Aus der Poliklinik für Zahnärztliche Prothetik,

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des Fachbereichs Medizin der Justus-Liebig-Universität Gießen

# Monolithische CAD/CAM-Kronenversorgungen im digitalen Workflow der Zahnärztlichen Prothetik

Kumulative Habilitationsschrift

zur Erlangung der Venia legendi

des Fachbereichs Medizin

der Justus-Liebig-Universität Gießen

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aus Bremen

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Meiner Familie

und

meinen Mentoren

# Inhaltsverzeichnis

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* In der vorliegenden Arbeit schließt die männliche Bezeichnung aller Personen die weibliche Bezeichnung mit ein.

# 1 Einleitung

## 1.1 Einführung

Die Überkronung eines natürlichen Zahnes ist vor allem dann erforderlich, wenn der Zahnerhalt durch konservierende Maßnahmen einer Füllungstherapie nicht mehr gewährleistet werden kann.[85] Neben dem Zahnerhalt ist darüber hinaus das Ziel einer Kronenversorgung, den Zahn zu stabilisieren bzw. seine Kaufunktion wiederherzustellen.[120]

Hierfür wurden historisch bedingt, zunächst primär Metalle – vorwiegend als Band- oder Gusskrone – verwendet. Später kamen Kronenversorgungen aus Feldspatkeramik (Jacketkronen) hinzu, welche aufgrund ihrer geringen Festigkeit jedoch nur im Frontzahnbereich Anwendung fanden. Zudem erforderte die für die Stabilität der Krone notwendige hohe Schichtstärke einen erheblichen Zahnhartsubstanzabtrag.[61]

Die zur Überkronung eines Zahnes zur Verfügung stehenden Materialien waren über Jahre hinweg begrenzt. Erst durch die industrielle Fertigung der computer-aided design/ computer-aided manufacturing (CAD/CAM)-Technologie wurde das Spektrum der Restaurationsmaterialien erweitert,[67,109,146] sodass gegenwärtig drei Werkstoffgruppen – Metalle, Keramiken und Komposite – zur definitiven Kronenversorgung verwendet werden können.[125] Dabei sind bis heute die technologischen Hard- und Softwareentwicklungen der Digitalisierungs- und Fertigungssysteme eng mit der Materialwissenschaft verbunden.[80,81,172] Erst durch die CAD/CAM-Technologie wurde eine sinnvolle Verarbeitung von modernen Restaurationswerkstoffen wie dem Zirkoniumdioxid oder industriell polymerisierten Kompositen möglich.[2,137]

Dabei eröffnet die digitale Prozesskette, im Gegensatz zur traditionellen Herstellung von Zahnersatz, die Fertigung patientenspezifischer Restaurationen unter standardisierten industriellen Bedingungen.[62,93] Dies beginnt im vollständigen digitalen Workflow bereits bei der digitalen Abformung mittels Intraoralscanners (IOS), anstelle der im Vergleich dazu fehlersensitiven konventionellen Abformung mittels Abformmasse und -löffel. Auch die an die Abformung anschließende Modellherstellung und Konstruktion der Restauration, kann in der digitalen Prozesskette direkt auf Basis des CAD-Datensatz erfolgen, wodurch die aufwendige manuelle Herstellung von Gipsmodellen und Wachsmodellationen entfällt. Während im subtraktiven CAM-Prozess die Restaurationen direkt aus industriell vorgefertigten Blöcken gefräst werden, müssen im konventionellen Workflow die Wachsmodellationen erst mit Hilfe der Guss- oder Presstechnik in die finale Restauration umgesetzt werden.[62,137] Die CAD/CAM-Fertigung von Zahnersatz erlaubt eine Minimierung möglicher prozessbedingter Fehler und ermöglicht dadurch die Herstellung von Restaurationen mit gleichbleibende Qualität.

In den letzten Jahren lag der Fokus der Entwicklung insbesondere auf der Herstellung ästhetisch ansprechender *monolithischer* – aus einem Stück bestehender – Kronen,[68] denn Metall- und Keramikrestaurationen müssen für eine ansprechende Ästhetik bis heute mit keramischen Massen verblendet werden.[141] Durch den Wegfall der Verblendung wird der manuelle Herstellungsaufwand erheblich reduziert und so eine zeitsparendere und kostengünstigere Patientenversorgung ermöglicht.[42,110,136,145,157,169] Auch die im Zusammenhang mit verblendeten Kronen häufig auftretende Komplikation der *Chipping-Fraktur* – Abplatzen der Verblendung vom Kronengerüst – sind vermeidbar.[42,110,136,145,157,169] Zudem entfällt der Platzbedarf für die Verblendung, denn es wird weniger Zahnhartsubstanz durch die Präparation entfernt.[55]

Neben dem Restaurationswerkstoff selbst, hat auch das Befestigungsmaterial an Bedeutung gewonnen. Historisch standen zunächst Zemente – Zinkphosphat-, Carboxylatzement und später Glasionomerzement – zur Verfügung. Allerdings stellen diese im Gegensatz zu adhäsiven Befestigungssystemen keine kraftschlüssige Verbindung zur Zahnhartsubstanz her, die jedoch insbesondere für glaskeramische und kompositbasierte Restaurationen notwendig ist.[68] Dies wurde im Jahr 2015 deutlich, als ein Hersteller seine Indikation für Kronenversorgungen eines neuen CAD/CAM-Komposits infolge eines erhöhten Debondings – Haftverlust zwischen Restauration und natürlichem Zahn – zurückgenommen hat.[76]

Bereits ein partieller Haftverlust kann zu einem marginalen Randspalt mit bakterieller Besiedlung bis hin zur Sekundärkaries bzw. Entzündung der Pulpa führen, welches einen

Zahnverlust zur Folge haben kann.[72] Daher ist der Langzeiterfolg einer Kronenversorgung direkt von der *Randdichtigkeit* der Befestigung abhängig.[41]

Außerdem sind Restaurationen in der Zahnärztlichen Prothetik immer wiederkehrenden Kaubelastungen ausgesetzt, die bei Patienten mit Parafunktionen (z.B. Bruxismus) auch als horizontale Scherkräfte mit erhöhter Kaukraft auftreten können.[50,104] Im Hinblick auf die *Ermüdungsbeständigkeit* wurden jedoch unterschiedliche mechanische Eigenschaften für keramische und kompositbasierte CAD/CAM-Restaurationsmaterialien beschrieben, weshalb hierfür verschiedene Indikationsbereiche in Betracht zu ziehen sind.[35,164,168]

Darüber hinaus ist die *Passgenauigkeit* der Kronenversorgungen ein weiterer wichtiger Parameter. Während ein zu großer marginaler Zementspalt zum Auswaschen des Befestigungsmaterials führt und so eine Randundichtigkeit entsteht, begünstigt ein zu großer Zementspalt im okklusalen Bereich – insbesondere bei Keramiken – das Auftreten von Ermüdungsschäden.[12,69,82,94,103,115,123]

Somit wird deutlich, dass die drei wesentlichen Kenngrößen zur Beurteilung von Kronenversorgungen – *Randdichtigkeit*, *Ermüdungsbeständigkeit* und *Passgenauigkeit* – unmittelbar miteinander im Zusammenhang stehen.

Bei allem technologischen Fortschritt sollte es stets das Ziel sein, Erkenntnisse aus der Forschung nicht nur in die tägliche Patientenbehandlung, sondern auch in die *zahnärztliche Ausbildung* zu implementieren. So können IOS als computer-aided simulation (CAS)-Lehrmittel eingesetzt werden, um Studierende bereits beim Erlernen von Präparationstechniken mittels digitaler Softwareapplikation zu unterstützen, sowie die Anforderungen an unterschiedliche CAD/CAM-Restaurationsmaterialien zu visualisieren.

## 1.2 Zielsetzung

Das Ziel der vorliegenden Arbeit war es, monolithische CAD/CAM-Kronenversorgungen aktueller Materialien systematisch in Bezug auf ihre wesentlichen Kenngrößen – *Randdichtigkeit, Ermüdungsbeständigkeit* und *Passgenauigkeit* – zu untersuchen.

Hierzu wurden folgende Themen behandelt:

1) Zur Untersuchung der *Randdichtigkeit* wurden monolithische CAD/CAM-Kronen unterschiedlicher Schichtstärke auf CAD/CAM-gefrästen humanen Molaren adhäsiv befestigt und einer künstlichen Alterung im Kausimulator unterzogen. Dabei wurden verschiedene Aushärtungsmethoden sowie herstellereigene und herstellerfremde Befestigungsmaterialien untersucht.

2) Die *Ermüdungsbeständigkeit* adhäsiv befestigter monolithischer CAD/CAM-Kronen wurde durch zyklische Belastung im Kausimulator analysiert. Dabei wurde neben der herkömmlichen lichtmikroskopischen Analyse von Schnittbildern auch eine neue, zerstörungsfreie Methode mittels optischer Kohärenztomographie (OCT) angewendet, welche erstmals ein Monitoring von Ermüdungsbeschädigungen erlaubte.

3) Die Untersuchung der *Passgenauigkeit* monolithischer CAD/CAM-Kronen erfolgte zunächst mit verschiedenen Zementspaltparametern am Modell und anschließend in einer klinischen Studie. Dabei wurde neben herkömmlichen Untersuchungsmethoden auch eine neue IOS-basierte Messmethode zur Bestimmung der Passgenauigkeit am Patienten (Chairside) analysiert.

Darüber hinaus war es das Ziel, die hier gewonnenen Erkenntnisse nicht nur zur Verbesserung der Patientenbehandlung in Hinblick auf Kronenversorgungen zu nutzen, sondern auch einen Know-how-Transfer von der Wissenschaft in die *zahnärztliche Ausbildung* zu erreichen und diesen durch Studierende zu evaluieren.

## 1.3 Verzeichnis eigener Publikationen zur kumulativen Habilitation

Alle Originalpublikationen zur vorliegenden kumulativen Habilitationsschrift wurden in englischsprachigen, international anerkannten peer-review Journalen mit Impact-Faktor veröffentlicht. Die insgesamt acht Publikationen sind im Folgenden den behandelten Themenkomplexen zugeordnet.

Randdichtigkeit

Publikation 1: **Schlenz MA**, Schmidt A, Rehmann P, Niem T, Wöstmann B. Microleakage of composite crowns luted on CAD/CAM-milled human molars: A new method for standardized in vitro tests. Clinical Oral Investigation. 2019;23(2):511-517.

Publikation 2: **Schlenz MA**, Skroch M, Schmidt A, Rehmann P, Wöstmann B. Influence of different luting systems on microleakage of CAD/CAM composite crowns: A pilot study. International Journal of Prosthodontics. 2019;32(6):530-532.

Publikation 3: **Schlenz MA**, Fiege C, Schmidt A, Wöstmann B. Microleakage of thin-walled monolithic zirconia and polymer-containing CAD/CAM crowns [published online ahead of print, 2020 Mar 6]. Journal of Prosthetic Dentistry.2020;S0022-3913(20)30071-8.

Ermüdungsbeständigkeit

Publikation 4: **Schlenz MA**, Schmidt A, Rehmann P, Wöstmann B. Fatigue damage of monolithic posterior computer aided designed/computer aided manufactured crowns. Journal of Prosthodontic Research. 2019;63(3):368-373.

Publikation 5: **Schlenz MA**, Skroch M, Schmidt A, Rehmann P, Wöstmann B, Monitoring fatigue damage in different CAD/CAM materials: A new approach with optical coherence tomography [published online ahead of print, 2020 Sep 9]. Journal of Prosthodontic Research.

## Passgenauigkeit

Publikation 6: **Schlenz MA**, Vogler J, Schmidt A, Rehmann P, Wöstmann B, Chairside measurement of the marginal and internal fit of crowns: A new intraoral-scan-based digital approach. Clinical Oral Investigations. 2020;24(7):2459-2468.

Publikation 7: **Schlenz MA**, Vogler J, Schmidt A, Rehmann P, Wöstmann B, New Intraoral Scanner-Based Chairside Measurement Method to Investigate the Internal Fit of Crowns: A Clinical Trial. International Journal of Environmental Research and Public Health. 2020;17(7):2182.

## Zahnärztliche Ausbildung

Publikation 8: **Schlenz MA**, Michel K, Wegner K, Schmidt A, Rehmann P, Wöstmann B, Undergraduate dental students' perspective on the implementation of digital dentistry in the preclinical curriculum: A questionnaire survey. BMC Oral Health. 2020;20(1):78.

Die Originalpublikationen sind im Anhang (Kapitel 7) der Habilitationsschrift beigefügt.

# 2 Wesentliche Kenngrößen von monolithischen CAD/CAM-Kronenversorgungen – Hintergrund, Ergebnisse und Diskussion

In dem folgenden Kapitel wird zunächst eine Übersicht über die untersuchten CAD/CAM-Restaurationsmaterialien gegeben. Anschließend wird der Hintergrund zu den wesentlichen Kenngrößen – *Randdichtigkeit*, *Ermüdungsbeständigkeit* und *Passgenauigkeit* – monolithischer CAD/CAM-Kronenversorgungen erläutert und mit den Ergebnissen diskutiert.

## 2.1 CAD/CAM-Restaurationsmaterialien

In den letzten Jahren wurde das Angebot an CAD/CAM-Restaurationsmaterialien, die zur Überkronung eines natürlichen Zahnes zur Verfügung stehen, deutlich erweitert.[131,146] Dabei lag der Fokus insbesondere auf den monolithischen, zahnfarbenen Materialien, dennoch finden Metalle aufgrund ihrer guten mechanischen Eigenschaften immer noch Anwendung bei der Kronenversorgung.[137]

Neben den Weiterentwicklungen von keramischen Restaurationswerkstoffen, wie der dritten und vierten Generationen von Zirkoniumdioxid oder zirkoniumdioxidverstärkter Lithiumsilikatkeramik, ist mit den Komposit-Keramik-Verbundmaterialien eine neue Werkstoffgruppe entstanden.[88,146] Somit können heute *Metalle*, *Keramiken* und *Komposite* zur monolithischen CAD/CAM-Kronenversorgung eines natürlichen Zahnes verwendet werden.[125] Daneben werden auch provisorische polymerbasierte CAD/CAM-Materialien angeboten, welche jedoch nicht Gegenstand der Betrachtung sind.

Im Bereich der *Metalle* kommen überwiegend Nichtedelmetalllegierungen (z.B. Kobalt-Chrom-Legierungen) zur Anwendung. Zwar ist technisch auch die Herstellung von Edelmetalllegierungen möglich, allerdings ist der Materialverlust durch die subtraktive Fertigung sehr hoch, welches eine wirtschaftliche Anwendung nicht erlaubt.[137] Durch die reduzierte Ästhetik werden Metallkronen häufig nur als Gerüstwerkstoff mit keramischer

Verblendung verwendet und werden monolithisch nur im nicht sichtbaren Seitenzahnbereich eingesetzt.[137,173] Im Vergleich zu den spröden keramischen Werkstoffen, zeigen Metalle jedoch eine hohe Verwindungsstabilität und Widerstandsfähigkeit, sowie plastische Verformung unter Belastung, welches ihre Anwendung auch bei Patienten mit höheren Kaubelastungen erlaubt.[97,137]

Dentale *Keramiken* werden in Glas- und Oxidkeramiken unterteilt.[125] Mit Glaskeramiken lassen sich aufgrund der hohen Transluzenz hochästhetische Restaurationen herstellen, womit eine monolithische Versorgungen möglich ist,[42,110] allerdings sind sie spröde und weisen im Vergleich zu Oxidkeramiken eine geringere Bruchfestigkeit – Spannung der eine Restauration widersteht ohne zu brechen – auf.[171] Sie benötigen daher eine Mindestschichtstärke von 1,5 mm, wodurch eine minimalinvasive Anwendung von Kronenversorgungen nicht möglich ist.[157] Hingegen können monolithische Oxidkeramiken, wie Yttrium-stabilisiertes Zirkoniumdioxid, aufgrund ihrer höheren Bruchfestigkeit auch mit reduzierter Schichtstärke verwendet werden.[102,110,119,134,145,166] Allerdings sind die ersten beiden Generationen *3 mol% yttria stabilized tetragonal zirconia polycrystal* (3Y-TZP) Zirkoniumdioxide durch eine hohe Opazität charakterisiert und weisen somit im Vergleich zu Glaskeramiken eine geringere Transluzenz auf.[167] Dies wurde jedoch durch Veränderungen in der Zusammensetzung bei den lichtdurchlässigeren neueren dritten und vierten Generationen Zirkoniumdioxid (*5 mol% yttria stabilized tetragonal zirconia polycrystal* (5Y-TZP) bzw. *4 mol% yttria stabilized tetragonal zirconia polycrystal* (4Y-TZP)) optimiert. Allerdings ist bei der dritten und vierten Generation die Biegefestigkeit – Kraft die eine Restauration aufnehmen kann bevor ein Riss oder eine Fraktur entsteht – im Vergleich zum 3Y-TZP nur noch halb so hoch, welches bei der Indikationsstellung berücksichtig werden sollte.[149,166]

Während *Komposite* früher entweder zur direkten Modellation in der Füllungstherapie verwendet oder zur indirekten Verblendung von Restaurationen im zahntechnischen Labor gepresst wurden, ermöglicht die CAD/CAM-Technologie heute die industrielle Herstellung von hochgefüllten Komposit-Keramik-Verbundmaterialien, welche im Vergleich zu den bisherigen Kompositen verbesserte mechanische Eigenschaften aufweisen. Dabei muss zwischen den *CAD/CAM-Kompositen*, welche aus einer Kompositmatrix mit keramischen Füllpartikeln bestehen und der *Hybridkeramik* mit kompositinfiltrierter Feldspatkeramikmatrix unterschieden werden.[6] Im Gegensatz zu keramischen Werkstoffen, weisen kompositbasierte CAD/CAM-Materialien zwar eine geringe Biegefestigkeit, aber auch eine höhere Elastizität auf, womit sie dentinähnliche physikalische Eigenschaften zeigen.[34,165] Durch den Kompositanteil verlieren Komposit-Keramik-Verbundmaterialien zudem an Sprödigkeit, wodurch im Vergleich zu Glaskeramiken eine höhere Bruchfestigkeit erzielt werden kann.[6,22,134] Auch Zugbelastungen, wie sie bei Patienten mit Parafunktionen (z.B. Bruxismus) auftreten, können kompositbasierte CAD/CAM-Materialien im Vergleich zu keramischen Werkstoffen besser widerstehen.[22,34,165] Außerdem zeigten CAD/CAM-Komposite verglichen mit Glaskeramiken beim Fräsen eine höhere Kantenstabilität, was die Herstellung von Kronenversorgungen mit reduzierter Schichtstärke ermöglicht.[6]

Nach Angaben der meisten Hersteller sind Komposit-Keramik-Verbundmaterialien für eine permanente Versorgung von Einzelzahnrestaurationen wie Inlays, Onlays, Veneers, Teilkronen und Kronen indiziert.[56] Allerdings wird insbesondere die Indikation zur Kronenversorgung diskutiert, da klinische Langzeitdaten fehlen und die mechanischen Eigenschaften gegenüber herkömmlichen Restaurationsmaterialien geringer sind.[68]

## 2.2 Randdichtigkeit

Hintergrund

Die Analyse der Randdichtigkeit von zahnärztlichen Versorgungen ist keine neue Untersuchungsmethode, sondern wurde bereits Anfang des 20. Jahrhunderts an Amalgamfüllungen durchgeführt.[72] Da es bisher jedoch kein standardisiertes Verfahren gibt, sind die Versuchsaufbauten und Analysemethoden teilweise sehr heterogen. Dies erschwert häufig einen direkten Vergleich zwischen unterschiedlichen Studien. In den letzten Jahren hat sich zur Untersuchung der Randdichtigkeit der Farbstoffpenetrationstest mit verschiedenen Lösungen etabliert.[3,11,140,152] Durch das Eindringen der Farbstofflösung über den marginalen Randspalt wird die Randundichtigkeit dargestellt, welche in situ zu einer bakteriellen Besiedlung mit Sekundärkaries bzw. Entzündung der Pulpa bis hin zum Zahnverlust führen könnte.[72]

Da die Untersuchung der Randdichtigkeit jedoch nur am extrahierten Zahn erfolgen kann, wird die klinische Mundsituation im Rahmen eines Laboraufbaus simuliert. Zwar wäre es auch technisch möglich, eine Krone auf dem natürlichen Zahn im Patientenmund zu inserieren und später den Zahn mit Krone zur Analyse zu extrahieren, allerdings ist dieses Vorgehen aus ethischen Gründen nicht vertretbar. Trotzdem sollte idealerweise der Versuchsaufbau möglichst der klinischen Situation im Munde des Patienten entsprechen und gleichzeitig zur besseren Vergleichbarkeit der Ergebnisse ein hohes Maß an Standardisierung beinhalten.

In bisherigen Untersuchungen wurden entweder künstliche Zahnstümpfe aus Komposit, Keramik oder Metall bzw. manuell präparierten bovinen oder humane Zähne verwendet.[118,126,128,140,165] Obwohl künstliche Zahnstümpfe hoch standardisierte und reproduzierbare Ergebnisse ermöglichen, stellen sie nicht die klinische Situation in Bezug auf den Haftverbund dar. Im Gegenteil, es besteht Konsens darüber, dass zur Untersuchung von Befestigungsmaterialien natürliche Zähne benötigt werden.[57] Allerdings ist eine manuelle Herstellung von identischen humanen Zahnstümpfen nicht möglich, selbst wenn nur ein Behandler alle Zähne präpariert. Auch unter Zuhilfenahme eines Parallelometers kann lediglich der Konvergenzwinkel einheitlich gestaltet werden.[63,64] Folglich reduzieren manuelle Präparationen und unterschiedliche Zahngrößen zwangsläufig die Reproduzierbarkeit der Versuche und erschweren damit eine objektive Analyse. Daher hat die Verfasserin bereits im Rahmen ihrer Dissertation ein Verfahren entwickelt, welches mit Hilfe der CAD/CAM-Technologie die Präparation humaner Zähne zu identischen Zahnstümpfen erlaubt und zur Durchführung der im Folgenden aufgeführten Untersuchungen Anwendung fand.[133] Mit Hilfe der CAD/CAM-Technologie kann der gesamte Prüfkörper – auch der Bereich unterhalb der Präparationsgrenze – gestaltet und reproduzierbar gefräst werden. Somit weist jeder Prüfkörper eine exakt gleichgroße Klebefläche auf und weder die Präparation, noch die individuelle Zahngröße beeinflussen die Ergebnisse. Für die Standardisierung nachteilig ist jedoch, dass natürliche Substrate sich in ihrer Zusammensetzung und Struktur stets unterscheiden.[92] Allerdings wird auch so die reale klinische Situation abgebildet.

### Eigene Arbeiten

Da im Zusammenhang mit CAD/CAM-Kompositkronen ein erhöhtes Debonding beschrieben wurde,[76] ergab sich zunächst die Fragestellung, wie CAD/CAM-Kompositkronen auf natürlichen Zahnstümpfen optimal befestigt werden müssen, so dass durch den Erhalt der marginalen Randdichtigkeit ein Haftverlust vermieden werden kann. *Lührs et al.* beschrieben für CAD/CAM-Komposite einen signifikant höheren Polymerisationsgrad des Befestigungsmaterials bei Anwendung von Lichthärtung, im Vergleich zur alleinigen Dunkelhärtung. Folglich wurde in der Publikation 1 (Kapitel 7.4) die Randdichtigkeit von vier unterschiedlichen CAD/CAM-Kompositkronen – Lava Ultimate (3M Espe, Seefeld, Deutschland), Brilliant Crios (Coltene, Altstätten, Schweiz), Cerasmart (GC, Tokyo, Japan) und Experimentalblock – mit dem vom Hersteller empfohlenen Befestigungssystem jeweils im Aushärtungsmodus Licht- und Dunkelhärtung untersucht. Zunächst wurde dabei die herstellerbedingte Mindestschichtstärke (okklusal 1,5 mm/ zervikal 1,0 mm) bei der Fertigung der CAD/CAM-Kronen berücksichtigt. Zur Simulation der Kaubelastung wurden die Prüfkörper einer künstlichen Alterung von 1 Mio. Zyklen unterzogen. Dies entspricht einer klinischen Belastungsdauer von circa vier Jahren.[132]

Unter der Kausimulation trat kein vollständiges Debonding auf, allerdings zeigte der Farbstoffpenetrationstest bei allen getesteten CAD/CAM-Kompositkronen mit Ausnahme des Restaurationsmaterials Lava Ultimate, an mindestens einer Stelle einen partiellen Haftverlust. Die statistische Analyse wies eine signifikant höhere Randdichtigkeit für alle lichtgehärteten Prüfgruppen im Vergleich zu denjenigen mit alleiniger Dunkelhärtung auf (Abbildung 1, p< 0,05). Darüber hinaus zeigten die dunkelgehärteten Prüfgruppen teilweise eine hohe Streuung in den Werten.

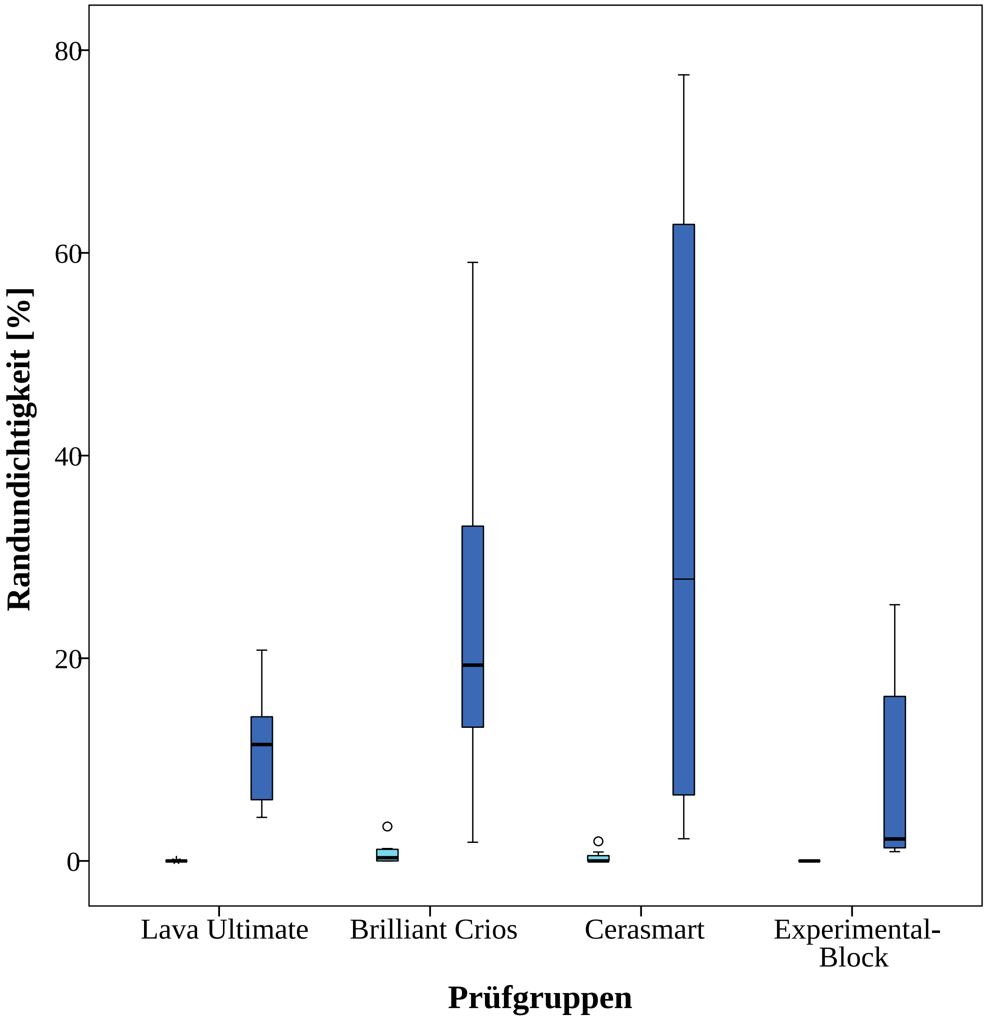

**Abbildung 1** Boxplot-Diagramm der Randundichtigkeit [%] in Bezug auf die Licht (hellblau)- und Dunkelhärtung (dunkelblau) des Befestigungsmaterials.

