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Mechanische und optische Eigenschaften von CAD/CAM Kompositen

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Inhaltsverzeichnis

1. Abkürzungsverzeichnis

BC	Brilliant Crios (Coltene/Whaledent, Altstätten, Schweiz)
Bis-EMA	Ethoxylated Bisphenol-A-diglycidyl Methacrylat
Bis-GMA	Bisphenol-A-diglycidyl Methacrylat
Bis-MEPP	2,2-Bis (4-methyacryloxypoly-ethoxyphenyl) Propan
CAD/CAM	Computer-Aided-Design/Computer-Aided-Manufacturing
CCS	Prophy-Paste CCS (Directa, Upplands, Vaesky, Schweden)
CLE	Cleanic (Kerr, Raststatt, Deutschland)
CLJ	CleanJoy (Voco, Cuxhaven, Deutschland)
CNC	Computerized Numerical Control
CPP	Clinpro Prophy Paste (3M, Seefeld, Deutschland)
DET	Détartrine (Septodont, Niederkassel, Deutschland)
DMA	Dodecyl Dimethacrylate
G	Surface Gloss
GC	Cerasmart (GC Europe, Leuven, Belgien)
LU	Lava Ultimate (3M, Seefeld, Deutschland)
MDP	10-methacryloyloxydecyl Dihydrogen Phosphate
MMA	Methyl-methacrylat
NUP	Nupro (Dentsply Sirona, Konstanz, Deutschland)
PMMA	Poly-methyl-methacrylat
PPP	Prophylactic Polishing Paste
PXT	Proxyt (Ivoclar Vicadent, Schaan, Liechtenstein)
Ra	Roughness Average
RDA	Relative Dentin Abrasion
RV	Roughness Values
Rv	Average Maximum Height of the Valley Depth
Rz	Average Maximum Height of the Profile
SEM	Scanning Electron Microscopy

SFE	Surface Free Energy
SH	Shofu Block HC (Shofu, Kyoto, Japan)
SiC	Silicon Carbide Papers
SPO	Clean/Super Polish (Kerr, Raststatt, Deutschland)
TBS	Tensile Bond Strength
TEGDMA	Triethylenglycol Dimethacrylate
UDMA	Urethane Dimethacrylate
ZIP	Zircate Prophy Paste (Dentsply Sirona, Konstanz, Deutschland)
ΔE	Discoloration

2. Publikationsliste

Reymus M, Roos M, Eichberger M, Edelhoff D, Hickel R, Stawarczyk B (2019) Bonding to new CAD/CAM resin composites: influence of air abrasion and conditioning agents as pretreatment strategy. Clin Oral Investig 2019;23:529-38 (doi: 10.1007/s00784-018-2461-7) IF 2016: 2.308

Liebermann A, Spintzyk S, Reymus M, Schweizer E, Stawarczyk B (2019) Nine prophylactic polishing pastes: impact on discoloration, gloss, and surface properties of a CAD/CAM resin composite. Clin Oral Investig 2019;23:327-35 (doi: 10.1007/s00784-018-2440-z) IF 2016: 2.308

Zimmermann M, Koller C, Reymus M, Mehl A, Hickel R (2018) Clinical Evaluation of Indirect Particle-Filled Composite Resin CAD/CAM Partial Crowns after 24 Months. J Prosthodont 2018;27:694-99 (doi: 10.1111/jopr. 12582) IF 2016: 1.452

3. Einleitung

Kavitierte kariöse Läsionen wurden in der Zahnheilkunde bis vor Kurzem hauptsächlich mit Hilfe von metallenen Werkstoffen versorgt. Je nach Defektgröße wurden dabei Amalgame als direkte Füllungsversorgungen oder Edelmetall- bzw. Nicht-Edelmetall-Legierungen für indirekte Restaurationen verwendet. Seit einigen Jahren werden jedoch, aufgrund der vermehrten Inakzeptanz gegenüber Amalgam[1], des hohen Goldpreises, sowie der in Frage gestellten Biokompatibilität metallischer Legierungen[2] verstärkt zahnfarbene Werkstoffe verwendet.

Komposite haben sich in der direkten Füllungstherapie mit gutem Langzeiterfolg[3] bewährt. Durch weiterentwickelte Materialeigenschaften[4] konnte ihre Indikationsbreite von der ästhetischen Region bis auf das Kaulast tragende Seitenzahngebiet ausgedehnt werden[5]. Komposit-Versorgungen erlauben aufgrund ihrer adhäsiven Befestigung einen minimal-invasiven Therapieansatz bei ästhetisch ansprechendem zahnfarbenem Erscheinungsbild. Durch ihre potentielle intraorale Reparaturmöglichkeit[6] können Zahnhartsubstanz opfernde Neuversorgungen vermieden werden[7]. Ihre Nachteile bleiben jedoch trotz aller Neuentwicklungen immanent. Schrumpfungsstress[8] bei der Polymerisation kann zu Randundichtigkeiten führen und die Lichthärtung ist in der Mundhöhle nur eingeschränkt möglich, was einen erhöhten Restmonomergehalt[9] nach sich ziehen kann. Des Weiteren ist ihre Indikation auf Läsionen beschränkt, die keine Höcker zu ersetzende Größe besitzen. Bei einer solchen sind indirekte Versorgungsmaterialien einzusetzen. Sie erlauben durch ihre extraorale Anfertigung eine bessere Gestaltung der Approximal- und Okklusionskontakte sowie die Verwendung von Werkstoffen mit höheren mechanischen Eigenschaften.

Solche Werkstoffe sind beispielsweise Glaskeramiken, die sich in den letzten Jahren aufgrund ihrer hohen Ästhetik und ihrer guten Biokompatibilität[10] immer größerer Beliebtheit erfreuen. Ihre Indikation erstreckt sich von der Frontzahnregion bis in das Seitenzahngebiet[11]. Durch ihre adhäsive, kraftbündige Befestigung erlauben sie eine Rehabilitation der Zahnhartsubstanz nicht nur in funktioneller und ästhetischer, sondern auch in biomechanischer Hinsicht. Jedoch sind keramische Werkstoffe im Vergleich zum duktilen Gold spröde Materialien, die einer erhöhten Mindestschichtstärke bedürfen, um Frakturen zu vermeiden[12]. Sie führen aufgrund ihres hohen E-Moduls zu einer erhöhten Abrasion der antagonistischen Zahnhartsubstanz[13], was besonders bei Patienten, die unter Bruxismus leiden, von großem Nachteil sein kann. Die intraorale Reparatur von vollkeramischen Werkstoffen ist nur eingeschränkt und mit hohem technischen Aufwand[14] möglich.

Die Anwendung der Technologie des Computer-Aided-Design/Computer-Aided-Manufacturing (CAD/CAM) hat die werkstoffkundlichen Möglichkeiten in der Zahnheilkunde von Grund auf verändert[15,16]. Dank der digitalen Prozesse konnten in letzter Zeit neue Materialien und Materialklassen entwickelt werden. Früher wurden Restaurationen hauptsächlich über den Schritt einer Wachsmodellation, dem Ausbrennen dieser in Einbettmaße und dem anschließenden Gießen oder Pressen von Legierungen bzw. keramischen Massen in den entstandenen Hohlraum (lost-wax-technique) hergestellt. Bei der CAD/CAM Technologie wird die durch eine spezifische Software designte Restauration aus einem vorgefertigten Block mittels einer CNC-Maschine (Computerized Numerical Control) herausgeschliffen bzw. gefräst. Bei den Blöcken handelt es sich um industriell-standardisiert hergestellte Werkstoffe, die in passender Größe und Form produziert und mit einem Ansatz für die jeweilige CNC-Maschine versehen wurden. Diese Herstellungsweise erlaubt die Anfertigung neuer Materialklassen, die unter den konventionellen Bedingungen nicht zu realisieren waren[17].

Zu diesen neuen Materialklassen sind CAD/CAM Komposite zu zählen. Sie entstammen meist konventionellen Kompositen, die aus der direkten Füllungstherapie bekannt sind, und werden unter hohem Druck und hoher Temperatur hergestellt. Nguyen et al.[18] verglichen mechanische Eigenschaften von direkten bzw. indirekten Kompositen, die zum einen in einem Lichtofen und zum anderen in einem Autoklaven bei 180°C und einem Druck von 250 MPa für 60 Minuten polymerisiert wurden. Sie stellten dabei fest, dass diese spezielle Vorbehandlung zu signifikant erhöhten Resultaten in Bezug auf die Biegefestigkeit, Bruchzähigkeit sowie Härte führte. Außerdem stellten sie eine geringere Anzahl und Größe von Defekten innerhalb dieser speziell vorbehandelten Prüfkörper fest. Weitere Untersuchungen konnten an CAD/CAM Kompositen eine höhere Polymerisationsrate, eine geringere Porosität[19] sowie einen homogeneren Aufbau ohne Einschlüsse von Verschmutzungen oder Luft[20] belegen. Aufgrund ihrer hohen mechanischen Eigenschaften eignen sie sich zur Austestung neuer Bisslagen, um in einer verlängerten Provisoriumsphase auf funktionelle, ästhetische und patientenbezogene Gesichtspunkte der späteren definitiven Versorgung besser eingehen zu können[21,22]. Von den Herstellern werden sie allerdings nicht als Langzeitprovisorien, sondern als definitives Versorgungsmaterial angeboten. Derzeit fehlen jedoch klinische Langzeituntersuchungen dieser Materialklassen. Eine erste klinische Beobachtung über einen Zeitraum von zwei Jahren verspricht positive Ergebnisse für Einzelzahnrestaurationen[23]. Ein Vorteil als definitives Versorgungsmaterial ist das verringerte E-Modul im Vergleich zu Keramiken. CAD/CAM Komposite sind dadurch weniger frakturanfällig, besonders bei einer verminderten Materialdicke. So lassen sie sich beispielsweise bei der Versorgung von minimal-invasiven Kauflächen-Veneers nutzen[24,25]. Zusätzlich weisen sie eine geringere Abnutzung des antagonistischen Zahnschmelzes auf[26]. Ein weiterer Vorteil dieser neuen Materialklasse ist ihre potentielle Nutzung in der so genannten chairside-Behandlung. Nach einer intraoralen, dreidimensionalen Aufnahme des Präparationssitus durch eine spezielle Kameraeinheit und dem digitalen Design der Versorgung, können CAD/CAM Komposite aus einer vorhandenen CNC-Maschine geschliffen werden und dem Patienten in derselben Sitzung eingegliedert werden. Durch ihre verringerte Härte im Vergleich zu Keramiken ist der Schleifprozess verkürzt und die Schleifkörper unterliegen geringerer Abnutzung. Sie benötigen keinen Kristallisations- oder Glanzbrand, sondern können am Zahnarztstuhl poliert werden und stehen danach sofort zur intraoralen Eingliederung bereit. Außerdem bieten sie, wie direkte Komposit-Füllungen, die Möglichkeit der intraoralen Reparatur[27,28].

CAD/CAM Komposite als Langzeitrestaurationen müssen adhäsiv mit der Zahnhartsubstanz verbunden werden, da ihre Biegefestigkeit unter 350 MPa liegt[29]. Die adhäsive Zahnheilkunde bietet entscheidende Vorteile: bei der Präparation ist nicht mehr auf die Schaffung retentiver Elemente zu achten, die einen vielleicht unnötigen Zahnhartsubstanzabtrag fordern. Vielmehr kann die Präparation nun defektorientiert und möglichst substanzschonend erfolgen. Es ist nur noch auf die Mindestschichtstärke der einzelnen Materialien zu achten, die eine Fraktur der Restauration verhindern soll. Hierbei weisen CAD/CAM Komposite, wie schon beschrieben, den Vorteil einer höheren Elastizität auf, die eine minimal-invasive Präparation erlaubt.

Die übergeordnete Fragestellung dieser Arbeit ist, ob CAD/CAM Komposite als definitives Versorgungsmaterial geeignet sind. Dabei werden zwei Aspekte, die unter anderem eine Voraussetzung für diese Klassifikation darstellen, näher betrachtet: ihre Verbundfestigkeit unter Einfluss verschiedener Vorbehandlungsstrategien und ihre optischen Eigenschaften in Abhängigkeit unterschiedlicher Prophylaxepasten.

Für den langfristigen Erfolg einer Restauration ist eine zuverlässige Befestigung zwischen ihr und der Zahnhartsubstanz von entscheidender Bedeutung. Bei der adhäsiven Befestigung beeinflussen zwei Interfaces den Verbund eines Restaurationsmaterials an der Zahnhartsubstanz: der Verbund des Befestigungskomposits am Zahn, der seit langer Zeit Gegenstand der Forschung ist und der Verbund zwischen Befestigungskomposit und CAD/CAM Komposit, der erst seit Kurzem in den Blickpunkt von Untersuchungen gerückt ist. Die Problemstellung liegt hierbei in dem hochvernetzten Gefüge, das nur eine sehr geringe Anzahl an Kohlenstoff-Kohlenstoff-Doppelbindungen zur Kopolymerisation bereitstellt. Eine Vorbehandlung der basalen Fläche der Restauration ist deshalb von zentraler Bedeutung, um eine erfolgsversprechende Befestigung sicher zu stellen. Es war deshalb das Ziel der hier zuerst vorgestellten Arbeit „*Bonding to new CAD/CAM resin composites: influence of air abrasion and conditioning agents as pretreatment strategy*“ den Einfluss verschiedener Vorbehandlungsstrategien auf die Verbundfestigkeit zwischen vier CAD/CAM Kompositen und einem Befestigungskomposit zu untersuchen. Der Anteil des Autors an dieser Veröffentlichung lag in der Herstellung der Prüfkörper in Kooperation mit ZT Marlis Eichberger, der Durchführung der Untersuchungen sowie dem Verfassen des Manuskripts. Bei letztem Punkt erfuhr er Unterstützung durch PD Dr. Malgorzata Roos hinsichtlich der statistischen Auswertung. Frau PD Dr. Dipl. Ing (FH) Bogna Stawarczyk, M.Sc., plante die Studie, kontrollierte deren Ablauf und unterstützte den Autor bei der Verfassung des Manuskripts. Prof. Dr. Hickel und Prof. Dr. Edelhoff stellten die benötigte Infrastruktur zur Verfügung und begleiteten die Erstellung des Manuskripts.

Für ihren Einsatz als definitives Versorgungsmaterial spielt neben der Verbundfestigkeit auch das ästhetische Erscheinungsbild eine wichtige Rolle. Von konventionellen sowie CAD/CAM Kompositen ist bekannt, dass sie im Vergleich zu Glaskeramiken schneller abradieren, ihren Oberflächenglanz verlieren und rauer werden[30,31]. Sie sollten daher regelmäßig im Rahmen professioneller Zahnreinigungen bzw. zahnärztlicher Kontrollen poliert werden. Die Zielsetzung der hier an zweiter Stelle vorgestellten Arbeit „*Nine prophylactic polishing pastes: impact on discoloration, gloss, and surface properties of a CAD/CAM resin composite*“ war es, die Abnahme der Verfärbung sowie die Änderung der Oberflächenbeschaffenheit nach Anwendung neun verschiedener Prophylaxepastensysteme zu untersuchen. Der Anteil des Autors als Ko-Autor an dieser Veröffentlichung lag in der Mitplanung des Studiendesigns, der Mitherstellung der Prüfkörper sowie im Mitverfassen des Manuskripts und der Unterstützung im Review-Prozess.

In-Vitro Untersuchungen sind zur Beurteilung neuer Materialklassen unabdingbar, um einzelne Aspekten, die klinisch von höchster Relevanz sind, zu erforschen. Jedoch bleiben klinische Langzeituntersuchungen der Goldstandard, um den langfristigen Erfolg eines Materials korrekt einschätzen zu können. Der Autor ist als Prüfarzt Teil zweier solcher Langzeituntersuchungen zu CAD/CAM Kompositen. Es werden dabei die Materialien *Lava Ultimate* (3M, Seefeld, Deutschland) und *Celtra Duo* (Dentsply Sirona, Konstanz, Deutschland) auf ihre klinische Performance untersucht. Bei der Arbeit „*Zimmermann M, Koller C, Reymus M, Mehl A, Hickel R (2017) Clinical Evaluation of Indirect Particle-Filled Composite Resin CAD/CAM Partial Crowns after 24 Months*” führte der Autor die 2-Jahresrecall-Untersuchungen durch, unterstütze die statistischen Auswertung und war an der Erstellung des Manuskripts beteiligt.

4. Eigene Arbeiten

Nachfolgend werden drei Originalarbeiten in englischer Sprache vorgestellt und diskutiert.

4.1 Originalarbeit: Reymus M, Roos M, Eichberger M, Edelhoff D, Hickel R, Stawarczyk B (2019) Bonding to new CAD/CAM resin composites: influence of air abrasion and conditioning agents as pretreatment strategy. Clin Oral Investig 2019;23:529-38 (doi: 10.1007/s00784-018-2461-7) IF 2016: 2.308

Zusammenfassung

Ziel. Das Ziel dieser Untersuchung war es, die Zugfestigkeit vier verschiedener CAD/CAM Komposite in Abhängigkeit von der Vorbehandlung zu untersuchen.

Material und Methode. Die Einflussfaktoren auf die Verbundfestigkeit waren:

1) die unterschiedlichen CAD/CAM Komposite (Brilliant Crios [Coltene/Whaledent], Cerasmart [GC Europa], Shofu Block HC [Shofu] und Lava Ultimate [3M]

2) Sandstrahlen gegen kein Sandstrahlen und

3) Vorbehandlung mit einem Silan (Clearfil Ceramic Primer, Kuraray) oder einem Universaladhäsiv (One Coat 7 Universal, Coltene/Whaledent).

