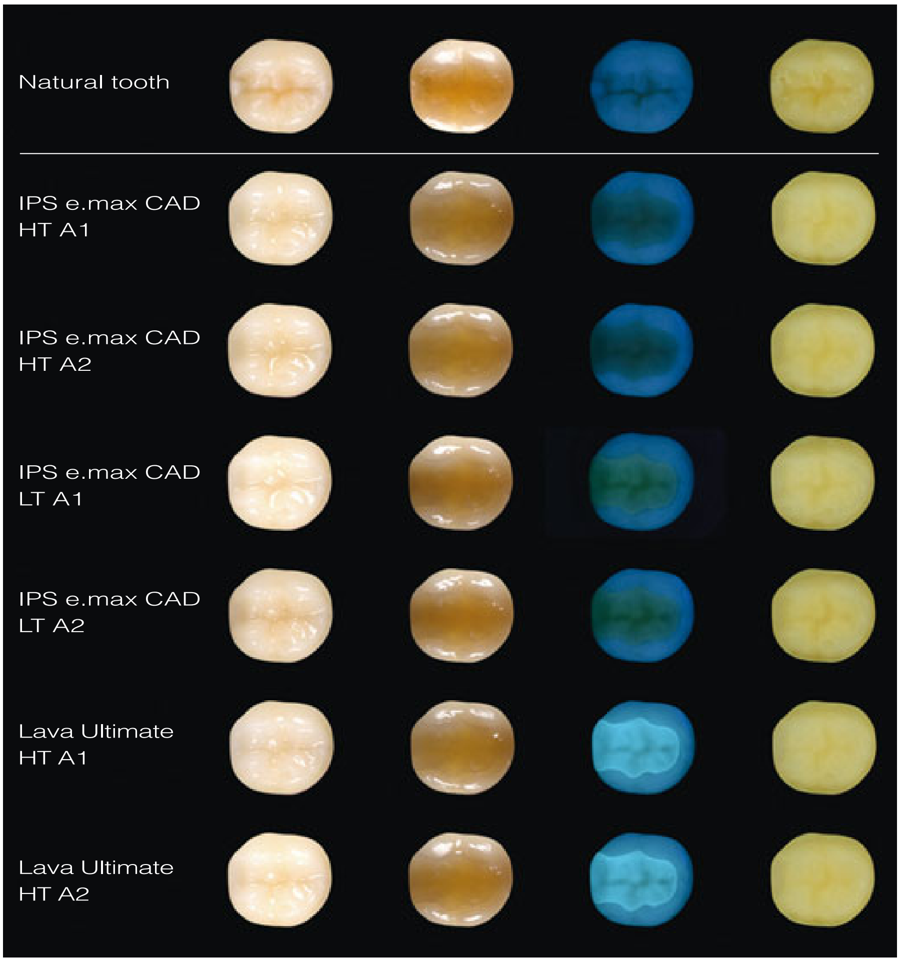

Fig 3b Six evaluators determined the optical integration score (OIS) from 0 ("worst OI") to 4 ("indistinguishable restoration"). A natural tooth was used as the reference.

graphs were presented to the evaluators on a MacBook Pro with a retina display (color LCD) at the highest brightness level. Evaluations took place at a dental laboratory under daylight-imitating light sources, with a color temperature over 5500 Kelvin and a color spectrum close to daylight. Each evaluator had 2 min to evaluate one material under the different illuminations. Viewing distance was about 50 cm.

All the reference photographs of the natural tooth were displayed in the top row, with the photographs of the test specimens presented below. All 18 tables (one per specimen) were presented randomly to the evaluators without brand names (number codes were used instead). As a control, one table displayed the natural tooth in the bottom line. The pooled tables are shown in Figure 3a to c.

Six evaluators participated in the study (two dental technicians, four dentists). Each evaluator independently defined the OIS as the "visibility" of the restoration in comparison to the remaining hard tissue, on a scale from 0 to 4 (0 = worst OI – restoration can be easily distinguished from remaining tissue;