Die Ergebnisse der Studie zeigten deutlich, dass der Aushärtungsmodus des Befestigungsmaterials einen signifikanten Einfluss auf die Randdichtigkeit verschiedener CAD/CAM-Kompositmaterialien hat. Daraus ergab sich die Fragestellung, ob nicht nur der Aushärtungsmodus, sondern auch das herstellereigene bzw. -fremde Befestigungsmaterial die marginale Randdichtigkeit von CAD/CAM-Kompositkronen beeinflusst. Diese Untersuchung ist im Hinblick auf die klinische Anwendung von CAD/CAM-Kompositen essentiell. Seitens der Hersteller werden zwar durchgängige Produktlinien – bestehend aus Adhäsiv, Befestigungskomposit und Restaurationsmaterial – entworfen und angeboten, in der täglichen Praxis ziehen es jedoch viele Anwender aus Kostengründen vor, nur ein Befestigungssystem für alle Restaurationen verschiedener Hersteller und Materialien anstelle des entsprechenden Befestigungssystems für jedes einzelne Restaurationsmaterial zu verwenden.

Zur besseren Vergleichbarkeit der Ergebnisse mit der vorherigen Studie wurde in der Publikation 2 (Kapitel 7.5) derselbe Versuchsaufbau gewählt. Dabei wurden CAD/CAM-Kronen von zwei verschiedenen Herstellern – Lava Ultimate und LuxaCam Composite (DMG, Hamburg, Deutschland) – mit dem jeweils herstellereigenen und einem -fremden Befestigungsmaterial in den Aushärtungsmodi Licht- und Dunkelhärtung analysiert.

Auch bei dieser Untersuchung trat kein vollständiger Haftverlust auf. Unabhängig vom herstellereigenen oder -fremden Befestigungsmaterial wiesen jedoch die lichtgehärteten Prüfkörper eine signifikant höhere Randdichtigkeit im Vergleich zur Dunkelhärtung auf (Abbildung 2, $p < 0{,}05$).

Alle Prüfkörper im Aushärtungsmodus Dunkelhärtung zeigten eine Reduktion der Randundichtigkeit (für LuxaCam Composite sogar signifikant, $p < 0{,}05$), sofern das herstellereigene Befestigungssystem verwendet wurde. Somit sollte insbesondere bei der Befestigung von CAD/CAM-Kronen im Aushärtungsmodus Dunkelhärtung das herstellereigene Befestigungsmaterial verwendet werden, andernfalls ist eine Lichthärtung zum Erreichen einer hohen Randdichtigkeit zu empfehlen.

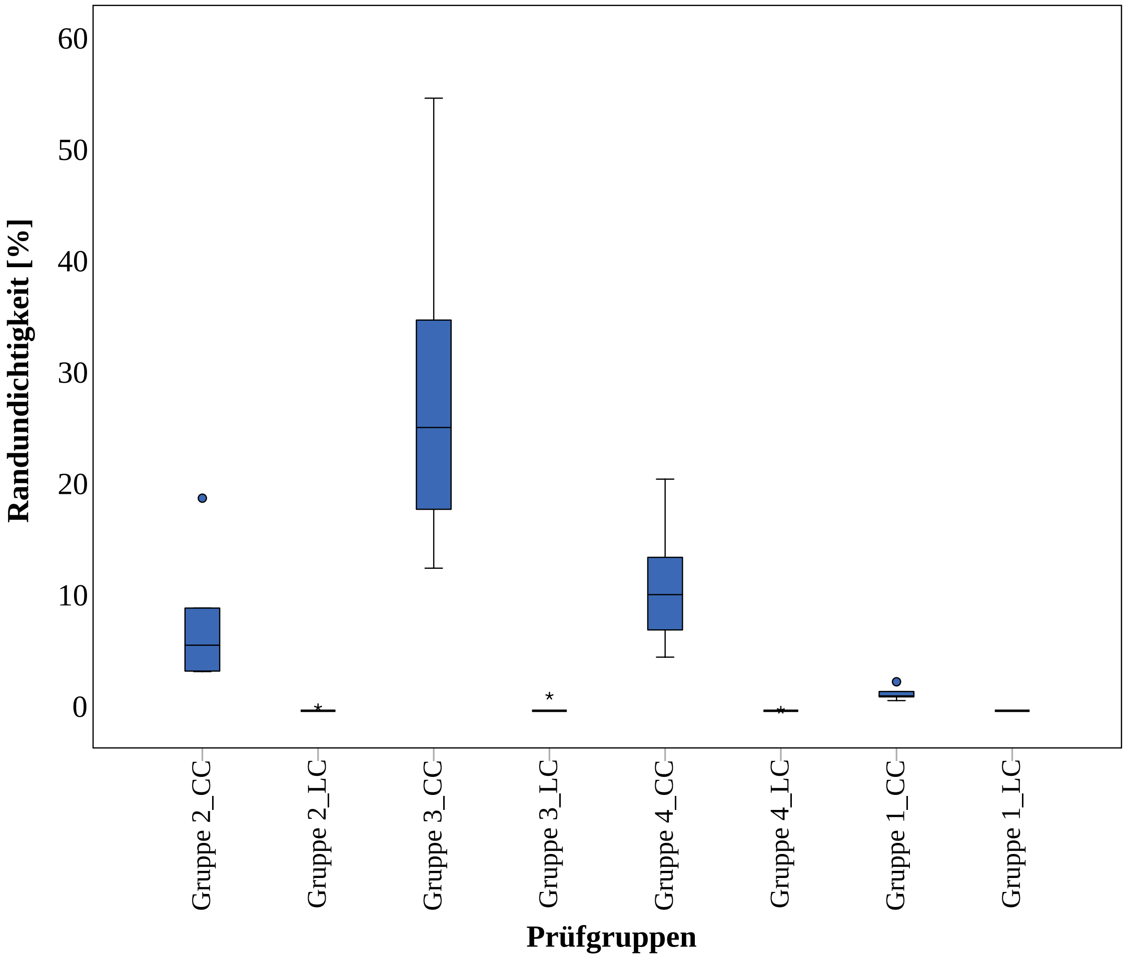

**Abbildung 2** Boxplot-Diagramm der Randundichtigkeit [%] in Bezug auf den Aushärtungsmodus (LC = Lichthärtung, CC = Dunkelhärtung) für verschiedene Kombinationen aus Restaurations- und Befestigungsmaterial: Gruppe 1 = LuxaCam Composite mit herstellereigenem Befestigungsmaterial, Gruppe 2 = LuxaCam Composite mit herstellerfremden Befestigungsmaterial, Gruppe 3 = Lava Ultimate mit herstellerfremden Befestigungsmaterial, Gruppe 4 = Lava Ultimate mit herstellereigenem Befestigungsmaterial.

Vor diesem Hintergrund entwickelte sich die Fragestellung, inwiefern die Randdichtigkeit von CAD/CAM-Kompositkronen auch bei Kronen mit reduzierter Schichtstärke gegeben ist. Daher wurden für die Publikation 3 (Kapitel 7.6) im Gegensatz zu den beiden vorherigen Studien die CAD/CAM-Kronen mit einer reduzierten Schichtstärke (okklusal 1,2 mm / zervikal 0,6 mm) untersucht. Neben einem CAD/CAM-Komposit wurden auch eine Hybridkeramik und zwei verschiedenen Generationen Zirkoniumdioxid analysiert. Die Kronen wurden mit dem vom Hersteller empfohlenen Befestigungssystem auf CAD/CAM-gefrästen Zahnstümpfen adhäsiv im Aushärtungsmodus Lichthärtung befestigt und anschließend einer Kausimulation unterzogen. Um zusätzlich einen möglichen

Einfluss des Kausimulationsprogramms auf die Randdichtigkeit zu analysieren, wurde die eine Hälfte der Prüfkörper allein horizontal (90 N) und die andere Hälfte horizontal-vertikal (100 N) für 1,2 Mio. Zyklen belastet.

Zwischen den beiden Kausimulationsprogrammen konnte kein signifikanter Unterschied festgestellt werden, weshalb im Folgenden die Daten zusammengefasst betrachtet wurden. Es wurde kein vollständiges Debonding der Kronen festgestellt, allerdings trat bei allen Prüfgruppen eine Randundichtigkeit auf. Mit einem Mittelwert (Standardabweichung) von 12,9 (16,4) % wies die Hybridkeramik die höchste Randundichtigkeit auf, gefolgt von dem 6Y-TZP Zirkoniumdioxid (4,8 (7,6) %), 3Y-TZP Zirkoniumdioxid (3,6 (7,5) %) und dem CAD/CAM-Komposit (2,9 (4,8) %). Allerdings zeigten die Hybridkeramik und die 3Y-TZP Zirkoniumdioxidkeramik einen signifikanten Unterschied (p< 0,05), während zwischen den Zirkoniumdioxidgruppen bzw. den kompositbasierten Materialien untereinander kein signifikanter Unterschied nachgewiesen werden konnte (Abbildung 3).

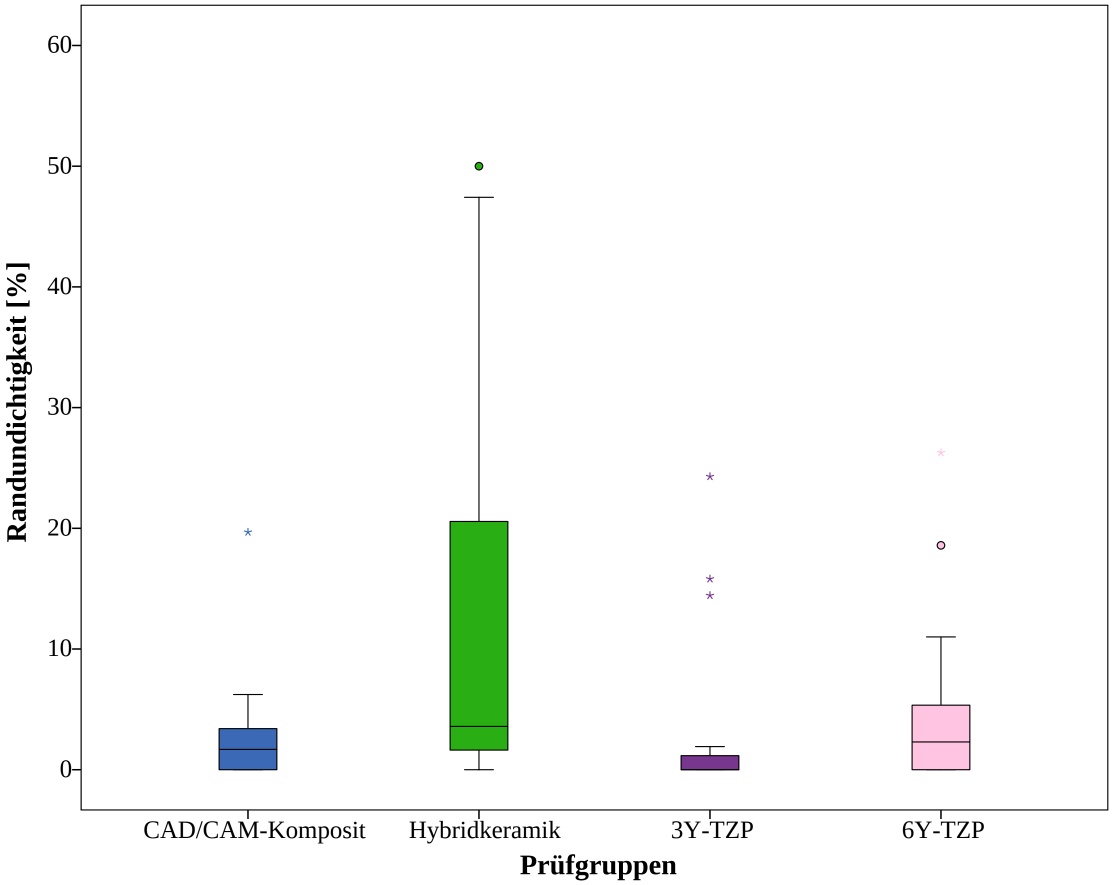

**Abbildung 3** Boxplot-Diagramm der Randundichtigkeit [%] unterschiedlicher CAD/CAM-Restaurationsmaterialien (beide Kausimulationsprogramme zusammengefasst).

Die Ergebnisse der Untersuchung zeigen, dass Zirkoniumdioxide, insbesondere 3Y-TZP, eine geringere Randundichtigkeit für Kronen mit reduzierter Schichtstärke als die Hybridkeramik aufweisen. Allerdings konnte auch für das CAD/CAM-Komposit eine hohe Randdichtigkeit gezeigt werden, welches sich damit ebenso, wie die beiden untersuchten Zirkoniumdioxide, im Hinblick auf die marginale Randdichtigkeit für Kronenversorgungen mit reduzierter Schichtstärke eignet.

## Diskussion

Für CAD/CAM-Komposite wird die adhäsive Befestigung mit dualhärtenden Befestigungssystemen empfohlen, allerdings erlauben die meisten Produkte eine Licht- und Dunkelhärtung.[108,148] Dies soll die Aushärtung des Befestigungsmaterials auch in schwer lichtzugänglichen Bereichen sicherstellen.[36] In der täglichen Praxis ist jedoch die zeitsparende Anwendung einer alleinigen Dunkelhärtung verbreitet. *De Souza et al.* zeigten, dass bei alleiniger Dunkelhärtung ein geringerer Polymerisationsgrad des Befestigungskomposits erreicht wird, welcher zu geringeren mechanischen Eigenschaften, erhöhter Löslichkeit und Randundichtigkeit führen kann.[32] Dies ist in guter Übereinstimmung mit den Ergebnissen der vorliegenden Publikationen 1 und 2 (Kapitel 7.4 und 7.5) in denen ebenfalls gezeigt werden konnte, dass die alleinige Dunkelhärtung von CAD/CAM-Kompositkronen zu einer erhöhten Randundichtigkeit im Vergleich zur Lichthärtung führt.

Eine Beeinträchtigung des chemischen Aushärtungsprozesses des Befestigungskomposits durch das saure Milieu von Universaladhäsiven wird in der Literatur diskutiert.[5,89] Die in den Untersuchungen verwendeten Universaladhäsive weisen einen pH-Wert von 1,5 bis 2,8 auf. Daher könnte die hohe Randundichtigkeit der CAD/CAM-Kompositkronen Cerasmart im Aushärtungsmodus Dunkelhärtung auf das saure Universaladhäsiv zurückzuführen sein. Deshalb enthalten einige Befestigungskomposite, wie z.B. RelyX Ultimate (3M Espe), ein neues Initiatorsystem auf Natriumsulfatbasis, welches den Aushärtungsprozess auch im sauren Milieu einleiten kann.[32] Allerdings wurde auch bei RelyX Ultimate ein geringer Polymerisationsgrad für die alleinige Dunkelhärtung im Vergleich zur Lichthärtung gezeigt, was auf eine unzureichend aktivierte Polymerisation hindeutet.[89] Die alleinige Dunkelhärtung mit einem dualhärtenden Befestigungskomposit kann zu einem geringeren Polymerisationsgrad bei reduzierter mechanischer Stabilität und erhöhter Löslichkeit führen.[5,148] Darüber hinaus kann der Polymerisationsgrad dualhärtender Befestigungskomposite vom jeweiligen Produkt und ihren individuellen Anforderungen an die Lichtaktivierung zur vollständigen Polymerisation abhängen.[32] Dies könnte die unterschiedliche Streuung der Daten für die dunkelgehärteten Prüfgruppen erklären.

Dabei deuten die Ergebnisse der Untersuchungen zur Randdichtigkeit herstellereigener und -fremder Befestigungssysteme von CAD/CAM-Kompositmaterialien darauf hin, dass die Hersteller ihre Systeme im Hinblick auf die Befestigung optimiert haben. Dies zeigt sich allerdings nur bei der Dunkelhärtung, bei welcher insbesondere bei der Verwendung herstellerfremder Befestigungssysteme eine erhöhte Randundichtigkeit gezeigt wurde, welche sich durch einen geringeren Polymerisationsgrad erklären lässt.[32,89] Zusammenfassend lässt sich feststellen, dass zur Vermeidung eines Haftverlustes von CAD/CAM-Kompositkronen auf natürlichen Zähnen die Lichthärtung des Befestigungssystems erforderlich ist und – sofern eine Dunkelhärtung angewendet wird – das herstellereigene zum Restaurationsmaterial korrespondierende Befestigungssystem dem herstellerfremden vorgezogen werden sollte.

Neben dem Befestigungssystem hat auch das CAD/CAM-Restaurationsmaterial selbst einen Einfluss auf die Randdichtigkeit. Im Vergleich zu keramischen Materialien weisen CAD/CAM-Komposite ein niedrigeres Elastizitätsmodul auf, so dass in der Literatur diskutiert wird, ob elastische Verformungen insbesondere im Randbereich zu einem Haftverlust der Restauration führen könnten.[6,33] Unter Berücksichtigung der Ergebnisse der vorliegenden Publikationen 1-3 (Kapitel 7.4-7.6) kann geschlussfolgert werden, dass CAD/CAM-Komposite eine hohe Haftfestigkeit benötigen, um Kaubelastungen standzuhalten. Dies kann durch eine getrennte Lichthärtung von Adhäsiv und Befestigungskomposit erreicht werden.

Die Lichtdurchlässigkeit eines Werkstoffs wird von der Zahnfarbe, der Restaurationsdicke und der inneren Struktur bestimmt.[32,36,148,155] Deshalb wurden alle CAD/CAM-Materialien in derselben Zahnfarbe untersucht. Während in den ersten beiden Studien die Kronen mit dem vom Hersteller empfohlenen Mindestschichtstärken von 1,5 mm okklusal und 1,0 mm zervikal untersucht wurden, erfolgte die Untersuchung der Randdichtigkeit nach Belastung an Kronen mit einer reduzierten Schichtstärke von 1,2 mm okklusal und 0,6 mm zervikal.

Im Gegensatz zu einer Studie von *Zimmermann et al.* überlebten in der vorliegenden Publikation 3 (Kapitel 7.6) auch Kronen mit reduzierter Schichtstärke aus Hybridkeramik die Kausimulation, allerdings wurde trotz Lichthärtung eine hohe Randundichtigkeit gezeigt.[171] Dies könnte in Zusammenhang mit der Lichtdurchlässigkeit des Restaurationswerkstoffs stehen. Aufgrund des höheren Füllstoffgehalts besitzt die Hybridkeramik zwar ein höheres Elastizitätsmodul und eine höhere Biegefestigkeit als CAD/CAM-Komposite,[131] allerdings ist dadurch die Durchtrittsmenge des Lichtes reduziert.[148] Eine unvollständige Polymerisation des Befestigungssystems könnte somit die höhere Randundichtigkeit erklären.

Für dünnwandige Restaurationen aus Zirkoniumdioxid wird eine gute Überlebensrate berichtet.[110,157] Auch in Bezug auf die Bruchfestigkeit wurde kein Unterschied zwischen 3Y-TZP und 6Y-TZP Zirkoniumdioxid beschrieben,[110] allerdings weist 6Y-TZP aufgrund seiner enthaltenen kubischen Phase eine geringere Biegefestigkeit als 3Y-TZP auf.[149,166] Dies könnte die erhöhte Randundichtigkeit von 6Y-TZP in der Publikation 3 (Kapitel 7.6) erklären.

In der Literatur wird immer wieder diskutiert, inwiefern Ergebnisse aus Laborversuchen auf die klinische intraorale Patientensituation übertragbar sind.[114,140] Da es aus ethischen Gründen nicht vertretbar ist, die oben beschriebenen Untersuchungen an Patienten durchzuführen, legen *Pashley und Shetty et al.* nahe, das zu vermuten sei, dass Produkte, die gute Laborergebnisse zeigen, in-vivo zumindest ähnliche Ergebnisse zeigen werden.[114,140] Auch wenn heute durch moderne mechanische und thermische Kausimulationen versucht wird, die klinische Mundsituation zu imitieren, sollte bei der Interpretation von Laborergebnissen immer berücksichtigt werden, dass für eine abschließende Beurteilung von Restaurationsmaterialien stets eine klinische Langzeitbeobachtung notwendig ist. Allerdings tragen Laborversuche, wie sie in den vorliegenden Publikationen 1-3 (Kapitel 7.4-7.6) durchgeführt wurden, dazu bei, Erkenntnisse für eine korrekte klinische Anwendung zu erlangen.

Die vorliegenden Ergebnisse zeigten damit, dass für CAD/CAM-Kompositkronen die Lichthärtung des Befestigungssystems zu einer höheren Randundichtigkeit im Vergleich zur alleinigen Dunkelhärtung führt. Sofern herstellerfremde Befestigungssysteme gewählt werden, sollte jedoch immer eine Lichthärtung erfolgen. Darüber hinaus konnte gezeigt werden, dass im Gegensatz zur Hybridkeramik, bei CAD/CAM-Kompositen und

3Y-TZP und 6Y-TZP Zirkoniumdioxiden die Randdichtigkeit auch bei Kronen reduzierter Schichtstärke gegeben ist. Dies ermöglicht die Herstellung von minimalinvasiven Restaurationen mit substanzschonenden Präparationen am natürlichen Zahn.

## 2.3 Ermüdungsbeständigkeit

Hintergrund

Im Hinblick auf die Ermüdungsbeständigkeit wurden für keramische und kompositbasierte CAD/CAM-Restaurationsmaterialien unterschiedliche mechanische Eigenschaften beschrieben.[35,164,168] So wurden die Bruch- und Versagensmechanismen von Keramiken vielfältig untersucht. Die meisten Studien analysierten CAD/CAM-Restaurationsmaterialien jedoch durch eine einmalige statische Belastung.[21,79,98,150,168,170] Die Kaubelastung besteht aber aus einer immer wiederkehrenden, dynamischen Belastung mit unterschiedlichen Kaukräften, daher müssen Restaurationen vor allem einer mechanischen Ermüdung über die Zeit standhalten.[50]

Untersuchungen zur Ermüdungsbeständigkeit zeigten, dass bei Keramiken Mikrorisse in Form von Kegelrissen (cone cracks) unterhalb der okklusalen Kontaktfläche (occlusal contact area – OCA) in einer quasi-plastischen Zone ursächlich für Frakturen sind.[21,43,78,106,147,156] Zusätzlich zur Beschädigung im Bereich der OCA zeigten Glaskeramiken an der Unterseite der Restauration durch Zugspannungen verursachte Radialrisse (radial cracks).[66,169] Hingegen wurden für Hybridkeramiken unter Belastung plastische Verformungen gezeigt, welche dem Kompositanteil zugeschrieben werden und dem Restaurationsmaterial eine verbesserte Rissbeständigkeit, Schadenstoleranz, Biegefestigkeit und Risszähigkeit verleihen sollen.[24-26] Dementsprechend scheint sich die Spannungsverteilung in Glas- und Hybridkeramiken zu unterscheiden.[21] *Leung et al.* diskutierten, dass die Kompositphase der Hybridkeramik dem CAD/CAM-Material Plastizität verleiht, wodurch das Weibull-Modul erhöht wird.[87] Darüber hinaus wurde für CAD/CAM-Komposite eine höhere Bruchzähigkeit im Vergleich zur Hybrid- und Glaskeramik beschrieben, welches mit einer Dissipation der Bruchenergie erklärt werden könnte.[107]

In der Literatur lassen sich unterschiedliche Methoden zur Erfassung von Mikrorissen in Restaurationsmaterialien finden. So wird in einigen Studien nur das Auftreten von Rissen dokumentiert,[42,64,143] während *Wendler et al.* analog der Publikation 4 (Kapitel 7.7) zur Untersuchung der Ermüdungsschäden die Bereiche ohne Risse analysierten.[161] *Shembish et al.* hingegen haben die maximale Risslänge vermessen.[139]

Herkömmliche Methoden untersuchen Ermüdungsschäden durch die Analyse von Schnittproben unter einem Lichtmikroskop oder Rasterelektronenmikroskop (REM), welches jedoch die Zerstörung der Prüfkörper erfordert.[9,64,139] So dokumentierten einige Autoren den Verlauf von Rissen mit einer Hochgeschwindigkeits-Videokamera, allerdings können mit Hilfe dieser Methode bei zahnfarbenen Werkstoffen nur Beschädigungen der Oberfläche untersucht werden, da für die Analyse innerer Beschädigungen transparente Materialien erforderlich sind.[20,83]

Eine in der Zahnmedizin neue Methode stellt die optische Kohärenztomographie (OCT) dar, bei der es sich um ein nicht-invasives Verfahren handelt, das biologische Strukturen in Mikrometerauflösung abbilden kann.[1,16,154,164] Die OCT wurde ursprünglich als diagnostisches Hilfsmittel in der Augenheilkunde entwickelt. Gegenwärtig nutzen jedoch auch andere medizinische Disziplinen wie die Dermatologie, Kardiologie und Neurologie diese Echtzeit-Bildgebungsmethode für die klinische Anwendung.[84] Darüber hinaus haben Studien gezeigt, dass die Anwendung der OCT in der Zahnmedizin zur Untersuchung von Komposit-Füllungsmaterialien,[142,154] zur Visualisierung des Polymerisationsprozesses,[47] zur Karies- und Zahnfrakturdiagnostik,[142] sowie Untersuchung des Parodontiums möglich ist.[100] Im prothetischen Bereich gibt es jedoch nur wenige Studien, welche die OCT als Methodik verwendeten.[1,144,164] Bisher wurden lediglich etwaige Beschädigungen an Glaskeramiken mittels OCT untersucht.[164] In der Literatur wurde jedoch noch keine Studie beschrieben, welche die Ermüdungsschäden im Laufe der Zeit für unterschiedliche keramisch- und kompositbasierte CAD/CAM-Materialien untersucht hat.

### Eigene Arbeiten

In der Publikation 4 (Kapitel 7.7) stellte sich daher zunächst die Frage, ob und inwiefern sich Glas-, Hybridkeramiken und CAD/CAM-Komposite in Bezug auf die Ermüdungsbeständigkeit unterscheiden. Für eine klinisch nahe und zugleich standardisierte Versuchsdurchführung wurden, wie bereits in den zuvor beschriebenen drei Studien zur Untersuchung der marginalen Randdichtigkeit (Kapitel 2.2), alle Kronen und humanen Zahnstümpfe mittels CAD/CAM-Technologie zu identischen Prüfkörpern gefräst und anschließend einer Kaubelastung unterzogen. Als Restaurationsmaterialien wurden die Glaskeramik IPS e.max CAD (Ivoclar Vivadent, Schaan, Lichtenstein), die Hybridkeramik Vita Enamic (Vita Zahnfabrik, Bad Säckingen, Deutschland) und die drei CAD/CAM-Komposite Lava Ultimate, Brilliant Crios und Cerasmart untersucht. Dabei wurde die Hälfte der Kronen mit dem vom Hersteller empfohlenen Befestigungssystem

lichtgehärtet und die andere dunkelgehärtet. Um die Ergebnisse mit den in der Literatur beschriebenen Untersuchungen vergleichen zu können, erfolgte die Auswertung der Risse anhand von Schnittbildern.
Alle Prüfkörper zeigten Ermüdungsbeschädigungen, welche drei verschiedene Risstypen zugeordnet werden konnten: Kegelrisse ausgehend von der Oberfläche der OCA, quasiplastische Verformung im Bereich der OCA und Radialrisse ausgehend von der Unterseite der Restauration. Dabei wiesen die drei CAD/CAM-Komposite im Vergleich zur Hybrid- und Glaskeramik eine signifikant größere okklusal intakte Schichtstärke auf (Abbildung 4, p< 0,05).