Für jede Kombination der drei Faktoren (4 (Materialien) × 2 (Sandstrahlen gegen kein Sandstrahlen) × 2 (Silan gegen Universaladhäsiv)) wurden n=15 (N=240) Prüfkörper hergestellt. Nach Vorbehandlung des Prüfkörpers wurde der Befestigungskomposit (DuoCem, Coltene/Whaledent) in eine spezielle Form appliziert und auf der Substratoberfläche polymerisiert. Nach 24 stündiger Wasserlagerung bei 37°C und 5.000 Thermozyklen (5°C/55°C) wurde die Zugfestigkeit gemessen und die aufgetretenen Fehlertypen registriert. Die gewonnenen Daten wurden mittels Kaplan-Meier nach Schätzung der kumulativen Fehlerverteilung nach Breslow-Gehan sowie nicht-parametrischer ANOVA (Kruskal-Wallis Test) mit darauffolgendem vielfach-paarweisen Mann-Whitney U-Test mit α-Fehleranpassung gemäß Benjamini-Hochberg und chi^2-Test ($p<0,05$) ausgewertet.

Ergebnisse. Prüfkörper, die unter Verwendung eines Universaladhäsivs vorbehandelt wurden, wiesen signifikant höhere Zugfestigkeitswerte und niedrigere Fehlerraten auf als diejenigen, die unter Verwendung eines Silans vorbehandelt wurden. Die höchsten Fehlerraten wurden für Gruppen beobachtet, die ausschließlich mit einem Silan vorbehandelt wurden. Innerhalb der Shofu Block HC-Gruppe wurde während des Thermocycling-Prozesses ein Debonding all derjenigen Prüfkörper festgestellt, die ohne Sandstrahlen und einfacher Applikation des Silans vorbehandelt wurden.

Schlussfolgerungen. Vor der Befestigung von CAD/CAM Kompositen sollten die Restaurationen mit einem MMA-haltigen Adhäsiv vorbehandelt werden, um eine erfolgreiche Verbindung mit dem Befestigungskomposit zu erreichen. Die Vorbehandlung des CAD/CAM Komposits unter Verwendung eines Silans führt nur zu einer mangelhaften Haftung.

Klinische Relevanz. Zur Befestigung von CAD/CAM Kompositen ist eine spezielle Vorbehandlungsstrategie notwendig, um vielversprechende Langzeitergebnisse sicherzustellen.

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ORIGINAL ARTICLE

Bonding to new CAD/CAM resin composites: influence of air abrasion and conditioning agents as pretreatment strategy

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Abstract

Objectives Because of their industrially standardized process of manufacturing, CAD/CAM resin composites show a high degree of conversion, making a reliable bond difficult to achieve.

Purpose The purpose of this experiment was to investigate the tensile bond strength (TBS) of luting composite to CAD/CAM resin composite materials as influenced by air abrasion and pretreatment strategies.

Material and methods The treatment factors of the present study were (1) brand of the CAD/CAM resin composite (Brilliant Crios [Coltene/Whaledent], Cerasmart [GC Europe], Shofu Block HC [Shofu], and Lava Ultimate [3M]); (2) air abrasion vs. no air abrasion; and (3) pretreatment using a silane primer (Clearfil Ceramic Primer, Kuraray) vs. a resin primer (One Coat 7 Universal, Coltene/Whaledent). Subsequently, luting composite (DuoCem, Coltene/Whaledent) was polymerized onto the substrate surface using a mold. For each combination of the levels of the three treatment factors (4 (materials) × 2 (air abrasion vs. no air abrasion; resin) × 2 (primer vs. silane primer)), $n = 15$, specimens were prepared. After 24 h of water storage at 37 °C and 5000 thermo-cycles (5/55 °C), TBS was measured and failure types were examined. The resulting data was analyzed using Kaplan–Meier estimates of the cumulative failure distribution function with Breslow–Gehan tests and non-parametric ANOVA (Kruskal–Wallis test) followed by the multiple pairwise Mann–Whitney U test with α-error adjustment using the Benjamini–Hochberg procedure and chi-square test ($p < 0.05$).

Results The additional air abrasion step increased TBS values and lowered failure rates. Specimens pretreated using a resin primer showed significantly higher TBS and lower failure rates than those pretreated using a silane primer. The highest failure rates were observed for groups pretreated with a silane primer. Within the Shofu Block HC group, all specimens without air abrasion and pretreatment with a silane primer debonded during the aging procedure.

Conclusions Before fixation of CAD/CAM resin composites, the restorations should be air abraded and pretreated using a resin primer containing methyl-methacrylate to successfully bond to the luting composite. The pretreatment of the CAD/CAM resin composite using merely a silane primer results in deficient adhesion.

Clinical relevance For a reliable bond of CAD/CAM resin composites to the luting composite, air abrasion and a special pretreatment strategy are necessary in order to achieve promising long-term results.

Keywords Tensile bond strengths · Failure type · CAD/CAM · Resin composite · Air abrasion

Introduction

In dentistry, computer-aided design and computer-aided manufacturing (CAD/CAM) have decisively changed the fabrication process of indirect restorations [1, 2] and their impact on other applications is constantly growing. New classes of CAD/CAM materials such as resin composites have been especially developed for milling processes. Their industrially standardized production and the avoidance of polymerization shrinkage during application [3] overcome the disadvantages associated with the use of direct resin composites. Since

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manufactured at high pressure and temperature, the material features a higher degree of conversion resulting in less monomer release, less voids, and improved mechanical properties [4, 5]. CAD/CAM composites compare favorably to ceramics because their higher edge stability allows for an optimized milling process [6], thus permitting lower thickness [7, 8]. Further advantages of CAD/CAM composites are their enhanced esthetic qualities and their color stability [9]. They offer improved repair options within the oral cavity [10]; they present advantageous wear tendencies [11, 12] and, last but not least, their cost effectiveness.

A reliable bond between the tooth and the internal part of the restoration is of crucial importance to the long-term success rate. Adhesive luting of restorations involves two interfaces: One of these, the interface between the tooth structure and the luting composite, has been extensively researched and documented [13–16], whereas much less is known about the other interface, namely the interface between the luting composite and the CAD/CAM resin composite.

One critical aspect of industrially produced CAD/CAM composites is their high degree of conversion resulting in only a limited number of accessible free carbon-carbon-double bonds on their surface. Hence, a treatment of their surface is required in order to obtain a reliable bond [17]. In previous studies [18, 19] the use of air abrasion with aluminum oxide particles of 50 μm at a low pressure of 1–2 bar showed convincing results. The procedure causes surface enlargement thus enhancing micro-mechanical retention as well as removing a possible smear layer from grinding or milling procedures. Equally, remains of organic matrix or an aqueous film can thus be removed and the surface energy increased. It must be noted, however, that the use of higher pressure or particles of greater dimension may result in the destruction of the surface and lead to negative results [20]. Long-lasting positive results require apart from the necessary mechanical retention the creation of a strong chemical bond. State-of-the-art resin composites consist of a resin matrix and fillers, which are made of dental glasses or glass ceramics [21]. In general, a reliable chemical bond to ceramic-based materials can be obtained with silane coupling agents [22, 23, 34]. It can be assumed that silane has the highest bond to fillers and to a lesser degree to the resin matrix [24]. Since recently, silane coupling agents can also contain 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP) as does Clearfil Ceramic Primer. This is the reason why we consider it a silane primer.

Alternatively, it is possible to create a chemical bond to the fillers making use of ionic interactions through acid groups. Such groups are also found in resin primers [25].

There are basically three ways to generate the adhesion to the resin matrix. Hydrogen bonds are one way; their effectiveness, however, is relatively low. The resin primer needs to contain hydroxyl or amino groups that link to the corresponding groups within the matrix. Another way to create adhesion is to ensure that monomers of the resin primer penetrate the matrix and polymerize there; this process may be called formation of an interpenetrating network. Finally, high bond strength can be obtained by forming new covalent bonds between monomers of the adherent and pending double bonds still available in the substrate. Therefore, pretreatment of the surface is an important prerequisite for preparing the surface of the substrate to allow this interaction. With materials based on poly-methyl-methacrylate (PMMA), a pretreatment with an adhesive containing methyl-methacrylate (MMA) yields good results since the PMMA partially dissolves setting free double bonds which then are available for chemical reaction with the luting composite [26].

In the present study, we investigated the tensile bond strength between four different CAD/CAM resin composites and a luting composite with and without air abrasion and using either a silane primer or a resin primer. The null hypothesis was that tensile bond strength does not differ among the different CAD/CAM blocs. Furthermore, the null hypothesis consisted in the assumption that the air abrasion step and the pretreatment method would not affect the tensile bond strength of the tested CAD/CAM materials.

Materials and methods

This study tested the tensile bond strength between four different CAD/CAM resin composites: (i) Brilliant Crios (BC) (Coltene/Whaledent), (ii) Cerasmart (GC) (GC Europe), (iii) Shofu Block HC (SH) (Shofu), and (iv) Lava Ultimate (LU) (3M) and a luting composite (DuoCem, Coltene/Whaledent) after air abrasion or no air abrasion and pretreatment using either a silane primer (Clearfil Ceramic Primer, Kuraray) or a resin primer (One Coat 7 Universal, Coltene/Whaledent). The particulars of the used materials are shown in Table 1. The study design is presented in Fig. 1.

Of each CAD/CAM material, 60 specimens were prepared ($N = 240$). The CAD/CAM blocks were cut into slices of 2.8 mm thickness with a low-speed diamond saw under constant water application (Secotom-50, Struers). The specimens were then embedded in self-curing acrylic resin (ScandiQuick, ScanDia). The bonding surfaces were half-automatically polished under water irrigation (Tegramin-20, Struers) with the use of a series of silicone carbide papers (SiC) up to P1200 (Struers). The specimens of each CAD/CAM resin composite were divided into two groups ($n = 30$) (Fig. 1). One group was air abraded for 10 s (Al_2O_3, 50 μm, pressure 0.1 MPa, basis Quattro IS, Renfert) at a 45° angle and a distance of 10 mm. The other group remained untreated. Specimens were subsequently cleaned with distilled water 10 min using an ultrasonic bath (L&R Keary) and carefully dried with compressed air.

Table 1 Summary of CAD/CAM blocks, compositions, manufactures, and applications

	Brands	Compositions	Manufacturers	Lot no.	Application
CAD/CAM composite	Brilliant Crios	Cross-linked methacrylates (Bis-GMA, BIS-EMA, TEGDMA), 71 wt% barium glass, and silicia particles	Coltene/Whaledent, Langenau, Germany	G46616	–
	Cerasmart	UDMA, Bis-MEPP, DMA, 71 wt% silicia, barium glass	GC Europe, Leuven, Belgium	1407311	–
	Shofu Block HC	UDMA, TEGDMA, 61 wt% silica powder, micro fumed silica, zirconium silicate	Shofu, Kyto, Japan	91501	–
	LAVA Ultimate	Bis-GMA, UDMA, Bis-EMA, TEGDMA, 80 wt% SiO2 and ZrO2 particles, and aggregated ZrO2/SiO2-nanoclusters	3M ESPE, Seefeld, Germany	N724894	–
Silane primer	Clearfil Ceramic Primer	3-Trimethoxysilylpropyl methacrylate silane, 10-MDP, ethanol	Kuraray, Tokyo, Japan	570002	Application with a microbrush and air drying
Resin primer	One Coat 7 Universal	HEMA, hydroxypropylmethacrylate, MMA-modified polyacrylyic acid, UDMA, amorphous silicic, MDP	Coltene/Whaledent, Langenau, Germany	G72766	Application with a microbrush and polymerization for 90 s (Elipar S10, 3M ESPE)
Resin composite cement	DuoCem	BASE/CATALYST: Bis-EMA, Bis-GMA, TEGDMA, barium glass silanized, amorphous silicic	Coltene/Whaledent, Langenau, Germany	G72424	Application via the automix syringe into the PMMA cylinder placed on the CAD/CAM material

TEGDMA triethylenglycol dimethacrylate, *Bis-MEPP* 2,2-Bis (4-methyacryloxypoly-ethoxyphenyl)propane, *DMA* dodecyl dimethacrylate, *MMA* methyl-methacrylate, *Bis-EMA* ethoxylated bisphenol-A-diglycidyl methacrylate, *Bis-GMA* bisphenol-A-diglycidyl methacrylate, *UDMA* urethane dimethacrylate, *MDP* 10-methacryloyloxydecyl dihydrogen phosphate

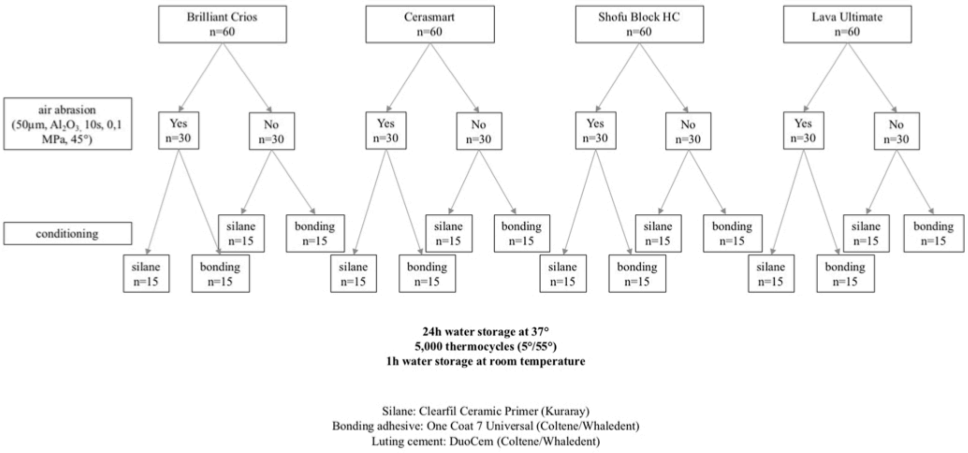


Fig. 1 Study design

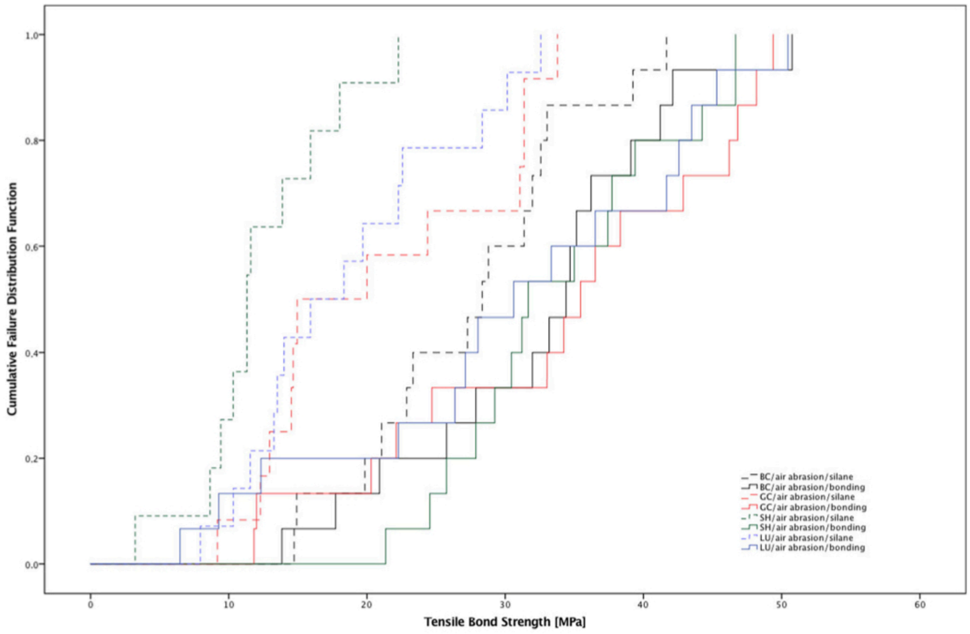
Each CAD/CAM resin composite group was further divided into 2 subgroups ($n = 15$) and pretreated with either silane primer (Clearfil Ceramic Primer, Kuraray) or resin primer (One Coat 7 Universal, Coltene/Whaledent). The silane primer was applied passively using a microbrush applicator without applying additional force onto the surface and air dried with compressed air after 5 s. Resin primer was applied for 20 s using a microbrush applicator and polymerized with a light emitting diode unit (Elipar S10, 3M) at a light intensity of 1200 mW/cm^2 for 10 s. Immediately after completing the pretreatment step, a PMMA cylinder (SD Mechatronik) was placed on the CAD/CAM composite surface and filled with luting composite (DuoCem, Coltene/Whaledent). The cylinder had a reducing design in one step from an outer diameter of 8 to 5.5 mm and an inner diameter from 5.2 to 2.9 mm with a height of in total 10 mm. Light polymerization lasting for a total of 90 s (30 s from three different sides each) followed immediately. The specimens were subsequently stored in distilled water for 24 h at a temperature of 37 °C before they were aged by a thermo-cycling process (Thermocycler THE- 1100, SD Mechatronik). They completed 5000 thermal cycles between 5 and 55 °C remaining for 20 s in each bath. Before testing the tensile bond strength, specimens were placed in distilled water at room temperature (23 °C) for 1 h.