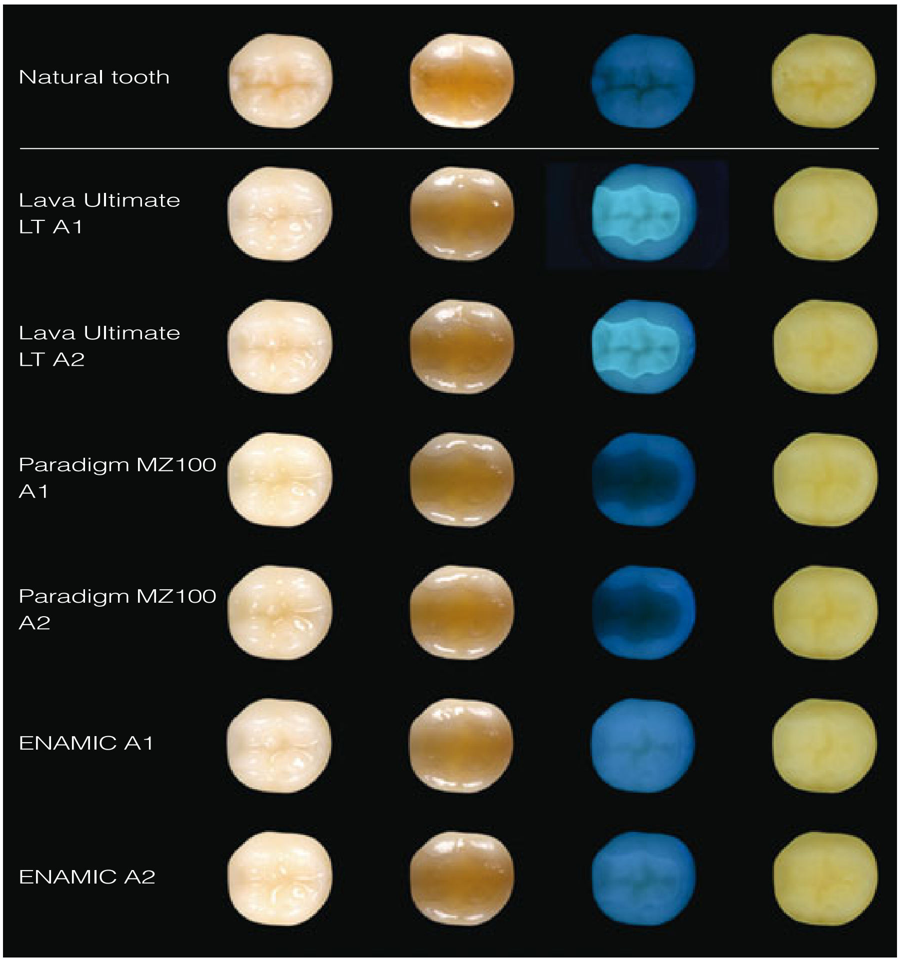

Fig 3c Six evaluators determined the optical integration score (OIS) from 0 (“worst OI”) to 4 (“indistinguishable restoration”). A natural tooth was used as the reference.

4 = optimal OI – restoration is indistinguishable from remaining hard tissue). The evaluators were allowed to grade with .5 decimals (eg, 0.5, 1.5, 2.5, 3.5). One OIS was determined for each of the four light conditions.

Descriptive statistics for OIS (mean, standard deviation [SD]) were calculated for each light condition and material. Normal distribution was tested using Kolmogorov-Smirnov and Shapiro-Wilk tests. One-way ANOVA, followed by Scheffé’s post hoc test, was applied to evaluate statistically significant differences between the different illuminations for each material, and also to evaluate differences between the materials at each illumination. For statistical analysis, the Statistical Package for the Social Sciences 20.0 (SPSS) was used. *P* values less than 0.05 were considered statistically significant.

Results

The mean (∅) OIS values, calculated from the scores of the six evaluators, and the SDs for each illumination condition, are shown in Table 2 and Figure 4.

Table 2 Optical integration scores (OIS) under different illuminations. One-way ANOVA showed statistical differences within all materials under different illuminations, except for ENAMIC A1 and ENAMIC A2. Lower-case letters (a, b, c, d, e) show the significant groups within one material.