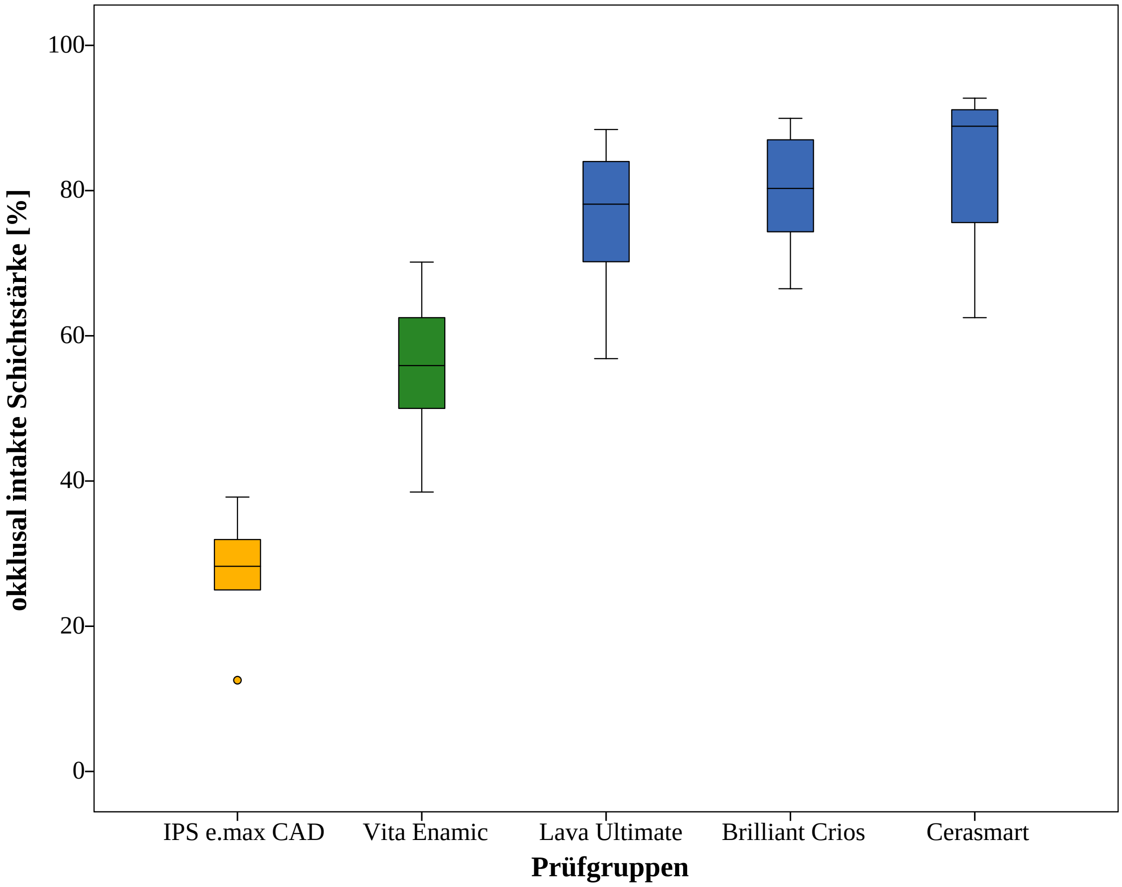

**Abbildung 4** Boxplot-Diagramm der okklusal intakten Schichtstärke [%] für unterschiedliche CAD/CAM-Restaurationsmaterialien.

Zusätzlich wurden bei der Glas- und Hybridkeramik in beiden Aushärtungsmodi Radialrisse festgestellt, hingegen konnten diese bei den CAD/CAM-Kompositen nur bei den Prüfkörpern mit alleiniger Dunkelhärtung detektiert werden.

Insgesamt konnte somit gezeigt werden, dass die Ermüdungsbeschädigungen von kompositbasierten CAD/CAM-Restaurationsmaterialien mit keramischen zwar hinsichtlich der Rissarten vergleichbar sind, jedoch die kompositbasierten Werkstoffe eine signifikant geringere Beschädigung nach Kausimulation im Vergleich zur Glaskeramik zeigten ($p < 0,05$).

Daraus entwickelte sich die Fragestellung, ob und inwiefern verschiedene Generationen Zirkoniumdioxid Ermüdungsbeschädigungen aufweisen. Darüber hinaus sollte untersucht werden, wie sich die Ermüdungsbeständigkeit zu unterschiedlichen Zeitpunkten der Belastung verhält.

Daher war es das Ziel der Publikation 5 (Kapitel 7.8), verschiedene CAD/CAM-Materialien aus Zirkoniumdioxid, Glas-, Hybridkeramik und CAD/CAM-Komposit vor (T0) und nach Kaubelastungen von 250.000 (T1), 500.000 (T2), 750.000 (T3) und 1.000.000 (T4) Zyklen mit Hilfe der OCT zu untersuchen. Zusätzlich wurden alle Prüfkörper nach Abschluss der Kausimulation und OCT-Analyse in vier äquidistante Scheiben geschnitten und die maximale horizontale und vertikale Beschädigung unter einem digitalen Lichtmikroskop (Smartzoom 5, Zeiss) vermessen, was einen Vergleich der neuen OCT-Methode mit der etablierten Lichtmikroskop-Methode erlaubte.

Die Ergebnisse der OCT-Untersuchung zeigten für alle Prüfgruppen (mit Ausnahme von 3Y-TZP und 4Y-TZP) Ermüdungsbeschädigungen. Es konnte ein signifikanter Unterschied zwischen den CAD/CAM-Materialien in Bezug auf die maximale Beschädigung in vertikaler und horizontaler Richtung gezeigt werden (Abbildung 5 und 6, $p < 0,05$).

Dabei wies die Glaskeramik die höchste Beschädigung auf, gefolgt von der Hybridkeramik, dem CAD/CAM-Komposit und dem 5Y-TZP. Während beim 5Y-TZP die Beschädigung erst nach einer Belastung von 750.000 Zyklen festgestellt wurden, zeigten alle anderen CAD/CAM-Materialien bereits nach 250.000 Zyklen erste Rissbildungen. Außerdem wurde bei allen Restaurationswerkstoffen eine Zunahme der Beschädigung mit steigendender Belastungszyklenzahl im Kausimulator festgestellt.

Aufgrund der geringen Lichtdurchdringung der OCT konnte die Beschädigung im äußeren Bereich nur mit dem Lichtmikroskop eindeutig untersucht werden. Daher zeigte sich unter dem Lichtmikroskop eine im Vergleich zum OCT größere Beschädigung. Für die Glas- und Hybridkeramik zeigte sich sogar ein signifikanter Unterschied zwischen den OCT-Bildern und dem Lichtmikroskop ($p < 0,05$).

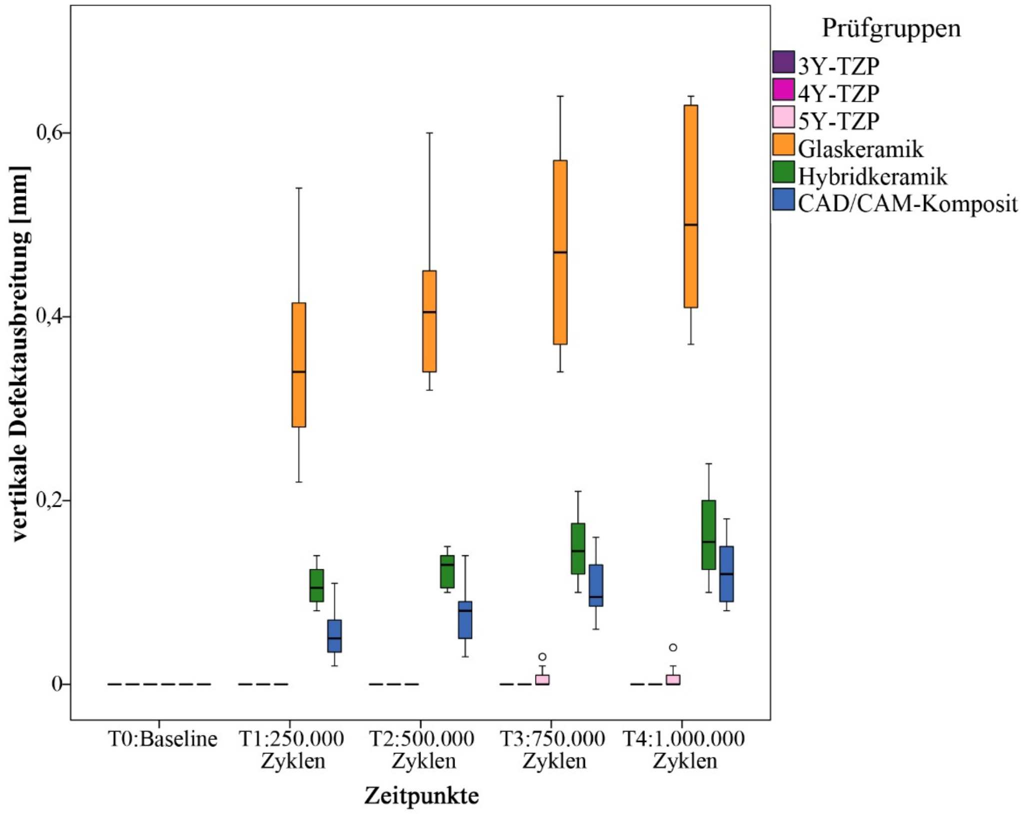

**Abbildung 5** Boxplot-Diagramm der vertikalen Defektausbreitung [mm] im OCT zu den Zeitpunkten T0-T4.

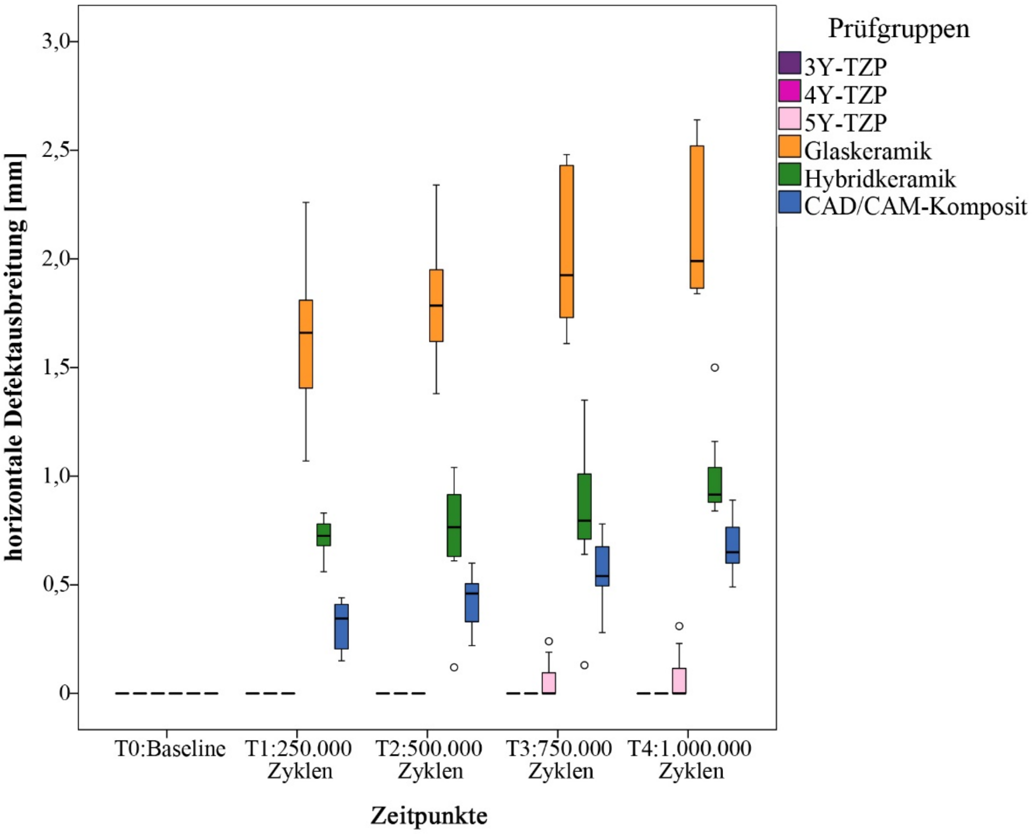

**Abbildung 6** Boxplot-Diagramm der horizontalen Defektausbreitung [mm] im OCT zu den Zeitpunkten T0-T4.

Abschließend konnte gezeigt werden, dass sich die OCT für ein Monitoring über verschiedene Belastungszeitpunkte hinweg zur Analyse von Ermüdungsschäden unterschiedlicher CAD/CAM-Restaurationsmaterialien eignet. Allerdings wurden Ermüdungsschäden in den äußeren Bereichen – sowohl in vertikaler als auch horizontaler Defektausbreitung – mittels OCT nicht vollständig erfasst.

## Diskussion

Mit Ausnahme der 3Y- TZP und 4-TZP Zirkoniumdioxide wiesen alle Restaurationsmaterialien nach 1 Mio. Zyklen Kausimulation okklusale Ermüdungsschäden auf. Zudem wurden in der Publikation 4 (Kapitel 7.7) teilweise Radialrisse an der Unterseite der Restauration detektiert. *Shembish et al.* untersuchten ebenfalls monolithische Kronen nach zyklischer Belastung und zeigten Kegelrisse ausgehend von der OCA sowohl für eine Glaskeramik als auch ein CAD/CAM-Komposit.[139] Zusätzlich zu Ermüdungsschäden, welche unter Belastung entstehen, können bereits während des CAD/CAM-Herstellungsprozesses der Kronen Mikrorisse verursacht werden. *Curran et al.* untersuchten Glas-, Hybridkeramiken und CAD/CAM-Komposite nach dem Fräsen und zeigten, dass kompositbasierte Verbundwerkstoffe weniger Beschädigungen aufwiesen als Glaskeramiken.[30]

Neben dem Herstellungsprozess könnte auch die Konditionierung der Zementierungsfläche und das Befestigungssystems einen Einfluss auf das Auftreten von Radialrissen darstellen. Dies wurde bereits für Zirkoniumdioxide beschrieben.[43] Insbesondere die Glas- und Hybridkeramik zeigten unabhängig vom Aushärtungsmodus Radialrisse, während bei den CAD/CAM-Kompositen im Aushärtungsmodus Lichthärtung keine Radialrisse nachgewiesen wurden. Dies wird durch die Ergebnisse einer Studie unterstützt, welche für die Befestigung von CAD/CAM-Kompositen mit lichthärtenden Befestigungssystemen höhere Haftfestigkeiten im Vergleich zu einer alleinigen Dunkelhärtung zeigten.[89]

Hinsichtlich der Bruchfestigkeit bei statischer Belastung beschrieben *Okada et al.* vergleichbare Ergebnisse zwischen Glaskeramiken und CAD/CAM-Kompositen.[113] Da der Kauvorgang jedoch keine einmalige statische Belastung ist, zeigen Untersuchungen mit zyklischen Ermüdungsversuchen im Vergleich zu statischen zuverlässigere Informationen über die mechanischen Eigenschaften.[7,127] So wurden in den Publikationen 4 und 5 (Kapitel 7.7 und 7.8) die Prüfkörper in einem Kausimulator mit einer linearen Zu- und

Abnahme von 50 und 500 N belastet. In anderen Studien wurden teilweise geringere Kräfte zwischen 50 und 80 N verwendet,[118,127] jedoch wird die Eignung monolithischer CAD/CAM-Restaurationswerkstoffe auch immer wieder bei Patienten mit erhöhter Kaubelastung diskutiert, welche Belastungen von bis zu 800 N erreichen können.[64] So untersuchten *Zierden et al*.[170] die Bruchfestigkeit nach zyklischer Belastung, wohingegen CAD/CAM-Komposite im Vergleich zur Glaskeramik höheren Belastungen widerstehen konnten. Die vorliegenden beiden Studien untersuchten zwar nicht die Bruchfestigkeit, jedoch wurden Ermüdungsschäden nach zyklischer Belastung analysiert. Dabei wiesen die Glaskeramiken im Vergleich zu den CAD/CAM-Kompositen und der Hybridkeramik signifikant höhere Beschädigungen auf.

Aufgrund des Kompositanteils weisen kompositbasierte Verbundmaterialien ein geringeres Elastizitätsmodul als Keramiken auf und sollen somit einwirkende Kräfte besser absorbieren können.[112] Studien, welche das Ermüdungsverhalten von CAD/CAM-Werkstoffen untersuchten, zeigten, dass Hybridkeramiken im Vergleich zu Glaskeramiken eine höhere Schadenstoleranz aufweisen.[51] Dies steht im Zusammenhang mit der Theorie, dass die Rissausbreitung an Fehlstellen beginnt.[51] *Ankyu et al.* berichteten von einem höheren Weilbull-Modul für CAD/CAM-Komposite im Vergleich zur Glaskeramik aufgrund von Fehlstellen und Hohlräumen innerhalb der Mikrostruktur.[4]

Obwohl Keramiken spröde sind, zeigten sie dennoch eine plastische Verformung unterhalb der OCA, was bedeutet, dass sie ebenfalls Energie absorbieren können. Bei Keramiken ist diese Materialeigenschaft jedoch extrem eingeschränkt.[78] *Zhang et al.* beschrieben drei verschiedene Arten von Ermüdungsschäden in verblendeten Zirkoniumdioxidkronen: plastische Verformung, Konus- und Radialrisse.[169] *Wang et al.* beschrieben die gleichen Ermüdungsschäden für verblendete Kronen aus Glaskeramik und Zirkoniumdioxid.[156]

Neben Untersuchungen im Kausimulator werden auch zunehmend numerische Simulationen wie die Finite-Elemente-Methode (FEM) verwendet, um Spannungsbereiche in Restaurationen zu analysieren.[156,168] Da CAD/CAM-Komposite im Vergleich zu Keramiken ein geringeres Elastizitätsmodul aufweisen, wurde in der Literatur eine unterschiedliche Spannungsverteilung beschrieben.[6] Mit der FEM berechneten *Duan et al.* für Glaskeramiken sowohl eine Spannungskonzentration unterhalb der OCA als auch an der Unterseite der Restauration zur Befestigungsfläche.[35] Im Vergleich dazu zeigten CAD/CAM-Komposite lediglich unterhalb der OCA eine Spannungskonzentration.[35] Dies könnte die radialen Risse bei den Glaskeramiken erklären, die auch von *Chen et al.* beschrieben wurden.[22]

In Übereinstimmung mit anderen in der Literatur beschriebenen Ergebnissen, wurden die meisten Ermüdungsbeschädigungen für die CAD/CAM-Komposite im Bereich der OCA, sowie für Glas- und Hybridkeramiken in der Peripherie gezeigt.[22,102,104] Darüber hinaus beschrieben *Chen et al.*, dass Keramiken eine hohe Spannungsverteilung durch eine Energieübertragung in äußere Bereichen kompensieren, welches mit den Beobachtungen der Publikationen 4 und 5 (Kapitel 7.7 und 7.8) übereinstimmt.[22]

*Homaei et al.* zeigten mittels FEM hohe Zugspannungen im Bereich der OCA, welche Kegelrisse verursachen können. Dabei wurde für die Glaskeramik eine maximale Spannung von 81 MPa und für die Hybridkeramik von 35 MPa beschrieben.[52] In den vorliegenden Publikationen 4 und 5 (Kapitel 7.7 und 7.8) wurde zwar nicht die Spannungskonzentration berechnet, aber es konnte eine signifikant höhere Ermüdungsbeschädigung für die Glaskeramik im Vergleich zur Hybridkeramik gezeigt werden. Dies deutet darauf hin, dass der Kompositanteil in der Hybridkeramik im Vergleich zur Glaskeramik mehr Rissenergie absorbieren kann.[24]

Da durch die Analyse von Schnittbildern unter dem Lichtmikroskop – wie in der Publikation 4 (Kapitel 7.7) angewandt – eine Zerstörung des Prüfkörpers einhergeht, wurde diese Methode in Publikation 5 (Kapitel 7.8) nach Abschluss aller Untersuchungen zum Vergleich der neuen OCT-Methode verwendet. *Yazigi et al.* zeigten, dass die OCT-Methode geeignet ist, um die Rissbildung in Glaskeramiken nachzuweisen.[164] Neben Rissen in Prüfkörpern aus Glaskeramik wurden in der Publikation 5 (Kapitel 7.8) auch Ermüdungsschäden in Zirkoniumdioxid, Hybridkeramik und CAD/CAM-Komposit gezeigt. *De Oliveira et al.* beschrieben eine höhere Auflösung für eine Spectral Domain (SD)-OCT im Vergleich zu Swept Source (SS)-OCT.[31] Daher wurde ein SD-OCT verwendet, um die Rissausbreitung zu untersuchen.

Im Vergleich zur OCT zeigte die lichtmikroskopische Analyse der Prüfkörper eine höhere maximale Rissausbreitung in vertikaler und horizontaler Richtung. Dieser Unterschied war jedoch nur für die Prüfkörper der Glas- und Hybridkeramik signifikant. In Abhängigkeit vom Material und der Wellenlänge der OCT variiert die Eindringtiefe zwischen 1 mm und 3 mm.[1,31] Somit wird deutlich, warum die Risse zwar unterhalb der OCA in allen Materialien gut dargestellt werden konnten, hingegen im Randbereich teilweise nicht vollständig erfasst wurden. In diesem Zusammenhang muss aber auch diskutiert werden, dass beim Schneiden der Prüfkörper ein Risiko zur Rissbildung und Rissfortpflanzung besteht, welches zum Entstehen von Artefakten führen kann.[31]

Die Rissbildung geht von der Restaurationsoberfläche im Bereich des Kontaktpunktes zum Antagonisten aus und setzt sich im Material unterhalb der OCA in Form von Mikrorissen fort.[17,30,127] *Homaei et al.* zeigten für Glas- und Hybridkeramiken mittels FEM-Analyse, dass sich die maximale Spannungskonzentration unterhalb des Kontaktpunktes im Bereich der OCA befindet.[52] In der vorliegenden Publikation 5 (Kapitel 7.8) traten während der ersten 250.000 Zyklen bereits Ermüdungsschäden im CAD/CAM-Komposit, der Hybridkeramik und der Glaskeramik auf. Im Gegensatz dazu konnten im 5Y-TZP Risse erst zwischen 500.000 und 750.000 Zyklen Kausimulation gezeigt werden. Außerdem zeigte 5Y-TZP im Vergleich zur Glaskeramik, Hybridkeramik und dem CAD/CAM-Komposit die geringsten vertikalen und horizontalen Ermüdungsschäden. *Rosentritt et al.* untersuchten die Belastungen bis zum Versagen und fanden eine höhere Anzahl von Zyklen bis zum Versagen für CAD/CAM-Komposit und eine geringere Anzahl von Bruchstücken im Vergleich zur Hybridkeramik.[127] In dieser Studie wurden die Proben nicht bis zum Versagen belastet, aber die Hybridkeramik zeigte im Vergleich zum CAD/CAM-Komposit einen signifikant höheren Bereich von Ermüdungsschäden, was zu einem früheren Versagen führen könnte. Außerdem zeigte die Hybridkeramik im Vergleich zur Glaskeramik weniger Schäden. *Choi et al.* beschrieben eine andere Spannungsverteilung und einen anderen Bruchmechanismus für die Hybridkeramik im Vergleich zur Glaskeramik, welches durch eine plastische Verformung der Polymerphase erklärt wird.[23] Dies könnte also eine Erklärung dafür sein, warum die komposithaltigen Proben im Vergleich zur Glaskeramik weniger Schäden zeigten.

Dennoch wiesen alle CAD/CAM-Materialien (mit Ausnahme von 3Y-TZP und 4Y-TZP) eine lineare Zunahme der Ermüdungsschäden über die Zeit auf. Darüber hinaus zeigte sich ein signifikanter Unterschied zwischen den Restaurationsmaterialien. Die kompositbasierten CAD/CAM-Materialien wiesen signifikant geringere Ermüdungsschäden als die Glaskeramik auf, so dass diese neben Zirkoniumdioxiden im Hinblick auf die Ermüdungsbeständigkeit bei Patienten mit erhöhter Kaubelastung Anwendung finden könnten.

## 2.4 Passgenauigkeit

Hintergrund

Die Passgenauigkeit einer Restauration auf dem Zahnstumpf steht in direktem Zusammenhang mit dem Langzeiterfolg festsitzender Restaurationen.[105,115] Einerseits kann ein zu großer marginaler Randspalt zum Auswaschen des Befestigungsmaterials führen, wodurch eine Randundichtigkeit bis hin zum Debonding entstehen kann. Andererseits begünstigt ein zu großer Zementspalt im okklusalen Bereich insbesondere bei keramischen Restaurationen die Entstehung von Ermüdungsschäden.[12,69,82,94,103,115,123] Daher ist vor dem Hintergrund neuer digitaler Workflows und einer zunehmenden Materialvielfalt, die exakte Bestimmung der Passgenauigkeit monolithischer CAD/CAM-Kronenversorgungen zwingend erforderlich.[23,60,74,105,115,146]

Zur Untersuchung der Passgenauigkeit festsitzender Restaurationen wurden zahlreiche Methoden beschrieben, die in destruktive oder zerstörungsfreie Verfahren unterteilt werden.[12,14,59,82,153,163] Die meisten beschriebenen Analysemethoden können jedoch bei Patienten nicht angewendet werden, da für die Untersuchung der Passgenauigkeit eine Extraktion des Zahnes erforderlich ist.[10,144,163] In den letzten Jahren hat sich die zerstörungsfreie analoge Replikatechnik etabliert, welche auf konventionellen Abformmethoden basiert und die am häufigsten angewandte Untersuchungsmethode zur Bestimmung der internen Passgenauigkeit von Restaurationen am Patienten darstellt.[27,65,71,117] Diese Methode ermöglicht jedoch nur eine zweidimensionale Analyse anhand von Schnittbildern, womit die Anzahl an möglichen Messpunkten eingeschränkt ist. Um diese Limitationen zu überwinden, wurden dreidimensionale Ansätze wie die Mikrocomputertomographie, [115] die Triple-Scan-Technologie,[14] die digitale Replikamethode,[73,90] sowie die OCT zur Analyse der Passgenauigkeit entwickelt.[144] Die Mikrocomputertomographie kann jedoch nur an extrahierten Zähne durchgeführt werden, womit eine klinische Anwendung entfällt.[14,99,115,153] Zudem können Artefakte von metallischen Restaurationen die Analyse beeinflussen.[144] Im Gegensatz dazu sind die Triple-Scan-Technologie und die digitale Replikamethode klinisch zwar anwendbar, erfordern jedoch ein komplexes Laborsetup und Expertenwissen zur Bestimmung der Passgenauigkeit.[14,73,82,90,91] In einigen Studien wurde die interne Passgenauigkeit auch mittels OCT untersucht.[144] So vielversprechend diese Methode jedoch in anderen Bereichen der Zahnmedizin ist (Kapitel 2.3), gibt es Einschränkungen hinsichtlich der Untersuchung metallischer Restaurationsmaterialien.

Zudem wäre für die klinische Untersuchung am Patienten ein spezielles OCT für die Zahnmedizin erforderlich, welches zum jetzigen Zeitpunkt noch nicht zur Verfügung steht.[1,144]

Die in der Literatur beschriebenen Methoden verhindern alle eine schnelle und unkomplizierte Kontrolle der Passgenauigkeit am Patienten in der Zahnarztpraxis, wodurch ihr Einsatz häufig auf die Anwendung in Studien beschränkt ist. Lediglich *Zimmermann et al.* untersuchten eine Messmethode, welche die Analyse der Passgenauigkeit mittels IOS ermöglicht.[174] Allerdings wurde bisher in der Literatur keine Studie beschrieben, die verschiedene analoge und digitale Auswertungsmethoden systematisch analysiert und gleichzeitig die marginale und interne Passgenauigkeit von Kronen mit allen drei zur Verfügung stehenden CAD/CAM-Werkstoffgruppen (Metalle, Keramiken, Komposite) im selben Versuchsaufbau untersucht.