Tensile bond strength (TBS) was measured with a universal machine (Zwick 1445, Zwick). The specimens were set axially to the loading direction in the jig of the test machine which provided a moment-free axial force application. A collet held the PMMA cylinder using its undercuts while an alignment jig allowed self-centering of the specimen as seen on Picture 1. The jig was attached to the load cell and tensioned at a crosshead speed of 5 mm/min apart by upper chain, allowing the whole system to be self-aligning. The load at failure was recorded and tensile bond strength was calculated according to the following equation: $TBS = F/A = N/mm^2 = MPa$, where F is the load at fracture (N) and A is the bond area (mm^2). Subsequently, the failure types were investigated under a stereomicroscope (Axioskop 2 MAT, Carl Zeiss Mikroskopie) and classified as follows:

(i) Adhesive—between the substrate and the luting composite
(ii) Cohesive in the luting composite
(iii) Cohesive in the CAD/CAM resin composite
(iv) Mixed cohesive in luting composite and CAD/CAM resin composite

The measured data was analyzed using SPSS version 23.0 (IBM, SPSS, Statistics). The level of statistical significance was set to $p < 0.05$. Specimens which showed debonding before tensile strength measurements and did not survive the aging processes were categorized as prefailures.

For the non-parametric analysis of the TBS, the Kaplan–Meier estimates of the cumulative failure distribution function together with the Breslow–Gehan tests were applied. The values of pre-test failure specimens were treated as censored and the actually measured values were treated as non-censored. Ninety-five percent CI for an unknown probability was looked up in the Ciba Geigy tables [27]. Associations between discrete variables were tested with a chi-square test. In addition, differences among groups were tested for



Picture 1 Experimental setup of the universal testing machine

statistical significance using non-parametric ANOVA (Kruskal–Wallis test). Differences between individual groups were identified using multiple pairwise Mann–Whitney *U* tests with α-error adjustment using the Benjamini–Hochberg procedure. For this post hoc analysis, the differences between each combination of treatment steps were tested for each material separately, and the differences between each pair of materials were tested for each combination of treatment steps separately.

Results

The interpretation of the results is based on the non-parametric Kaplan–Meier analysis. Pre-test failures (debonding of specimens during thermo-cycling) were observed only in the four groups with the treatment no air abrasion and silane primer (Table 2, chi-square $p < 0.001$). After bond strength testing, failures were either adhesive or cohesive within the luting composite. Failures including the CAD/CAM blocks have not been observed. For all materials, failure was predominantly cohesive in the groups with air abrasion and resin primer (Table 3, 87–100%) and predominantly adhesive in all other groups (Table 3, 67–100%; $p < 0.001$). For the cumulative failure distribution analysis, the specimens that debonded before bond strength testing were treated as censored observations, whereas the bond strength values of all remaining specimens were treated as non-censored observations. Table 4 reports the median failure estimates of tensile bond strength given by Kaplan–Meier methodology and the results of the Breslow–Gehan test ($p <= 0.004$) observed in different test groups as presented in Figs. 2 and 3. In summary, the lowest median TBS values were observed in groups which had been pretreated without air abrasion and with silane primer. In general, non-air-abraded groups showed lower median TBS values than air-abraded ones. In the non-air-abraded group of Shofu Block HC which had been pretreated using a silane primer, all specimens debonded during the aging procedure, thus producing a median TBS value of 0 MPa. Descriptive statistics of TBS are shown in Table 5 and Fig. 4. The overall difference among treatment groups is highly significant (Kruskal–Wallis test, $p < 0.001$). The results of the post hoc analysis are presented in Table 5. The pretreatment strategy "air abrasion + resin primer" produced the highest bond strength values in all four materials, which in turn were not significantly different. For the other three materials, the combination of air abrasion and resin primer produced the highest, the use of either air abrasion or resin primer produced intermediate, and failure to use either of those produced the lowest bond strength values.

Table 2 Relative frequency with 95% confidence interval (95% CI) for probability of debonded (pre-test failure) specimens before TBS measurement. All values are listed in percent

Material pretreatment	BC		GC		SH		LU	
	Rel. frequency	95% CI	Rel. frequency	95% CI	Rel. frequency	95% CI	Rel. frequency	95% CI
Air abrasion + resin primer	0	[0;22]	0	[0;22]	0	[0;22]	0	[0;22]
Air abrasion + silane primer	0	[0;22]	20	[4;49]	27	[7;56]	7	[0;32]
Resin primer	0	[0;22]	0	[0;22]	13	[1;41]	0	[0;22]
Silane primer	27	[7;56]	73	[44;93]	100	[77;100]	73	[44;93]

Discussion

This study showed that air abrasion and an accurate pretreatment strategy are mandatory for creating a reliable bond to luting composite. Air abrasion as a pretreatment step resulted in superior values regarding the bond strength compared to no air abrasion. The use of the resin primer One Coat Universal resulted in superior values regarding the bond strength as well compared to the use of the silane primer Clearfil Ceramic Primer. This result is highly important for the choice of the right bonding strategy for new CAD/CAM resin composites. Some previous studies found that the use of a resin primer yields superior results to the mere use of silane [28] or the combined use of silane followed by a resin primer [29, 30]. One probable explanation for these results is that silane is capable of creating a solid bond to fillers within the resin composite, but that at the same time, its bond to the resin matrix is less strong [24]. These results, however, are in contradiction to other studies which favor the use of silane in the pretreatment strategy for the repair of resin composites [31] or the bonding of CAD/CAM resin composites [23]. A possible explanation for this may lie in the fact that the studies which advocate the mere use of a resin primer were based on resin primers containing methyl-methacrylate (MMA) in those studies which prefer the use of a resin primer alone. In this study, One Coat Universal was used as a resin primer containing a modified MMA with polyacrylic acid. This monomer dissolves the surface of CAD/CAM resin composites where free carbon double bonds of the material can bond with those from the resin primer [28]. Consequently, this study advocates the use of resin primers containing MMA for a successful bonding of this new class of CAD/CAM materials while at the same time pointing out clearly that more comparative research is necessary between resin primers containing MMA and primers which do not.

The air abrasion step is another crucial factor when developing a bonding strategy for CAD/CAM resin composites. Along with pretreatment, this step has the highest impact on TBS and its proper use is of utmost importance. Yoshihara et al. have demonstrated that too much pressure during the sand blasting procedure may damage the surface of the materials [20]. There was notable evidence of this fact in the treatment of the Shofu Block HC material which seems to be very vulnerable in this regard. Nevertheless, during this study, Shofu Block HC showed convincing qualities when air abraded and pretreated with resin primer from which can be concluded that the settings in the air abrasion step were appropriate. The mechanical factor of air abrasion as well as the removal of a smear layer seems to be responsible for the fact that the air-abraded silane primer subgroups showed comparable results to the non-air-abraded resin primer subgroups regardless of the CAD/CAM material.

Most interestingly, the resin primer Brilliant Crios showed similar TBS values whether air abraded or not. This may indicate a higher concentration of carbon-carbon double bonds on the surface of this material but this assumption needs further investigation. It should be kept in mind that the resin primer as well as the luting

Table 3 Relative frequency with 95% confidence intervals (95% CI) for failure types

Material pretreatment	BC		GC		SH		LU	
	Adhesive	Cohesive	Adhesive	Cohesive	Adhesive	Cohesive	Adhesive	Cohesive
Air abrasion + resin primer	7 (0;32)	93 (67;100)	13 (0;41)	87 (58;99)	0 (0;22)	100 (77;100)	13 (0;41)	87 (58;99)
Air abrasion + silane primer	93 (67;100)	7 (0;32)	73 (43;93)	27 (6;56)	87 (58;99)	13 (0;41)	80 (50;96)	20 (3;49)
Resin primer	87 (58;99)	13 (0;41)	100 (77;100)	0 (0;22)	93 (67;100)	7 (0;32)	67 (37;89)	33 (10;62)
Silane primer	93 (67;100)	7 (0;32)	93 (67;100)	7 (0;32)	100 (77;100)	0 (0;22)	100 (77;100)	0 (0;22)

Table 4 Median estimates of the cumulative distribution function of TBS and 95% confidence intervals (95% CI) for the median obtained by the Kaplan–Meier analysis in all subgroups. All values are listed in megapascal

Material pretreatment	BC		GC		SH		LU	
	Median	95% CI	Median	95% CI	Median	95% CI	Median	95% CI
Air abrasion + resin primer	34.4	[31.0;37.9]	35.4	[30.9;40.0]	31.7	[26.0;37.5]	30.6	[22.6;38.5]
Air abrasion + silane primer	28.3	[21.3;35.3]	15.0	[5.8;24.1]	11.3	[0.6;10.0]	15.9	[7.8;23.9]
Resin primer	28.6	[15.5;41.7]	15.7	[9.3;22.1]	10.5	[5.7;15.1]	12.7	[5.6;20.0]
Silane primer	14.4	[7.7;20.9]	9.9	[4.4;15.3]	0	0	8.2	[4.9;11.5]
p values	$p < 0.001$		$p < 0.001$		$p < 0.001$		$p = 0.004$	

composite may have a certain influence on higher TBS values for Brilliant Crios since they are produced by the same manufacturer and are chemically adapted to each other.

In the subgroup of Shofu Block HC which was neither air abraded nor treated with a silane primer, no bond could be established and all specimens debonded during the aging process. This may be due to the rather low amount of fillers in this CAD/CAM material. In fact, of all materials tested, Shofu Block HC has the lowest amount of fillers with only 61 wt%.

In conclusion, the null hypothesis stating that tensile bond strength would not differ between different CAD/CAM blocs and that the air abrasion step and the pretreatment method would not affect the tensile bond strength of the tested CAD/CAM materials had to be rejected. As a consequence, the results of this study are in accordance with other studies concerning the influence of air abrasion on CAD/CAM resin composites [18, 19] and the pretreatment method [28].

In their review of the methodology of bond strength tests [32], Van Meerbeek et al. advocate the limitation of the pretreatment to the actual bonding area instead of including the entire surface of the specimens. They argue that to deviate from this practice entails a substantially larger bonding area, and that in consequence, the load is rather applied rather to the

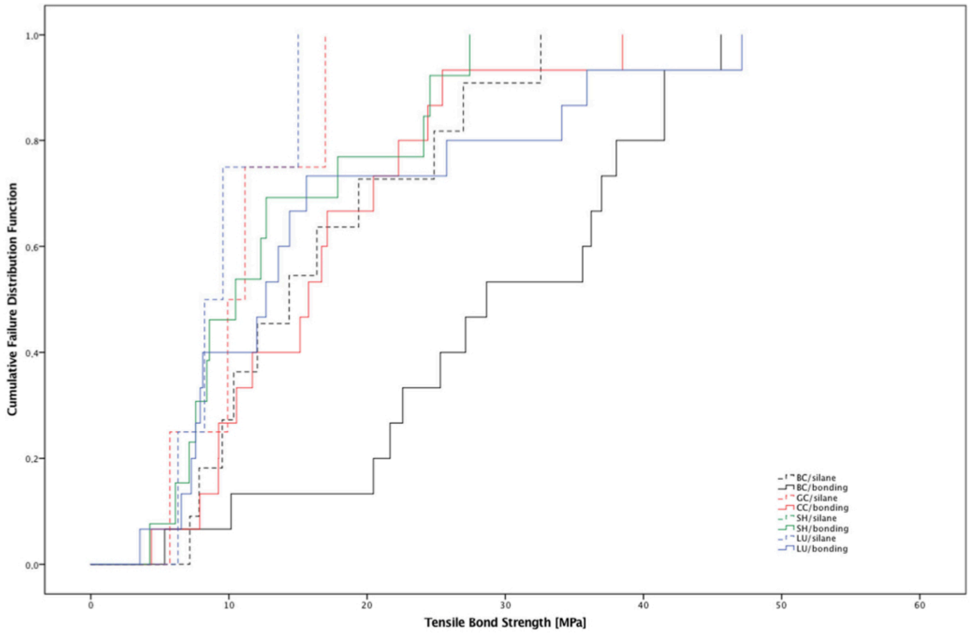


Fig. 2 Non-parametric Kaplan–Meier estimates of the cumulative failure distribution for TBS (MPa) for the air abrasion subgroups

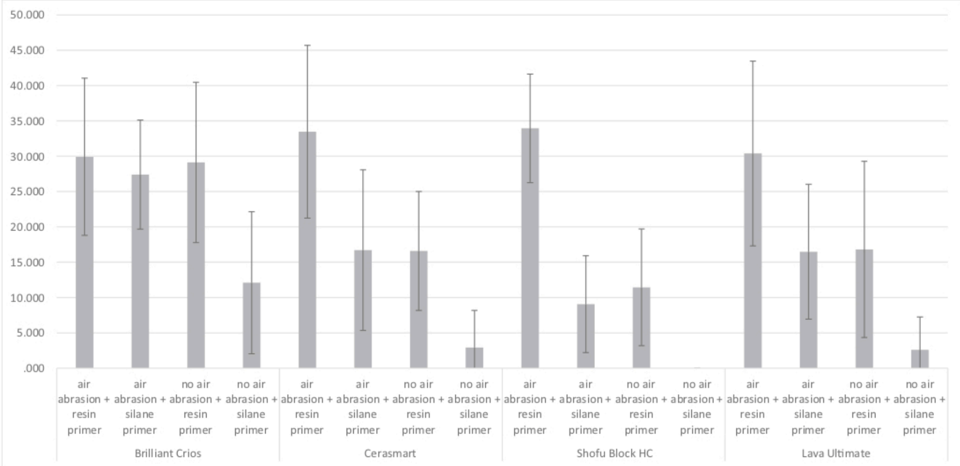


Fig. 3 Non-parametric Kaplan–Meier estimates of the cumulative failure distribution for TBS (MPa) for the non-air abrasion subgroups

adhesive-composite interface than to the adhesive-tooth interface. Their publication presents the example of a piece of bonding agent which is still attached to the specimen after load application. In this study, the entire surfaces of all specimens were pretreated, thus making the results comparable. The analysis of the failure types lists no specimens registered as shown on the review mentioned above. Nevertheless, this fact could have led to results tending to be higher in tensile bond strength and should be noted for further studies and comparisons.

The aging process restorations suffer in the oral cavity was simulated by means of a thermo-cycling process (5000 cycles in two baths of 55 and 5 °C with a dwell time of 20 s in each). It seems possible that this simulation has some impact on the testing TBS. Volumetric changes resulting in mechanical stress leading to cracks and inferior bond strength can occur. Equally, the upper temperature of thermal cycling may increase post-irradiation curing. For the purpose of this study, the artificial aging process was exclusively performed by thermo-cycling without previous long-term water storage. While certain studies prove differences on bond strength after different aging procedures [22], these findings do not affect this study. As we only aimed at assessing the influence of air abrasion and pretreatment strategy on the tensile bond strength of the single subgroups, different aging procedures were not the subject of this study. Hence, regarding artificial aging, we treated all specimens in an equal manner to obtain comparable results.

For the non-parametric approach, the Kaplan–Meier estimates of the cumulative failure distribution function (Figs. 2 and 3) and the robust estimates for median failure estimates (Table 4) were provided. This non-parametric analysis not

Table 5 Overview of descriptive statistics included mean, standard deviation (SD), and 95% confidence interval (95% CI) for tensile bond strength mean values (in MPa) for all tested subgroups under assumption of approximate normality of measurements

Material pretreatment	BC		GC		SH		LU	
	Mean (SD)	95% CI	Mean (SD)	95% CI	Mean (SD)	95% CI	Mean (SD)	95% CI
Air abrasion + resin primer	32 (10)^{a,A}	[26;38]	34 (13)^{c,A}	[26;41]	34 (8)^{f,A}	[29;39]	30 (14)^{i,A}	[22;38]
Air abrasion + silane primer	27 (8)^{a,B}	[22;32]	17 (12)^{d,D}	[10;24]	9 (7)^{g,D}	[5;13]	17 (9)^{j,C}	[12;23]
Resin primer	29 (12)^{a,E}	[22;36]	17 (9)^{d,F}	[11;22]	11 (9)^{g,F}	[6;17]	17 (13)^{j,F}	[9;24]
Silane primer	12 (10)^{b,G}	[6;18]	3 (6)^{e,H}	[−0.1;6]	0^{h,H}	0	3 (5)^{k,H}	[−0.1;6]

a–k: comparisons between pretreatments for each material separately (comparison within columns). Identical small letters specify groups not significantly different ($p \geq 0.05$; results of multiple pairwise Mann–Whitney U tests with α-error adjustment using the Benjamini–Hochberg procedure). A–H: comparisons between materials for each pretreatment separately (comparison within rows). Identical capital letters specify groups not significantly different ($p \geq 0.05$; results of multiple pairwise Mann–Whitney U tests with α-error adjustment using the Benjamini–Hochberg procedure)

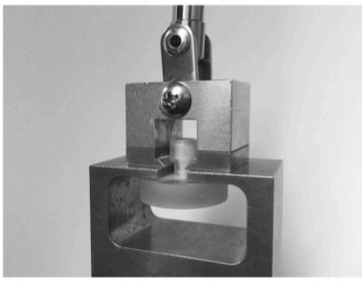


Fig. 4 Tensile bond strength in megapascal (mean ± SD) under assumption of approximate normality of measurements

only correctly handles the violation of normality but also correctly adjusts for the second difficulty in the data pertaining to prefailures. The inclusion of prefailures in the parametric analysis may lead to an underestimation of the true tensile bond strength whereas the Kaplan–Meier analysis correctly treats the values for pre-test failure specimens as censored and the actually measured values as non-censored observations.

In statistics, the estimation of the cumulative failure distribution function is termed with the general name of survival analysis. Frequently, survival time is assumed in applications. The non-parametric Kaplan–Meier methodology is very useful for analysis of other primary outcomes subject to censoring, where the survival time is replaced by, for example, the tensile bond strength, i.e., the amount of stress necessary to destroy a specimen. An example of the successful use of such an analysis is described in the work of Stawarczyk et al. [33].