	Neutral white light/ direct illumination				Neutral white light/ indirect illumination				Fluorescent light/ direct illumination				Cross-polarized light/ direct illumination				Overall IOS			
	Ø OIS		SD	Conf.-Int.	Ø OIS		SD	Conf.-Int.	Ø OIS		SD	Conf.-Int.	Ø OIS		SD	Conf.-Int.	Ø OIS		SD	Conf.-Int.
VITABLOCS Mark II A1	**3.58**	a	0.49	3.05 / 4.10	**2.25**	ab	0.52	1.68 / 2.81	**2.83**	abc	0.52	2.28 / 3.38	**3.33**	a	0.68	2.60 / 4.06	**3.00**	a	0.74	2.67 / 3.32
VITABLOCS Mark II A2	**3.33**	a	0.26	3.05 / 3.61	**1.92**	ab	0.49	1.39 / 2.44	**2.83**	abc	0.68	2.10 / 3.56	**3.00**	a	0.55	2.41 / 3.58	**2.77**	a	0.72	2.45 / 3.08
IPS Empress CAD HT A1	**3.33**	a	0.52	2.78 / 3.88	**2.08**	ab	0.38	1.67 / 2.48	**1.67**	bcde	0.75	0.66 / 2.49	**3.58**	a	0.38	3.17 / 3.98	**2.65**	a	1.01	2.21 / 3.08
IPS Empress CAD HT H2	**3.42**	a	0.38	3.01 / 3.82	**2.08**	ab	0.49	1.55 / 2.60	**1.83**	bcde	0.82	0.96 / 2.70	**3.50**	a	0.45	3.02 / 3.97	**2.71**	a	0.93	2.30 / 3.11
IPS Empress CAD LT A1	**3.33**	a	0.75	2.53 / 4.13	**1.92**	ab	0.66	1.20 / 2.62	**2.08**	abcde	0.66	1.37 / 2.79	**2.75**	a	0.61	2.09 / 3.40	**2.52**	a	0.85	2.15 / 2.89
IPS Empress CAD LT A2	**3.17**	a	0.88	2.23 / 4.09	**2.08**	ab	0.92	1.11 / 3.05	**2.25**	abcde	0.52	1.68 / 2.81	**3.42**	a	0.49	2.89 / 3.94	**2.73**	a	0.90	2.34 / 3.11
IPS e.max CAD HT A1	**3.83**	a	0.26	3.55 / 4.11	**1.58**	ab	0.66	0.87 / 2.29	**1.08**	cde	0.74	0.30 / 1.86	**3.58**	a	0.38	3.17 / 3.98	**2.52**	a	1.33	1.94 / 3.09
IPS e.max CAD HT A2	**3.58**	a	0.58	2.95 / 4.20	**1.67**	ab	0.88	0.73 / 2.59	**1.00**	cde	0.78	0.17 / 1.82	**3.75**	a	0.27	3.45 / 4.04	**2.50**	a	1.37	1.91 / 3.08
IPS e.max CAD LT A1	**2.67**	a	1.08	1.52 / 3.81	**1.67**	ab	0.61	1.02 / 2.31	**0.92**	de	0.58	0.29 / 1.54	**2.50**	a	0.71	1.74 / 3.25	**1.94**	a	1.01	1.49 / 2.37
IPS e.max CAD LT A2	**3.42**	a	0.49	2.89 / 3.94	**1.58**	ab	0.74	0.80 / 2.36	**0.83**	de	0.41	0.39 / 1.27	**3.25**	a	0.27	2.95 / 3.54	**2.27**	a	1.22	1.74 / 2.79
Lava Ultimate HT A1	**3.25**	a	0.94	2.25 / 4.24	**1.75**	ab	0.94	0.75 / 2.74	**0.75**	e	0.42	0.30 / 1.19	**3.33**	a	0.75	2.53 / 4.13	**2.27**	a	1.33	1.70 / 2.84
Lava Ultimate HT A2	**3.42**	a	0.80	2.56 / 4.26	**1.58**	ab	0.92	0.62 / 2.55	**0.75**	e	0.42	0.30 / 1.19	**3.75**	a	0.42	3.30 / 4.19	**2.38**	a	1.42	1.76 / 2.98
Lava Ultimate LT A1	**2.92**	a	1.02	1.83 / 3.99	**1.92**	ab	0.86	1.00 / 2.83	**0.75**	e	0.42	0.30 / 1.19	**3.08**	a	0.80	2.23 / 3.93	**2.17**	a	1.21	1.64 / 2.68
Lava Ultimate LT A2	**2.75**	a	1.33	1.34 / 4.15	**1.25**	b	0.69	0.51 / 1.98	**0.75**	e	0.42	0.30 / 1.19	**3.08**	a	0.74	2.30 / 3.86	**1.95**	a	1.28	1.40 / 2.51
Paradigm MZ100 A1	**3.75**	a	0.27	3.45 / 4.04	**1.00**	b	0.61	0.17 / 1.82	**0.75**	e	0.42	0.30 / 1.19	**3.42**	a	0.38	3.01 / 3.82	**2.23**	a	1.47	1.59 / 2.85
Paradigm MZ100 A2	**3.50**	a	0.32	3.15 / 3.84	**1.17**	b	0.82	0.29 / 2.03	**0.75**	e	0.42	0.30 / 1.19	**3.67**	a	0.41	3.22 / 4.10	**2.27**	a	1.44	1.65 / 2.88
ENAMIC A1	**2.67**	a	1.25	1.34 / 3.99	**2.41**	ab	1.02	1.33 / 3.48	**3.25**	ab	0.42	2.80 / 3.69	**2.42**	a	0.86	1.50 / 3.33	**2.69**	a	0.94	2.27 / 3.09
ENAMIC A2	**2.75**	a	1.25	1.42 / 4.07	**2.00**	ab	1.00	0.94 / 3.05	**2.67**	abcd	0.75	1.86 / 3.44	**2.75**	a	0.76	1.94 / 3.55	**2.54**	a	0.95	2.12 / 2.95
Natural tooth	**4.00**	a	0.00	0 / 0	**3.83**	a	0.26	3.55 / 4.11	**3.92**	a	0.20	3.69 / 4.11	**4.00**	a	0.00	0 / 0	**3.94**	b	0.17	3.85 / 4.01
Mean	**3.28**				**1.88**				**1.67**				**3.27**				**2.53**			
SD	0.40				0.60				1.03				0.44				0.44			