Eigene Arbeiten

Es war das Ziel der Publikation 6 (Kapitel 7.9), eine neue IOS-basierte digitale Messmethode (D-IOS) zur einfachen, kostengünstigen und präzisen Beurteilung der Passgenauigkeit von CAD/CAM-Kronen zu entwickeln, die gleichzeitig für die klinische Anwendung am Patienten geeignet ist. Dabei sollte die neue D-IOS-Methode mit der herkömmlichen, analogen Silikon-Replika-Technik (CV-SR) und einer digitalen Replikamethode mit externer Laborsoftware (D-GOM) anhand von zwei verschiedenen Modellen (A und B) systematisch untersucht werden.[82,116]

Darüber hinaus wurde analysiert, inwiefern die Größe des voreingestellten Zementspalts in der CAD-Software (50 µm oder 80 µm) einen Einfluss auf die Passgenauigkeit der CAD/CAM-Kronen hat. Im digitalen Herstellungsprozess von Kronenversorgungen wird der Zementspalt als Fräsparameter in der CAD-Software definiert. Dabei sollte der Zementspalt so groß gewählt werden, dass zum einen bei der Befestigung der Restauration auf dem Zahnstumpf das Befestigungsmaterial im Zementspalt ausreichend Platz hat und zum anderen der Zementspalt frästechnisch dargestellt werden kann.[8,137]

Neben den relativen Messwerten wurde auch die absolute Diskrepanz zwischen dem tatsächlich gemessenen Zementspalt und dem voreingestellten Zementspaltparameter in der CAD-Software berechnet, um zu untersuchen, inwiefern der Zielparameter für verschiedene Restaurationsmaterialien frästechnisch erreicht werden kann.

Die Ergebnisse der Studie zeigten, dass zwischen den drei verschiedenen Auswertungsmethoden (D-IOS, CV-SR, D-GOM) weder für das Modell A noch das Modell B ein signifikanter Unterschied festgestellt werden konnte (p> 0,05). Ebenso wiesen die drei CAD/CAM-Restaurationsmaterialien CAD/CAM-Komposit, Zirkoniumdioxidkeramik (3Y-TZP) und Nichtedelmetall (NEM) hinsichtlich der gesamten internen Passgenauigkeit keinen signifikanten Unterschied auf (p> 0,05).

Jedoch konnten für die einzelnen Messpositionen (marginal, axial, okklusal) teilweise signifikante Unterschiede gezeigt werden (p< 0,05). Unabhängig vom CAD/CAM-Restaurationsmaterial wurden an den okklusalen Messpositionen im Vergleich zu den axialen und marginalen signifikant höhere Passungenauigkeiten festgestellt (Abbildung 7, p< 0,05). Dabei wiesen die NEM-Kronenkappen im Vergleich zu den CAD/CAM-Komposit- und 3Y-TZP-Kappen eine signifikant höhere okklusale Passungenauigkeit auf.

In Bezug auf den Zementspaltparameter zeigten die Ergebnisse, dass der in der CAD-Software voreingestellte Zementspalt für beide Parameter (50 µm und 80 µm) nicht mit der tatsächlich gemessenen internen Passgenauigkeit der Restauration übereinstimmte (Abbildung 7). Lediglich beim CAD/CAM-Komposit (50 µm) in Modell A war im Bereich der marginalen Messposition eine absolute Diskrepanz von 48,9 ± 6,5 µm feststellbar, welches nahezu dem voreingestellten Zementspaltparameter von 50 µm entsprach. Für den Zementspaltparameter von 80 µm konnten insbesondere für die okklusalen und marginalen Messpositionen tendenziell geringe absolute Diskrepanzen gezeigt werden, als für den Zementspaltparameter von 50 µm.

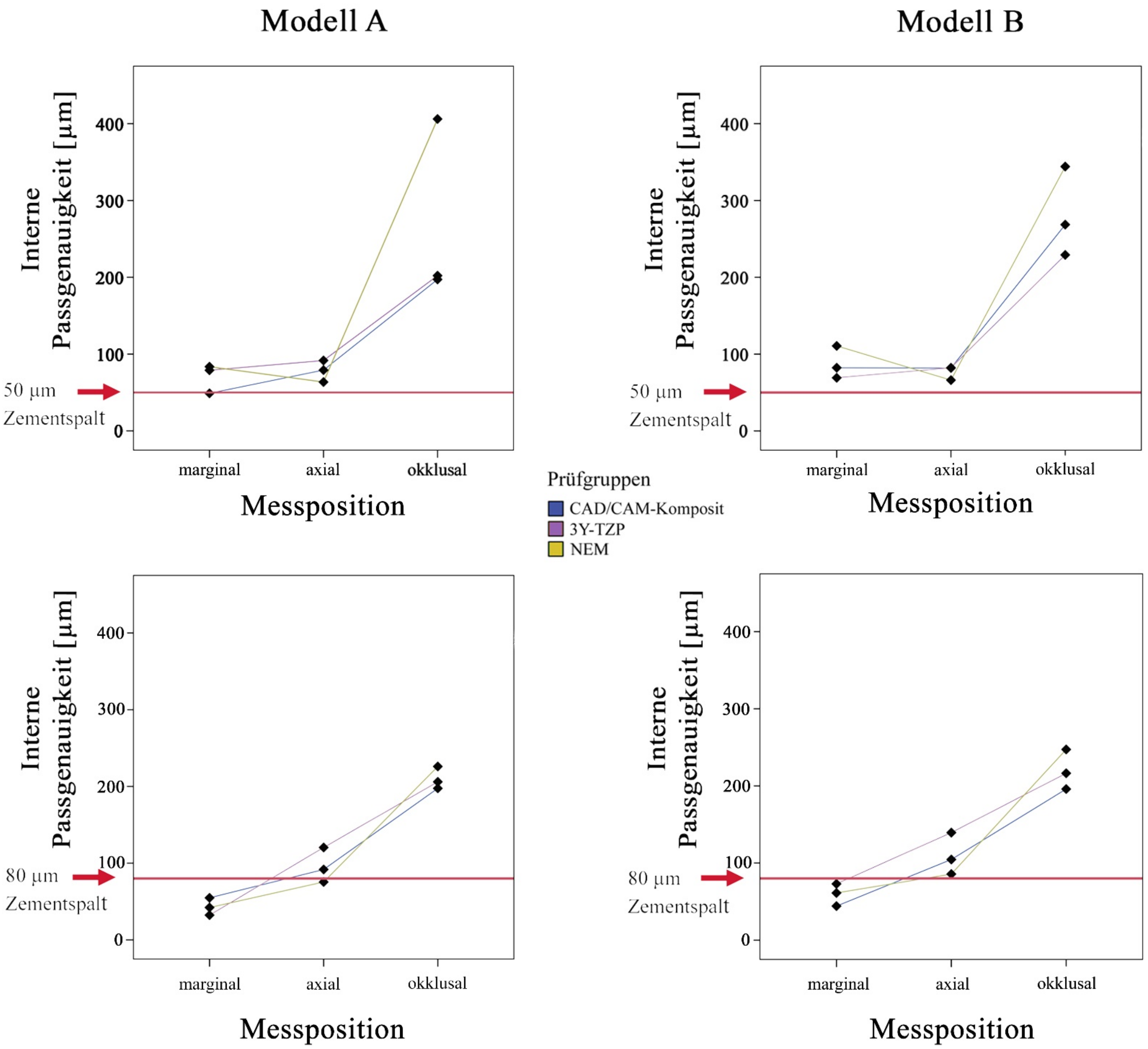

**Abbildung 7** Liniendiagramme zur Darstellung der Korrelation zwischen Messposition und CAD/CAM-Restaurationsmaterial mit jeweils 50 µm bzw. 80 µm Zementspalt (Modell A = zahnbegrenzte Situation, Modell B = Freiendsituation).

Die Ergebnisse der Untersuchung im Labor zeigten, dass zwischen der neuen IOS-basierten Auswertungsmethode (D-IOS), der herkömmlichen, analogen Silikon-Replika-Technik (CV-SR) und der digitalen Replikamethode mit externer Laborsoftware (D-GOM) kein signifikanter Unterschied feststellbar war. Allerdings könnten klinische Einflussfaktoren wie Speichel, Patientenbewegung, verschiedene Präparationsgeometrien der Zahnstümpfe, subgingivale Präparationsränder oder anatomische Begrenzungen der Mundhöhle die Anwendung und Zuverlässigkeit der neuen IOS-basierten Auswertungsmethode beeinflussen.[46,174,175] Deshalb stellte sich die Frage, inwieweit die neue IOS-basierte Auswertungsmethode auch klinisch anwendbar ist und welche Passgenauigkeiten am Patienten für unterschiedliche CAD/CAM-Restaurationsmaterialien zu erzielen sind.

In der Publikation 7 (Kapitel 7.10) wurden insgesamt 30 Präparationen an 20 Patienten mit den bereits in der vorherigen Untersuchung verwendeten drei Auswertungsmethoden D-IOS, CV-SR und D-GOM untersucht. Da die Ergebnisse der Laborstudie tendenziell eine geringere absolute Diskrepanz zwischen voreingestelltem Zementspaltparameter und interner Passgenauigkeit für 80 µm zeigten, wurde auf die Untersuchung des Zementspaltparameters von 50 µm verzichtet.

Auch in der klinischen Studie konnte kein signifikanter Unterschied zwischen den drei Auswertungsmethoden (D-IOS, CV-SR und D-GOM) gezeigt werden (p> 0,05). Darüber hinaus wurde kein signifikanter Unterschied zwischen den unterschiedlichen Zahntypen und den beiden klinischen Situationen (zahnbegrenzt und Freiendsituation) gefunden (p> 0,05).

Dagegen wiesen jedoch die CAD/CAM-Restaurationsmaterialien (CAD/CAM-Komposit, 3Y-TZP und NEM), die einzelnen Messpositionen (marginal, axial und okklusal) und die Interaktion zwischen Kappenmaterial und Messposition signifikante Unterschiede auf (Abbildung 8, p< 0,05).

Das CAD/CAM-Komposit zeigte die höchste Passgenauigkeit, gefolgt von 3Y-TZP und NEM. Unabhängig vom CAD/CAM-Restaurationsmaterial war im Bereich der okklusalen Messposition die höchste Passungenauigkeit zu finden. Die Analyse der absoluten Diskrepanz zeigte nur für die marginale Messposition annähernd den voreingestellten Zementspaltparameter von 80 µm.

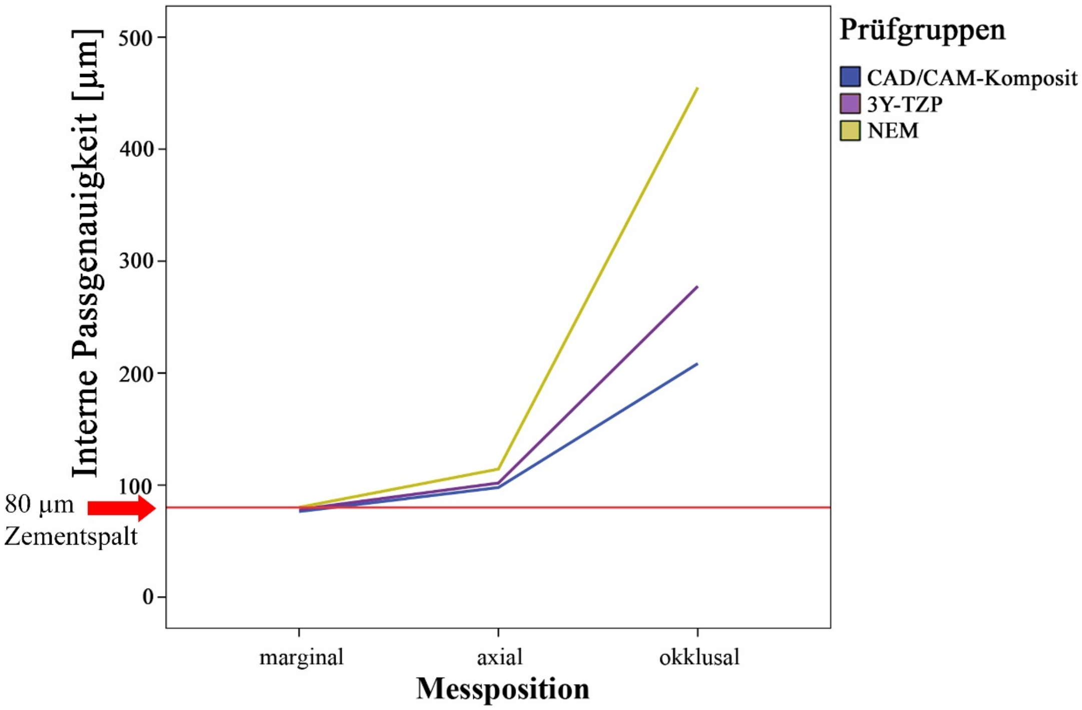

**Abbildung 8** Liniendiagramm zur Darstellung der Korrelation zwischen Messposition und CAD/CAM-Restaurationsmaterial mit 80 µm Zementspalt.

Diskussion

Sowohl in der Laborstudie, als auch am Patienten konnte gezeigt werden, dass die drei Analysemethoden (D-IOS, CV-SR, D-GOM) keinen signifikanten Unterschied in den Messwerten zur Bestimmung der Passgenauigkeit aufwiesen. *Rudolph et al.* und *Mai et al.* untersuchten jeweils eine digitale Replikamethode basierend auf einer Laborsoftware, welche in etwa mit der in den beiden vorliegenden Publikationen 6 und 7 (Kapitel 7.9 und 7.10) untersuchten D-GOM-Methode vergleichbar ist und zeigten ebenfalls keinen signifikanten Unterschied zwischen den Methoden.[91,129]

Auch für verschiedene klinische Situationen (zahnbegrenzt und Freiendsituation) und Zahntypen (Incisivi, Prämolar, Molar) konnte in den beiden vorliegenden Publikationen 6 und 7 (Kapitel 7.9 und 7.10) kein signifikanter Unterschied gezeigt werden. *Bosniac et al.* untersuchten die marginale Passgenauigkeit von Einzelkronen mit dem IOS caraTrios (3Shape), ein Vorläufermodell des in den beiden vorliegenden Untersuchungen verwendeten IOS Trios 3. Sie beschrieben eine signifikant höhere Passungenauigkeit für Restaurationen im Molarenbereich im Vergleich zu allen anderen Zahntypen und führten dies auf die Größe des Handstücks und die damit eingeschränkte Zugänglichkeit des IOS im posterioren Bereich der Mundhöhle zurück.[15] In den letzten Jahren wurden die Handstücke des Trios IOS kleiner konstruiert, welches ein einfacheres Scannen in der Mundhöhle ermöglicht und damit die abweichenden Studienergebnisse erklären könnte.

Um die Passgenauigkeit verschiedener CAD/CAM-Kronenkappenmaterialien einerseits unter standardisierten Laborbedingungen zu vergleichen, andererseits aber die klinische Patientensituation möglichst gut zu simulieren, wurden in der ersten Laborstudie zwei Modelle (A und B) hergestellt. Auch wurden im Gegensatz zu anderen Studien, welche künstliche Zähne aus Kunststoff,[14,59,73,103] Gips,[82] Zirkoniumoxid,[99,123] oder Metall verwendeten,[73,90,91] extrahierte, humane Zähne präpariert. Die Abformung der präparierten Zahnstümpfe wurde ebenfalls unter klinisch nahen Bedingungen durchgeführt. Während andere Studien einen Laborscanner verwendeten,[13,14,73,82,91] wurden in den beiden vorliegenden Untersuchungen digitale Abformungen mittels IOS durchgeführt.

*Zimmermann et al.* beschrieben eine Analysemethode zur Beurteilung der Passgenauigkeit mit dem Cerec-System (Dentsply Sirona, Bensheim, Deutschland) in Kombination mit der Software OraCheck (Cyfex, Zürich, Schweiz), wobei zur Überlagerung die Nachbarzähne verwendet wurden.[174] Für die Analyse der beiden digitalen Auswertemethoden (D-IOS und D-GOM) in den beiden vorliegenden Publikationen 6 und 7 (Kapitel 7.9 und 7.10) wurden ebenfalls die STL-Datensätze mit Best-Fit-Ausrichtung über die Nachbarzähne ausgerichtet.[38,82,174] *Mennito et al.* beschrieben, dass die Überlagerung über Hartgewebe im Vergleich zu Weichgewebe eine signifikant bessere Überlagerung zeigte.[96] *Lee et al.* überlagerten über eine Kerbe am Modell, welches jedoch eine Untersuchung der Passgenauigkeit am Patienten nicht zulässt.[82] *O'Toole et al.* untersuchten verschiedene Überlagerungsmethoden und zeigten signifikant geringere Fehler bei der Überlagerung über Referenzkörper im Vergleich zur Best-Fit-Ausrichtung.[111] Im Laborversuch am Modell ist das Anbringen eines Referenzwürfels o.Ä. problemlos möglich, jedoch gibt es in der Mundhöhle keine Referenzstruktur, weshalb in einigen Studien ein zusätzliches Referenzhilfsmittel verwendet wurde.[70,135] Dies ist jedoch für Messungen in der täglichen Praxis ohne einen komplexen Laboraufbau nicht anwendbar.

Neben der Untersuchung verschiedener Analysemethoden, war es das Ziel der vorliegenden Publikationen 6 und 7 (Kapitel 7.9 und 7.10), die Passgenauigkeit verschiedener CAD/CAM-Restaurationsmaterialien zu untersuchen. Dabei repräsentieren die drei verwendeten CAD/CAM-Materialien die heute hauptsächlich verwendeten Werkstoffgruppen. Bisherige Studien zur Passgenauigkeit festsitzender Restaurationen analysierten hingegen meistens nur ein Restaurationsmaterial[73,90,91,174] oder verglichen maximal zwei Werkstoffgruppen miteinander (z.B. Keramiken und Polymere[37,176] oder Keramiken und Legierungen[53,124]).

Sowohl in der Laborstudie als auch am Patienten konnte in den vorliegenden Publikationen 6 und 7 (Kapitel 7.9 und 7.10) kein signifikanter Unterschied zwischen den drei CAD/CAM-Restaurationsmaterialien (CAD/CAM-Komposit, 3Y-TZP und NEM) in Bezug auf die gesamte interne Passgenauigkeit gezeigt werden. Die in den vorliegenden Publikationen 6 und 7 (Kapitel 7.9 und 7.10) erreichten marginalen Passgenauigkeiten entsprechen in ihrer Größenordnung den in der Literatur beschriebenen Messwerten von weniger als 120 µm.[12,14,105,115,153] Auch die höheren Passungenauigkeiten im Bereich der okklusalen Messpositionen im Vergleich zu den marginalen und axialen, stehen in guter Übereinstimmung mit der Literatur.[13,174] *Zimmermann et al.* untersuchten die marginale, axiale und okklusale Passgenauigkeit von Endokronen mit einem Zementspaltparameter von 80 µm und zeigten ebenfalls höhere Passungenauigkeiten im okklusalen Messbereich im Vergleich zum marginalen und axialen.[176] *May et al.* diskutierten, dass die marginale Passgenauigkeit von Restaurationen oft im Fokus steht, jedoch eine hohe interne Passgenauigkeit ebenso wichtig sei, denn eine okklusale Passungenauigkeit von 500 µm im Vergleich zu 50 µm halbiert die Bruchlast der Restauration.[94] Auch *Rezende et al.* beschrieben eine Zunahme der Spannungskonzentration in Kronen mit einem großen Zementspalt.[123]

Neben Messwerten zur internen Passgenauigkeit wurden in den beiden vorliegenden Publikationen 6 und 7 (Kapitel 7.9 und 7.10) auch die absolute Diskrepanz zwischen voreingestelltem Zementspaltparameter und tatsächlich gemessenem Zementspalt bestimmt. Dabei zeigten sich in beiden Studien insbesondere im okklusalen Bereich hohe Diskrepanzen. *Boitelle et al.* beschrieben ebenfalls, dass der voreingestellte Zementspaltparameter und die tatsächlich gemessene interne Passgenauigkeit nicht übereinstimmen würden.[13] *Hmaidouch et al.* zeigten für Kronen mit einem voreingestellten Zementspaltparameter von 100 µm eine höhere Passgenauigkeit als für Kronen mit einem Zementspaltparameter von 50 µm.[48] Dies stimmt mit den Ergebnissen der Publikation 6 (Kapitel 7.9) überein, bei welcher die Kronenkappen mit einem voreingestellten Zementspaltparameter von 80 µm eine geringere absolute Diskrepanz zeigten als bei einem voreingestellten Zementspaltparameter 50 µm. *Praca et al.* erläuterten die Entscheidung für eine Zementspaltparameter von 80 µm damit, dass auf diese Weise eine hohe Passgenauigkeit ohne manuelle Anpassung möglich sei.[116] Da *Hasanzade et al.* beschrieben, dass die manuelle Nachbearbeitung der Kronen zu einem signifikant höheren internen Zementspalt führt, wurde auf eine manuelle Anpassung der Kronenkappen in den beiden vorliegenden Publikationen 6 und 7 (Kapitel 7.9 und 7.10) verzichtet.[45]

Die insbesondere im okkusalen Bereich beschriebenen hohen Diskrepanzen zwischen voreingestelltem Zementspaltparameter und tatsächlich gemessenem Zementspalt, könnte auf die Fräsradiuskorrektur der CAM-Strategie zurückzuführen sein.[137] *Zimmermann et al.* zeigten signifikante Unterschiede zwischen verschiedenen CAM-Strategien in Bezug auf die Passgenauigkeit von Keramikkronen.[175] Heute ermöglicht die digitale Präparationsanalyse (z.B. prepCheck, Dentsply Sirona) eine Kontrolle der Präparation mittels IOS am Patienten, wodurch eine schnelle Korrektur der Präparation möglich ist. Zukünftige Software-Entwicklungen könnten neben der Analyse der Substanzreduktion und des Präparationswinkels den erforderlichen, materialspezifischen Fräsradius anzeigen, damit die Passgenauigkeit insbesondere im okklusalen Bereich erhöht wird.

*Huang et al.* zeigten in ihrer Studie im Bereich der marginalen und axialen Messpositionen eine signifikant geringere Passungenauigkeit für NEM im Vergleich zu Keramiken.[53] Diese Ergebnisse stehen im Gegensatz zu denen von *Pimienta et al.* und den Ergebnissen der beiden vorliegenden Publikationen 6 und 7 (Kapitel 7.9 und 7.10), wo NEM die höchste interne Passungenauigkeit im Vergleich zu der 3Y-TZP und dem CAD/CAM-Komposit zeigte.[115] Hinsichtlich der okklusalen Messpositionen beschrieben *Huang et al.* jedoch ebenfalls signifikant höhere Passungenauigkeiten für NEM, welches mit den Ergebnissen der beiden vorliegenden Publikationen 6 und 7 (Kapitel 7.9 und 7.10) übereinstimmt.[53]

Die neue IOS-basierte Methode ermöglicht eine einfache, schnell anwendbare Beurteilung der Passgenauigkeit von Kronen verschiedener Restaurationsmaterialien am Patienten in der Zahnarztpraxis ohne zusätzliche Laborgeräte oder spezielle Softwareanwendungen.[115] Dies trägt zur Verbesserung der Restaurationsqualität bei, denn mögliche Passungenauigkeiten, die vom Verlust der Restauration bis hin zur Zahnextraktionen führen können, werden so bereits vor dem Einsetzen diagnostiziert.

# 3 CAD/CAM-Kronenversorgungen in der zahnärztlichen Ausbildung

Hintergrund

Bereits heute ist eine zunehmende Digitalisierung, insbesondere in den Bereichen CAD/CAM-Fertigung, Röntgen und Verwaltung, sowohl in Zahnarztpraxen als auch Dentallaboren zu verzeichnen.[39,121] Daher ist für eine zeitgemäße zahnärztliche Ausbildung die Implementierung digitaler Lehrmethoden dringend erforderlich.

Um von Beginn an Studierende optimal auf die klinische Anwendung digitaler Workflows vorzubereiten, sollten bereits in den vorklinischen Semestern Kenntnisse zum theoretischen und praktischen Hintergrund der CAD/CAM-Technologie vermittelt werden.

Für den zahnärztlichen Beruf ist jedoch das Erlernen von manuellen Fertigkeiten unverzichtbar, weshalb die Herausforderung besteht, zwar neue digitale Lehrmethoden, sogenannte computer-aided simulation (CAS) anzuwenden, jedoch nach wie vor die Studierenden auch auf herkömmliche Behandlungsmethoden vorzubereiten.[19,29,40,160,162] Daher wurde in der Poliklinik für Zahnärztliche Prothetik der Justus-Liebig-Universität Gießen im Wintersemester 2017/18 ein digitales, strukturiertes Curriculum in den bestehenden Lehrplan implementiert.

Während die meisten Studien im Bereich digitaler Lehrmethoden allein die Leistungsfähigkeit von CAS-Systemen untersuchten,[19,39,40,95,101,162] wurde die Perspektive der Studierenden bisher nur spärlich analysiert. Diese ist jedoch für eine erfolgreiche Implementierung neuer Lehrkonzepte wichtig.[162]

An vielen Universitäten besteht auch heute die Ausbildung von Studierenden noch immer ausschließlich aus konventionellen Lehrmethoden mit der Vermittlung von traditionellen Workflows zur Zahnersatzherstellung wie dem Aufwachsen und Gießen. Auch besteht ein großer Teil der praktischen Lehre aus Zahnpräparationsübungen am Phantomkopf mit alleiniger Bewertung durch Lehrende.

Im vorklinischen Studienabschnitt der Justus-Liebig-Universität Gießen werden in den Phantomkursen der Zahnersatzkunde I im 3. Fachsemester sowie Zahnersatzkunde II im 5. Fachsemester in Bezug auf festsitzenden Zahnersatz unter anderem die korrekte Präparation von Kronen- und Brückenversorgungen erlernt. Zudem sollen Studierende den gesamten Workflow von der Präparation über die Abformung bis zur Herstellung von Zahnersatz selbst durchzuführen können. Dabei erfolgt die Betreuung ausschließlich durch Zahnärzte. Die in der Vorklinik erlernten theoretischen und praktischen Grundlagen zur Zahnärztlichen Prothetik werden später in den klinischen prothetischen Kursen des 8. und 9. Fachsemesters am Patienten angewendet.