In the present study, we concentrated on the cumulative failure distribution function (CFDF), which relates mathematically to survival by the following equation: CFDF = 1 − survival. In order to check the appropriateness of the sample size, the post hoc power analysis was computed within the Brillant Crios CAD/CAM resin composite with the pretreated resin primer or silane primer. The observed difference equal to 17 MPa confirms that the power of the test is equal to 97% given specimen size equal to 15, standard deviation equal to 11.7 MPa, and the significance level equal to 0.05.

The failure analysis (Table 3) shows for all groups "with air abrasion + resin primer" higher percentages of cohesive failures, whereas in all other groups, cohesive failures are rare. Therefore, in all groups "with air abrasion + resin primer" it can be expected that the bond strength values represent the strength of the luting composite rather than bond strength to the substrate, which may have been even higher.

Finally, it should be emphasized that one in vitro study regime is unable to simulate all the individual conditions a restoration is exposed to the oral cavity over years. To get a more comprehensive picture, it is therefore necessary to collect a large amount of data generated from various studies testing different aspects of the characteristics certain materials possess. Nevertheless, controlled, randomized clinical trials remain the gold standard for assessing the clinical performance of materials.

Conclusion

Within the limitations of the present study, we can conclude that successful adhesive bonding of CAD/CAM resin composites to luting composite requires air abrasion and pretreatment. Pretreating the surface of the material with One Coat Universal as a resin primer containing MMA shows the best results in tensile bond strength and is preferable to the mere use of silane primer.

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Authors' contributions Marcel Reymus: performed experiments, wrote manuscript.

Malgorzata Roos: performed statistical analyses, approval of final manuscript.

Marlis Eichberger: assistance by experiments.

Daniel Edelhoff: provision of the infrastructure, approval of final manuscript.

Reinhard Hickel: provision of the infrastructure, approval of final manuscript.

Bogna Stawarczyk: idea, experimental design, hypothesis, performed statistical analyses, and wrote manuscript.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any authors.

Informed consent Informed consent was obtained from all individual participants in the study.

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Zusammenfassung

Ziel. Das Ziel dieser Studie war es, die Veränderung der Verfärbung sowie der Oberflächeneigenschaften eines CAD/CAM Komposits nach 14-tägiger Lagerung in Rotwein und anschließender Politur mit neun verschiedenen Prophylaxepasten (PPP) zu untersuchen.

Material und Methoden. Aus dem CAD/CAM Komposit GC Cerasmart (GC Europe) wurden N=172 Prüfkörper hergestellt und diese 14 Tage in Rotwein (Rioja) gelagert. Nach dieser Zeit wurden die Prüfkörper neun verschiedenen Polierprotokollen mit aufeinander abgestimmten Pasten (insgesamt 22 Pasten) unterzogen. Folgende Polierpastensysteme wurden dabei untersucht:

- Cleanic / CLE (Kerr)
- CleanJoy / CLJ (Voco)
- Clean Polish / Super Polish/ SPO (Kerr)
- Clinpro Prophy Paste / CPP (3M)
- Détartrine / DET (Septodont)
- Nupro / NUP (Dentsply Sirona)
- Prophy Paste CCS / CCS (Directa)
- Proxyt / PXT (Ivoclar Vivadent) und
- Zircate / ZIR Prophy Paste (Dentsply Sirona)

Oberflächeneigenschaften (Rauigkeitswerte (RV)/Ra, Rz, Rv, freie Oberflächenenergie/SFE, Oberflächenglanz/G und Verfärbung/ΔE) wurden vor und nach der Lagerung sowie zusätzlichem Polieren untersucht. Die Daten wurden mittels Kolmogorov-Smirnov-Test, dreifaktorielle Varianzanalyse, gefolgt vom Tukey-B-Post-hoc-, Mann-Whitney-U- und Kruskal-Wallis-H-Test (α <0,05) ausgewertet.

Ergebnisse. Bei den Rauigkeitswerten wurden für CLE, gefolgt von CCS und CPP die höchsten Werte festgestellt; die niedrigsten präsentierten SPO und DET ($p<0,001$). Bei der Verfärbung wurde kein Einfluss der Polierpasten beobachtet ($p=0,160$). Die niedrigste Oberflächenenergie zeigte DET, gefolgt von SPO; am höchsten fielen die Werte für CCS, gefolgt von NUP und CPP ($p<0,001$) aus. Beim Oberflächenglanz wurden die niedrigsten Werte für CLE und NUP beobachtet, gefolgt von CCS, ZIP und CLJ ($p<0,001$); den höchsten Wert präsentierte SPO ($p<0,001$). Das Polieren zeigte im Allgemeinen einen positiven Einfluss auf die Oberflächenenergie ($p<0,001$ - $p=0,007$), außer für ZIP ($p=0,322$) und CLE ($p=0,083$). Grundsätzlich nahm der Oberflächenglanz nach dem Polieren zu und die Rauigkeitswerte ab ($p<0,001$), mit Ausnahme von SPO.

Schlussfolgerungen. Das Polieren mit PPPs verbessert die Oberflächeneigenschaften und wird generell empfohlen. Die Wahl des jeweiligen PPP spielt eine untergeordnete Rolle bei der Entfernung von Verfärbungen. Mehrstufige Systeme sollten gemäß Herstellerangaben ausgeführt werden.

Klinische Relevanz. Die richtige Auswahl von PPPs ist entscheidend für das klinische Ergebnis der Oberflächeneigenschaften von prothetischen Restaurationen. Die Oberflächenqualität ist abhängig von der verwendeten Prophylaxepaste.

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ORIGINAL ARTICLE

Nine prophylactic polishing pastes: impact on discoloration, gloss, and surface properties of a CAD/CAM resin composite

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Abstract

Objectives To investigate discoloration reduction and changes of surface properties of a CAD/CAM resin composite after 14 days´ storage in red wine and polishing with nine different prophylactic polishing pastes (PPPs).

Materials and methods Rectangular discs ($N = 172$) were fabricated and polished (P4000) using GC Cerasmart (GC Europe) to investigate different polishing protocols with 1–4 related descending PPPs (22 in total): Cleanic/CLE-Kerr, CleanJoy/CLJ-Voco, Clean Polish/Super Polish/SPO-Kerr, Clinpro Prophy Paste/CPP-3M, Détartrine/DET-Septodont, Nupro/NUP-Dentsply Sirona, Prophy Paste CCS/CCS-Directa, Proxyt/PXT-Ivoclar Vivadent, and Zircate/ZIR Prophy Paste-Dentsply Sirona. Surface properties (roughness values (RV)/Ra, Rz, Rv, surface free energy (SFE), surface gloss (G), and discoloration (ΔE)) were analyzed before and after storage and additional polishing. Data were examined using Kolmogorov-Smirnov test, three-way ANOVA followed by Tukey-B post hoc, Mann-Whitney U, and Kruskal-Wallis H tests ($\alpha < 0.05$).

Results Regarding RV, CLE, followed by CCS, and CPP showed the highest values; the lowest presented SPO and DET ($p < 0.001$). No impact of PPP was observed on ΔE values ($p = 0.160$). The lowest SFE presented DET, followed by SPO; highest showed CCS followed by NUP and CPP ($p < 0.001$). Within G, lowest values were observed for CLE and NUP, followed by CCS, ZIP, and CLJ ($p < 0.001$); the highest presented SPO ($p < 0.001$). Polishing showed generally a positive impact on SFE values ($p < 0.001$–$p = 0.007$), except ZIP ($p = 0.322$) and CLE ($p = 0.083$). G increased and RV decreased after polishing ($p < 0.001$), except SPO, with no significant change for G ($p = 0.786$).

Conclusions Polishing with PPPs improves the surface properties and is generally recommended. The choice of PPP has a minor role in removing discolorations. Multi-step systems should be carried out conscientiously.

Clinical relevance The proper selection of PPP is essential for the clinical outcome of surface properties of prosthetic restorations. Not every polishing paste leads to the same final surface quality.

Keywords Prophylactic polishing paste · CAD/CAM resin composite · Surface gloss · Surface roughness · Surface free energy · Discoloration

Introduction

Tooth-colored ceramic and resin composite restorations offer an optimal solution for the increasing demand of esthetic and natural appearing restorations. The continuous development of Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) technology and compatible materials has enlarged their range of application. With the help of an industrially standardized manufacturing process of the blocks, the physical, mechanical, and optical properties of the materials could be increased. This is especially true for CAD/CAM resin composites when compared to manually fabricated ones [1–4]. CAD/CAM resin composites are used either as long-

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term provisional or as definite restorations depending on the material brand, though the potential use as definitive restorations is increasingly in the focus of science. However, the mechanical and optical properties should be convincing over long-term use.

Most prosthodontically treated patients regularly undergo professional teeth cleaning in which the hygienist frees the teeth of discolorations and plaque deposits. In this procedure, a polish of all teeth and restorations with a prophylactic polishing paste (PPP) is usually performed. Depending on which material is used for the restorations, the wear behavior is different, e.g., resin composites show higher wear tendencies than ceramics, they lose their gloss more quickly and get rougher in a shorter time. That is why they should be repolished more often [5–8]. A large number of different PPPs and polishing protocols are available. PPPs are offered as one-step or multi-step systems and can be used from coarse to fine depending on the degree of discoloration and necessity in order to clean and smoothen the surface [9–12]. After a prophylaxis, the patient expects a pleasant smooth and clean feeling on the teeth and restoration surfaces [13, 14]. Restorations with a smooth surface appear much more esthetically pleasing and are better accepted by patients [15, 16]. Additionally, increased surface roughness in restorative materials can lead to increased plaque accumulation. This accumulated biofilm can lead to discoloration of the restorative material, gingival inflammation, and the development of secondary caries, which significantly reduces the clinical longevity [9, 16–21]. A roughness value of 0.2 μm is described as the threshold for an increased biofilm accumulation, though the study was performed for titanium implant surfaces [22].

Nevertheless, there is very little information in the literature about the impact of different PPPs and compatible protocols concerning the reduction of discoloration rates, the surface roughness/depth, gloss, and surface free energy (SFE) of each individual polishing step. In addition, there are no studies available comparing the different PPPs and analyzing the impact of diverse polishing protocols on surface properties. The aim of this study was to investigate discoloration reduction and surface properties after a CAD/CAM resin composite is stored for 14 days in red wine followed by polishing with nine different PPPs. The null hypothesis investigated whether all PPPs show similar outcome, regarding discoloration rate, material gloss, SFE, roughness, and surface topographies.

Materials und methods

A total of 172 rectangular discs were fabricated out of the CAD/CAM resin composite material GC Cerasmart (GC Dental Products, Leuven, Belgium) to investigate the different polishing protocols with one to four related descending pastes (22 PPP in total). A first operator performed the fabrication and measurement of SFE and discoloration. Then, a second operator analyzed surface roughness, surface gloss, and scanning electron microscopy (SEM). All of the materials used are listed in Table 1. The CAD/CAM resin composite blocks were half-automatically cut into discs of 1.5-mm thickness with a low-speed diamond saw under constant water cooling (Secotom-50, Struers, Ballerup, Denmark) and mechanically polished (Tegramin-20, Struers) to high gloss with ascending silicon carbide papers (SiC) up to P4000 (Struers).

After initial measurements of optical and surface properties (Ra/Rz/Rv/gloss for $n = 14$ specimens; ΔE/SFE for $n = 172$ specimens), two of them were used for SEM measurement. The remaining 170 discs were afterwards stored for 14 days in red wine (Rioja, Spain) in an incubator at a constant temperature of 37 °C (HERA cell 150, Thermo Fisher Scientific, Waltham, USA). Following the storage time, all specimens were randomly divided into ten sub-groups (nine polishing protocols and one control group) and polished according to the PPP procedure/pastes. Manual polishing on both sides for 60 s with a latex-free rubber brush (Pro-Cup light blue, Kerr, Rastatt, Germany) was performed a hand piece at 3.000 rpm according to the nine polishing protocols in descending roughness order (course to fine or even super fine) beginning with the course PPP and one-step PPP. After final polishing, the remaining 14 discs of each PPP protocol were analyzed again to determine their surface properties.

Surface roughness and depth

Quantitative surface characterization was performed at 14 initial and all final polished specimens by using a profilometer (S6P, Mahr, Göttingen, Germany). The surface topography was measured within a field of 3 mm × 3 mm (50 orthogonal measurements). The roughness average (Ra), average maximum height of the profile (Rz), and maximum profile valley depth (Rv) were analyzed by software Mountains Map V7.2 (Digital Surf, Besançon, France).

Discoloration measurement

All specimens were measured for their optical properties as transmission and discoloration rates (ΔE) in a spectrophotometer (Lambda 35 PerkinElmer, PerkinElmer Inc., Massachusetts, USA). Before each measurement with the spectrophotometer, the device was calibrated to 100% transmission. The first measurement was performed before storing in red wine. All specimens were measured again after 14 days of storage in red wine, and the values served as the baseline for the longitudinal data of ΔE compared to values measured after the final PPP step. All ΔE values were finally analyzed using the Color Application Software (PerkinElmer Inc.).

Table 1 Summary of products, abbreviations (Abbr.), manufacturers, Lot. no., and material compositions in alphabetical order

CAD/CAM material	Manufacturer	Particle size	Abbr.	Composition	Lot. no.
GC Cerasmart	GC Europe, Leuven, Belgium		*GCC*	Bis-MEPP, UDMA, DMA, silica (20 nm), barium glass (300 nm)	H56719
Prophylactic polishing paste (PPP)					
Cleanic	Kerr, Rastatt, Germany		*CLE*	Titandioxide, glycerine, natriumfluoride < 0.25%, ethanol < 1%	6106420
CleanJoy	Voco, Cuxhaven, Germany	Coarse RDA 195; Medium RDA 127; Fine RDA 16	*CLJ*	Tenside TB < 2.5%, peppermint flavor < 2.5%, natriumfluoride < 2.5%	Coarse: 1641198 Medium: 1642311 Fine: 1643257
Clean/Super Polish (no. 360/361)	Kerr, Rastatt, Germany		*SPO*	Pumice mixture, flavor, colorant E122, preservatives, excipient	Clean polish: 6067984 Super polish: 5880346
Clinpro Prophy Paste	3 M, Seefeld, Germany	Coarse RDA 250; Medium RDA 170; Fine RDA 120	*CPP*	Natriumfluoride < 3; water 1–20; polyethylenglycol 5–25; glycerine 15–40; flavor 1–5; pumice 30–50; trinatriumorthophosphate < 5; silicic acid, sodium salt < 5	Coarse: 042216G Medium: 051916C Fine: 051916A
Détartrine 100ZF/150ZF	Septodont, Niederkassel, Germany	RDA 150; RDA 100	*DET*	Quartz 25–50%, glycerin 10–25%, ethanol < 2.5%, zircon in silicate	150ZF: 16158AB 100ZF: 16218AA
Nupro	Dentsply Sirona, Konstanz, Germany	Coarse; Medium; Fine	*NUP*	Novamin, glycerol 25–50%, natriumfluoride 2.5–10%, pumice, diatomite, natriumsilicate, methylsalicylate, mononatriumphosphate, natriumsaccharine, natriumcarboxymethycellulose	Coarse: 16061401 Medium: 16062908 Fine: 16062004
Prophy-Paste CCS	Directa, Upplands Vaesby, Sweden	Coarse RDA 250; Medium RDA 170; Fine RDA 120; Superfine RDA 40	*CCS*	Glycerine, hydrated silica, water, aluminiumhydroxide, sodium-dihydrogenphosphatedihydrate, titaniumdioxide, PEG-25 hydrogenated castor oil, sodium-methylparaben, sodium-saccahrin, flavor, prophylparaben	Coarse: 28197 Medium: 28217 Fine: 28096 Superfine: 28098
Proxyt	Ivoclar Vivadent, Schaan, Liechtenstein	Coarse RDA 83; Medium RDA 36; Fine RDA 7	*PXT*	Water, glycerine 41.0; sorbite, xylit 21.0; anorganic fillers 35.0; excipient 1.2; natriumfluoride 0.12; flavor and pigments < 1.68	Coarse: V16059 Medium: V03269 Fine: V32179
Zircate Prophy Paste	Dentsply Sirona, Konstanz, Germany		*ZIP*	Zirconiumsilicate, tin oxide, glyerol	160620

Surface free energy

The SFE was tested at room temperature by the sessile drop technique using a drop shape analysis system (DSA 25, EasyDrop, Krüss, Hamburg, Germany) with two different liquids of different polarity: distilled water and diiodomethane 99% (cat: 15.842-9, Sigma-Aldrich, Steinheim, Germany, lot. no.: S65447-448), separately. The water- or diiodomethane-drop is registered with a CCD-camera that makes a standardized digitalized photo after exactly 5 s. Surface energy is calculated on the basis of the contact angle measurements with water and diiodomethane according to the Ström database:

$$\cos\theta = \frac{\sigma S - \sigma LS}{\sigma L}$$

with σL: surface free energy of the liquid; σS: surface free energy of the solid; and σLS: interface surface free energy.

Gloss measurement

The surface gloss of all 14 specimens per group was performed with a glossmeter (PICOGLOSS 560 MC-XS, Erichsen, Hemer, Germany) on five randomly chosen areas on each specimen. The measured values were expressed by mean gloss unit (GU). The device was calibrated for each group according to the manufacturer's instructions. For this, the device was placed on a gloss standard tile (black) and calibrated.