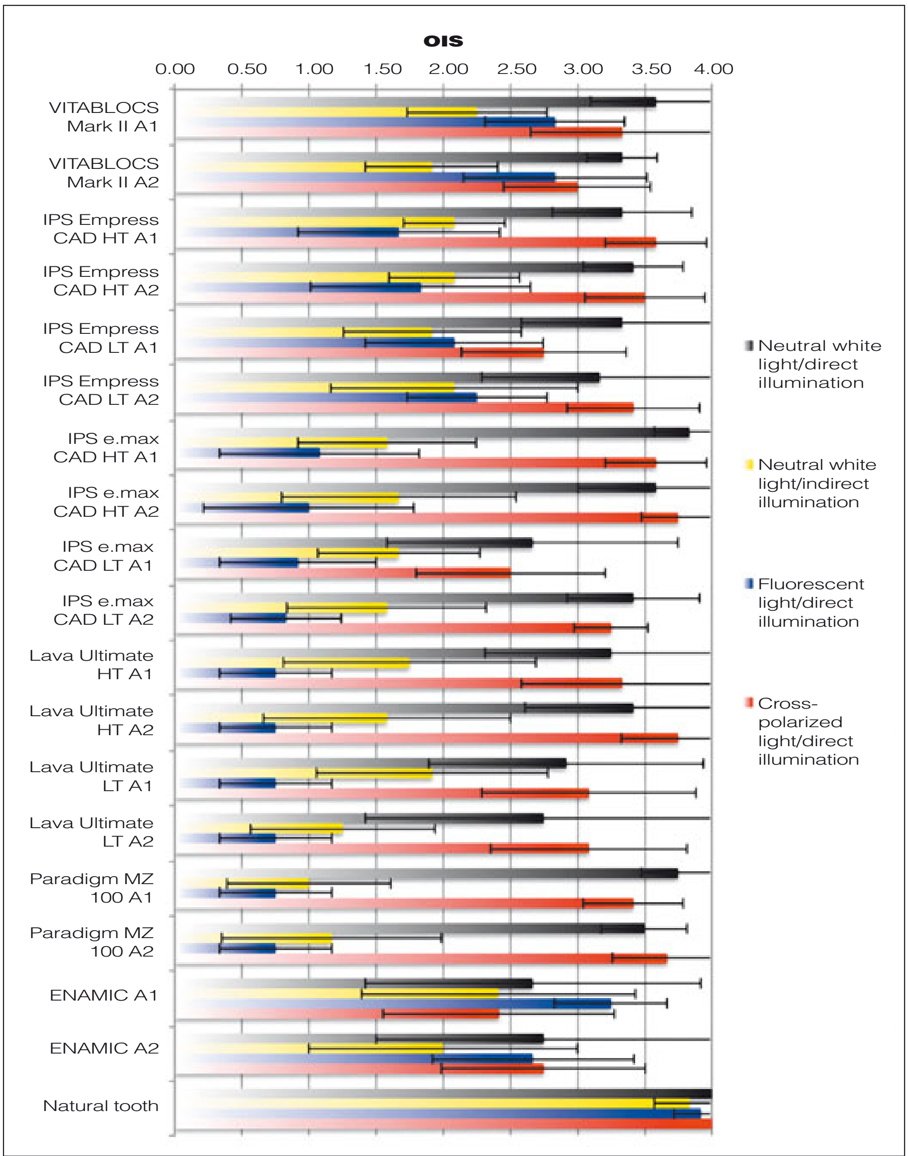

Fig 4 Optical integration scores (OIS) for the tested materials under different illuminations.