Wichtig ist hierbei neben der Schulung manueller Fertigkeiten, dass das eigene Beurteilungsvermögen von Präparationen und zahntechnischen Werkstücken geschult wird, sowie Kenntnisse über die Biomaterialwissenschaft erworben werden.[39]

So führen die Studierenden ihre Übungen nach wie vor an den Phantomköpfen durch, nutzen aber die CAS-Software des IOS zur Präparationsanalyse. Besonders für Studierende, die zum ersten Mal einen Zahn präparieren, ist es schwierig, die Präparationsvoraussetzungen zu verstehen und zu erfüllen. *Knight* gab den Hinweis darauf, dass es wichtig sei, eine genaue Vorstellung vom Endergebnis für das Training der manuellen Fertigkeiten zu haben.[75] Hier kann CAS-Software helfen das Bewusstsein der Studierenden für den Zahnhartsubstanzverlust durch die dreidimensionale Abbildung der eigenen Präparationen zu schärfen und das Beurteilungsvermögen durch die Überlagerung der eigenen Präparation auf dem Originalzahn zu verbessern. Dies ist besonders wichtig, da Studien gezeigt haben, dass die Selbsteinschätzung die Lernmotivation erhöht und das lebenslange Lernen unterstützt.[44,162] Gegenwärtig können also CAS-Ansätze die traditionellen Lehrmethoden unterstützen.[95]

Um aus ihren Fehlern zu lernen und ein Gefühl für ihre Leistungen zu bekommen, benötigen die Studierenden ein individuelles Feedback zu ihrer Leistung.[75] Daher ist eine hohe Zuverlässigkeit der Bewertung unerlässlich. Studien zur traditionellen Beurteilung von Präparationen nach dem *Glance and grade*-Prinzip haben jedoch eine geringe interrater (zwischen verschiedenen Prüfern) und intrarater (ein Prüfer zu verschiedenen Zeiten) Zuverlässigkeit festgestellt.[58,151,162] Darüber hinaus fordern Studierende häufig ein sofortiges Feedback anhand objektiver Beurteilungskriterien sowie Verbesserungsvorschläge.[28,44] Aufgrund unterschiedlicher Arbeitserfahrungen und Bewertungsstandards sowie Zeitmangel ist dies im Lehralltag jedoch nur schwer zu erfüllen. Dies kann einen Mangel an Objektivität und Uneinigkeit zwischen Studierenden und betreuenden Zahnärzten zur Folge haben.[44,162] *Renne et al.* berichteten, dass Studierende Beurteilungen oft als subjektiv und willkürlich empfinden.[122] Diese Wahrnehmung kann zu einer verminderten Selbstwahrnehmung führen und die Leistung der Studierenden negativ beeinflussen.[138]

Digitale Methoden wie CAS sind in solchen Situationen besonders geeignet, da sie ein objektives und unmittelbares Feedback liefern. Sie ermöglichen ein individuelles Lerntempo und stehen auch außerhalb der Kurszeiten zur Verfügung.[19,29,39,40,121,130] Dadurch wird die Arbeitsbelastung der Lehrenden langfristig reduziert.[162] Allerdings erfordert die Digitalisierung zu Beginn hohe Investitionskosten und die Implementierung in ein bestehendes Curriculum ist sehr zeitaufwendig.[18,40,86]

### Eigene Arbeiten

Da für eine erfolgreiche Umsetzung neuer Lehrinhalte die Studierendenperspektive unabdingbar ist, stellte sich die Frage, wie die Studierenden die Implementierung digitaler Workflows in die zahnärztliche Ausbildung bewerten. Somit war es das Ziel der Publikation 8 (Kapitel 7.11), die beiden Trainingsmodule *digitale Präparationsanalyse* und *Chairside gefertigter Zahnersatz* des Gießener Lehrkonzeptes zur Implementierung digitaler Prothetik in den vorklinischen Semestern durch jeweils 100 Studierende in Bezug auf die Handhabung des IOS und der CAS-Software, den didaktischen Nutzen, die Motivation sowie die Gesamtbewertung mit Hilfe von zwei Fragebögen zu evaluieren.

Alle Studierenden (n=104) des Trainingsmoduls I (Ph1) und alle Studierenden (n=97) des Trainingsmoduls II (Ph2) haben an der vorliegenden Studie der Publikation 8 (Kapitel 7.11) teilgenommen. Aufgrund der Möglichkeit der Enthaltung bewegte sich die Anzahl der gültigen Antworten pro Frage jedoch zwischen 84,6 bis 95,2 % (Ph1) und 84,5 bis 97,9 % (Ph2).

Im Allgemeinen bewerteten die Studierenden die Aspekte Handhabung, didaktischer Nutzen und Motivation in beiden Fragebögen positiv. Allerdings beschrieben Studierende des Trainingsmoduls I teilweise Schwierigkeiten beim intraoralen Scannen der Präparation und dem Verständnis des prepCheck-Reports (Tabelle 1). Bei der Analyse der Präparation bevorzugten die Studierenden, insbesondere in Bezug auf Tipps und Rückmeldung, die Bewertung durch die betreuenden Zahnärzte und nicht durch die Software. Jedoch könnten sich 86,2 % der Studierenden vorstellen, die digitale Präparationsanalyse zukünftig in ihrer Zahnarztpraxis zu verwenden.

Auch die Studierenden des Trainingsmoduls II berichteten teilweise über Schwierigkeiten beim intraoralen Scannen der Präparation (Tabelle 2). Darüber hinaus stellte zum Teil die digitale Modellation der Restauration eine Herausforderung dar. Dabei bevorzugten die Studierenden den digitalen Arbeitsablauf im Vergleich zur konventionellen Herstellung von Zahnersatz insbesondere im Hinblick auf die Aspekte Zeitaufwand, mehr Tipps und besseres Feedback, einfachere Handhabung, angenehmere Praxiserfahrung sowie größere Fehlertoleranz. Unter den Studierenden des Trainingsmoduls II könnten sich 96,8 % der Studierenden vorstellen, zukünftig einen intraoralen Scanner in der täglichen Praxis einzusetzen.

**Tabelle 1** Items und deskriptive Statistik zum Trainingsmoduls I – Digitale Präparationsanalyse.

| Item | Itemformulierung | 25 % Perzentil | Median | 75 % Perzentil | N |
|---|---|---|---|---|---|
| Handhabung 1* | Die Menüführung des intraoralen Scanners und der prepCheck-Software ist gut nachvollziehbar. | 4 | 4 | 5 | 95 |
| Handhabung 2* (rec.) | Der Scanvorgang mit dem Handstück bereitet mir keine Schwierigkeiten. | 3 | 4 | 5 | 98 |
| Handhabung 3* | Die Analyse der Präparation mit prepCheck ist gut durchführbar. | 4 | 4 | 5 | 96 |
| Handhabung 4* | Durch die Demo und Übung fühle ich mich imstande, prepCheck selbstständig durchführen zu können. | 4 | 4 | 5 | 97 |
| Didaktischer Nutzen 1* | Der Arbeitsablauf beim digitalen Scannen und der Präparationsanalyse ist gut abgestimmt und für mich verständlich. | 4 | 4 | 5 | 96 |
| Didaktischer Nutzen 2* | Durch die Darstellung der eigenen Präparation auf dem Monitor und die Analyse mit prepCheck wird mein eigenes Beurteilungsvermögen für Präparationen geschult. | 4 | 5 | 5 | 98 |
| Didaktischer Nutzen 3* | Ich denke, durch die Möglichkeit prepCheck zu benutzen habe ich Kenntnis gewonnen über den digitalen Workflow beim intraoralen Scannen. | 4 | 4 | 5 | 98 |
| Didaktischer Nutzen 4* | Ich empfinde das Evaluationsprotokoll meiner Präparation in prepCheck hilfreich, um meine eigene Leistung bezüglich Präparationen zu verbessern. | 4 | 4 | 5 | 99 |
| Didaktischer Nutzen 5* | Die Analyseergebnisse von meiner Präparation in prepCheck sind gut verständlich. | 3 | 4 | 5 | 97 |
| Motivation 1* | Die Anwendung moderner Techniken - wie z.B. von prepCheck in der Zahnheilkunde - motiviert mich. | 4 | 4,5 | 5 | 98 |
| Motivation 2* | Die eigene Präparation mittels prepCheck zu analysieren, motiviert mich. | 4 | 4 | 5 | 96 |
| Motivation 3* (rec.) | Ich empfinde prepCheck als zusätzlichen Kursbestandteil nicht als lästige Pflicht. | 3 | 4 | 5 | 94 |
| Bewertung# | Wenn Sie die folgenden Aspekte der Beurteilung ihrer Präparation berücksichtigen, welche Art der Beurteilung würden Sie eher bevorzugen (Beurteilung durch Assistent oder prepCheck)? (1=Assistent, 5=prepCheck) | | | | |
| Bewertung 1# | geringerer Zeitaufwand | 2 | 3 | 4 | 90 |
| Bewertung 2# | einfachere Handhabung / Umgang | 2 | 3 | 4 | 88 |
| Bewertung 3# | größere Fehlertoleranz | 1 | 2 | 3 | 88 |
| Bewertung 4# | mehr Tipps / bessere Rückmeldung | 1 | 2 | 3 | 90 |
| Bewertung 5# | mehr Freude an der Arbeit | 2 | 3 | 3 | 92 |

N =Anzahl gültiger Antworten (Gesamt: N=104)
* Antwortformat: 1=trifft nicht zu, 5=trifft voll zu
\# Antwortformat: 1=Beurteilung durch Assistent, 5=Beurteilung durch prepCheck
rec: Frage Handhabung 2 und Motivation 3 wurden vor der Analyse umkodiert, so dass auch hier höhere Werte eine positivere Beurteilung ausdrücken.

**Tabelle 2** Items und deskriptive Statistik zum Trainingsmoduls II – Chairside gefertigter Zahnersatz.

| Item | Itemformulierung | 25 % Perzentil | Median | 75 % Perzentil | N |
|---|---|---|---|---|---|
| Handhabung 1* | Die Menüführung des intraoralen Scanners ist gut nachvollziehbar. | 4 | 4 | 5 | 93 |
| Handhabung 2* (rec.) | Der Scanvorgang mit dem Handstück bereitet mir keine Schwierigkeiten. | 3 | 4 | 4 | 94 |
| Handhabung 3* | Die digitale Modellation der Restauration ist gut durchführbar. | 3 | 4 | 5 | 95 |
| Handhabung 4* | Durch die Teilnahme am Cerec-Curriculum fühle ich mich imstande, den gesamten Arbeitsablauf vom intraoralen Scannen bis zur fertigen Modellation der Restauration selbstständig durchführen zu können. | 4 | 4 | 5 | 94 |
| Didaktischer Nutzen 1* | Der Arbeitsablauf beim digitalen Scannen ist gut abgestimmt und für mich verständlich. | 4 | 4 | 5 | 94 |
| Didaktischer Nutzen 2* | Durch die Darstellung der eigenen Präparation auf dem Monitor wird mein eigenes Beurteilungsvermögen für Präparationen geschult. | 4 | 5 | 5 | 95 |
| Didaktischer Nutzen 3* | Ich denke, durch das Cerec-Curriculum habe ich Kenntnis gewonnen über den digitalen Workflow beim intraoralen Scannen. | 4 | 5 | 5 | 93 |
| Motivation 1* | Die Anwendung moderner Techniken - wie z.B. das intraorale Scannen in der Zahnheilkunde - motiviert mich. | 4 | 5 | 5 | 91 |
| Motivation 2* | Die eigene Präparation mittels CAD/CAM-Technik zu versorgen, motiviert mich. | 4 | 5 | 5 | 92 |
| Motivation 3* (rec.) | Ich empfinde das Cerec-Curriculum als zusätzlichen Kursbestandteil nicht als lästige Pflicht. | 4 | 5 | 5 | 92 |
| Bewertung# | Welchen Arbeitsablauf würden Sie bei der Abformung unter Berücksichtigung der folgenden Aspekte bevorzugen? (1=konventionell, 5=digital) | | | | |
| Bewertung 1# | geringerer Zeitaufwand | 4 | 5 | 5 | 89 |
| Bewertung 2# | einfachere Handhabung | 3 | 4 | 4 | 92 |
| Bewertung 3# | größere Fehlertoleranz | 2 | 3 | 4 | 82 |
| Bewertung 4# | mehr Bearbeitungsoptionen | 3 | 4 | 5 | 90 |
| Bewertung 5# | mehr Freude an der Arbeit | 3 | 4 | 4 | 86 |

N=Anzahl gültiger Antworten (Gesamt: N=97)
* Antwortformat: 1=trifft nicht zu, 5=trifft voll zu
# Antwortformat: 1=konventioneller Arbeitsablauf, 5=digitaler Arbeitsablauf
rec: Item Handhabung 2 und Motivation 3 wurden vor der Analyse umkodiert, so dass auch hier höhere Werte eine positivere Beurteilung ausdrücken. Dargestellt sind die originalen Itemformulierungen.

## Diskussion

Die digitale Präparationsanalyse wurde von Beginn an durch die Studierenden der Justus-Liebig-Universität Gießen akzeptiert, auch wenn diese nur zu Übungszwecken und nicht zur Bewertung der Präparationen verwendet wurde. Hingegen beschrieben *Callan et al.* das Studierende objektive CAS-Lernmittel nur akzeptieren würden, wenn diese auch zur Benotung eingesetzt werden.[19]

*Wolgin et al.* erörterten, dass Studierende mit digitalen Bewertungsmethoden teilweise unzufrieden seien.[162] In der vorliegenden Studie der Publikation 8 (Kapitel 7.11) gaben die Studierenden an, die Bewertung durch die betreuenden Zahnärzte im Vergleich zur digitalen Präparationsanalyse zu bevorzugen. *Kunkel et al.* beschrieben, dass die subjektive Bewertung durch den Zahnarzt häufig besser sei, als bei einer objektiven Analyse mittels Software, welches eine mögliche Erklärung für die Präferenz der Studierenden für eine Präparationsanalyse durch Zahnärzte in der vorliegenden Umfrage sein könnte.[77] Inwiefern CAS-Software zur Unterstützung der Zahnärzte in Prüfungssituationen eingesetzt werden kann, müssen zukünftige Untersuchungen zeigen.

Neben einer objektiveren Lehre ermöglichen CAS-Lernsysteme eine digitale Präparationsanalyse auch außerhalb der Kurszeiten.[86] Dies wird im Gießener Konzept durch die Möglichkeit der Nutzung von prepCheck auch in den freien Übungszeiten ermöglicht, in denen keine Betreuung durch Zahnärzte zur Verfügung steht.

Die Ergebnisse der vorliegenden Publikation 8 (Kapitel 7.11) zeigten, dass sich die meisten Studierenden vorstellen können, in Zukunft einen IOS für die Patientenbehandlung in der Zahnarztpraxis zu verwenden. *Holman et al.* beschrieben, dass Studierende das während des Studiums Erlernte bei zukünftigen Behandlungen umsetzen würden.[49] Daher sollte bereits während der zahnärztlichen Ausbildung die Chance genutzt werden, Studierenden theoretisches Wissen und praktische Fähigkeiten der digitalen Prothetik zu vermitteln, um möglichst vielen Patienten moderne Behandlungsmöglichkeiten auf aktuellen Stand der Forschung zu ermöglichen. Diese Ausbildung kann jedoch nicht auf kostenneutrale Weise erreicht werden, insbesondere nicht im Hinblick auf die notwendigen Investitions- und Personalkosten.

Anhand der vorliegenden Publikation 8 (Kapitel 7.11) wird deutlich, dass die Implementierung digitaler Prothetik in die vorklinische Ausbildung von den Studierenden als überwiegend positiv empfunden wurde. Jedoch wurden auch Schwierigkeiten mit CAS-Systemen berichtet und die meisten Studierenden bevorzugten eine Beurteilung der Präparation durch die Zahnärzte und nicht die Software. Daher können CAS-Ansätze Lehrende in der zahnärztlichen Ausbildung nicht ersetzen, sondern stellen eine zusätzliche Lehrmethode neben der traditionellen Vermittlung manueller Fertigkeiten dar.

# 4 Zusammenfassende Darstellung und Ausblick

In der vorliegenden Arbeit wurden aktuelle monolithische CAD/CAM-Materialien zur Kronenversorgung im digitalen Workflow der Zahnärztlichen Prothetik systematisch in Bezug auf ihre wesentlichen Kenngrößen – *Randdichtigkeit*, *Ermüdungsbeständigkeit* und *Passgenauigkeit* – untersucht. Darüber hinaus wurde die Perspektive der Studierenden auf die Implementierung digitaler Prothetik in die *zahnmedizinische Ausbildung* mittels Fragebögen evaluiert.

Zunächst wurde die adhäsive Befestigung von monolithischen CAD/CAM-Kronenversorgungen aus neuen kompositbasierten Werkstoffen in Bezug auf die *Randdichtigkeit* untersucht, da ein erhöhter Haftverlust (Debonding) in der Literatur beschrieben wurde.[76] Bereits ein partielles Debonding kann zu einem marginalen Randspalt mit bakterieller Besiedlung und der Entstehung einer Sekundärkaries bis hin zum Zahnverlust führen.[72] Somit ist der Langzeiterfolg einer Kronenversorgung wesentlich von der korrekten Anwendung des geeigneten Befestigungssystems abhängig.[41] Da die Analyse der Randdichtigkeit anhand von Schnittbildern erfolgt, ist eine Untersuchung am Patienten nicht möglich. Somit wurden zur Simulation der Kaubelastung die auf CAD/CAM-gefrästen humanen Molaren adhäsiv befestigten CAD/CAM-Kronen einer künstlichen Alterung im Labor unterzogen.

Nachdem in der Publikation 1 (Kapitel 7.4) gezeigt wurde, dass die separate Lichthärtung des Befestigungsmaterials einen signifikanten Einfluss auf die Randdichtigkeit der CAD/CAM-Kronen hat, wurde in der Publikation 2 (Kapitel 7.5) untersucht, inwiefern herstellereigene bzw. -fremde Befestigungssysteme die Randdichtigkeit beeinflussen. Für herstellereigene Befestigungssysteme konnte eine signifikant höhere Randdichtigkeit gezeigt werden, sofern eine Dunkelhärtung durchgeführt wurde. Hingegen zeigte sich für die Lichthärtung kein signifikanter Unterschied zwischen herstellereigenen und -fremden Systemen. Diese Ergebnisse sind im Hinblick auf die klinische Anwendung von CAD/CAM-Kompositen essentiell, denn seitens des Herstellers werden zwar durchgängige Produktlinien entworfen, in der täglichen Praxis ziehen es jedoch viele Anwender aus Kostengründen vor, nur ein Befestigungssystem für alle Restaurationsmaterialien anstelle des entsprechenden Befestigungssystems für jedes einzelne Restaurationsmaterial zu verwenden.

Darüber hinaus konnte in der Publikation 3 (Kapitel 7.6) nachgewiesen werden, dass im Gegensatz zu Kronen aus Hybridkeramik, bei CAD/CAM-Kompositen und Zirkoniumdioxiden neuerer Generationen auch mit reduzierter Schichtstärke die Randdichtigkeit bei Lichthärtung des Befestigungssystems gegeben ist. Dies ermöglicht die Herstellung von minimalinvasiven Restaurationen mit substanzschonender Präparation am natürlichen Zahn.

Bei den Untersuchungen zur Randdichtigkeit zeigte sich, dass durch die simulierte Kaubelastung Ermüdungsschäden im Kronenmaterial unterhalb des Kontaktpunktes (OCA) auftraten. Somit stellte sich die Frage, ob sich die *Ermüdungsbeständigkeit* zwischen den verschiedenen CAD/CAM-Materialien unterscheidet. So zeigten in der Publikation 4 (Kapitel 7.7) die CAD/CAM-Komposite signifikant geringe Ermüdungsschäden als die Hybrid- und Glaskeramik. Allerdings wurden die Prüfkörper hier nur am Ende der Kaubelastung mittels herkömmlicher lichtmikroskopischer Analyse von Schnittbildern untersucht. Um ein Monitoring von Ermüdungsbeschädigungen erstmals untersuchen zu können, wurde in der Publikation 5 (Kapitel 7.8) eine neue, zerstörungsfreie Methode mittels OCT angewendet. Somit konnte erstmalig untersucht werden, zu welchem Zeitpunkt die Ermüdungsschäden auftreten bzw. ob sich die Ausbreitung zwischen den CAD/CAM-Materialien unterscheidet. Allerdings weist die OCT-Untersuchungsmethode eine Limitation der Eindringtiefe auf, so dass periphere Ermüdungsschäden nicht erfasst werden können.

Neben einem CAD/CAM-Komposit, einer Hybridkeramik und einer Glaskeramik wurden auch drei verschiedene Generationen Zirkoniumdioxid untersucht. Die Ergebnisse der Versuche zeigten, dass ein linearer Anstieg der Ermüdungsschäden mit zunehmender Kaubelastung für alle CAD/CAM-Materialien mit Ausnahme von 3Y-TZP und 4Y-TZP Zirkoniumdioxid zu sehen war, letztere zeigten als einzige Materialien keine Ermüdungsschäden im Belastungszeitraum. Dabei wiesen die kompositbasierten CAD/CAM-Materialien signifikant geringere Ermüdungsschäden als die Glaskeramik auf, so dass diese neben Zirkoniumdioxiden im Hinblick auf die Ermüdungsbeständigkeit bei Patienten mit erhöhter Kaubelastung Anwendung finden könnten. Trotzdem fehlen für eine abschließende Beurteilung klinische Langzeitdaten zu neuen CAD/CAM-Materialien.

Für eine hohe Randdichtigkeit und Ermüdungsbeständigkeit ist die *Passgenauigkeit* der CAD/CAM-Restaurationen entscheidend. So kann einerseits ein großer marginaler Randspalt zum Auswaschen des Befestigungsmaterials führen, wodurch ein Debonding entsteht und andererseits ein zu großer Zementspalt im okklusalen Bereich Ermüdungsschäden insbesondere von keramischen Restaurationen begünstigen.[12,69,82,94,103,115,123]

Da CAD/CAM-Materialien im subtraktiven Herstellungsverfahren gefertigt werden, spielt auch der voreingestellte und reale Zementspalt eine große Rolle. Daher erfolgte zunächst in der Publikation 6 (Kapitel 7.9) eine Untersuchung der Passgenauigkeit monolithischer CAD/CAM-Kronen mit zwei verschiedenen Zementspaltparametern am Modell. Es konnte gezeigt werden, dass ein voreingestellter Zementspalt von 80 µm zu einer besseren Übereinstimmung zwischen voreingestelltem und realem Zementspalt führt. Somit wurden in der anschließenden klinischen Studie der Publikation 7 (Kapitel 7.10) nur CAD/CAM-Kronen mit einem Zementspalt von 80 µm untersucht. Um alle drei zur Verfügung stehenden Werkstoffgruppen zu berücksichtigen, wurden sowohl in-vitro als auch in-vivo CAD/CAM-Kronen aus Metall, Keramik und Komposit analysiert. Teilweise wurde ein signifikanter Unterschied zwischen den CAD/CAM-Materialien in Bezug auf die Passgenauigkeit festgestellt. Dabei zeigten die Komposite die höchste Passgenauigkeit, gefolgt von Zirkoniumdioxid und Nichtedelmetall.

Während die Passgenauigkeit im marginalen und axialen Bereich in-vitro und in-vivo bei allen CAD/CAM-Materialien im Mittel einen Zementspalt von weniger als 120 µm aufwies, wurde eine signifikant geringere Passgenauigkeit im okklusalen Bereich unabhängig vom CAD/CAM-Material festgestellt. Dies lässt sich auf eine Fräsradiuskorrektur der CAM-Strategie zurückführen. Somit sollte zukünftig bereits im IOS angezeigt werden, welche Bereiche aufgrund herstellungstechnischer Limitation nicht korrekt ausgefräst werden können, damit dies bereits während der Präparation berücksichtigt werden kann. An dieser Stelle könnten auch additive Herstellungstechnologien, welche im Gegensatz zu subtraktiven Verfahren frei in der geometrischen Ausführung sind, helfen, Restaurationen auch im okklusalen Bereich mit einer höheren Passgenauigkeit herzustellen. Allerdings reichen hier zurzeit die werkstoffkundlichen Entwicklungen insbesondere bei den Keramiken und Kompositen noch nicht für definitive Restaurationen aus.

Da die herkömmlichen Untersuchungsmethoden zur Passgenauigkeit ein aufwendiges Laborsetup mit Expertenwissen erfordern und somit nur einer kleinen Gruppe von Zahnärzten zur Verfügung stehen, wurde in den vorliegenden Publikationen 6 und 7 (Kapitel

7.9 und 7.10) eine neue IOS-basierte Messmethode zur Chairside-Bestimmung der Passgenauigkeit am Patienten untersucht. Die Ergebnisse zeigten, dass die neue IOS-Methode auf verschiedene CAD/CAM-Materialien klinisch anwendbar ist. Da durch die zunehmende Digitalisierung bereits in naher Zukunft zu erwarten ist, dass neue CAD/CAM-Materialien und Workflows entstehen, welche eine Anpassung von Fräs- oder Druckparameter erfordern, stellt die Chairside-Kontrolle der Passgenauigkeit ein einfach anwendbares Werkzeug zum Qualitätsmanagement und der Entwicklung neuer Workflows für alle Zahnärzte mit entsprechendem IOS dar.

Die letzten Jahre haben gezeigt, dass die Digitalisierung die Zahnmedizin erreicht hat, sodass in absehbarer Zeit eine flächendeckende Anwendung in der Zahnarztpraxis mit hoher Wahrscheinlichkeit erfolgen wird. Umso wichtiger ist es daher, den Studierenden eine moderne *zahnärztliche Ausbildung* zu ermöglichen. Im Jahr 2002 wurden alle deutschen Hochschulen in Bezug auf die Verwendung von CAS-Lernsystemen in der zahnmedizinischen Ausbildung befragt. Es konnte zwar eine überwiegend positive Grundeinstellung festgestellt werden, die jedoch eine große Diskrepanz zur eher geringen praktischen Umsetzung darstellte.[159] Dies bestätigte eine Hochschulumfrage aus dem Jahr 2010, wo nur an einer einzigen Universität in Deutschland CAD/CAM-Technologie als zusätzlicher Kursbestandteil in der studentischen Ausbildung angeboten wurde.[54]
Vielfach besteht auch heute noch die Ausbildung von Studierenden ausschließlich aus konventionellen Lehrmethoden mit der Vermittlung von traditionellen Workflows zur Zahnersatzherstellung, wie dem Aufwachsen und Gießen von Restaurationen. Auch besteht ein großer Teil der praktischen Lehre aus Zahnpräparationsübungen am Phantomkopf. Dabei ist die Ausbildung manueller Fähigkeit für die zahnärztliche Behandlung unerlässlich, sodass die Herausforderung darin besteht, neue digitale Technologien und Workflows zu implementieren, ohne traditionelle Behandlungskonzepte vollständig zu ersetzen.[19,29,40,158,162] Dies wurde an der Justus-Liebig-Universität Gießen durch die Implementierung zweier Trainingsmodule in den vorklinischen Studienabschnitt gelöst. Für den Erfolg eines Studienkonzeptes ist es jedoch wichtig, auch die Studierenden nach ihren Erfahrungen und ihrer Sichtweise zu befragen.[162] Daher wurde das Gießener Konzept über zwei Jahre systematisch mittels Fragebögen evaluiert, so dass die Perspektive der Studierenden untersucht werden konnten.

Die Ergebnisse der Publikation 8 (Kapitel 7.11) zeigten, dass die Implementierung digitaler Prothetik in die vorklinische Ausbildung von den Studierenden als überwiegend positiv empfunden wurde und sich 96,8 % aller Studierenden vorstellen können, einen IOS bei der späteren Patientenbehandlung in der Zahnarztpraxis zu verwenden. Durch die Integration von CAS-Lehrmethoden ist es zudem möglich, Studierende für eine substanzschonende Präparation zu sensibilisieren und ihnen anhand ihrer eigenen Präparationen zu visualisieren, welche Präparation und Schichtstärke für welches CAD/CAM-Material notwendig ist.

Obwohl die Studierenden in der Studie eine hohe Motivation in Bezug auf digitale Workflows und CAS-Lernsysteme angaben, bevorzugten die meisten Studierenden die Beurteilung der Präparation durch die betreuenden Zahnärzte und nicht durch die Software. Daher können CAS-Ansätze Lehrende in der zahnärztlichen Ausbildung nicht ersetzen, sondern sollten vielmehr als eine zusätzliche Lehrmethode neben der traditionellen Wissensvermittlung manueller Fertigkeiten gesehen werden.

Anhand der vorliegenden Arbeit wird deutlich, dass die Digitalisierung bereits zu großen Fortschritten in der Zahnärztlichen Prothetik geführt hat. Allerdings gibt es bisher noch nicht das *eine* Restaurationsmaterial, welches den natürlichen Zahn perfekt imitiert. Inwiefern hier additive Technologien im Hinblick auf Multimaterial-Druck eine Lösung finden, müssen zukünftige Entwicklungen und Studien zeigen.