Scanning electron microscopy

For qualitative surface observations, SEM (LEO 1430, Zeiss, Germany) was used. One specimen per PPP after the final polishing step was analyzed three times operating at 10 kV with a working distance of18–21 mm. All specimens were sputter coated by gold-palladium with a sputter coater (SCD 005, Bal-

Tec, Liechtenstein) for 100 s. Additionally, all 22 pastes were dried on SEM sample holders for 28 days at 80 °C.

Statistical analysis

The measured data were analyzed using descriptive statistics. The normality of data distribution was tested using the Kolmogorov-Smirnov test. Three-way ANOVA followed by the Tukey-B post hoc test was computed to determine the significant differences among the tested groups. The differences between the groups were determined using the Mann-Whitney *U* and Kruskal-Wallis H tests. The statistical tests were performed with SPSS version 24.0 (SPSS Inc., Chicago, IL, USA). All *p* values smaller than 0.05 were considered statistically significant in all tests performed.

Results

The Kolmogorov-Smirnov test indicated violation of the assumption of normality for 61% of the tested groups. Therefore, for all further statistical tests, the no assumption of normal distribution was used. Table 2 provides the descriptive statistics for all tested PPPs and all individual surface parameters after the final polishing step.

Comparison of surface roughness and gloss values before discoloration storage

No differences in surface roughness and initial gloss values between the tested materials were found.

Comparison of all PPPs after last polishing step

With regard to the last polishing step, no impact of PPP was observed on the ΔE values ($p = 0.160$). In contrast, the choice of PPP showed an influence on Ra ($p < 0.001$), SFE ($p < 0.001$), and gloss values ($p < 0.001$). Since all roughness values Ra, Rz, and Rv show the same tendencies, the focus of the evaluation was placed on the Ra results.

When comparing the Ra values, polishing with CLE, followed by CCS, CPP, and NUP showed the highest values; the lowest Ra was obtained for polishing using SPO, DET, and PXT ($p < 0.001$). The lowest SFE was showed for DET, followed by SPO; the highest was observed for CCS followed by NUP, CPP, PXT, and CLJ ($p < 0.001$). With respect to gloss values, the lowest were observed for CLE and NUP, followed by CCS, ZIP, CLJ, CPP, and DET ($p < 0.001$). The highest gloss values presented the PPP SPO followed by PXT ($p < 0.001$).

Impact of polishing on individual surface parameters

Polishing showed a positive impact on SFE values for all tested PPPs ($p < 0.001$–$p = 0.007$), with the exception of ZIP ($p = 0.322$) and CLE ($p = 0.083$). The gloss values significantly increased and the Ra values decreased after polishing ($p < 0.001$). The exception was the PPP SPO, where no significant change in the gloss values was observed ($p = 0.786$).

SEM pictures

Figure 1 presents each dried PPP with all polishing steps separately. A visibly fine-grained paste structure can be seen in ZIP, CLJ, and the coarser polishing pastes of CCP and SPO. Coarser grain paste structures were found for NUP, CLE, and the fine pastes of CCS. The fine paste of CPP revealed organic components.

SEM images of the nine polished material surfaces after the final polishing step are presented in Fig. 2. CLE, CCS, NUP, CLJ, and ZIP showed a distinctly

Table 2 Descriptive statistics of all surface parameters tested after final polishing step for each PPP, separately

Final	ΔE	SFE	Gloss	Ra	Rz	Rv
CLE	2.44 ± 0.97a	48.72 ± 1.82bc	10.38 ± 1.58a	0.17 ± 0.04d	1.29 ± 0.29e	0.78 ± 0.20d
CLJ	2.44 ± 1.16a	49.46 ± 1.48bc	24.16 ± 3.74bc	0.11 ± 0.01bc	0.80 ± 0.09cd	0.49 ± 0.06bc
SPO	1.75 ± 0.80a	46.19 ± 2.95b	65.34 ± 3.96*e	0.07 ± 0.02a	0.52 ± 0.12a	0.32 ± 0.09a
CPP	2.88 ± 1.42a	50.53 ± 2.74c	25.98 ± 3.23bc	0.13 ± 0.02c	0.84 ± 0.12cd	0.47 ± 0.08bc
DET	2.49 ± 1.06a	41.38 ± 3.04a	28.20 ± 4.07c	0.06 ± 0.01a	0.57 ± 0.09ab	0.31 ± 0.06a
NUP	1.90 ± 0.86a	51.49 ± 3.07c	14.69 ± 1.32a	0.12 ± 0.01c	0.86 ± 0.09cd	0.48 ± 0.07bc
CCS	2.42 ± 0.92*a	55.2 ± 1.52d	21.69 ± 2.77b	0.13 ± 0.01c	0.94 ± 0.10d	0.54 ± 0.06c
PXT	2.53 ± 0.92a	50.14 ± 2.25c	54.62 ± 6.30*d	0.08 ± 0.01ab	0.67 ± 0.08abc	0.39 ± 0.05ab
ZIP	2.41 ± 1.08a	48.67 ± 2.14*bc	22.70 ± 4.70bc	0.09 ± 0.01ab	0.72 ± 0.07bc	0.40 ± 0.04ab

Letters a, b, c, d, and e present significant differences between the PPP within the parameters ΔE, SFE, gloss, Ra, Rz, and Rv

*Not normally distributed

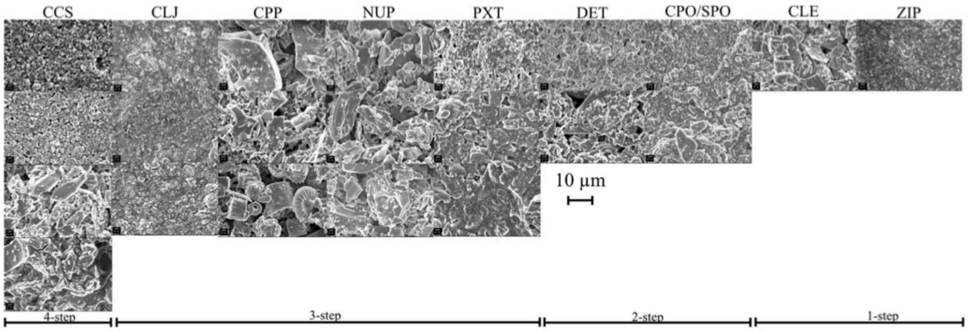

Fig. 1 SEM images of dried PPPs

irregular surface with partly visible streaks and minor structural defects. The most obvious irregular surface with scratches could be seen on CLE. On the other hand, SPO, DET, and PXT have more regular finer surface structures.

Discussion

With regularly performed professional teeth cleaning using specific products at 6-month intervals, the PPP must be suitable for various restorative materials since patients are usually supplied

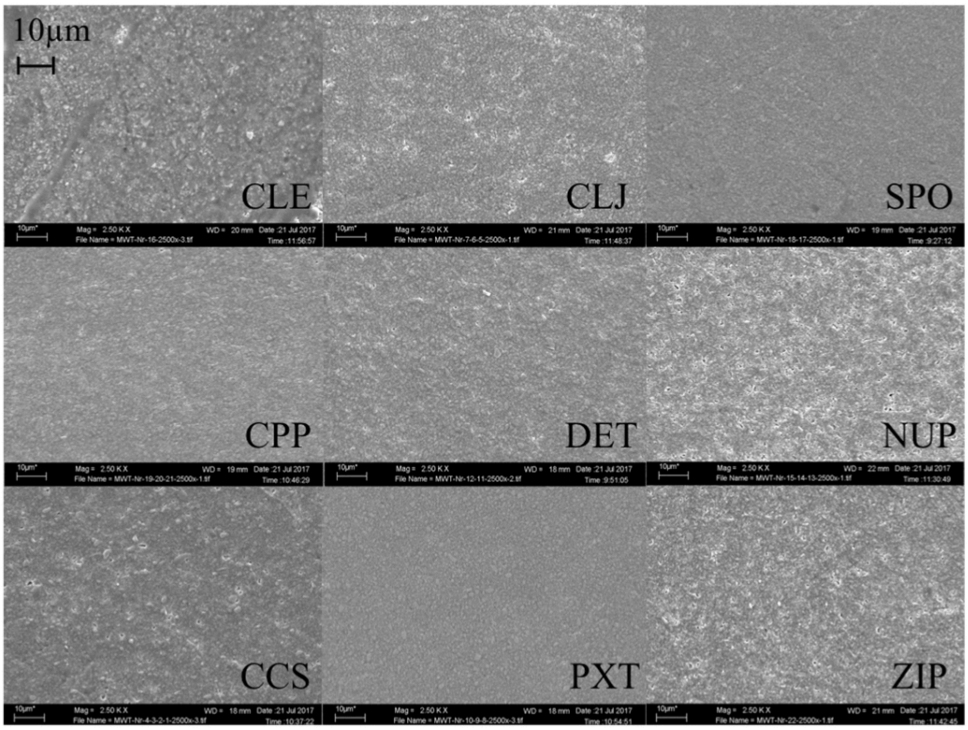

Fig. 2 SEM images of CAD/CAM surfaces after final polishing

with different materials intraorally. For relatively new CAD/CAM materials, in particular, there is no general recommendation from manufacturers regarding the preferred PPPs.

Numerous PPPs on the dental market are offered for professional teeth cleaning, some of which differ greatly in the composition and size and geometry of the polishing fillers. These differences can be clearly seen in the SEM images of the dried PPP. Regarding the size of the polishing grains and the geometry, in particular, the naked eye can see differences on the SEM images that seem to affect the results. For SPO, there are rounded and slightly smaller polishing grains, whereas CLE shows larger grains with tips. This could be a possible cause of the low surface roughness of SPO unlike CLE after the final polishing step. Generally, the polishing pastes are offered in descending surface roughness with a different number of polishing steps. The use of PPPs normally depends on the extent of the deposits and the degree of discoloration of the tooth and restoration surfaces. The PPPs with only one polishing step, like CLE, seem quite interesting in saving time and money in the dental practice. For ZIR, polishing with a fine PPP is usually recommended in practical applications. Therefore, in contrast to CLE, this paste is only to a limited extent regarded as a one-step system. In contrast, the PPP systems have several polishing steps, in which the practitioner can choose (depending on the patient) between different PPPs in descending order. Any polishing in the context of prophylaxis should, however, be completed with the finest paste to polish the surfaces as smooth as possible. In this investigation, only one CAD/CAM resin composite material was deliberately selected for examination to compare the different PPPs and polishing steps.

Apart from the large selection of PPP materials, the performance of professional teeth cleaning as well as the selection of products are highly dependent on the operator. The operator may use, for example, a polishing brush, a polishing cup, or both, except for the water-powder systems; the operator themselves can further determine the choice and amount of PPP used, the polishing pressure and the duration of the polishing time per surface. The optimum pressure is given in the literature as 2N [23, 24], whereas in practice, it is not realistic to constantly apply this pressure to every surface. In general, the contact pressure and the duration of the polishing vary to some extent on each surface. In the present study, the nature and implementation can also be considered as a limitation. Although the manual polishing of the specimens was carried out by only one experienced operator, standardization is hardly feasible since a small variation in the contact pressure or the movements performed during polishing cannot be avoided. The amount of PPP used may also vary slightly, as the consistency of the various PPPs is significantly different. In the present study, this could also have led to higher standard deviation of the results of all surface values analyzed.

In addition, the surface was polished for 1 min per specimen side with the specific PPP and a drop of distilled water in a circular motion, which does not clearly correspond to the clinical situation. During professional tooth cleaning, the polishing time per surface will be lower and thus the results could differ, if perhaps a shorter polish times, lower amount of PPP, or lower contact pressure were chosen. It has already been described in the literature that the changes in the surface roughness after polishing of resin-based materials are strongly material dependent and depend on the contact pressure as well as the duration of the respective polishing [24–26]. Since this study tried to use the same contact pressure as much as possible on the same material, this influence was probably rather inferior. However, significantly different results were seen between the different PPPs. Polishing with the different PPPs also had an influence on the surface parameters of the SFE, surface roughness, and gloss values in the present study.

Generally, the gloss of a restoration material has a decisive influence on esthetics and the color effect and, as already mentioned previously, depends crucially on the surface roughness [15, 16]. The rougher a material surface, the more light is scattered on its surface when a light beam strikes [27]. In addition, the influence of the number of fillers and filler size in the resin composite material on the gloss is high. For quartz fillers, it has been described that the gloss increases as the number of fillers decreases [28]. This can be explained by the fact that the light scattering by the larger number of refractions probably takes place at the border lines of the fillers integrated. The restoration thus takes on a dull appearance and the color effect changes [28]. The restoration surfaces should be smooth, as the surface roughness has an influence on the wearing comfort and well-being of the patient. The risk of increased plaque accumulation, which can lead to inflammation of the gums or secondary caries, also increases [29].

A closer look at the surface roughness and the influence of prophylaxis on the surface parameters showed that the use of PPP significantly influenced the surface roughness of indirect resin-based and ceramic materials [30]. The roughness increased significantly with an increased contact pressure at polishing of 4N instead of 2N and the gloss decreased, but these results were analyzed especially in direct microhybrid composite materials [24]. These results are therefore not exactly comparable to the results for CAD/CAM resin composite materials. A mechanical, as opposed to manual polishing, usually shows the best gloss for all materials [24]. A mechanical polishing was performed on the specimens in this study, which led to an initial high-gloss. Any further polishing could probably have significant effects, which could be confirmed in this study. For indirect resin composite materials, a correlation of the two surface parameters roughness and gloss could also be found in the literature [31]. As the roughness increases, the gloss decreases and vice versa. In another study, a strong correlation of microroughness and gloss was confirmed [32]. This correlation could not be clearly determined in the present study; however, the surface roughness values generally decreased significantly after polishing while the gloss increased significantly.

The highest final roughness values were found for CLE, followed by CCS and CPP. The surface roughness can be clearly seen in the SEM images (Fig. 2). No correlation can be drawn with the number of polishing steps, since CLE represents a one-step system, CCS a four-step, and CPP a three-step system. Moreover, it is very difficult to determine to what extent the compositions of individual PPPs have an influence. The SEM images, however, suggest that these pastes contain larger polishing fillers. After final polishing, SPO showed the lowest surface roughness, followed by DET and PXT. These pastes show slightly smaller polishing fillers than those mentioned above in the SEM pictures. In addition, the RDA value (relative dentine abrasivity) could play a role since lower RDA values are indicated for these PPPs (CPO/SPO 43.8/9.8, DET 150/100, PXT 83/36.7).

The PPPs also showed an influence on the gloss values and, apart from a PPP, increased significantly after polishing. The lowest gloss after final polish was found for CLE, followed by NUP, CCS, and ZIP. SPO and PXT showed the highest gloss. Although no correlation could be drawn at this point, as already mentioned previously, the surfaces with the roughest surfaces usually showed the lowest gloss and vice versa. This was visible for SPO presenting the lowest roughness values and the highest surface gloss. This could be due to the low RDA values of the two-step PPP SPO and the finer-grained structure with rounder polishing fillers.

Aside from polishing the surfaces with a PPP, even everyday teeth brushing has shown to have an impact on the roughness and gloss of various CAD/CAM materials. A significant material-dependent decrease in gloss and an increase in surface roughness were observed, with the tested ceramic showing the best gloss retention, in contrast to the resin-based CAD/CAM materials [5]. Comparing the results analyzed there, slightly lower final surface roughness was found after tooth brushing of the CAD/CAM material surfaces (e.g., Lava Ultimate (3M): 0.05 ± 0.006 µm) compared to after polishing with PPP in the present study (GC Cerasmart with the final least roughness with the PPP DET: 0.06 ± 0.01 µm). These roughness values, however, cannot be compared due to the different examination setup, as the toothpastes also contain, in contrast to the PPPs, finer polishing fillers. Other studies are also difficult to compare since none of the studies used comparable polishing protocols.

In the case of resin-based materials, it has already been described several times in the literature that the surface roughness of a material after polishing depends both on the composition of the material to be polished and on the composition of the PPP. In these studies, direct composite materials were mostly examined. The number of fillers, particle size, and hardness play an important role in roughness [33–38]. However, these results may differ from those of the CAD/CAM materials, although the chemistry is similar, but the fabrication method is completely different. In the present study, only one material was used to better compare the PPP. Differences in the individual PPPs were found, which could have led to different results. With regard for changing the surface parameters after polishing of CAD/CAM fabricated materials, there is little information or comparable investigations available.

Some studies have already reported a material-dependent increase in surface roughness after polishing and a simultaneous decrease in gloss [24, 39, 40], though, as mentioned previously, these investigated direct composites. Although the final polishing took place with a fine grain size, it was reported that even the fine PPP was unable to restore the initial gloss and smooth surface when the specimens had an initial high gloss (usually mechanical polishing of the specimens) [40]. Most of the studies analyzed, to the authors' best knowledge, involve only a few different polish pastes (e.g., Detartrine, Topex, Merssagen, Nupro, and Clinpro) in contrast to the nine polishing protocols analyzed here in one investigation. PPP in a medium or fine grain seem to cause a lower surface roughness than the coarse PPP [30, 39, 40]. Further studies showed that after the polishing of composites and compomers with pumice paste, the surface roughness does not change [13] and the roughness values improved [37]. The analyzed results of the present study confirm the results of the last study, as the roughness values after polishing improved. For all final roughness values of each PPP, the threshold of 0.2 µm, which is cited in the literature, was not exceeded [22, 41].