The Kolmogorov-Smirnov test showed normal distribution; therefore, one-way ANOVA could be applied.

Under direct illumination with neutral white light, OIS values ranged between 2.67 (IPS e.max CAD LT A1, ENAMIC A1) and 3.83 (IPS e.max CAD HT A1) with a mean value of 3.28 (± 0.339). One-way ANOVA showed no significant differences (P = .089) between the materials and the natural tooth under this illumination. For indirect illumination using neutral white light, Scheffe's test showed that only Paradigm MZ100 A1 and A2, and Lava Ultimate LT A2 differed significantly from the natural tooth. OIS values starting from 1.00 (Paradigm MZ100 A1) up to 2.41 (ENAMIC A1) with a mean value of 1.88 (± 0.6) could be observed under indirect illumination.

Under direct illumination with fluorescent light, the greatest distribution of OIS values could be observed. An OIS range between 0.75 and 3.25 with a mean value of 1.67 (±1.03) could be found. One-way ANOVA ($P = 0.001$) and Scheffe's post hoc test showed several significantly different groups, which are shown in Table 2. Under direct illumination with cross-polarized light, an OIS range between 2.42 and 3.75 with a mean of 3.27 (±0.438) was observed, however no statistical differences could be found.

Taking all the OIS values of all the examiners for one material into account, the overall OI (mean value) could be determined, independently from the light source. All materials showed different OIS values compared to the natural tooth, but not between each other.

One-way ANOVA and Scheffe's post hoc tests showed different OI values within one material under different illuminations (Table 2).

The most obvious differences between the materials could be found under direct illumination with fluorescent light. Here, ENAMIC and VITABLOCS Mark II showed the best optical integration, independent of their color (A1/A2). Under this illumination, materials with a very low (IPS e.max CAD, Paradigm MZ100) and a very high (Lava Ultimate) level of fluorescence could be identified.

Discussion

The color of the restorative material is often considered to be a crucial element in the esthetic success of a restoration. However, the optical characteristic of an intact tooth is influenced by the interaction of the specific light conditions with the enamel, dentin, and subjacent pulp. The interaction of different parameters such as the degree of translucency, opacity, opalescence, iridescence, and especially fluorescence of the dental hard tissue varies, also depending on the location of the tooth. This makes it difficult when we try to emulate nature.[21] Further criteria such as form, surface structure, and opacity also play an important role in the color integration of a restoration, and, when they are well respected, contribute to minimizing errors of color choice.[22]

Unlike direct composite restorations, CAD/CAM-fabricated restorations milled from monochromatic and monocolored blanks offer less possibility for individually modifying the esthetic appearance of restorations. As natural teeth mostly exhibit a color gradient, and different area-dependent levels of translucency, sometimes a restoration from a brighter block interacts better with the surrounding tooth structure than a restoration from a block of the "correct" color. Therefore, the optical properties of milled restorations from two colors and their potential for OI with dental hard tissue are of special importance to achieving appealing dental restorations.

In this study, a standardized, simple, and clinically relevant evaluation method was applied to evaluate the OI of CAD/CAM materials. To obtain results that would be as comprehensive as possible, various light conditions were taken into account, and a substantial amount of intact, remaining tooth structure was used for direct comparison, which was why posterior teeth were used with inlay restorations. Glycerin gel, which has a refractive index close to that of composite resins, was applied between the restoration and the tooth to allow the simulation of bonding.[20] It could be argued that a single molar surely does not represent all variations of optical phenomena; however, the natural tooth structure seems to be the reference with which to compare different materials with each other. Clinicians work under varying conditions and therefore have to find the optimal solution based on their individual clinical situation. Therefore, the presented approach is clinically relevant because all the procedures that were used in this *in vitro* investigation can be used *in vivo* in daily practice.

The mean OIS values were calculated from OIS values given by six independent, clinically experienced and calibrated examiners. The comparatively large SDs show how different the individual perception of OI is. Nonetheless, similar tendencies could be recognized within each evaluator's scores during the study.