Hingegen sind im Bereich der IOS bereits heute Funktionen vorhanden, die über die alleinige digitale Abformung hinausgehen. Hier könnte in Zukunft durch Kombination unterschiedlicher Technologien die diagnostische Anwendung verbessert werden. So wäre die Integration eines OCTs in einen IOS denkbar, um mögliche Ermüdungsschäden oder Karies frühzeitig zu erkennen. Auch im Bereich der automatisierten Qualitätskontrolle von Präparationen und Zahnersatz mittels IOS könnten vorhersagbarere Behandlungsergebnisse erzielt werden.

# 5 Fazit

Erst die Digitalisierung der Arbeitsprozesse in der Zahnärztlichen Prothetik ermöglichte die Verwendung zahlreicher neuer Restaurationsmaterialien. Dabei zeigen die der vorliegenden kumulativen Habilitationsschrift zugrundeliegenden Studien, dass für eine erfolgreiche Anwendung monolithischer CAD/CAM-Kronenversorgung verschiedene Aspekte beachtet werden müssen.

Eine hohe *Randdichtigkeit* kann auch für die in der Literatur kontrovers diskutierten CAD/CAM-Kompositkronen bei entsprechender Befestigung erreicht werden. Zudem können CAD/CAM-Komposite und Zirkoniumdioxide in reduzierter Schichtstärke verwendet werden, wodurch eine minimalinvasive Behandlung möglich ist.

Weiterhin zeigten Zirkoniumdioxide und kompositbasierte Materialien eine hohe *Ermüdungsbeständigkeit*, so dass diese sich für höhere Kaubelastungen eignen.

Im Hinblick auf die *Passgenauigkeit* von CAD/CAM-Kronen ist bei der Fertigung ein voreingestellter Zementspaltparameter von 80 µm zu empfehlen. Da der Zementspalt jedoch insbesondere im okklusalen Bereich fertigungstechnisch häufig nicht erreicht wird, sollte eine Kontrolle der Passgenauigkeit erfolgen. Hierzu können aktuelle IOS verwendet werden, die eine Chairside-Passgenauigkeitskontrolle ermöglichen.

Die vorliegende kumulative Habilitationsschrift zeigt eindrücklich, dass die aufgeführten eigenen Studien nicht ohne die Entwicklung neuer Untersuchungsmethoden möglich gewesen wären. Dabei seien insbesondere beispielhaft die erstmalige Verwendung CAD/CAM-gefräster humaner Zahnstümpfe, das Monitoring von Ermüdungsschäden mittels OCT und die Applikation von IOS über die alleinige Abformung hinaus erwähnt.

Dass auch in der *zahnärztlichen Ausbildung* eine Implementierung digitaler Prothetik dringend notwendig ist, zeigte die Umfrage unter den Studierenden, denn über 95 % der Befragten können sich vorstellen später in der Zahnarztpraxis digital zu behandeln.

Insgesamt wird anhand der Ergebnisse deutlich, dass eine Weiterentwicklung der digitalen Prothetik neue wissenschaftliche Methoden und Lehrkonzepte erfordert. Darüber hinaus sollte auch zukünftig das Potenzial der Digitalisierung gezielt und bei geeigneten Indikationen eingesetzt werden, um eine innovative Patientenversorgung zu ermöglichen.

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# 7 Anhang

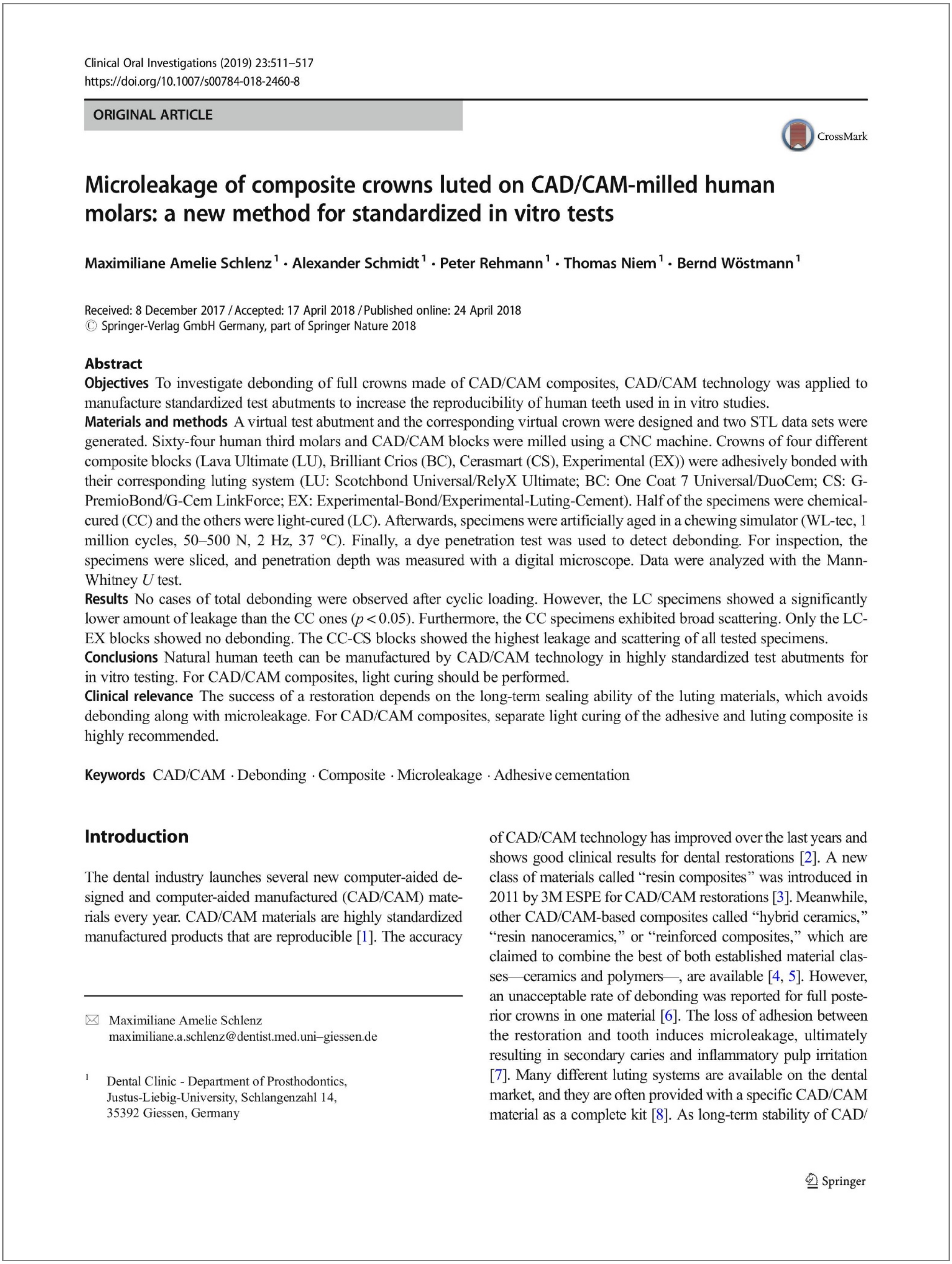
## 7.1 Abkürzungsverzeichnis

| | |
|---|---|
| 3Y-TZP | 3 mol% yttria stabilized tetragonal zirconia polycrystal |
| 4Y-TZP | 4 mol% yttria stabilized tetragonal zirconia polycrystal |
| 5Y-TZP | 5 mol% yttria stabilized tetragonal zirconia polycrystal |
| 6Y-TZP | 6 mol% yttria stabilized tetragonal zirconia polycrystal |
| CAD/CAM | computer-aided design/ computer-aided manufacturing |
| CAS | computer-aided simulation |
| CNC | Computerized Numerical Control |
| FEM | Finite-Elemente-Methode |
| IOS | Intraoralscanner |
| Mio. | Million(en) |
| OCA | occlusal contact area |
| OCT | optischer Kohärenztomographie |
| SD-OCT | Spectral Domain optische Kohärenztomographie |
| SS-OCT | Swept Source optische Kohärenztomographie |
| STL | Standard Tessellation Language |

## 7.2 Abbildungsverzeichnis

## 7.3 Tabellenverzeichnis

## 7.4 Publikation 1



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ORIGINAL ARTICLE

# Microleakage of composite crowns luted on CAD/CAM-milled human molars: a new method for standardized in vitro tests

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## Abstract

**Objectives** To investigate debonding of full crowns made of CAD/CAM composites, CAD/CAM technology was applied to manufacture standardized test abutments to increase the reproducibility of human teeth used in in vitro studies.

**Materials and methods** A virtual test abutment and the corresponding virtual crown were designed and two STL data sets were generated. Sixty-four human third molars and CAD/CAM blocks were milled using a CNC machine. Crowns of four different composite blocks (Lava Ultimate (LU), Brilliant Crios (BC), Cerasmart (CS), Experimental (EX)) were adhesively bonded with their corresponding luting system (LU: Scotchbond Universal/RelyX Ultimate; BC: One Coat 7 Universal/DuoCem; CS: G-PremioBond/G-Cem LinkForce; EX: Experimental-Bond/Experimental-Luting-Cement). Half of the specimens were chemical-cured (CC) and the others were light-cured (LC). Afterwards, specimens were artificially aged in a chewing simulator (WL-tec, 1 million cycles, 50–500 N, 2 Hz, 37 °C). Finally, a dye penetration test was used to detect debonding. For inspection, the specimens were sliced, and penetration depth was measured with a digital microscope. Data were analyzed with the Mann-Whitney *U* test.

**Results** No cases of total debonding were observed after cyclic loading. However, the LC specimens showed a significantly lower amount of leakage than the CC ones ($p < 0.05$). Furthermore, the CC specimens exhibited broad scattering. Only the LC-EX blocks showed no debonding. The CC-CS blocks showed the highest leakage and scattering of all tested specimens.

**Conclusions** Natural human teeth can be manufactured by CAD/CAM technology in highly standardized test abutments for in vitro testing. For CAD/CAM composites, light curing should be performed.

**Clinical relevance** The success of a restoration depends on the long-term sealing ability of the luting materials, which avoids debonding along with microleakage. For CAD/CAM composites, separate light curing of the adhesive and luting composite is highly recommended.

**Keywords** CAD/CAM · Debonding · Composite · Microleakage · Adhesive cementation

## Introduction

The dental industry launches several new computer-aided designed and computer-aided manufactured (CAD/CAM) materials every year. CAD/CAM materials are highly standardized manufactured products that are reproducible [1]. The accuracy of CAD/CAM technology has improved over the last years and shows good clinical results for dental restorations [2]. A new class of materials called "resin composites" was introduced in 2011 by 3M ESPE for CAD/CAM restorations [3]. Meanwhile, other CAD/CAM-based composites called "hybrid ceramics," "resin nanoceramics," or "reinforced composites," which are claimed to combine the best of both established material classes—ceramics and polymers—, are available [4, 5]. However, an unacceptable rate of debonding was reported for full posterior crowns in one material [6]. The loss of adhesion between the restoration and tooth induces microleakage, ultimately resulting in secondary caries and inflammatory pulp irritation [7]. Many different luting systems are available on the dental market, and they are often provided with a specific CAD/CAM material as a complete kit [8]. As long-term stability of CAD/

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CAM composite blocks correlates with the luting system used, this approach seems to be reasonable [9].

Though several studies on the material characteristics and luting protocols for these CAD/CAM composites are available, investigations on microleakage are rare [5, 9–12]. In these studies, restorations were either adhesively luted on artificial test abutments or on manually prepared teeth [13]. Even the most recent studies used manually prepared human molars for the investigation of new CAD/CAM materials [14–17]. Though artificial test abutments allow for highly standardized and reproducible results, they do not represent the clinical situation with regard to the luting process. For analyzing luting materials, there is a consensus that either bovine or human teeth are required [18]. However, up to now, bovine and human teeth in all studies were prepared manually. This inevitably reduces standardization and the reproducibility of the experiments, thus impeding an objective analysis. To the authors' knowledge, this is the first study that takes advantage of the progressive digitalization process for research purposes in manufacturing standardized test abutments of human teeth to increase experimental reproducibility.

Artificial aging of dental restorations in a chewing simulator is a common method to simulate the clinical oral situation [12, 15, 19]. A recurring load simulates the weakening of material as a result of the chewing process [20, 21].

Therefore, this study analyzed microleakage in full-crown CAD/CAM composite restorations luted with their corresponding luting system on CAD/CAM-milled test abutments of human molars after artificial aging. For all systems, both curing modes—chemical curing and light curing—were analyzed and the following null hypothesis was tested: After artificial aging, there is no difference in microleakage between CAD/CAM-milled human molars and full posterior crowns, regardless of the curing mode.

## Materials and methods

### Manufacturing of CAD/CAM-milled test abutments of human teeth

Sixty-four human caries-free and undamaged third molars ($n = 8$ per group) extracted for therapeutic reasons were anonymously collected with the consensus of the patients. After cleaning, the teeth were stored according to ISO/TS 11405 (first in 0.5% chloramine-T trihydrate solution (Lysoform, Berlin, Germany) for 7 days, followed by distilled water for a maximum of 6 months). A special sample holder made of polyoxymethylene was designed for placing the tooth in a CNC milling machine (Mikron HSM 400, GF Machining Solutions, Geneva, Switzerland). Before adhesive cementation, the occlusal tooth relief was ground flat under water cooling with a plate grinding machine (Struers, Willich, Germany). Subsequently, the flat occlusal surface was adhesively bonded (LuxaBond-Total Etch Primer A+B, DMG, Hamburg, Germany) to the bottom of a Perspex carrier plate. A template was used for accurate positioning. There was a distance of 8 mm between the flat occlusal surface of the tooth and the top of the holder (Fig. 1). First, the root dentine was etched with 37% phosphoric acid (Etching Gel, DMG, Hamburg, Germany) for 15 s, cleaned under flowing water, and gently air-dried. A dual-curing bonding system (LuxaBond-Total Etch Primer A+B, DMG, Hamburg, Germany) was applied and light-cured (LC). Afterwards, the tooth was mounted in a core buildup material (LuxaCore Z-dual, DMG, Hamburg, Germany). For anti-rotational support, three miniature screws were inserted. For CAD/CAM milling of natural teeth, a virtual test abutment was constructed with the CAD software Rhinoceros 5 (Service Release 12, McNeel Europe, Barcelona, Spain) and a Standard Tissue Language (STL) file was generated. The test abutment was designed with a height of 4.0 mm, a mesio-distal width of 9.5 mm, and a bucco-oral width of 7.5 mm, with a convergence angle of 6°, a 1.0 mm chamfer with an angle of 30°, and an anatomically shaped surface with round edges (Fig. 2). The sample holder with the tooth was mounted into the CNC machine, and the test abutments were milled under permanent water cooling. Figure 3 shows the finalized test abutment in the sample holder. The teeth were kept continuously damp throughout the process.

### Manufacturing of CAD/CAM-milled crowns

First, a crown corresponding to the virtual test abutment was designed with CAD software (version 2.8.8.5, Dental System, 3shape, Copenhagen, Denmark). A total of four CAD/CAM composite blocks were selected for this investigation: Lava

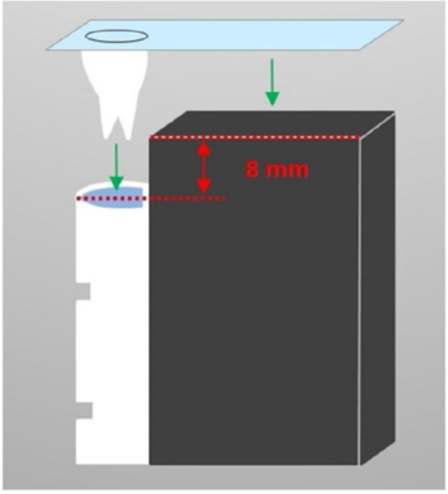


**Fig. 1** Positioning of the tooth in the sample holder

**Fig. 2** STL data set of the test abutment

Ultimate (LU), Brilliant Crios (BC), Cerasmart (CS), and Experimental (EX). The parameters of the crown design were defined according to the smallest common denominator of all manufacturers' instructions (occlusal layer thickness 1.5 mm, cervical thickness 1.0 mm, cement gap 80 μm, parameter of fit 15 μm). All crowns were milled in the same CNC machine with the test abutments under water cooling, according to the manufacturers' instructions. After the milling process, the integrity of all specimens was verified under a digital microscope (Smartzoom 5, Zeiss, Jena, Germany), and the surface of each crown was manually polished with the recommended polishing system (Table 1).

## Adhesive cementation of specimens

All crowns were adhesively luted on a randomly selected test abutment according to the instructions for the specific luting system. The adhesive surface was sandblasted with aluminum oxide powder (50 μm, Edelkorund, Harnisch+Rieth, Winterbach, Germany) at 1.5 bar for BC and CS and 2.0 bar for LU and EX. Before the cementation procedure, all teeth were cleaned with pumice powder and distilled water. The milled surface was etched with 37% phosphoric acid for 15 s (Etching Gel, DMG, Hamburg, Germany, batch no: 749665), cleaned with distilled water, and gently air-dried. A loading device was used to ensure that all specimens were cemented under a standardized pressure of 6 N [22].

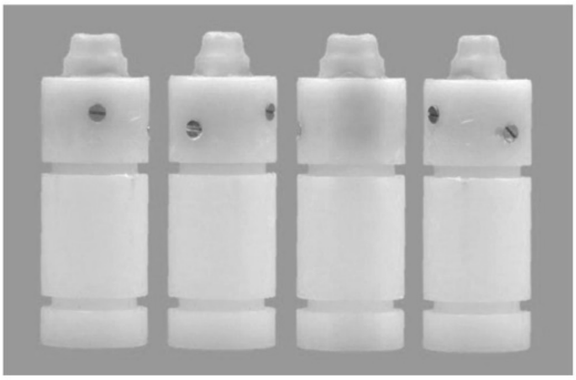


**Fig. 3** CAD/CAM-milled human test abutment in the sample holder

Half of the specimens of each material were only chemical-cured (CC) and the others were additionally light-cured (LC). For the LC specimens, a tungsten-halogen light polymerization unit that produces 800 mW/cm$^2$ (Elipar Trilight, 3M ESPE, St. Paul, USA) was used. Before each application, the light intensity was checked. Both the adhesive and luting cements were separately LC at all five surfaces. The polymerization time for the LC specimens depended on their instructions of use. For the CC specimens of BC and CS groups, a second component for the adhesive was applied. Finally, all specimens were stored in distilled water at 37 °C for 24 h according to the ISO/TC 11405:2003. Table 1 shows the material combinations for each group.

## Artificial aging

All specimens were artificially aged by compressive cyclic loading in a high load chewing simulator (PrematecF1000, wl-tec GmbH, Wertheim, Germany). The sample holder was made of aluminum and polyetherketone (PEAK). A standardized stainless steel antagonist (R1, SD Mechantronik GmbH, Feldkirchen, Germany) with a radius of 3.18 mm was used, which corresponds to an average cuspal radius of 2–4 mm [19]. A uniaxial vertical load of 50–500 N was applied for 1 million cycles, which simulates 4 years of oral service [12]. All specimens were tested in distilled water at 37 ± 2 °C.

## Analysis of microleakage

For the investigation of microleakage, a dye penetration test was performed using a 0.5% aqueous fuchsin solution (C.l. 42510, Carl Roth GmbH + Co KG, Karlsruhe, Germany, batch no: 276244301).The specimens were stored for 24 h at room temperature and afterwards cleaned with distilled water [12]. Dye penetration over the apex or lateral canals was prevented by mounting the specimens in core built-up material. To analyze microleakage, the specimens were sectioned mesio-distally into four equidistant slices under constant water cooling (IsoMet1000, Buehler, IL, USA) in a special sample holder to ensure that all specimens were sliced in the same area. Each slice was investigated with a digital microscope (Smartzoom 5, Zeiss, Jena, Germany). The percentage of leakage in relation to the heights of the test abutment was determined at sixteen points per specimen using microscopy analysis software (Smartzoom 5, version 1.1, Zeiss, Jena, Germany). Finally, the arithmetic mean of all sixteen single values was calculated for each specimen.

**Table 1** Materials and combinations used in the study (information provided by manufacturer)

| Code | Curing mode | Manufacturer | Block name (batch no.)/color | Adhesive (batch no.)/ pH value | Luting cement (batch no.) | Polishing system (manufacturer) |
|---|---|---|---|---|---|---|
| LU | Light curing (LC)<br>Chemical curing (CC) | 3M ESPE (St. Paul, MN, USA) | Lava Ultimate (N763596)/A2 | Scotchbond Universal (625559)/2.7 | RelyX Ultimate (623858) | Renfert all-in-one (Renfert, Hilzingen, Germany) |
| BC | Light curing (LC) | Coltene (Altstätten, Switzerland) | Brilliant Crios (H16204)/A2 | One Coat 7 Universal (G84296)/2.8 | DuoCem (H13220) | Diatech Polishers (Coltene) |
|  | Chemical curing (CC) |  |  | One Coat 7 Universal (G84296)/2.8, One Coat 7.0 Activator (H19891) |  |  |
| CS | Light curing (LC) | GC (Tokyo, Japan) | Cerasmart (1412101)/A2 | G-Multi Primer (1607131), G-Premio Bond (1607141)/1.5 | G-Cem LinkForce (1607061) | Diapolisher Paste (GC) |
|  | Chemical curing (CC) |  |  | G-Multi Primer (1607131), G-Premio Bond (1607141)/ 1.5, G-Premio Bond DCA (1604041) |  |  |
| EX | Light curing (LC)<br>Chemical curing (CC) | – | Experimental-Block/A2 | Universalbond/2.6 | Dual-curing composite | Renfert all-in-one (Renfert, Hilzingen, Germany) |

The statistical analysis was performed using SPSS Statistics (version 24, IBM, Armonk, USA). The data were subjected to a Mann-Whitney *U* test because the distribution was not normal. The number of specimens per group ($n = 8$) was low, so non-parametric testing was used. Due to the risk of alpha-error accumulation, *p* values were corrected with the Bonferroni-Holm method. The level of significance was $p < .05$.

## Results

During the chewing simulations, no crown failed or debonded totally. However, the dye penetration test detected a partial loss of adhesion for all tested groups except the LC experimental material. Additionally, the LC-LU group only showed leakage at a single measurement site. The statistical analysis indicates a significant reduction of microleakage for all LC groups, compared to CC groups (Fig. 4, $p > .05$). It is worth noting that all CC groups showed widely scattered microleakage. Figure 5 shows an example of a measurement point with leakage up to the occlusal surface of the test abutment (CS-CC) and one with no leakage (LU-LC).

The null hypothesis that there is no difference in microleakage between CAD/CAM-milled human molars and full posterior crowns regardless of the curing mode had to be rejected. The results clearly show that the curing mode has a significant impact on the sealing ability of the CAD/CAM composites with their corresponding luting system.

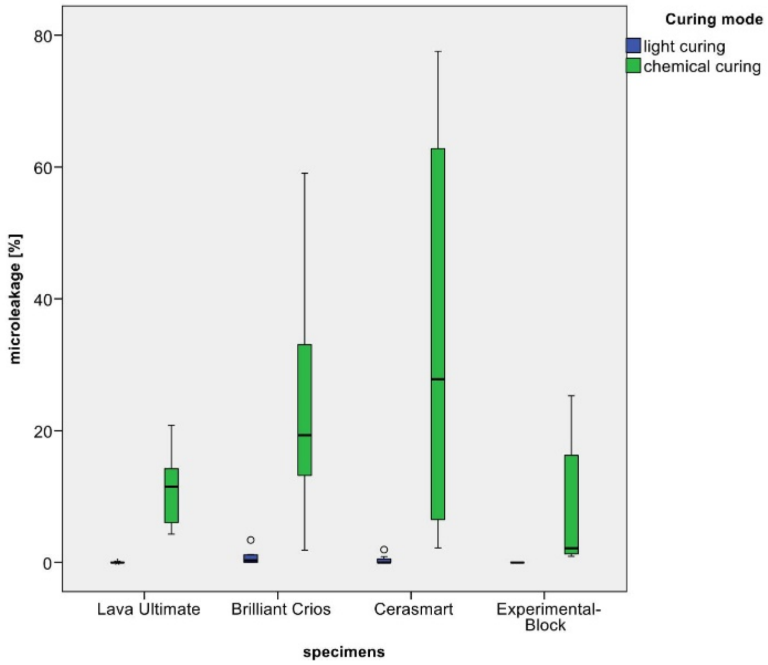
## Discussion

Numerous authors have discussed whether in vitro results are transferable to an intraoral situation. However, it can be assumed that products that show good laboratory results will at least show similar results during in vivo performance [16, 23]. To compare different studies, highly standardized and completely described setups are necessary.

Milling of crowns and test abutments on the basis of one STL data set enabled a highly standardized manufacturing of the test components. Other studies used manually prepared teeth [14–17]. Manually manufacturing identical test abutments is not possible even when only one examiner prepares all specimens. Even with the use of a parallelometer for preparation, only the convergence angle can be standardized [12, 24]. However, with CAD/CAM techniques, the whole shape, including the area below the margin line, can be designed and reproducibly milled. Thus, each specimen examined had the same exact adhesive surface size. Neither the preparation nor the individual tooth size was influencing variables. However, human teeth are natural substrates which differ in their composition and structure [25]. Due to the limited availability of caries-free and undamaged third molars with sufficient size for the CAD/CAM process, only eight specimens per group were used, which is a clear limitation of the present study. However, a number of eight specimens per group have been established for in vitro testing with natural tooth substrate [8, 12, 26].

The sealing ability of the restoration depends, on the one hand, on the luting system and, on the other hand, on the

**Fig. 4** Boxplot of all specimens



restoration material itself. In general, composite crowns require adhesive cementation [11, 27]. Due to the reported debonding cases with CAD/CAD composite restorations, we decided to investigate the dual-curing luting system of each CAD/CAM composite block for two curing modes—light curing (LC) and chemical curing (CC) [6]. Meanwhile, most modern composite cements are dual-curing products combining both curing modes to warrant polymerization even in difficult light accessible areas [28]. But in daily practice, time-saving applications without LC are popular. However, if LC is omitted (sole CC), it shows a lower degree of conversion (DC) which results in lower mechanical properties, increased solubility, and microleakage [29]. The results of the present study show that LC is absolutely recommend. This is in good accordance to the literature [16].

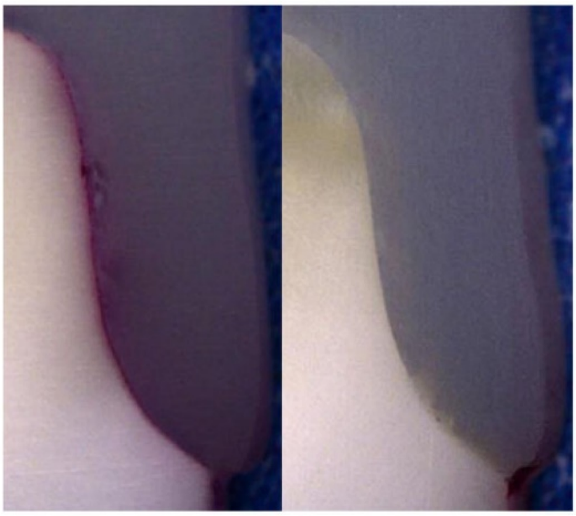


**Fig. 5** Example of a measurement point with leakage up to the occlusal surface (left) and another with no leakage (right)

Crown cementation was carried out under laboratory conditions with a constant load. The cementation procedures given in the manufacturers' instructions were followed strictly. Taking into account that the luting materials were developed for intraoral temperatures, all specimens were stored for 24 h at 37 °C before loading. As only the manufacturer's recommended luting system was used, only comparisons between the curing modes within each material were possible and not comparisons between the materials themselves. Impairment of the chemical curing process of the luting composite by the acidic environment of universal adhesives has also been repeatedly discussed [9, 30]. Some luting composites, such as RelyX Ultimate, contain a new sodium sulfate-based initiator system, which should be able to initiate the curing process even in an acidic environment [29]. However, the most recent studies showed a low degree of conversion for chemical curing of RelyX Ultimate, which indicates an insufficiently activated polymerization [9]. The pH value of the universal adhesives used ranges from 1.5 to 2.8. Acid adhesive may possibly be the cause of the high microleakage that occurred with chemical curing in the CS group. Using chemical curing alone with a dual-curing luting composite can result in a lower degree of polymerization, with reduced mechanical stability and increased solubility [27, 30]. In the present study, the CC groups showed a significantly higher degree of microleakage than the LC groups. *Cassina* et al. found a significantly lower mechanical stability for the CC DuoCem luting composite, used in the present study [31]. *De Souza* et al. discussed that the degree of polymerization of dual-curing luting composites depends on the particular product and their individual requirements for light activation to achieve complete polymerization [29]. This could explain the different scattering of data for all CC groups based on the different amounts of chemical initiators.