Concerning the influence of polishing on the SFE values, a positive influence was observed, apart from ZIP and CLE. The lowest SFE values were displayed by DET and SPO, which showed the lowest roughness and the highest gloss in the analysis of the other surface parameters. The highest SFE values were found for CCS and NUP. Again, it is difficult to establish a link based on the composition of the PPPs. Further investigations would be necessary.

Apart from the already mentioned surface parameters, e.g., gloss or roughness values, the tendency of resin-based restorative materials to become discolored plays a decisive role in the longevity of a prosthetic restoration. Concerning the influence of the polishing is important to be able to react to any discoloration. In a study with a lithium-disilicate ceramic (e.max CAD), a reduction of the translucency was found after a successful polishing with PPPs, which seemed to be strongly paste dependent [26]. However, these results cannot be compared with the results of this study because a different material class was tested. There was no influence found regarding polishing on ΔE values. Since the discoloration values were evaluated with the help of a specific computer software program from the measured translucency values and color spectra, there appears to be no influence on these values. All values measured were below the value of 3.3 reported in the literature, the value at which 50% of the observers considered the discoloration of the surface as unacceptable [42].

The specimens tested were stored for 14 days in red wine, since in the literature, this media usually presents the highest ΔE values after a longer period of aging. Perhaps the influence of a longer storage time or other storage medium such as curry would have been more apparent. These questions could be further investigated in another study.

Discoloration of composite specimens after storage in coloring food media, professional tooth cleaning with gentle water-powder devices, and subsequent post-polishing can result in a significant reduction in discoloration values [6, 7]. Post-polishing, however, is essential because of the resulting increased roughness after the water-powder treatment. The present study also showed a reduction in discoloration due to the PPP used, which, cannot be compared with the above-mentioned study. After any professional cleaning with a water-powder system, the surfaces should be polished, and here, is the influence of different PPPs on the surface properties is also important.

Given the results discussed previously, the null hypothesis based on the different PPPs is rejected. An exception was the discoloration values, which showed no significant differences between the PPPs in the final polishing results. This investigation focused mainly on the final polished values, being the clinically most important ones.

The present study illustrates that the proper selection of PPPs is essential for the clinical outcome of surface properties of prosthetic restorations. To conclude, not every polishing paste leads to the same final surface quality.

Conclusion

1. Polishing with PPPs had no impact on discolorations and therefore presented a minor role in removing them.
2. Polishing improved the surface properties and is generally recommended. Multi-step systems should be carried out conscientiously.
3. The lowest roughness and SFE values were presumably obtained after polishing with SPO and DET. SPO additionally presented the highest final surface gloss.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent For this type of study, formal consent is not required.

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4.3 Originalarbeit: Zimmermann M, Koller C, Reymus M, Mehl A, Hickel R (2018) Clinical Evaluation of Indirect Particle-Filled Composite Resin CAD/CAM Partial Crowns after 24 Months. J Prosthodont 2018;27:694-99 (doi: 10.1111/jopr. 12582) IF 2016: 1.452

Zusammenfassung

Ziel. CAD/CAM Komposite sind zwar eine vielversprechende Alternative für Einzelzahnrestaurationen, doch liegen aktuell nur unzureichende klinische Daten über diese neue Materialklasse vor. Das Ziel dieser Studie war es, In-Vivo Ergebnisse über die klinische Performance eines CAD/CAM Komposit-Materials nach 24-monatigem Beobachtungszeitraum zu überprüfen.

Material und Methode. Es wurden indirekte Restaurationen aus einem Komposit-Material (Lava Ultimate, 3M) von kalibrierten Studenten über eine CAD/CAM Methode (Intraoralscanner CEREC Bluecam, Scheifeinheit CEREC MCXL) hergestellt. Dabei wurden insgesamt 42 Teilkronen an 30 Patienten mit kariösen Läsionen oder insuffizienten Versorgungen adhäsiv eingesetzt (Baseline). Im 12-Monatsrecall konnten 40 und im 24-Monatsrecall 33 Restaurationen nachkontrolliert werden. Als Evaluationskriterien dienten die modifizierten FDI-Kriterien (Federation Dentaire International) mit den Graden (1) bis (5), wobei Grad (5) als klinischer Fehler gewertet wurde. Die statistische Auswertung erfolgte mit Hilfe des Wilcoxon-Tests ($p<0,05$).

Ergebnisse. Die klinische Erfolgsrate CAD/CAM Komposit betrug nach 12 Monaten 95%, wobei zwei Debondings festgestellt wurden. Nach 24 Monaten betrug die kumulative Erfolgsrate 85,7% bei zwei festgestellten Zahnfrakturen und einem Debonding. Bezüglich der Kriterien *Anatomische Form* und *Randpassung* konnte ein signifikanter Unterschied zwischen der Baseline und dem 24 Monatsrecall festgestellt werden (Wilxocon-Test, $p<0,05$).

Schlussfolgerungen. Die Studie zeigt für das Partikel gefüllte CAD/CAM Komposit-Material eine klinische Erfolgsrate von 85,7% nach 24 Monaten. Ein längerer Beobachtungszeitraum ist notwendig, um weitere Schlussfolgerungen ziehen zu können.

Klinische Relevanz. Das Protokoll zum adhäsiven Einsetzen von CAD/CAM Kompositen muss streng befolgt werden, um einen klinisch erfolgversprechenden Verbund gewährleisten zu können.

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Clinical Evaluation of Indirect Particle-Filled Composite Resin CAD/CAM Partial Crowns after 24 Months

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Keywords
Particle-filled composite resin; CAD/CAM; CEREC; clinical study; Lava Ultimate.

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Abstract

Purpose: Resin-based CAD/CAM compound materials might be promising for single-tooth restorations. Insufficient clinical data are available for this new material class. The purpose of this study was to describe initial clinical in vivo results for indirect particle-filled composite resin CAD/CAM restorations after 24 months.
Materials and Methods: Indirect particle-filled composite resin restorations were fabricated with a CAD/CAM method (CEREC Bluecam intraoral scanner, CEREC MCXL milling unit) by calibrated dental students. Forty-two partial crown restorations were seated adhesively in 30 patients with caries lesions or insufficient restorations (baseline). Strict inclusion criteria were defined for the patient collective. Follow-up evaluation comprised 40 restorations after 12 months and 33 restorations after 24 months. Evaluation criteria were modified FDI criteria with grades (1) to (5). Rating with FDI criteria (5) was defined as clinical failure. Statistical analysis was performed with Wilcoxon-Test ($p < 0.05$).
Results: The success rate of indirect particle-filled composite resin CAD/CAM restorations after 12 months was 95.0% with two debondings observed. The cumulative success rate for indirect particle-filled composite resin CAD/CAM restorations after 24 months was 85.7% with two tooth fractures and one debonding. Statistically significant differences were found for baseline and 24-month follow-up evaluation for anatomic form and marginal adaptation criterion examined in respect to FDI criteria guidelines (Wilcoxon-Test, $p < 0.05$).
Conclusions: This study demonstrates particle-filled composite resin CAD/CAM restorations having a clinical success rate of 85.7% after 24 months. Adhesive bonding procedures need to be ensured carefully. A longer clinical evaluation period is necessary to draw further conclusions.

Composite resin materials have been shown to have a high clinical success rate in restorative therapy.[1,2] Clinical indications for composite resin materials are limited because of material characteristics such as polymerization shrinkage and abrasion coefficient.[3] Indirect restorations have been shown to strengthen the remaining tooth substance and might be preferable if the tooth defect exceeds a certain dimension.[4] Several material classes have been used for indirect restoration fabrication.[5] Ceramics are more brittle and more susceptible to fracture than composite resins if overload or inappropriate load is exerted.[6] Adhesive seating is mandatory for ceramic materials with flexural strengths below 200 MPa.[7] Resin-based CAD/CAM compound restorative materials might be promising. Initial results in our laboratories (not yet published) show that the minimum thickness of resin-based CAD/CAM restorations might be reduced. Compared to ceramics, resin-based compound materials showed fewer material fractures and a higher margin stability after milling.[6] The first resin-based composite material, Paradigm MZ 100 (3M ESPE; St. Paul, MN), was introduced for use in fabricating single-tooth CAD/CAM restorations in 2001.[8]

The resin-based CAD/CAM material Lava Ultimate (3M ESPE) was among the first compound CAD/CAM materials available for single-tooth restoration. The material consists of a polymeric composite framework with embedded ceramic particles. These particles make up to 80% of the material by weight and can be as small as 4 to 11 nm. The flexural strength of Lava Ultimate is reported to be 200 MPa.[9,10] At this moment, no clinical data are available for particle-filled composite resin CAD/CAM restorations. The aim of this study was to evaluate

Table 1 Inclusion and exclusion criteria for patient recruitment; in total 30 patients participated (13 female patients, 17 male, average age 56.4 ± 14.8 years)

Inclusion criteria	Exclusion criteria
Oro-vestibular defect size: >50% of tooth cusp distance	Oro-vestibular defect size: <50% of tooth cusp distance
Complete or partial reconstruction of tooth cusp	Need of direct/indirect capping prior to reconstruction
Molars or premolars with antagonist	Patient suffering from bruxism/CMD

the clinical outcome of indirect particle-filled composite resin CAD/CAM restorations after 24 months.

Materials and methods

Ethical approval and recruitment criteria

All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its amendments or comparable ethical standards. The study was performed as part of protocol number 490-13 accepted by the ethical committee of the Ludwig-Maximilians-University Munich.

Patients with decayed caries lesions or insufficient restorations were recruited from the daily patient collective of the Department of Restorative Dentistry and Periodontology of the Ludwig-Maximilians-University Munich. Strict inclusion criteria were defined for the patient collective. The inclusion and exclusion criteria are shown in Table 1. All patients gave written consent for participation in the study. Thirty patients were included in the study. The distribution of gender was seventeen male and thirteen female patients. The patients' average age was 56.4 ± 14.8 years. Good general health status (ASA-criteria 1) was mandatory. Forty-two indirect restorations were fabricated by calibrated dental students under strict supervision of an experienced dentist. Fifteen maxillary teeth and twenty-seven mandibular teeth were treated (29 molars, 13 premolars). Evaluation criteria in this study were modified FDI criteria.[11-14] Baseline evaluation was performed a day after restorations seating (baseline). Recall evaluation was performed after 12 months (follow-up 12M) and again after 24 months (follow-up 24M).

Clinical protocol

Prior to tooth preparation, local anesthesia (Ultracain D-S 2%; Sanofi Aventis, Paris, France) was administered. The teeth were prepared according to guidelines for full ceramic preparation.[7] The preparation margins ended within the enamel or dentin. If the remaining wall thickness was below 1.5 mm after caries removal, shortening of the cusp in terms of a partial crown preparation was performed. Conventional full-arch impressions of the preparation were obtained with polyether material Impregum Penta (3M ESPE). Conventional impressions of the opposing arch were made with alginate material (Omnident Dental, Rodgau Nieder-Roden, Germany). Plaster stone casts were poured for both maxillary and mandibular arch with Type IV scannable gypsum (CEREC Stone BC; Dentsply Sirona, York, PA). Quadrant scans of the maxillary and mandibular cast were taken with the CEREC Bluecam (Dentsply Sirona) with a strictly observed scanning strategy.[15] Interim prostheses were provided for the prepared teeth (Luxatemp; DMG, Hamburg, Germany) and seated with RelyX Temp NE (3M ESPE). CAD design of final restorations was performed with CEREC CAD software (software v4.0.). Resin based particle-filled blocks were selected as restorative CAD/CAM material (Lava Ultimate) and milled with the CEREC MCXL milling unit (cylinder pointed bur 12 and step bur 12s, milling mode "standard"). Forty-two partial crowns were fabricated. The postprocessing method was a three-step extraoral polishing procedure (polishing set 4313B; Brasseler, Lemgo, Germany) using a standardized protocol (5000 to 6000 rpm, time per instrument: 30 seconds, water cooling 50 ml/min, light contact pressure).

The particle-filled composite resin restorations were seated adhesively. The luting surfaces of the restorations were airborne-particle abraded with Si-coated aluminum oxide (Cojet; 3M ESPE) (diameter ≤ 50 μm, 200 kPa). Restorations were cleaned with alcohol and air dried with oil- and water-free air. Silane (Espe-Sil; 3M ESPE) was applied to the restorations' luting surface for a period of at least 60 seconds prior to adhesive luting. The prepared teeth were isolated with rubber dam and etched with 37% phosphoric acid (application time: 30 seconds enamel, 15 seconds dentin). Syntac was used as adhesive bonding agent (application time: 15 seconds primer, 10 seconds adhesive, no light curing of Heliobond) with Variolink II high viscosity (Ivoclar Vivadent AG, Schaan, Lichtenstein) dual-polymerizing composite resin system. After any excess was removed, an oxygen layer inhibitor material was applied to the cementation interface (Airblock; Dentsply DeTrey, Konstanz, Germany). Luting composite resin was polymerized with a polymerization lamp (Satelec MiniLED; KaVo, Biberach, Germany) using 16 J/cm^2 from the occlusal, mesial, distal, buccal, and lingual aspects for 60 seconds each. The restoration margins were finished, and the occlusal contacts were adjusted using fine diamond rotary instruments coupled with constant water-cooling. A three-step ceramic polishing kit (ceramic polishing set 4313B; Brasseler) was used for the final intraoral polishing procedure.

Evaluation criteria and statistical analysis

Evaluation criteria were modified FDI criteria.[11-14] The evaluation was performed a day after adhesive seating (baseline), at 12-month recall (follow-up 12M) and at 24-month recall (follow-up 24M). There were three evaluation categories (esthetics, function, biology) each with five subcategories. From best to worst, the subcategories were: (1) clinically excellent, (2) clinically good, (3) clinically sufficient, (4) clinically not sufficient but repairable, and (5) clinically unacceptable. Evaluation with category (5) was rated as a clinical failure. A blinded, calibrated, and experienced dentist performed follow-up evaluation. Statistical analysis for baseline and follow-up criteria was performed with Wilcoxon-Test ($p < 0.05$) (SPSS; IBM, Chicago, IL).

Results

Evaluation after 12 months

Twenty-eight of 30 patients appeared for follow-up evaluation after 12 months, and 40 of 42 restorations could be evaluated (dropout rate 4.8%; follow-up rate 95.2%). Fifteen maxillary and 25 mandibular teeth (28 molars, 12 premolars) were evaluated. The distribution of gender was 15 male and 13 female patients. Two restorations were rated as a clinical failure as a result of debonding (failure rate 5.0%). Both restorations required refabrication. The success rate of indirect particle-filled composite resin CAD/CAM restorations after 12 months was 95.0%.

Evaluation after 24 months

Twenty-three of 28 patients appeared for follow-up evaluation after 24 months, and 33 of 38 restorations could be evaluated (dropout rate 13.2%, follow-up rate 86.8%). Thirteen maxillary and 20 mandibular teeth (22 molars, 11 premolars) were evaluated at follow-up. The distribution of gender was 14 male and 9 female patients. Three restorations were rated as a clinical failure. There was one debonding, and two tooth fractures. Restorations required refabrication. The cumulative success rate for indirect particle-filled composite resin CAD/CAM restorations after 24 months was 85.7%. Detailed results for baseline and 12M follow-up and 24M follow-up evaluation are summarized in Table 2.

Restoration failures

Two restorations clinically failed as a result of debonding at the 12-month evaluation. Both restorations required refabrication. Restoration failure (1) was the debonding of a partial crown on the mandibular first right molar. Debonding of the restoration occurred 2 months after insertion. Neither a fracture of tooth substance nor any other clinical abnormality could be detected. Percussion test was negative. The tooth surface of the prepared tooth was covered completely with luting composite (Figs 1 and 2). After photographic documentation, the composite resin was carefully removed from the preparation, and a new partial crown was fabricated with Lava Ultimate and CEREC. Restoration failure (2) was the debonding of a restoration on the maxillary first left molar. Debonding of the restoration occurred a month after insertion. The patient instantly showed up in person at the clinic. There were no cracks within the tooth substance. The percussion test of the vital tooth was negative. The tooth surface was covered with luting composite, whereas small areas no longer showed adhesive sealing. The patient agreed with the fabrication of a new partial crown with Lava Ultimate and CEREC. The remaining composite was carefully removed, and the new restoration was adhesively seated according to the standardized protocol.

Three restorations clinically failed at the 24-month evaluation. Restoration failure (3) was the fracture of the mesio-oral cusp of the maxillary left first molar. The fracture occurred 13 months after insertion. No other clinical abnormality could be detected. Percussion test was negative. The tooth had been treated with a root canal treatment prior to restoration. The fracture line was located directly epigingival from the mesial to the distal aspect. No other cracks could be detected within the surrounding tooth substance (Fig 3). A new particle-filled composite resin partial crown restoration was fabricated and seated adhesively. Restoration failure (4) was a debonding of a partial crown restoration of the mandibular second right molar after 22 months. The tooth surface was covered with luting composite (Fig 4). Percussion test of the vital tooth was negative. The patient agreed with the refabrication of a new particle-filled composite resin partial crown after the remaining luting composite had been removed carefully. Restoration failure (5) was a probable tooth fracture at the oral aspect of the upper right first molar (Fig 5). Percussion test of the vital tooth was negative. The patient preferred the refabrication of a new particle-filled composite resin crown.

Statistical analysis

The clinical success rate of indirect particle-filled composite resin restorations after 12 months was 95.0% and 85.7% after 24 months. Statistical analysis between baseline and follow-up criteria using Wilcoxon-Test ($p < 0.05$) revealed statistically significant differences for anatomic form criterion ($p = 0.028$) and marginal adaptation criterion ($p = 0.042$) for groups 0M (baseline) and 24M (24-month follow-up). There were no statistically significant differences for all criteria for groups 0M (baseline) and 12M (12-month follow-up).