Under direct illumination with neutral white light, the restorations showed no difference to the natural tooth. This means the OI under direct illumination was independent of the material and color (A1/A2), showed a good "chameleon effect" with the remaining tooth structure, and therefore showed no difference to the intact tooth. Furthermore, under indirect illumination with neutral white light, the materials showed no significant difference from each other; however, they differed from the natural tooth. This may be because under this illumination, and taking into account the position of the flashes, the incident light was perpendicular to the adhesive interface of the inlay, scattering and breaking the light (unlike in the natural tooth).

A further point for discussion is whether the polarizing filter and the fluorescent filter affected the overall color perception of the samples. Nevertheless, the filters seem to be the most standardized method to capture cross-polarized and fluorescent photographs. Therefore, for study purposes, the use of filters can be justified because their influence might be negligible for the results (bearing in mind that the perception of the tooth may also be altered by the filters in the same way that the perception of the materials is altered by them).

A better differentiation between the test materials was possible under the illumination with cross-polarized light (polar_eyes filter and flashes). Reflective cross-polarized light photography mitigates unwanted specular reflections that obscure the fine details of dental structures, while providing a high contrast/hyper-saturated dental image to be objectively analyzed (Emulation). Under direct illumination with cross-polarized light, four materials (ENAMIC A1, ENAMIC A2, IPS e.max CAD LT A1, and IPS Empress CAD LT A1) differed from the natural tooth. However, the most obvious differences between the materials could be found under direct illumination with fluorescent light. Here, ENAMIC and VITABLOCS Mark II showed the best OI, independent of their color (A1/A2).

Fluorescence in dental materials is achieved by the utilization of luminescence rare earths such as europium, cerium, and ytterbium. Although the level of fluorescence can be controlled by the amount of these elements in a material, it is known that the transfer energy of several rare earths mixed together is not equivalent to the sum of their individual fluorescence.[23,24]

Thus, in the present study, materials with a comparably low (IPS e.max CAD, Paradigm MZ100) and a very high (Lava Ultimate) level of fluorescence could be identified, which indicates that the adjustment of the fluorescence level seems to be a challenge for material manufacturers. This may cause major problems, and caution is called for when these materials are used in the anterior dentition. As fluorescence makes teeth appear whiter, brighter, and more "alive" in daylight, no fluorescence or a very low level of it might cause esthetic problems, eg, too dark and greyish-appearing restorations. The very high fluorescence level of Lava Ultimate could be explained by an overcompensation, compared to the previous block (Paradigm MZ100), which exhibited almost no fluorescent properties. For ceramic materials with a low level of fluorescence, the use of a fluorescent glaze (eg, IPS e.max Ceram Glaze, Fluo Paste), or veneering ceramic, might be a solution to compensate in certain situations, where necessary. However, this was not applied in this study.

Regarding the results, the null hypothesis that different illuminations do not influence the OI of CAD/CAM inlays from ceramic and HPPs has to be rejected. Overall, in summary, the main differences in OI between the materials are caused by their individual fluorescent properties. Manufacturers and users should be aware of this parameter during development and application of monolithic materials.

It must be mentioned that the four types of illumination used in this study are not recommended by the International Commission on Illumination (CIE) for performing visual judgments, which is a limitation of the results of this study. Therefore, the authors have been very careful when drawing conclusions based on these results. However, the conducted study represents a simple method accessible to clinicians for additional evaluation of CAD/CAM materials in daily practice. Also, the chosen illuminants are of importance to the appearance of a natural tooth and dental restorations.

One important parameter about a monolithic material is its translucency parameter (TP). The TP and also the initial color difference (DE*) between the tooth and the material might influence and correlate the OI under direct illumination with neutral white light. However, the TP and DE* would not represent the optical behavior under different illuminations. This study focuses on the OI of the materials to the natural tooth structure and the interaction between them under different light conditions. It would be interesting, as a further part of this study, to examine this comparison of the presented results with TP values of the individual materials, and with the DE* between the tooth and the materials.

A trend towards monolithic restorations also in the anterior dentition is currently occurring. Therefore, the knowledge of the optical properties of monolithic materials under different light conditions is crucial to achieve the individual functional and esthetic optimum. This article presents a simple method accessible to the clinician for additional evaluation of new CAD/CAM materials in daily practice.

Clinical significance

A trend towards monolithic restorations also in the anterior dentition is currently occurring. However, little is known about the OI to the natural tooth of monolithic CAD/CAM materials under different illuminations. Since patients are seen under various illuminations, the ability to assess appearance-matching characteristics under diverse lights will help practitioners to tailor the material choice more precisely to the individual needs of the patient.

Conflict of interest

The authors do not have any financial interest in the companies whose materials were used in this study.

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