In addition to the luting system, the CAD/CAM material has an impact on the sealing ability. The amount of light transmission through the restoration depends on factors such as tooth color, restoration thickness, and internal structure [27–29, 32]. Therefore in the present study, all CAD/CAM composites had the same color and restoration thickness.

Compared to ceramic materials, the new CAD/CAM composites have a lower elastic modulus, and other authors have discussed the possibility that elastic deformation occurs, especially in the marginal area of the crown and that this may cause debonding [5, 33]. Taking into account the results of the present study, it has to be concluded that CAD/CAM composites need a high bond strength to withstand high loads. This can be achieved by a separate light curing of the adhesive and the luting composite.

Normal masticatory loads range from 50 to 250 N, but patients with parafunctions such as bruxism show maximum loads of 500–800 N [12, 34]. Moreover, chewing does not impose a single static load but a recurring dynamic one, whereby the restorative material is weakened [20, 21]. The use of CAD/CAM composites is advertised by many manufacturers for use in patients with bruxism, which is why we tested the crowns under higher loads. However, it has to be considered that the load was applied in a uniaxial direction as occurs during parafunctions such as pressing, whereas in bruxism, lateral shear forces occur, for which no statement can be made.

## Conclusion

The present study showed that it is possible to achieve a standardized preparation of human teeth for in vitro testing using a CAD/CAM process. For the cementation of CAD/CAM composites, following the manufacturer instructions for use is strictly recommended. Within the limitation of this in vitro study, a separate light curing of adhesives and dual-curing composite is recommended for the cementation of CAD/CAM composite full crowns.

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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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## 7.5 Publikation 2

FUNDAMENTAL RESEARCH

# Influence of Different Luting Systems on Microleakage of CAD/CAM Composite Crowns: A Pilot Study

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***Purpose***: To investigate whether *(1)* the curing mode and *(2)* the use of the corresponding or noncorresponding crown luting system have an impact on the microleakage of computer-aided design/computer-assisted manufacture (CAD/CAM) composite crowns after chewing simulation. ***Materials and Methods:*** Two CAD/CAM composite blocks (Lava Ultimate [n = 20] and LuxaCam Composite [n = 20]) and their luting systems and curing modes (light curing [LC] or chemical curing [CC]) were investigated. A dye penetration test was used to detect the presence of microleakage. ***Results:*** Independently of the luting system, the LC groups showed a significantly lower microleakage compared to the CC groups ($P < .05$). Furthermore, the CC groups exhibited a reduction of microleakage if the CAD/CAM block and luting system were from the same manufacturer. ***Conclusion:*** For the CC mode, the corresponding block and luting system should be used. *Int J Prosthodont 2019;32:530–532. doi: 10.11607/ijp.6210*

A new class of computer-aided design/computer-assisted manufacture (CAD/CAM) materials called nanoceramic resins, indicated for single-tooth restorations, has been introduced to the dental market. The materials, developed with the aim of combining the mechanical and esthetic advantages of composite and ceramic materials,[1] consist of a composite matrix embedded with different ceramic particles. In vitro studies have shown a higher resistance to fracture of nanoceramic resins compared to some glass-ceramics and a low antagonist wear due to their polymer phase.[1–3] However, long-term clinical data are lacking.

The sealing ability of the luting system has a strong impact on the long-term success of a restoration.[4,5] Studies investigating the sealing between CAD/CAM composites and their corresponding luting systems (ie, the luting systems provided by the block manufacturer for the respective CAD/CAM materials) showed that light curing of adhesive and dual-curing composite result in a significantly lower microleakage compared to solely chemical curing systems.[4,5] In daily practice, many clinicians prefer to use only one luting system instead of the corresponding luting system for each material for practical reasons. However, the effect of noncorresponding material/luting systems on microleakage has not been yet investigated. Therefore, the aim of this in vitro study was to investigate whether the curing mode and the use of the corresponding or noncorresponding crown luting system have an impact on the microleakage of CAD/CAM composite crowns after chewing simulation.

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## MATERIALS AND METHODS

For the manufacturing of standardized test specimens (n = 40), one standard tessellation language (STL) dataset for the abutments (4.0-mm height, 9.5-mm mesio-distal width, 7.5-mm bucco-oral width, 6-degree convergence angle, 1.0-mm chamfer) and one for the crowns (1.5-mm occlusal layer thickness, 1.0-mm cervical thickness) were designed (Rhino 5 SR 12, McNeel Europe).[5] The abutments were CAD/CAM–milled third molars, and the crowns were made of two different CAD/CAM composite blocks (LuxaCam Composite [LX], DMG [n = 20]; Lava Ultimate [LU], 3M ESPE [n = 20]).[5] Before adhesive cementation, the inner surfaces of the crowns were sandblasted with aluminum oxide powder (50 µm, Edelkorund, Harnisch+Rieth) at 2.0-bar pressure according to the manufacturer's instructions. The test abutments were etched with 37% phosphoric acid (Etching Gel, DMG) for 15 seconds. Specimens were divided into four groups (n = 10):

1. LX crowns with LuxaBond Universal/PermaCem Universal (DMG)
2. LX crowns with Scotchbond Universal/RelyX Ultimate (3M ESPE)
3. LU crowns with LuxaBond Universal/PermaCem Universal
4. LU crowns with Scotchbond Universal/RelyX Ultimate

Each group was divided into two subgroups, in which half of the specimens (n = 5) were light cured (LC) and the other half (n = 5) were chemically cured (CC) (Fig 1). Before chewing simulation, all specimens were stored in distilled water at 37°C for 24 hours. Thereafter, cyclic loading (50 to 500 N) was applied in distilled water at 37 ± 2°C in a chewing simulator (prematec F1000, WL-tec) for 1 million cycles with a standardized stainless steel antagonist (R1, SD Mechatronik).[6] Finally, a dye penetration test with 0.5% aqueous fuchsin solution (C.I. 42510, Carl Roth, batch no.: 276244301) was used to detect microleakage.[5,7] For the measurement of the penetration depth, the specimens were sectioned mesiodistally in equidistant slices (IsoMet 1000, Buehler) and inspected under a digital microscope (Smartzoom 5, Zeiss).[5] The percentage of microleakage was calculated for each specimen with microscopy analysis software (Smartzoom 5, version 1.1, Zeiss).

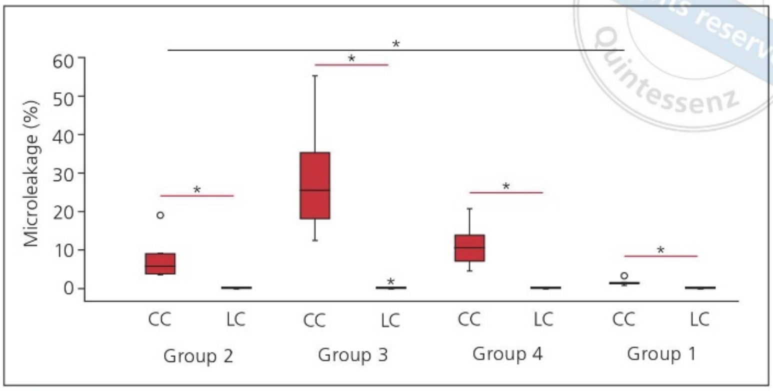

**Fig 1** Boxplots of all test groups. Group 1 = LuxaCam (LX) crowns with LuxaBond Universal/PermaCem Universal; Group 2 = LX crowns with Scotchbond Universal/RelyX Ultimate; Group 3 = Lava Ultimate (LU) crowns with LuxaBond Universal/PermaCem Universal; Group 4 = LU crowns with Scotchbond Universal/RelyX Ultimate; LC = light curing; CC = chemical curing. $^{*}P < .05$.

For statistical analyses, SPSS Statistics (version 24, IBM) was used. Because some test groups showed distribution differences, values of zero, and wide scattering, a nonparametric median test was performed. The level of statistical significance was set at $P < .05$.

## RESULTS

All specimens survived chewing simulation. Regardless of the luting system and CAD/CAM block, the LC specimens showed a significantly lower microleakage compared to the CC specimens (Fig 1, $P < .05$). All CC groups exhibited a reduction of microleakage (significant only for LX, $P < .05$) if the corresponding luting system and block were used. Group 1 showed the lowest microleakage of the CC groups (mean ± standard deviation 1.57% ± 0.65%), followed by group 2 (8.26% ± 6.49%), group 4 (11.42% ± 6.23%), and group 3 (29.28% ± 16.64%). Figure 2 shows an example of specimens with and without microleakage.

## DISCUSSION

Because of the pilot nature of this study and the low number of specimens, the results must be interpreted with care. Nevertheless, CAD/CAM composites showed almost no microleakage if the LC mode was applied, which is in good agreement with the literature.[5] A higher microleakage rate was found for the CC groups, which can be readily accounted for by a lower degree of conversion for the sole CC mode.[4,8] Furthermore, the specimens with a corresponding luting system and block showed a significantly lower microleakage. This finding leads to the assumption that manufacturers optimized

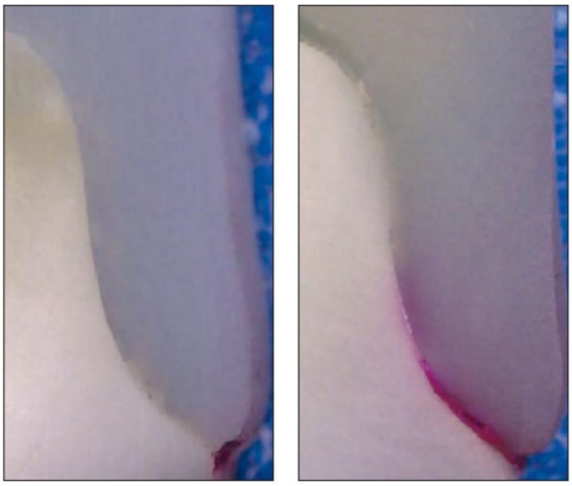

**Fig 2** Example of a specimen without (left) and with (right) microleakage.

their adhesive luting systems for their composite blocks. As loss of adhesion may result in secondary caries or inflammatory pulp irritation, the avoidance of microleakage is extremely important for the long-term success of restorations.[9] Thus, it is advisable in daily practice—despite the extra effort—to use a CAD/CAM material with its corresponding luting system.

## CONCLUSIONS

Within the limitations of this pilot study, the results support the use of a CAD/CAM composite with its corresponding luting system from the same manufacturer, especially if the CC mode has to be applied. Overall, the LC specimens showed significantly lower microleakage compared to CC specimens.

## ACKNOWLEDGMENTS

The authors would like to thank the dental company DMG for donation of their materials. In addition, they gratefully acknowledge the support of their biostatistician, Dr Johannes Herrmann, for the statistical analyses. The authors reported no conflicts of interest related to this study.

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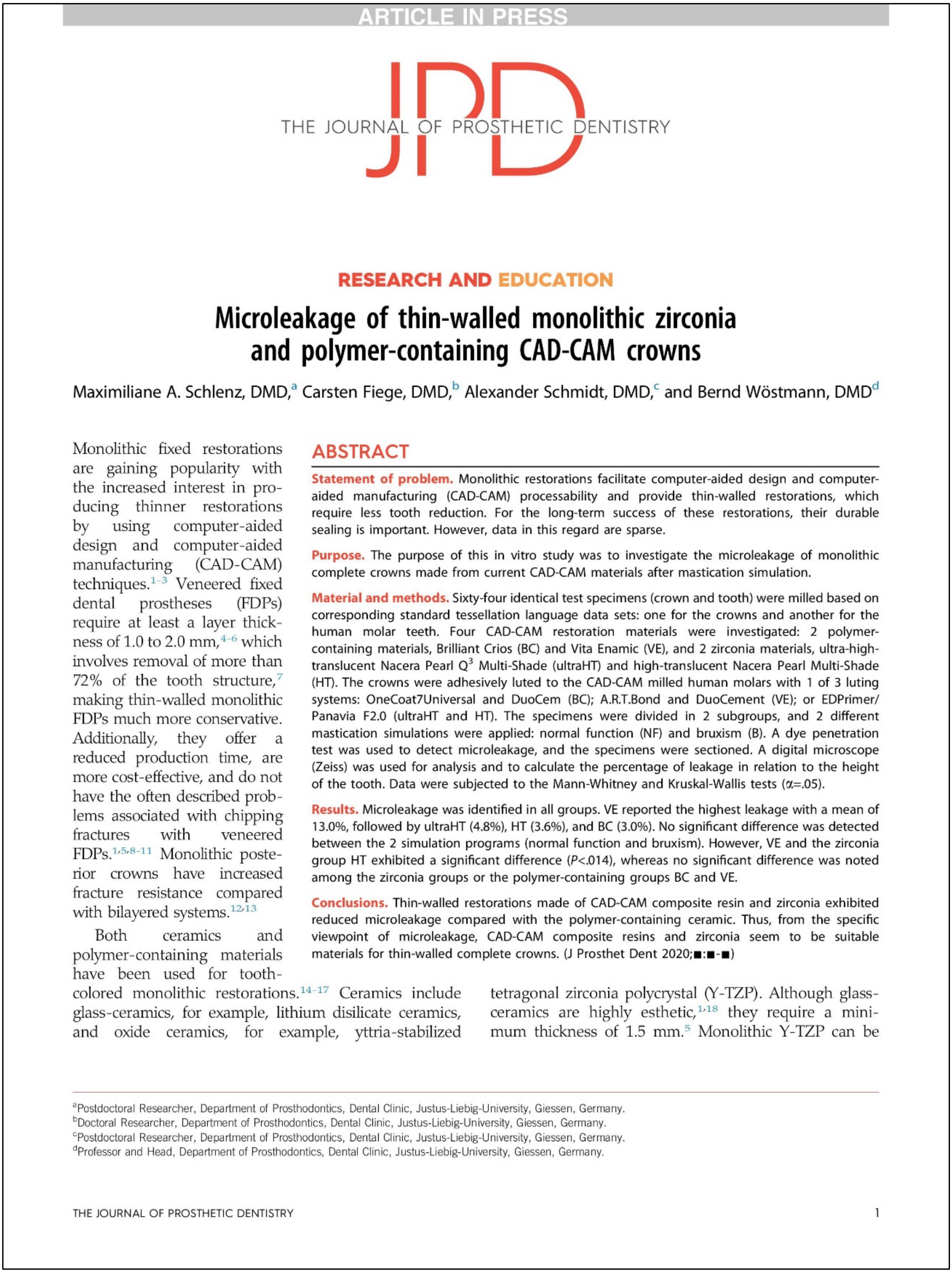
Literature Abstract

### Performance and Outcome of Zirconia Dental Implants in Clinical Studies: A meta-Analysis

The purpose of this study was to evaluate implant survival, peri-implant marginal bone loss, technical and biologic complications, and esthetic outcomes of zirconia implants in clinical studies. Electronic (MEDLINE, EmBase) and hand searches were performed to identify clinical studies published between January 2004 and March 2017 investigating zirconia dental implants with a mean follow-up of at least 12 months. Primary outcomes were implant survival and peri-implant marginal bone loss. Secondary outcomes included technical and biologic complications, as well as esthetic outcomes. Meta-analyses were performed to estimate implant survival and marginal bone loss. From 943 titles, 264 abstracts were selected. Subsequently, 80 full-text articles were screened, and 18 studies were included for data extraction. One-piece (14 studies) and two-piece (4 studies) zirconia implants were investigated. Commercially available (CA) (510 implants, 398 patients) and not commercially available (NCA) (618 implants, 343 patients) zirconia implants were identified. For CA implants (follow-up: 12 to 61.20 months), technical complications (1.6%), implant fractures (0.2%), and biologic complications (4.2%) were reported. Meta-analyses estimated 1- and 2-year survival rates of 98.3% (95% confidence interval [CI] 97.0% to 99.6%) and 97.2% (95% CI 94.7% to 99.7%), respectively, and a mean 1-year marginal bone loss of 0.7 mm (95% CI 0.4 to 1.0 mm). Since 2004, the survival rates of CA implants have significantly improved compared to NCA implants. CA one-piece zirconia implants showed similar 1- and 2-year mean survival rates and marginal bone loss after 1 year compared to published data for titanium implants. However, more clinical long-term data are needed to confirm the presently evaluated promising short-term outcomes.

**Roehling S, Schlegel KA, Woelfler H, Gahlert M.** *Clin Oral Implants Res* 2018 Oct;29(suppl 16):s135–s153. **References:** 58.
**Reprints:** Stefan Roehling, s.roehling@me.com —*Brian Fitzpatrick, Australia*

## 7.6 Publikation 3



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RESEARCH AND EDUCATION

# Microleakage of thin-walled monolithic zirconia and polymer-containing CAD-CAM crowns

Maximiliane A. Schlenz, DMD,[a] Carsten Fiege, DMD,[b] Alexander Schmidt, DMD,[c] and Bernd Wöstmann, DMD[d]

## ABSTRACT

**Statement of problem.** Monolithic restorations facilitate computer-aided design and computer-aided manufacturing (CAD-CAM) processability and provide thin-walled restorations, which require less tooth reduction. For the long-term success of these restorations, their durable sealing is important. However, data in this regard are sparse.

**Purpose.** The purpose of this in vitro study was to investigate the microleakage of monolithic complete crowns made from current CAD-CAM materials after mastication simulation.

**Material and methods.** Sixty-four identical test specimens (crown and tooth) were milled based on corresponding standard tessellation language data sets: one for the crowns and another for the human molar teeth. Four CAD-CAM restoration materials were investigated: 2 polymer-containing materials, Brilliant Crios (BC) and Vita Enamic (VE), and 2 zirconia materials, ultra-high-translucent Nacera Pearl $Q^3$ Multi-Shade (ultraHT) and high-translucent Nacera Pearl Multi-Shade (HT). The crowns were adhesively luted to the CAD-CAM milled human molars with 1 of 3 luting systems: OneCoat7Universal and DuoCem (BC); A.R.T.Bond and DuoCement (VE); or EDPrimer/Panavia F2.0 (ultraHT and HT). The specimens were divided in 2 subgroups, and 2 different mastication simulations were applied: normal function (NF) and bruxism (B). A dye penetration test was used to detect microleakage, and the specimens were sectioned. A digital microscope (Zeiss) was used for analysis and to calculate the percentage of leakage in relation to the height of the tooth. Data were subjected to the Mann-Whitney and Kruskal-Wallis tests ($\alpha$=.05).

**Results.** Microleakage was identified in all groups. VE reported the highest leakage with a mean of 13.0%, followed by ultraHT (4.8%), HT (3.6%), and BC (3.0%). No significant difference was detected between the 2 simulation programs (normal function and bruxism). However, VE and the zirconia group HT exhibited a significant difference ($P<.014$), whereas no significant difference was noted among the zirconia groups or the polymer-containing groups BC and VE.

**Conclusions.** Thin-walled restorations made of CAD-CAM composite resin and zirconia exhibited reduced microleakage compared with the polymer-containing ceramic. Thus, from the specific viewpoint of microleakage, CAD-CAM composite resins and zirconia seem to be suitable materials for thin-walled complete crowns. (J Prosthet Dent 2020;■:■-■)

Monolithic fixed restorations are gaining popularity with the increased interest in producing thinner restorations by using computer-aided design and computer-aided manufacturing (CAD-CAM) techniques.[1-3] Veneered fixed dental prostheses (FDPs) require at least a layer thickness of 1.0 to 2.0 mm,[4-6] which involves removal of more than 72% of the tooth structure,[7] making thin-walled monolithic FDPs much more conservative. Additionally, they offer a reduced production time, are more cost-effective, and do not have the often described problems associated with chipping fractures with veneered FDPs.[1,5,8-11] Monolithic posterior crowns have increased fracture resistance compared with bilayered systems.[12,13]

Both ceramics and polymer-containing materials have been used for tooth-colored monolithic restorations.[14-17] Ceramics include glass-ceramics, for example, lithium disilicate ceramics, and oxide ceramics, for example, yttria-stabilized tetragonal zirconia polycrystal (Y-TZP). Although glass-ceramics are highly esthetic,[1,18] they require a minimum thickness of 1.5 mm.[5] Monolithic Y-TZP can be

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**Clinical Implications**

With respect to microleakage, thin-walled monolithic CAD-CAM crowns made of zirconia or composite resin seem to be suitable for clinical application. However, other aspects (for example, wear or fracture resistance) also need to be considered.

used with a reduced thickness because of its high fracture resistance,[1,2,4,10] which provides adequate strength even for posterior FDPs.[4,19,20] Earlier zirconia formulations have been thoroughly investigated and exhibit the highest flexural strength in ceramics without chipping.[1,2,8,10] However, these 3 mol% yttria zirconias (3Y-TZP) are opaque and have poorer esthetics than glass-ceramics.[12] This limitation is overcome by more translucent 5 or 6 mol% yttria cubic zirconias (5Y-TZP or 6Y-TZP) but at the cost of reduced flexural strength, which is half that of 3Y-TZP.[9,20] Additionally, increased antagonist wear of zirconia compared with natural enamel has been reported.[21,22]

Polymer-containing CAD-CAM materials have been marketed as a less brittle alternative.[23-27] Schlichting et al[19] reported that 0.6-mm CAD-CAM composite resin veneers exhibited more fatigue resistance than ceramics. Other studies have also reported comparable survival rates and fatigue strength,[27,28] with some studies even reporting that polymer-containing CAD-CAM materials withstand high masticatory forces if they are appropriately luted.[29,30] Nevertheless, patients with parafunction often do not only have increased masticatory forces but also generate shear stress.[31] Beier et al[30] reported a 2.3-fold increased risk of restoration failure if provided for patients with bruxism. A prevalence of bruxism of 20% has been reported.[32]

In addition to fracture resistance, the long-term stability of a restoration depends on marginal sealing.[33] However, studies investigating microleakage of CAD-CAM crowns are sparse. Therefore, the purpose of this in vitro study was to compare microleakage after 2 different mastication simulations (normal function [NF] and bruxism [B]) in thin-walled complete crowns made from zirconia (3Y-TZP and 6Y-TZP) and polymer-containing CAD-CAM materials. The null hypothesis tested was that after mastication simulation, the amount of microleakage would not be affected by the loading program (NF or B) or the CAD-CAM material.

## MATERIAL AND METHODS

To manufacture standardized test specimens (n=16), 2 standard tessellation language (STL) data sets were generated. The natural tooth test specimen was designed anatomically with a cervical reduction of 0.6 mm and a rounded chamfer line of 30 degrees (Rhinoceros 5 Service Release 12; McNeel Europe). The height was 4.0 mm, and the mesiodistal width was 9.5 mm. The buccolingual width was 7.5 mm with a convergence angle of 6 degrees (Fig. 1). Only caries-free and undamaged extracted human molar teeth were used.[34,35] After obtaining patient consent, the teeth were immediately stored according to ISO/TS 11405.[36] The CAD-CAM milling of teeth occurred in a computerized numerical control (CNC) milling machine with constant water cooling as described in a previous study.[28] The prepared teeth were stored in moist conditions at all times.

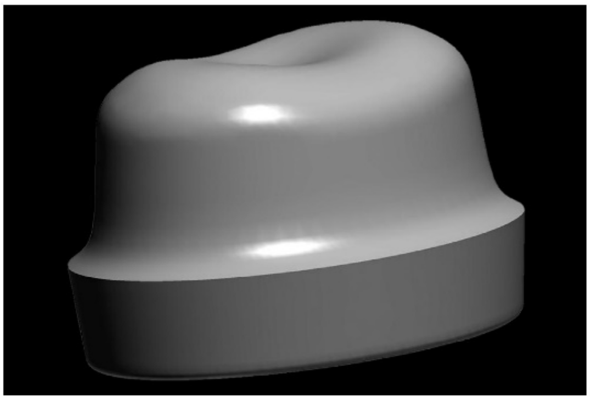

**Figure 1.** Standard tessellation language (STL) data set of tooth[28] with minimal invasive preparation (0.6 mm cervical reduction).

The second STL data set was designed for the crowns with an occlusal layer thickness of 1.2 mm, a cervical layer thickness of 0.6 mm, a cementation gap of 80 µm, and a 20 µm parameter of fit (Version 2.8.8.5 Dental System; 3Shape). Four different CAD-CAM materials were used: a composite resin (Brilliant Crios [BC]), a polymer-containing ceramic (Vita Enamic [VE]), a 6Y-TZP ultrahigh-translucent zirconia (Nacera Pearl $Q^3$ Multi-Shade [ultraHT]), and a 3Y-TZP high-translucent zirconia (Nacera Pearl Multi-Shade [HT]), which served as a reference. After milling in a CNC milling machine, the crowns were manually polished according to the manufacturer's instructions (Table 1). Both zirconia materials were soft machining milled with a proximal 20% oversize regarding shrinkage during the sintering process. Sintering was performed in a calibrated dental ceramic oven (Austromat 664 iSiC; Dekema) for 7 hours 45 minutes, according to the manufacturer's instructions (L9 T008 C1500 T7200 T008 C150 C0 L0 T2).

Before cementation, the integrity of the prepared teeth and crowns was controlled under a digital light microscope (Smartzoom 5; Carl Zeiss Microscopy). The natural tooth substrate was etched with 35% phosphoric

**Table 1.** CAD-CAM materials and polishing information (provided by manufacturer)

| Code | Manufacturer | Block Name (Batch No.)/Color | Material | Polishing System (Manufacturer) |
|---|---|---|---|---|
| BC | Coltène | Brilliant Crios (H16204)/A2 | CAD-CAM composite resin | Diatech Polishers |
| VE | VITA Zahnfabrik | Vita Enamic mC (60140)/2M2 | Polymer-containing ceramic | Vita Enamic Polishing Set technical |
| ultraHT | Doceram Medical Ceramics | Nacera Pearl $Q^3$ Multi-Shade (5039305)/A-Light | Yttria-stabilized 40% tetragonal and 60% cubic zirconia polycrystal (6 mol% $Y_2O_3$) | Nacera Shine Zr |
| HT | Doceram Medical Ceramics | Nacera Pearl Multi-Shade (5015490)/A | Yttria-stabilized 100% tetragonal zirconia polycrystal (3 mol% $Y_2O_3$) | Nacera Shine Zr |

CAD-CAM, computer-aided design and computer-aided manufacturing.

**Table 2.** Luting systems (provided by manufacturer)

| Code | Manufacturer | Pretreatment of Bonding Surface (Batch-No.; Expiration Date) | Adhesive (Batch-No.; Expiration Date) | Luting Composite Resin (Batch-No.; Expiration Date) |
|---|---|---|---|---|
| BC | Coltène | One Coat 7 Universal (H88319; 05/2019) | One Coat 7 Universal (H88319; 05/2019) | DuoCem (H76142; 06/2019) |
| VE | VITA Zahnfabrik | Vitasil (62750; 01/2019) | Vita A.R.T. Bond (A: H50607; 05/2019 B: H45852; 01/2019 Bond: H62577; 12/2018) | Vita Duo Cement (H65331; 04/2019) |
| ultraHT | Kuraray | Clearfil Ceramic Primer Plus (4s0025; 01/2020) | ED Primer II (A: 3D0037 B:3E0036; 02/2019) | Panavia F 2.0 (000059; 02/2019) |
| HT | Kuraray | Clearfil Ceramic Primer Plus (4s0025; 01/2020) | ED Primer II (A: 3D0037 B:3E0036; 02/2019) | Panavia F 2.0 (000059; 02/2019) |

BC, Brilliant Crios; HT, high-translucent Nacera Pearl Multi-Shade; ultraHT, ultra-high-translucent Nacera Pearl $Q^3$ Multi-Shade; VE, Vita Enamic.