Discussion

The aim of this study was to evaluate the clinical outcome of indirect particle-filled composite resin CAD/CAM restorations after 24 months. The clinical success rate of indirect Lava Ultimate restorations after 12 months was 95.0% and 85.7% after 24 months. Five clinical failures for Lava Ultimate partial crown restorations occurred after 24 months (3 debondings, 2 fractures within the tooth substance). Several aspects should be discussed.

First, there is no typical control group. This study is a prospective observation study without a control group. Because the particle-filled composite resin material is one of the first representatives of a new class of CAD/CAM materials, no comparable CAD/CAM restorative material was available at the moment the study was conducted. In this study, instead of adding more control groups with different material characteristics, the clinical behavior of the new material class particle-filled composite resin was the main focus of interest.

Several published studies refer to the clinical survival of CAD/CAM fabricated CEREC restorations.[16-18] Results are available both for ceramic and composite materials. Fasbinder et al reported that resin-based Paradigm MZ 100 composite inlays performed as well as Vita Mark II ceramic inlays at 3 years in all categories, with clinical advantages noted in fracture resistance and better color match to the tooth.[18] Reiss showed high clinical success rates for indirect ceramic inlays fabricated with the CEREC system with 84.4% after 18 years.[19] In a systematic review of clinical studies for CEREC ceramic inlays, Martin and Jedynakiewicz reported a mean survival rate of 97.4% after 4 years.[20] Clinical data for partial crown ceramic restorations fabricated with the CEREC system are scarce.[21,22]

Table 2 Clinical evaluation of indirect particle-filled composite resin CAD/CAM restorations; esthetics, functional, and biological criteria at baseline evaluation (0M), 12-month evaluation (12M), 24-month evaluation (24M); FDI criteria from best to worst (1) to (5)

	Surface gloss			Surface/Marginal staining			Color match			Anatomic form			
	0M	12M	24M	0M	12M	24M	0M	12M	24M	0M	12M	24M	
(1)	27	24	15	–	30	12	24	18	4	35	31	4	**Esthetic criteria**
(2)	15	14	15	–	8	16	14	16	20	5	5	24	
(3)	0	0	0	–	0	2	4	4	6	2	2	2	
(4)	0	0	0	–	0	0	0	0	0	0	0	0	
(5)	0	0	0	-	0	0	0	0	0	0	0	0	
	Fracture/Retention			Marginal adaptation			Wear			Contact point			
	0M	12M	24M	0M	12M	24M	0M	12M	24M	0M	12M	24M	
(1)	42	38	30	34	30	25	–	34	17	37	33	9	**Functional criteria**
(2)	0	0	0	8	8	4	–	2	12	0	0	9	
(3)	0	0	0	0	0	1	–	2	1	1	1	11	
(4)	0	0	0	0	0	0	–	0	0	4	4	1	
(5)	0	2	1	0	0	0	–	0	0	0	0	0	
	Postoperative hypersensitivity			Caries/Erosion/Abfraction			Tooth integrity			Periodontal response			
	0M	12M	24M	0M	12M	24M	0M	12M	24M	0M	12M	24M	
(1)	–	18	17	–	38	28	42	38	30	–	32	30	**Biological criteria**
(2)	–	0	0	–	0	0	0	0	0	–	1	0	
(3)	–	0	0	–	0	2	0	0	0	–	4	0	
(4)	–	0	0	–	0	0	0	0	1	–	1	0	
(5)	–	0	0	–	0	0	0	0	1	–	0	0	

In this study partial crown restorations fabricated from particle-filled resin CAD/CAM blocks were investigated. The survival rate after 24 months was 85.7%; however, a longer clinical observation period is mandatory to draw further conclusions.

The specific material characteristics of particle-filled composite resin restorations should be discussed. In this study, no chipping fracture of particle-filled composite resin restorations could be observed. A complex, cohesive fracture of the restoration material including a fracture of the tooth substance could not be observed. These observations might refer to the resilient material characteristics of a compound material such as Lava Ultimate. Compound materials might thus be advantageous for postendodontic restorative treatment. Restorations on endodontically treated teeth are reported to be more susceptible to fracture, as pulpal proprioceptive mechanisms are missing.[23] Compound materials might buffer occlusal overloads and reduce chipping failures; however, the resilient characteristics of composite CAD/CAM materials are discussed controversially in the literature. Duan and Griggs investigated the effect of elasticity on the stress distribution in CAD/CAM-fabricated crowns made of ceramics and composite materials.[24] Based on the results found in their study, Duan and Griggs suggested that composite crowns would probably not be indicated for patients known to exhibit bruxism because of the increased stress that the composite material developed under lateral loading.[24] A high elasticity of a restoration material may result in stress on the phase boundary of the luting interface and may result in debonding. The fact that the manufacturer recently has limited the clinical indication for Lava Ultimate restorations to not use the material for crowns and to prepare the tooth for maximum mechanical retention appears to be also relevant for this aspect.

The tooth fracture observed in this study was related to a partial crown preparation where a small cusp had not been included in the preparation. The authors assume that a prior micro-crack had not been detected prior to the restoration's seating.

The bonding strength of the particle-filled composite resin material and its clinical relevance needs to be discussed. Frankenberger et al recently published in vitro results for the bonding strength of different CAD/CAM materials including Lava Ultimate using a microtensile bond strength approach.[25] The highest bond strength for Lava Ultimate restorations was found to be 17.9 ± 4.5 MPa if sandblasting of the restoration was performed prior to its adhesive seating. Compared to conventional ceramics these values are low. Lithium-disilicate ceramics such as e.max CAD were found to have a microtensile bond strength of 26.3 ± 7.7 MPa if HF and silane were applied to the restoration prior to its adhesive seating. For compound materials, no ceramic framework is available for bonding. Particle-filled composite resin materials have a limited bonding strength and might thus be more susceptible to bonding failure if the bonding protocol is not respected exactly.

Figure 1 Clinical failure of particle-filled composite resin partial crown after 2 months; lower first right molar; debonding of restoration: FDI criterion fracture/retention (5). [Color figure can be viewed at wileyonlinelibrary.com]

Figure 2 Oral view of debonding failure (1); tooth surface covered completely with luting composite. [Color figure can be viewed at wileyonlinelibrary.com]

Figure 3 Clinical failure of particle-filled composite resin partial crown after 13 months; upper first left molar; fracture of mesio-oral cusp: FDI criterion tooth integrity (5). [Color figure can be viewed at wileyonlinelibrary.com]

The fact that three out of the five restoration failures occurred in this study were related to debonding supports this theory from the clinical point of view. In fact, for each debonding failure reported in this study, the luting composite covered the tooth surface. The compound luting resin composite and restoration

Figure 4 Clinical failure of particle-filled composite resin partial crown after 22 months; lower second right molar; debonding of restoration: FDI criterion fracture/retention (5). [Color figure can be viewed at wileyonlinelibrary.com]

Figure 5 Clinical failure of particle-filled composite resin partial crown detected at 24-month recall; upper right first molar; fracure of oral aspect: FDI criterion tooth integrity (4). [Color figure can be viewed at wileyonlinelibrary.com]

material might have been the weak spot. Mandatory observance of the manufacturer's instructions is recommended, and strict moisture control is mandatory while adhesively seating particle-filled composite resin restorations.

Compound materials, such as particle-filled composite resin, might be advantageous because of their postprocessing procedure. The postprocessing procedure used in this study was a three-step polishing procedure. The surface gloss was stable over the period of 12 months; however, after 24 months significant differences could be observed for the surface gloss criterion. These findings are in accordance with recently published literature. Koizumi et al reported that the surface roughness and gloss of CAD/CAM resin composite might be altered by external manipulations such as toothbrush abrasion.[26]

5. Diskussion

In diesem Abschnitt werden die jeweiligen Untersuchungen einzeln diskutiert.

5.1 Verbundfestigkeit von CAD/CAM Kompositen

Anhand der Untersuchungsergebnisse konnte gezeigt werden, dass Sandstrahlen und eine korrekte Vorbehandlung entscheidend für einen zuverlässigen Verbund von CAD/CAM Kompositen sind. Das Sandstrahlen der Substratoberfläche führte zu einem überlegenen Verbund mit dem Befestigungskomposit im Vergleich zum Unterlassen dieses Schrittes. Hierbei ist anzumerken, dass alle Prüfkörper initial auf ein vergleichbares Niveau halb-automatisch poliert wurde. Dies kann zu einer glatteren Oberfläche als bei klinischer Herstellung einer Restauration geführt haben. Ebenso führte die Anwendung des Universaladhäsivs *One Coat* Universal (Coltene/Whaledent, Altstätten, Schweiz) zu einer höheren Verbundfestigkeit als die Anwendung des Silans *Clearfil Ceramic Primer* (Kuraray, Tokyo, Japan). Dieses Ergebnis ist entscheidend für die Auswahl der korrekten Befestigungsstrategie. Frühere Studien wiesen nach, dass die Anwendung eines Adhäsivs zu höheren Verbundfestigkeiten führt als eine reine Silan-Applikation[47] oder die Kombination von Silan und darauffolgender Adhäsiv-Anwendung[48,49]. Eine mögliche Erklärung hierfür ist, dass Silan zwar einen festen Verbund zu den Füllkörpern innerhalb des Komposits herstellen kann, jedoch nur einen geringen zur Harzmatrix[44]. Die hier vorgestellten Untersuchungsergebnisse liegen jedoch in Widerspruch zu anderen Studien, welche die Anwendung eines Silan als Vorbehandlungsstrategie bei Komposit-Reparaturen[50] oder zur Befestigung von CAD/CAM Kompositen[43] bevorzugen. Eine mögliche Erklärung dieser widersprüchlichen Studienergebnisse besteht darin, dass bei denjenigen Untersuchungen, welche höhere Verbundfestigkeiten bei der Anwendung eines Adhäsivs feststellten, Adhäsive mit Methyl-Methacrylat (MMA) als Inhaltsstoff verwendet wurden. In der hier vorgestellten Untersuchung wurde *One Coat Universal* als Universaladhäsiv verwendet, welcher MMA mit Polyacrylsäure beinhaltet. Dieses Monomer löst die Oberfläche der CAD/CAM Komposite teilweise auf, wodurch freie Kohlenstoff-Kohlenstoff-Bindungen zu solchen des Adhäsivs binden können[47].

Aus diesem Grund befürwortet die hier vorgestellte Untersuchung die Anwendung eines Adhäsivs mit MMA als Inhaltsstoff für eine erfolgreiche Befestigungsstrategie von CAD/CAM Kompositen. Gleichzeitig stellt sie fest, dass weitere, vergleichende Analysen zwischen Adhäsiven mit MMA und solchen ohne anzustreben sind.

Das Sandstrahlen des Substrats ist ein entscheidender Faktor für eine erfolgreiche Befestigung. Neben der Konditionierungsmethode weist dieser Schritt den höchsten Einfluss auf die Verbundfestigkeit auf und seine korrekte Anwendung ist von hoher Bedeutung. Yoshihara et al. haben gezeigt, dass zu viel Druck beim Sandstrahlen zu einer Zerstörung der Oberfläche von CAD/CAM Kompositen führen kann[41]. Dieser Fakt scheint besonders für das Material *Shofu Block HC* (Shofu, Kyoto, Japan) zu gelten. In der hier vorgestellten Untersuchung konnten bei diesem Material nach Sandstrahlen und Applikation des Universaladhäsivs überzeugende Resultate aufgezeigt werden. Daraus lässt sich folgern, dass der hier gewählte Druck beim Sandstrahlen als nicht zu hoch eingestuft werden kann. Die Schaffung eines mikro-retentiven Oberflächenmusters wie auch die Entfernung der Schmierschicht scheinen dafür verantwortlich zu sein, dass sandgestrahlte Proben, die mit Silan konditioniert wurden, vergleichbare Ergebnisse aufwiesen wie nicht-sandgestrahlte Proben, die mit Adhäsiv vorbehandelt wurden. Interessanterweise zeigte das Material *Brilliant Crios* (Coltene/Whaledent) ähnliche Verbundfestigkeiten unabhängig davon, ob es sandgestrahlt wurde oder nicht. Dies könnte ein möglicher Hinweis auf eine höhere Konzentration von freien Kohlenstoff-Kohlenstoff-Doppelbindungen an dessen Oberfläche sein. Jedoch bedarf es zur Bestätigung dieser Annahme noch weiterer Untersuchungen. Außerdem sollte beachtet werden, dass der verwendete Befestigungskomposit *DuoCem* als auch das Material *Brilliant Crios* vom selben Hersteller stammen und chemisch aufeinander abgestimmt sein könnten, was einen positiven Einfluss hätte. Bei den Prüfkörpern des Materials *Shofu Block HC*, die nicht sandgestrahlt wurden und mit Silan vorbehandelt wurden, konnte kein zuverlässiger Verbund hergestellt werden; bei allen Prüfkörpern wurde ein Debonding während des Thermocycling-Prozesses festgestellt. Dies könnte an der geringeren

Konzentration an Füllkörpern in diesem Material liegen. Tatsächlich weist dieses Material die geringste Konzentration von allen Materialien auf, nämlich 61%.

Zusammenfassend kann festgestellt werden, dass die Nullhypothese verworfen werden kann. Somit befindet sich diese Untersuchung in Übereinstimmung mit anderen Studien, die sich mit dem Einfluss des Sandstrahlens[27,40] sowie der Vorbehandlungsstrategie[47] befassen.

In ihrer Übersichtsarbeit zur Methodik der Messung der Verbundfestigkeit[51] befürworten Meerbeek et al. die Begrenzung der vorzubehandelnden Oberfläche des Substrats auf diejenige Fläche, an der tatsächlich geklebt wird, statt die gesamte Oberfläche des Prüfkörpers zu behandeln. Sie behaupten, dass ein Abweichen von dieser Methodik zu einer viel höheren Klebefläche führt, wodurch der Zug eher auf das Adhäsiv-Komposit-Interface verteilt wird als auf das Adhäsiv-Zahn-Interface. In ihrer Publikation zeigen sie ein Bespiel, in der eine Fläche des Adhäsivs nach der Messung immer noch mit dem Prüfkörper verbunden ist. In der hier vorgestellten Untersuchung wurde die gesamte Substratoberfläche vorbehandelt. Jedoch konnte der von Meerbeek et al. beschriebene Fehlertyp nicht festgestellt werden. Die Vergleichbarkeit der Ergebnisse ist durch die gleiche Vorbehandlung aller Prüfkörper gegeben. Jedoch könnte diese Art der Substrat-Vorbehandlung zu allgemein höheren Werten führen als sie in vergleichbaren Studien, die der Empfehlung von Meerbeek et al. folgen, zu finden sind.

Der Alterungsprozess, welchen Restaurationen in der Mundhöhle ausgesetzt sind, wurde in dieser Untersuchung mit Hilfe eines Thermocycling-Prozesses (5.000 Zyklen in zwei Bädern mit 55°C und 5°C vorgewärmten Wasser bei einer Verweilzeit von jeweils 20 Sekunden) nachgeahmt. Es ist gut möglich, dass dies Einfluss auf die Verbundfestigkeit hatte. Volumetrische Veränderungen, die in mechanischem Stress resultieren und zu Frakturen führen, können die Verbundfestigkeit negativ beeinflussen. Demgegenüber kann die erhöhte Temperatur zu einer höheren Polymerisationsrate führen und somit die Verbundfestigkeit positiv beeinflussen. Das Ziel dieser Untersuchung war es, alleine den Einfluss der Vorbehandlungsstrategie auf die Verbundfestigkeit zu untersuchen. Deshalb wurde im Gegensatz zu anderen Studien[42] nicht der Einfluss anderer Alterungsprozeduren erforscht.

Die Analyse der Fehlertypen zeigt für alle Untergruppen, die sandgestrahlt und mit Adhäsiv behandelt wurden, höhere Anteile an kohäsiven Fehlern. Deshalb kann davon ausgegangen werden, dass die gemessenen Werte eher die Verbundfestigkeit des Befestigungskomposits widerspiegeln als die des Substrates, welche noch höher sein kann.
Schlussendlich muss darauf hingewiesen werden, dass eine in-vitro Untersuchung nicht in der Lage ist, alle Umstände zu simulieren, welche in der Mundhöhle über Jahre hinweg auftreten können. Um ein umfassenderes Bild von CAD/CAM Kompositen zu erhalten ist daher die Sammlung weiterer umfangreicher Daten notwendig. Dennoch bleiben randomisierte, klinische Langzeituntersuchungen der Goldstandard, um die klinische Performance eines Materials zu beurteilen. Für die Materialklasse der CAD/CAM Komposite fehlt es bisher an solchen.

5.2 Optische Eigenschaften von CAD/CAM Kompositen

Polierpasten, die in der individuellen Prophylaxe sowie der professionellen Zahnreinigung Anwendung finden, müssen für all die unterschiedlichen Materialklassen geeignet sein, die bei einem Patienten vorhanden sind. Für die neue Klasse der CAD/CAM Komposite gibt es von Seiten der Hersteller keine grundsätzlichen Empfehlungen bezüglich der Anwendung von Prophylaxepasten.

Die in dieser Untersuchung verwendeten Pasten weichen in ihrer Zusammensetzung, Größe und Form der Polierkörper stark voneinander ab. Diese Unterschiede sind sehr deutlich auf den in dieser Arbeit präsentierten Bildern des Elektronenmikroskops zu erkennen. Das Material *Clean Polish/Super Polish* zeigt eher abgerundete und relativ kleine Polierkörper, wohingegen die Polierkörper des Materials *Cleanic* körnig erscheinen. Dies könnte ein Grund für die geringere Oberflächenrauigkeit nach Anwendung der *Clean Polish/Super Polish* im Vergleich zur *Cleanic* sein.

Neben der Auswahl der geeigneten Polierpaste, ist das Resultat der Politur auch stark vom Behandler abhängig. Er kann zwischen einem Polierbürstchen und einem Polierkelch wählen, er kann die Abfolge der Polierpasten sowie ihre Applikationsdauer bestimmen und nicht zuletzt auch über den ausgeübten Druck entscheiden. Dieser wird in der Literatur als optimaler Wert mit 2 N[74] angegeben - in der praktischen Durchführung ist eine solch konstant gleiche Druckausübung selbstverständlich nicht möglich. Dasselbe gilt auch für diese in-vitro Untersuchung: Zwar wurde die Politur stets von dem gleichen Behandler unter optimalen Bedingungen durchgeführt, dennoch kann der Druck minimal variieren. Auch die Menge und Konsistenz des Pasten-Wasser-Gemisches lässt sich nur schwer standardisieren. Diese Faktoren können zu der erhöhten Standardabweichung geführt haben. In der Literatur wurde bereits beschrieben, dass Veränderungen der Oberflächenrauigkeit von Komposit-Materialien stark von dem jeweiligen Material sowie dem Anpressdruck abhängig sind[74-76]. Aus diesem Grund wurde in der vorliegenden Untersuchung nur ein einziges Material verwendet und auf einen konstanten Anpressdruck bei allen Prüfkörpern geachtet. Auch ist die in-vitro Politur mit einer Dauer von einer Minute pro Prüfkörper unter Verwendung eines Tropfens destilliertem

Wassers nicht gleichzusetzen mit der praktischen Durchführung am Patienten: Die Polierdauer pro Fläche ist geringer und eine exakte Flüssigkeitsdosierung ist durch den Speichelfluss unmöglich.

Generell hat der Glanz einer Restauration einen entscheidenden Einfluss auf dessen ästhetisches Erscheinungsbild, wobei der Glanz von der Oberflächenrauigkeit abhängt[65,66]. Frühere Studien konnten einen signifikanten Einfluss von Polierpasten auf die Rauigkeit von indirekten Komposit-Restaurationen als auch auf keramische Werkstoffe feststellen[80]. Die mechanische Anwendung der Politur zeigte im Vergleich zur manuellen Anwendung bessere Resultate in Bezug auf den Glanz[74].

In der vorliegenden Studie wiesen Prüfkörper nach Anwendung von *Cleanic*, gefolgt von *Prophy Paste* und *Clinpro Prophy Paste* die höchsten Oberflächenrauigkeitswerte auf. Dabei kann kein Einfluss auf die Anzahl der aufeinander abgestimmten Polierschritte festgestellt werden, da *Cleanic* ein 1-Schritt-, *Prophy Paste* ein 4-Schritt- und *Clinpro Prophy Paste* ein 3-Schritt-System ist. Es ist schwierig zu bestimmen, welchen Einfluss die Zusammensetzung der einzelnen Polierpasten auf die Rauigkeitswerte besitzt, jedoch enthalten die drei genannten Pasten größere Polierkörper als diejenigen Pasten, welche die geringste Rauigkeit am Material hervorriefen: *Super Polish*, gefolgt von *Détartrine* und *Proxyt*.

Die Anwendung der Polierpasten hatte auch Auswirkungen auf den Oberflächenglanz, der nach der Politur zunahm. Der geringste Glanz wurde nach Anwendung von *Cleanic*, gefolgt von *Nupro* und *Zircate* festgestellt, während sich bei *Polish* und *Proxyt* der höchste Oberflächenglanz zeigte. Für *Polish* war neben dem höchsten Oberflächenglanz auch die geringste Rauigkeit zu verzeichnen, was in Zusammenhang mit dessen geringem RDA-Wert (Relative Dentin Abrasion) sowie der feineren und runderen Polierkörper stehen könnte.

Abgesehen von *Zircate* und *Cleanic* hatten alle Polierpasten einen positiven Einfluss auf die freie Oberflächenenergie des verwendeten CAD/CAM Komposits. Die geringste freie Oberflächenenergie wurde nach Anwendung von *Détartrine* und *Super Polish* festgestellt, für welche gleichzeitig die geringsten Rauigkeiten und der höchste Glanz registriert wurden.

Die Anwendung der Prophylaxepaste hatte hingegen keinen Einfluss auf die Verfärbungsabnahme. Alle Werte lagen unter dem in der Literatur genannten Wert von 3.3, bei welchem die Hälfte der Beobachter eine Verfärbung der Oberfläche als inakzeptabel betrachtet[92]. Die Prüfkörper wurden 14 Tage lang in Rotwein gelagert, da dieses Medium in anderen Studien die höchsten Verfärbungswerte nach längerer Lagerung provozierte. Möglicherweise wäre ein Einfluss auf die Verfärbungsabnahme nach prolongierter Lagerungsdauer oder unter Verwendung eines anderen Mediums deutlicher erkennbar gewesen.

Zusammenfassend kann feststellt werden, dass die Nullhypothese abgelehnt werden kann. Eine Ausnahme stellt die Verfärbung dar, da bei diesem Punkt kein signifikanter Unterschied zwischen den einzelnen Polierpasten festgestellt werden konnte. Die hier vorgestellte Untersuchung illustriert, dass die richtige Auswahl des Polierpastensystems von entscheidender Bedeutung für die Oberflächeneigenschaften von CAD/CAM Kompositen ist.

5.3 Klinische Performance von CAD/CAM Kompositen

Das Ziel dieser Studie war es, die klinische Performance eines CAD/CAM Komposit-Materials nach 24-monatigem Beobachtungszeitraum zu bewerten. Die klinische Erfolgsrate von indirekten Restaurationen aus dem Material *Lava Ultimate* (3M, Seefeld, Deutschland) betrug nach 12 Monaten 95%, nach 24 Monaten 85,7%. Insgesamt wurden 5 Fehler (3 Debondings, 2 Frakturen innerhalb der Zahnhartsubstanz) innerhalb dieses Beobachtungzeitraums festgestellt.

Bei der hier vorgestellten Studie handelt es sich um eine prospektive klinische Beobachtungsstudie ohne Kontrollgruppe. Das Material *Lava Ultimate* war zum Zeitpunkt der Baseline der einzige Vertreter der neuen Klasse von CAD/CAM Kompositen, weshalb kein vergleichbares Material für die Verwendung in einer Kontrollgruppe zu Verfügung stand. Es wurde darauf verzichtet, Materialien anderer Werkstoffklassen zum Vergleich heranzuziehen. Stattdessen konzentrierte sich die Studie auf die Beschreibung der klinischen Performance des CAD/CAM Komposit-Materials *Lava Ultimate*.

Mehrere Veröffentlichungen beschreiben die klinische Performance von CAD/CAM gefertigten CEREC-Restaurationen[107-109], wobei sowohl Keramiken als auch Komposite untersucht wurden. Fassbinder et al.[109] berichten beispielsweise von vergleichbaren Resultaten für Inlays die aus dem CAD/CAM Komposit *Paradigm MZ 100* (3M, Seefeld, Deutschland) und der Keramik *Vita Mark II* (Vita, Bad Säckingen, Deutschland) hergestellt wurden. Für das Komposit-Material wurden dabei Vorteile wie eine höhere Bruchfestigkeit oder auch eine bessere Farbübereinstimmung mit der Zahnhartsubstanz festgestellt. Reiss[107] zeigte für Keramik-Inlays, die mit dem CEREC-System hergestellt wurden, eine hohe klinische Erfolgsrate von 84,4% bei einem Beobachtungszeitraum von über 18 Jahren. Für Teilkronen, die mit dem CEREC-System hergestellt wurden, ist die Datenlage hingegen gering[112,113].

In der hier aufgeführten Studie wurden Teilkronen aus einem CAD/CAM Komposit untersucht. Die Überlebensrate betrug nach 24 Monaten 85,7%. Es ist jedoch darauf hinzuweisen, dass ein längerer Beobachtungszeitraum notwendig ist, um weitreichendere Schlüsse über das Material ziehen zu können.

Innerhalb des Beobachtungzeitraums wurde weder eine Chipping-Fraktur des CAD/CAM Komposit-Materials noch eine kohäsive Fraktur von Material und Zahnhartsubstanz festgestellt. Diese Beobachtung könnte auf die resiliente Eigenschaft des Verbundmaterials *Lava Ultimate* zurückzuführen sein. Damit könnte diese Eigenschaft von CAD/CAM Kompositen große Vorteile für postendodontische Versorgungen bieten, denn es deutet vieles darauf hin, dass Restaurationen auf wurzelkanalbehandelten Zähnen anfälliger für Frakturen sind, weil der propriozeptive Schutzmechanismus fehlt[23]. Verbundmaterialien könnten okklusale Überbelastungen abpuffern und somit Frakturen verhindern. Jedoch werden die resilienten Eigenschaften von CAD/CAM Kompositen in der Literatur kritisch diskutiert. Duan und Griggs untersuchten den Effekt der Elastizität auf die Spannungsverteilung innerhalb CAD/CAM gefertigter Kronen aus Keramik und Komposit[115]. Auf Grundlage ihrer Ergebnisse empfahlen die Autoren, keine Verbundmaterialien bei Patienten, die unter Bruxismus leiden, anzuwenden. Der Grund hierfür war die erhöhte Spannung auf das Restauration-Bonding-Interface, welches das elastische CAD/CAM Komposit unter lateraler Belastung erfuhr. Diese Erkenntnis könnte der Grund dafür gewesen sein, dass der Hersteller die Indikation von *Lava Ultimate* für Kronen strich und eine Präparation mit maximaler mechanischer Retention empfiehlt.

Der Fraktur der Zahnhartsubstanz, die in der hier vorgestellten Studie beobachtet wurde, liegt wohl ein geschwächter Höcker zu Grunde, der bei der Teilkronen-Präparation nicht mit überkuppelt wurde. Auch eine nicht erkannte Mikro-Fraktur der Zahnhartsubstanz könnte der Grund für diesen Fehler gewesen sein.

Des Weiteren muss die Verbundfestigkeit von CAD/CAM Kompositen und deren klinische Bedeutung diskutiert werden. Frankenberger et al haben in einer in-vitro Studie die Verbundfestigkeit verschiedener CAD/CAM Materialien, darunter auch Lava Ultimate, untersucht[116]. Die höchste Verbundfestigkeit für Lava Ultimate von 17,9 +/- 4,5MPa konnte dabei nach Sandstrahlen des Materials festgestellt werden. Dieser Wert ist viel geringer im Vergleich zur Lithiumdisilikat-Keramik *e.max CAD*, die bei korrekter Vorbehandlung eine Verbundfestigkeit von 26,3 +/- 7,7MPa aufweist. CAD/CAM Komposite besitzen keine keramische Matrix, an die ein adhäsiver Verbund hergestellt werden könnte. Sie haben eine geringere Verbundfestigkeit und sind deshalb anfälliger für Debondings, wenn das Einsetzprotokoll nicht genau befolgt wird. Das könnte der Grund dafür sein, dass drei von fünf beobachteten Fehlern aufgrund eines Debondings festgestellt wurden. Tatsächlich bedeckte bei diesen Fällen das Befestigungskomposit die Präparation immer noch komplett, was die Schlussfolgerung erlaubt, dass das Interface zwischen Befestigungskomposit und Verbundmaterial die Schwachstelle war. Hierbei ist zu erwähnen, dass das Befestigungsprotokoll der Baseline der damaligen Herstellerangabe entsprach, nämlich der Applikation eines Silans (Espe-Sil, 3M). Dieses Protokoll wurde zwischenzeitlich modifiziert und empfiehlt nun die Applikation eines Universaladhäsivs (Scotchbond Universal, 3M). Dies steht in Einklang mit den Ergebnissen, die der Autor in der Originalarbeit 1 „Bonding to new CAD/CAM resin composites: influence of air abrasion and conditioning agents as pretreatment strategy" präsentierte. In dieser Arbeit wurden höhere Verbundfestigkeitswerte bei der Anwendung eines Adhäsivs im Vergleich zu einem Silan festgestellt.

CAD/CAM Komposite könnten aufgrund ihrer einfacheren Nachbearbeitung vorteilhaft sein. Zur Politur wurde ein drei-Stufen-System verwendet, welches sowohl extra- als auch intraoral anwendbar ist. Der Oberflächenglanz blieb über 12 Monate hinweg stabil. Nach 24 Monaten konnten signifikante Unterschiede beim Glanz im Vergleich zur Baseline festgestellt werden. Diese Ergebnisse stehen in Übereinstimmung mit einer Untersuchung von Koizumi et al[117], in der berichtet wurde, dass die Oberflächenrauigkeit und der Glanz von CAD/CAM Kompositen durch externe Manipulationen, wie Zähneputzen, verändert werden können. Wie der Autor in der Originalarbeit 2 „Nine prophylactic polishing pastes: impact on discoloration, gloss and surface properties of a CAD/CAM resin composite" bereits diskutiert hat, hat die Anwendung von Prophylaxepasten einen positiven Einfluss auf die Oberflächeneigenschaften des CAD/CAM Komposit-Materials.

Verbundmaterialien scheinen vorteilhaft bezüglich Verschleiß und Abrasion zu sein. Nach 12 Monaten waren nur minimale Abrasionstendenzen feststellbar. Nach 24 Monaten konnte kein signifikanter Unterschied zur Baseline bezüglich des Kriteriums Verschleiß festgestellt werden.

Diese klinischen Ergebnisse passen zu in-vitro Resultaten von Mörmann et al[56], in welcher die Zwei-Körper-Verschleißwerte von *Lava Ultimate* bei 48,1 µm auf der Kontaktgegend und bei 25,3 µm beim Schmelz-Antagonisten lagen. Bei der Schmelz-Schmelz-Kontrollgruppe lagen diese Werte bei 42,1 µm bzw. 54,5 µm. Daraus könnte geschlussfolgert werden, dass das CAD/CAM Komposit Schmelz ähnliche Abrasionstendenzen aufweist und die natürliche Zahnhartsubstanz schont.

6. Zusammenfassung

Anhand der hier vorgestellten Ergebnisse zur Untersuchung der Verbundfestigkeit kann festgestellt werden, dass CAD/CAM Komposite einer besonderen Vorbehandlung bedürfen, um eine erfolgversprechende adhäsive Befestigung gewährleisten zu können. Das Sandstrahlen der Oberfläche ist dabei von entscheidender Bedeutung. Das Unterlassen dieses Schrittes führte bei den meisten untersuchten CAD/CAM Kompositen zu Resultaten, die unzureichend in der klinischen Anwendung wären. Die zusätzliche Applikation des Universaladhäsivs *One Coat 7 Universal* konnte die Verbundfestigkeit im Vergleich zur Applikation des Silans *Clearfil Ceramic Primer* deutlich erhöhen.

Des Weiteren kann festgestellt werden, dass die Anwendung von Polierpasten einen positiven Einfluss auf die Oberflächenbeschaffenheit des untersuchten CAD/CAM Komposits besitzt. Es kommt zu einer Verringerung der Oberflächenenergie, die gemessene Rauigkeit nimmt ab, und der Oberflächenglanz steigt in seinen Werten an. Demgegenüber konnte kein Einfluss auf die Verfärbung festgestellt werden, was jedoch wahrscheinlich auf die Art der durchgeführten Lagerung zurückzuführen ist. Es kann angenommen werden, dass eine prolongierte Einlagerungsdauer und/ oder ein anderes Medium zu eindeutigeren Werten geführt hätten.

Trotz der hohen Bedeutung der Datensammlung durch umfangreiche in-vitro Untersuchungen, können diese nicht alle Bedingungen widerspiegeln, welchen ein Material in der Mundhöhle über Jahre hinweg ausgesetzt ist. Klinische Langzeituntersuchungen bleiben daher weiterhin der Goldstandard zur Bewertung der Performance eines Materials. Für CAD/CAM Komposite liegen noch keine ausreichend langen Untersuchungszeiträume vor. Die ersten klinischen Ergebnisse weisen der Materialklasse aber erfolgsversprechende Eigenschaften zur Versorgung von Einzelzahnrestaurationen zu. Jedoch ist ihre Verbundfestigkeit sehr stark von der korrekten Vorbehandlung abhängig.

7. Englische Zusammenfassung

Based on the presented results regarding the bond strength it can be stated that CAD/CAM composites require a special pretreatment in order to ensure a promising adhesive attachment. Air abrasion of the surface is of crucial importance. Failure to do so resulted in clinically insufficient outcomes for most of the tested CAD/CAM composites. The additional application of the adhesive *One Coat 7 Universal* significantly increased the bond strength compared to the application of the silane *Clearfil Ceramic Primer*.

Furthermore, it can be stated that the use of polishing pastes has a positive influence on the surface quality of the examined CAD/CAM composite. Its surface gloss increased while the measured roughness and the free surface energy decreased. In contrast, no influence on discoloration could be detected. It is probable that this is due to the storage effected. A prolonged storage period or another medium would probably have led to more apparent values regarding this point.

Although the collection of in-vitro results is crucial to obtain a clearer picture of dental material long-term clinical observational studies still remain the gold standard to evaluate their performance. For CAD/CAM resin composites such studies are scarce. However, first observations after two years show promising results for this new class of material provided the fact that the correct pre-treatment strategy is carried out.

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