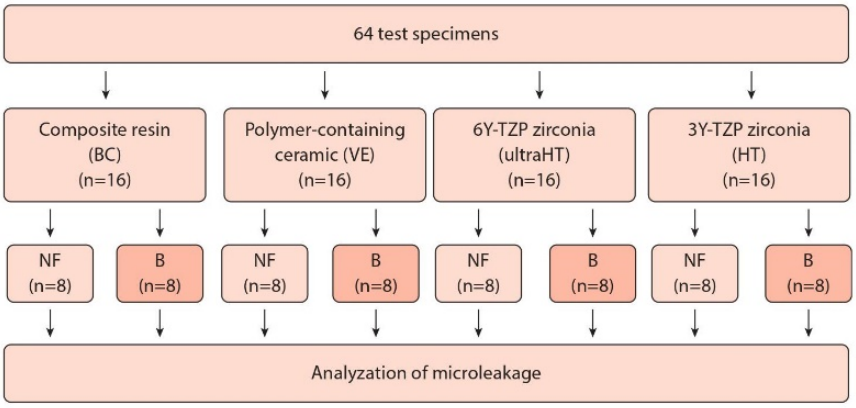

**Figure 2.** Flow scheme of investigation (mastication simulation: normal function [NF] and bruxism [B]).

acid (Vococid, batch no. 1720203; VOCO) for 15 seconds, cleaned under running distilled water, and gently air-dried.[37] All crowns were adhesively luted with the recommended luting system provided in the manufacturer's information (Table 2). Thus, not only the material but the entire system of material and luting system was tested.

The bonding surface of the BC, ultraHT, and HT crowns was airborne particle abraded with aluminum oxide (Edelkorund, 50 µm; Harnisch+Rieth) at 0.15 MPa. The bonding surface of VE crowns was etched with 5% hydrofluoric acid (IPS Ceramic Ätzgel, batch no. W84630; Ivoclar Vivadent AG) for 60 seconds. After cleaning and drying with oil-free compressed air, the bonding surface was pretreated. Separate light polymerization of the adhesive and dual-polymerizing composite resin was applied for the BC and VE. According to the manufacturer's information, only the composite resin was light polymerized for the ultraHT and HT groups. The light intensity (>800 mW/cm$^2$) of the polymerization device (Bluephase; Ivoclar Vivadent AG) was assessed before each use. A special cementation device was applied for cementation of test specimens under a constant load (6 N).[38] Finally, all specimens were stored in distilled water for 24 hours at 37 °C, according to the ISO/TC 11405:2003 before artificial aging in a mastication simulator.[2,33,36]

For artificial aging, the specimens were mechanically loaded in a mastication simulator (CS 4.8; SD Mechatronik) for 1.2 million cycles in 37 °C distilled water reported to simulate clinical service of 5 years.[39,40] Two different mastication programs (n=8) were used according to the manufacturer's instruction: NF and B (Fig. 2 and Table 3). The NF program simulated vertical and horizontal loading, whereas the B program tested shear

**Table 3.** Parameters of mastication simulation

| Parameters | Normal Function Vertical and Lateral Loading | Bruxism Lateral Loading |
|---|---|---|
| Number of cycles | 1.2 million | 1.2 million |
| Upward stroke/ Downward stroke | 2 mm/1 mm | 0 mm/0mm |
| Loading | 100 N | 90 N |
| Sideshift/Speed | 0.7 mm/40 mm/s | 1.5 mm/20 mm/s |

**Table 4.** Descriptive statistics of mastication simulation and CAD-CAM material with mean, SD, and minimum and maximum percentage of microleakage

| Mastication Simulation | CAD-CAM Material | Mean [%] | SD | Minimum [%] | Maximum [%] |
|---|---|---|---|---|---|
| Normal function | BC | 1.1 | 0.4 | 0 | 2.7 |
| | VE | 10.2 | 6.1 | 0 | 50.0 |
| | ultraHT | 8.3 | 3.4 | 0 | 26.3 |
| | HT | 2.3 | 1.9 | 0 | 15.8 |
| Bruxism | BC | 4.8 | 2.3 | 0 | 19.7 |
| | VE | 15.6 | 5.7 | 2.6 | 47.4 |
| | ultraHT | 1.4 | 0.7 | 0 | 4.5 |
| | HT | 4.8 | 3.3 | 0 | 24.3 |

BC, Brilliant Crios; CAD-CAM, computer-aided design and computer-aided manufacturing; SD, standard deviation; VE, Vita Enamic.

**Table 5.** Pairwise comparison of mastication simulation

| Normal Function | Bruxism | *P* Value |
|---|---|---|
| BC_NF | BC_B | .105 |
| VE_NF | VE_B | .234 |
| ultraHT_NF | ultraHT_B | .130 |
| HT_NF | HT_B | .645 |

BC, Brilliant Crios; HT, high-translucent Nacera Pearl Multi-Shade; NF, normal function; ultraHT, ultra-high-translucent Nacera Pearl $Q^3$ Multi-Shade; VE, Vita Enamic.

stress with exclusive horizontal movement. For both, loading was applied on the central slope from the distobuccal cusp down to the central fissure with a standardized steel antagonist (R1; SD Mechatronik). The radius of 3.18 mm corresponded to an average cuspal radius of 2 to 4 mm.[41,42] The positioning of the specimens in the simulator was controlled by using articulating paper. All experiments were performed by 1 investigator (C.F.).

After artificial aging, the specimens were stored in 0.5% aqueous fuchsin solution (C.I. 42510, batch no: 276244301; Carl Roth GmbH+Co KG) for 24 hours at room temperature to investigate microleakage, which is a standardized testing procedure.[28,33,43-45] Before sectioning each specimen in 4 equidistant slices of 1 mm (IsoMet1000; Buehler), they were cleaned of residual dye solution under distilled water. Dye penetration was investigated at 16 measurement points per specimen (4 slices with 4 measurement points each) with a digital microscope (Smartzoom 5; Zeiss), and the percentage of leakage in relation to the height of the tooth was calculated. After averaging, the mean of all 16 measurement points, statistical analysis was performed. First, a Mann−Whitney test was applied for pairwise comparison of the 2 mastication simulations (NF and B). No significant difference was detected. Therefore, only the CAD-CAM material itself was subjected to the Kruskal−Wallis test and corrected with the Bonferroni tests for multiple testing ($\alpha$=.05).

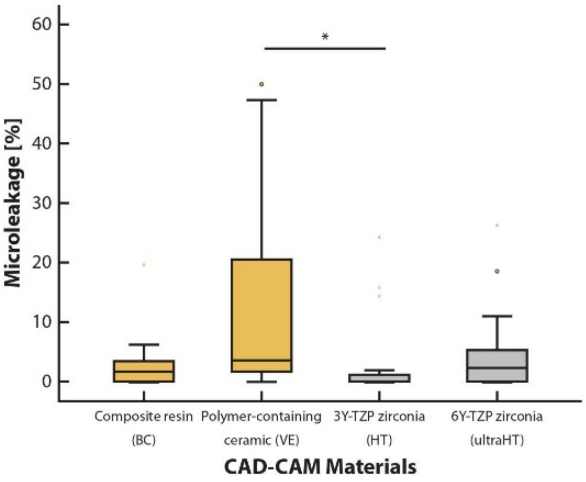

**Figure 3.** Box plots of polymer-containing materials (*orange*) and zirconia materials (*grey*); bars represent significant differences summarized for both mastication simulations. * indicates extremes and o indicates outliers.

## RESULTS

All specimens survived artificial aging of 1.2 million cycles in the mastication simulator. However, microleakage was identified in all the groups (Table 4). The pairwise comparisons revealed no significant difference between the 2 mastication simulations (Table 5). Thus, the null hypothesis was accepted concerning the loading program.

For the pairwise comparisons of the CAD-CAM materials, only VE and HT revealed a significant difference (Fig. 3 and Table 6, *P*<.014). A difference was noted between the 2 polymer-containing materials BC and VE as well; however, no difference in significance could be shown. A slight difference was noted between the 2 zirconia groups, but the ultraHT groups exhibited an increased amount of microleakage compared with the HT group. Some groups reported a wide range of microleakage among single specimens. The polymer-containing ceramic VE exhibited the highest microleakage, whereas 3Y-TZP exhibited the lowest. Consequently, the null hypothesis was rejected in terms of the CAD-CAM material. Figure 4 depicts an example of measurement points with leakage (VE) and no leakage (ultraHT).

**Table 6.** Pairwise comparison of CAD-CAM material

| | BC | VE | ultraHT | HT |
|---|---|---|---|---|
| BC | | | | |
| VE | .244 | | | |
| ultraHT | 1.000 | .394 | | |
| HT | 1.000 | .014 | 1.000 | |

BC, Brilliant Crios; CAD-CAM, computer-aided design and computer-aided manufacturing; HT, high-translucent Nacera Pearl Multi-Shade; ultraHT, ultra-high-translucent Nacera Pearl Q$^3$ Multi-Shade; VE, Vita Enamic.

## DISCUSSION

A typical problem of studies involving biological materials is the reproducibility of the specimen. By implementing CAD-CAM technology in the manufacturing process of dental restorations, standardization with consistent material quality could be achieved.[37] In addition, standardization was also possible for the manufacturing of natural teeth for in vitro testing.[28] Therefore, in this in vitro study, CAD-CAM milled human molars and crowns were used to eliminate the influencing factor of manual preparation. Nevertheless, differences in the composition of the tooth substrate were expected because human teeth are natural products.[37] Alternative artificial teeth provide standardized and reproducible results but do not represent the clinical luting process. Either bovine or human teeth are required.[34,35]

For this study, the crowns were designed with a reduced layer thickness based on the findings of Magne et al,[3] who investigated the fatigue resistance of thin-walled CAD-CAM crowns and reported acceptable failure rates. Nevertheless, Nakamura et al[4] found that the occlusal layer thickness has a significant influence on the fracture resistance compared with the cervical layer thickness. For this reason, in this study, the occlusal thickness was twice that of the cervical thickness.

Dynamic fatigue in a mastication simulator was used because occlusal function subjects the restorations to repetitive stress.[11,34] Testing under high masticatory forces to simulate bruxism has suggested that monolithic restorations provide good stability and sealing ability.[29,43,45] However, bruxism also causes horizontal shear stress, and Nakamura et al[24] considered this as a critical factor for the success analysis of composite resin crowns.

Although polymer-containing materials are controversial as a definitive restorative material, they are less brittle than ceramics and have lower elastic modulus.[23,26] They exhibit a smooth milled margin with less edge roughness than ceramics, which facilitates the fabrication of thin restorations.[23] In addition to polymer-containing materials, zirconia also exhibits good survival rates for thin restorations.[1,5] Regarding fracture load, no difference was identified between the 3Y-TZP and 6Y-TZP zirconia.[1] Zirconia can be luted with a conventional cement, such as glass ionomer, but has less microleakage and increased fracture strength if luted with resin cement.[2,5,14,33] CAD-CAM composite resins require adhesive cementation and separate light polymerization of adhesive, and dual polymerization composite resin has been reported to reduce microleakage.[15,28] In the present study, the specimens were luted with their recommended luting system based on the manufacturer's instruction, and separate light polymerization of adhesive and luting composite resin was applied unless explicitly contraindicated.

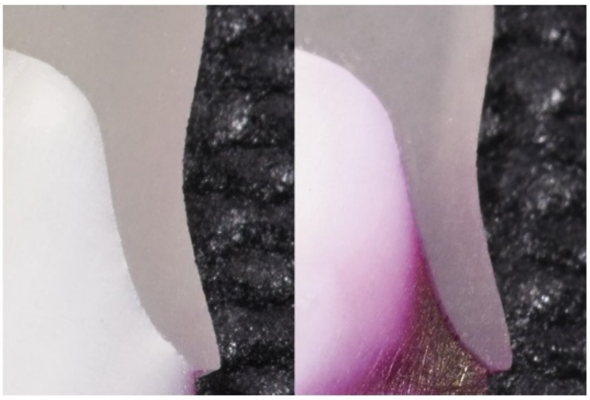

**Figure 4.** Example of measurement point without leakage of ultraHT specimen (left) and with leakage of VE specimen (right).

All specimens survived the loading process, consistent with Magne et al,[3] who reported the good survival of ultrathin CAD-CAM composite resin crowns (0.7 mm) after mastication simulation of normal masticatory forces. However, the fracture strength of the crowns was less than that of restorations with a layer thickness of 1.5 mm.

All test groups, regardless of the CAD-CAM material, exhibited microleakage. For microleakage, layer thickness seems to be less influential, given that a study that investigated crowns with greater layer thickness (1.0 mm cervical and 1.5 mm occlusal) reported comparable results.[28] The present study did not find a significant difference between the 2 zirconia materials and CAD-CAM composite resins; however, zirconia had an increased flexural strength and higher elastic modulus.[25] This suggests the importance of the bonding between tooth substrate and restoration, which stabilizes the restoration.[33] El Zohairy et al[15] also reported reduced microtensile bond strength among resin bonding materials to ceramics compared with composite resin blocks. In the present study, the polymer-containing ceramic (VE) exhibited increased microleakage than the CAD-CAM composite resin BC. In contrast with the composite resin, polymer-containing ceramics have a ceramic matrix impregnated with polymer.[16] They have increased elastic modulus and flexural strength than CAD-CAM composite resins because of their higher filler content.[17]

However, the specimens were light polymerized, and significantly less light is transmitted through Vita Enamic than through composite resin.[14] Thus, incomplete polymerization of the bonding material might explain the inferior results. Zimmermann et al[6] investigated VE and glass-ceramics of different layer thicknesses. VE with a layer thickness of 0.5 mm did not survive fatigue testing. Dejak et al[25] used the finite element method (FEM) to calculate the strength of thin crowns made of gold alloy, zirconia, and composite resin and reported that crowns made of stiffer material did not debond. Weigl et al[5] reported that a 0.5-mm thickness zirconia crowns bonded with the same bonding system as in the present study had adequate fracture strength after mastication simulation. The present study did not investigate the fracture strength, but marginal sealing is also a part of the long-term stability of a restoration.

Two zirconia materials were investigated in the present study. The ultraHT zirconia has lower flexural strength than HT because of its cubic phase.[9,20] This difference could explain the increased microleakage of the ultraHT group. Nordahl et al[1] did not report a difference among different zirconia formulations regarding fracture strength. However, they suggest caution when reducing layer thickness, given that 31% more strength can be gained by increasing the layer thickness from 0.5 to 0.7 mm.

In the present study, solely microleakage of CAD-CAM crowns and no other aspects such as fracture resistance or wear were investigated, which is a limitation of this study. In addition, the investigations of other materials such as 4Y-TZP or glass ceramics might be interesting as well. Even though a clinical-close set-up by using human teeth and a mastication simulator was simulated in this study, further research should be conducted to investigate the clinical performance of different thin-walled monolithic CAD-CAM materials in patients.

## CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. The 2 mastication simulation programs did not result in a significant difference in microleakage among all 4 CAD-CAM materials.
2. Thin-walled restorations made of CAD-CAM composite resin and zirconia (3Y-TZP and 6Y-TZP) reported less microleakage than with the polymer-containing ceramic.

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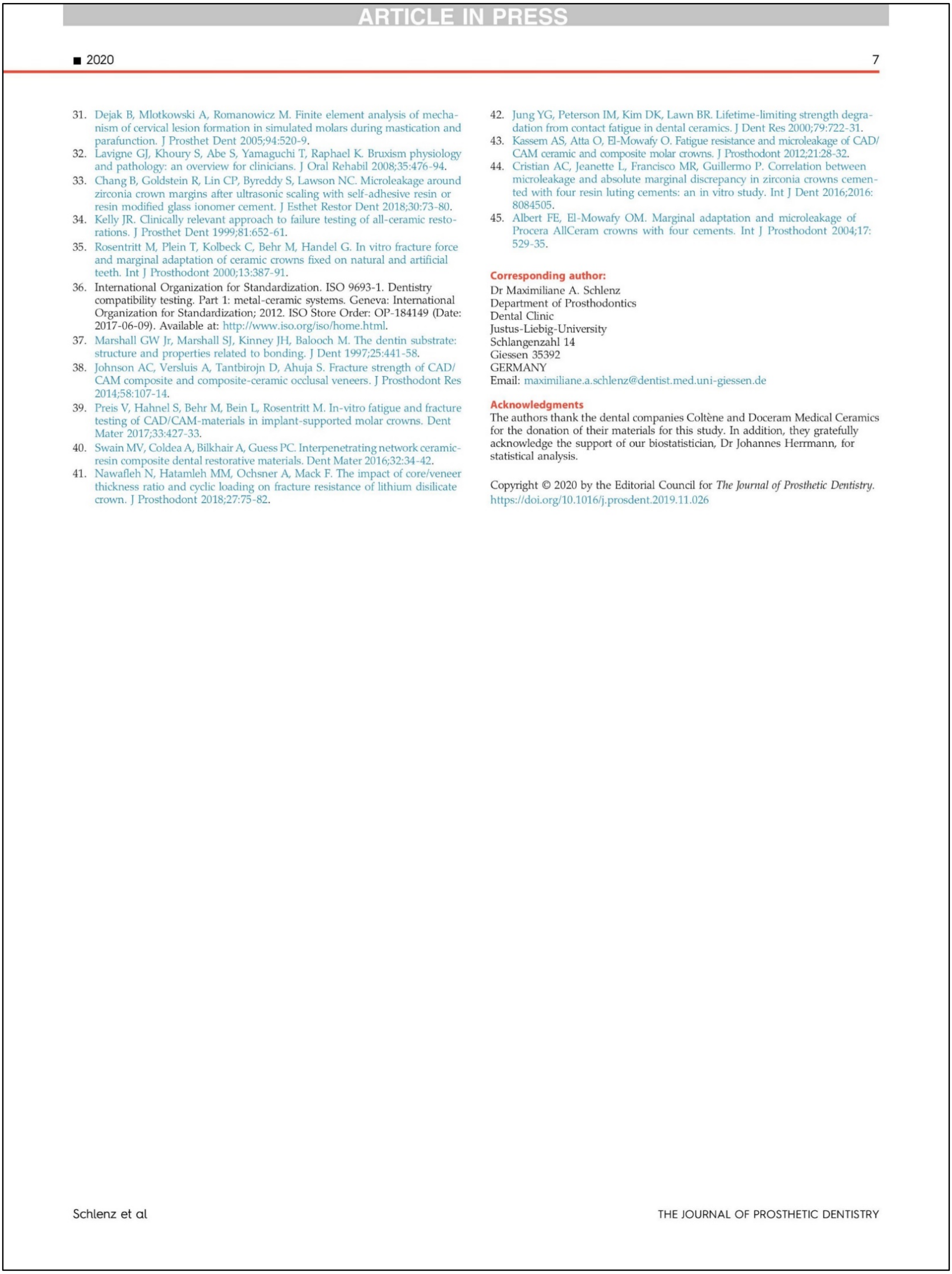

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Original article

# Fatigue damage of monolithic posterior computer aided designed/computer aided manufactured crowns

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ABSTRACT

*Purpose:* To analyse fatigue damage of monolithic computer-aided-designed/computer-aided-manufactured (CAD/CAM)-materials after loading with high masticatory forces in standardized posterior crowns in a mouth-motion-simulator.
*Methods:* For manufacturing of test specimens (5 groups, 16 specimens each), two corresponding Standard-Tessellation-Language-(STL)-data-sets (one for the teeth and one for the crowns) were designed. The teeth were CAD/CAM-milled of human third molars and the crowns of three different CAD/CAM composite blocks (Lava Ultimate,'LU'; Brilliant Crios'BC'; Cerasmart,'CS'), one polymer-infiltrated-ceramic network (Vita Enamic,'VE') and a control group of lithium disilicate ceramics (IPS e.max CAD,'EM'). Crowns were adhesively cemented with their corresponding luting system on the human teeth. Half of the specimens were light-cured ('LC') and the others were chemical-cured ('CC'). A mouth-motion-simulator (WL-tec, 2 Hz, 37 °C) applied dynamic cyclic loading between 50–500 N for a period of 1 million cycles. Afterwards, a dye penetration test (aqueous basic-fuchsine) revealed damage of test specimens. Each specimen was sectioned into four equidistant slices and the area without damage was measured with a digital microscope (Zeiss) and radial cracks at the cementation surface were assessed. Data were subjected to Tukey's test.
*Results:* All specimens showed fatigue damage in the occlusal contact area. LU, BC and CS exhibited a significant greater area without damage compared to VE and EM ($p < .05$). EM and VE showed additional radial cracks at the cementation interface in both curing modes, whereas LU, BC and CS showed only radial cracks with chemical-cured luting cement.
*Conclusions:* Monolithic CAD/CAM composite crowns showed significantly lower fatigue damage, particularly if the luting system was light-cured.

## 1. Introduction

Today, tooth coloured monolithic materials made of composite, glass ceramics and zirconia are increasingly used, especially for posterior restorations [1–4]. Their application simplifies the manufacturing process and minimize chipping fractures, the most frequent complication of veneered restorations [2,5–7]. Ceramics such as lithium disilicate or zirconium dioxide are brittle materials, even if they are processed monolithically [8,9]. However, their application is still under discussion in particular in patients with parafunctions such as bruxism [5–7,10]. Therefore, new polymer-containing materials (PCM) called *hybrid ceramics* or *CAD/CAM (computer-aided design/computer-aided manufacturing) composites* may be an alternative. Due to their polymer phase, they are more elastic and may withstand higher masticatory forces without failure, even though their lower elastic modulus allows plastic deformations and may cause other complications such as debonding [5,11–13].

Fracture mechanism and failure mode, including microcracks of different glass ceramics, are well investigated [2,9,14–16]. Studies show that damage occurs under the occlusal contact area (OCA) in a quasi-plastic zone where microcracks initiate fracture mechanism [8,9,16]. In addition to damage in the occlusal contact area glass ceramics show radial cracks at the cementation surface under the restoration caused by tensile stress [17,18].

Further studies described that the polymer-infiltrated-ceramic-network (PICN) Vita Enamic exhibits plastic deformation under loading due to their polymer phase. This improves the crack resistance, damage tolerance, strength and toughness [19–21]. So, the stress distribution of glass ceramics and PICN might be

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different [2]. Leung et al. discussed that the polymer phase of the PICN gives the CAD/CAM material plasticity, which increases the Weibull modulus [22]. For CAD/CAM composites a higher modulus of toughness compared to PICN and lithium disilicate ceramics was reported, which might dissipate fracture energy [23].

Moreover, other authors discussed positive aspects of this damping effect on implant-supported crowns fabricated especially of composite materials and for patients with bruxism [24–27]. However, studies on fatigue damage of the new PCMs are rare. Most studies tested wear and fracture strength; the latter mostly by single static loading [2,3,28–30], but Homaei et al. was the first to use the indentation staircase cyclic loading method to evaluate lithium disilicate and hybrid ceramics CAD/CAM blocks luted on human pre-molars [6]. Mastication is a repeated dynamic loading process with changing forces. Thus, the restorations have to resist mechanical fatigue [6]. Patients with parafunctions can apply masticatory loads between 500–800 N, whereas normal masticatory loads ranges between 50–250 N [31,32].

Consequently, the aim of this study was to investigate fatigue damage of several new CAD/CAM crowns adhesively luted on human molars. For this investigation, an in vivo close setup with identically CAD/CAM-milled human teeth was designed [13]. The following null hypothesis was tested: After mouth-motion-simulation with higher loads (up to 500 N), there is no difference in fatigue damage in between PCMs and established lithium disilicate ceramics.

## 2. Materials and methods

### 2.1. Manufacturing of test specimens

Eighty human caries-free and undamaged third molars (n = 16 per group), extracted for therapeutic reasons, were used for this study in consensus with the patients and the approval of the local ethics committee (Ref. no. 143/09). The teeth were carefully cleaned and stored until usage according to ISO/TS 11,405 for a maximum period of half a year [33]. For identical tooth preparation one Standard Tessellation Language (STL) dataset were anatomically designed with CAD software (Service Release 12, McNeel Europe, Barcelona, Spain). The geometric dimensions of the tooth design were a height of 4.0 mm, a mesio-distal width of 9.5 mm, a bucco-oral width of 7.5 mm, a convergence angle of 6° and a 1.0 mm chamfer with 30° angle. For CAD/CAM-milling the teeth were embedded in a special sample holder that fitted in a numerical control milling machine (CNC) (Mikron HSM 400, GF Machining Solutions, Geneva, Switzerland) [13]. In sum the tooth preparation was based on one STL file and was carried out in the CNC milling machine under constant water-cooling to prepare identical teeth.

The posterior crowns were manufactured in the same manner as described for the teeth. First one STL datatset was designed (Version 2.8.8.5, Dental System, 3Shape, Copenhagen, Denmark) with corresponding geometric dimensions to the one STL dataset of the teeth. The parameters of the occlusal-layer thickness (1.5 mm), the cervical thickness (1.0 mm), the cement gap (80 µm) and the parameter of fit (15 µm) were defined according to the smallest common denominator of all manufacturer's instructions (Fig. 1). Three types of materials were investigated: lithium disilicate ceramics (IPS e.max CAD (EM)), polymer-based ceramic network (PICN) (Vita Enamic (VE)) and CAD/CAM composite blocks (Lava Ultimate (LU), Brilliant Crios (BC), Cerasmart (CS)) (Table 1). The milling procedure was the same as that for the teeth. All crowns were inspected after milling using a digital light microscope (Smartzoom 5, Zeiss, Jena, Germany) to ensure their integrity before testing. The crowns' surfaces were polished manually with the manufacturer's recommended polishing systems (Table 1). The CAD/CAM composite crowns LU and CS were polished with a goat hair brush and their recommended polishing paste, whereas BC was polished with rubber polisher in a two-step system with pre-and high-gloss polishing.

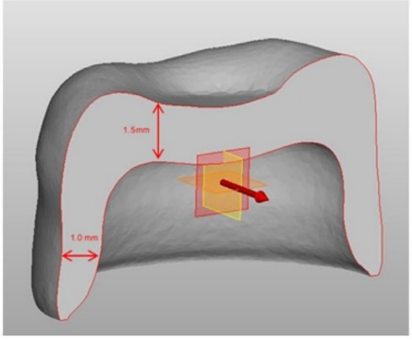

**Fig. 1.** STL data set of the crown.

The hybrid ceramic VE crowns were polished with the recommended Vita Enamic polishing set technical, which is also a two-step system. For better comparison to the PCMs groups EM was polished in the pre-crystallized state (self glaze technique) first with a diamond rubber polisher and afterwards with a high-gloss rubber polisher. Subsequently EM specimens were crystallized in the Programat EP3000 (Program: B 403 °C, S 6 min, $t_1$ 90 °C/min, $T_1$ 820 °C, H 10 s, $t_2$ 30 °C/min, $T_2$ 840°, H 7 min, vacuum 1 550/820 °C, vacuum 2 820/840 °C, L 700 °C, $t_l$ 0 °C; Ivoclar Vivadent, Schaan, Lichtenstein).

Before cementation, the teeth were etched with 37% phosphoric acid for 15 s (Etching Gel, DMG, Hamburg, Germany). For adhesive cementation the test specimen groups (n = 16) were sectioned into two subgroups (n = 8) (Fig. 2) and luted according to the manufacturers' instructions (Table 2). One subgroup of each CAD/CAM material was luted with a light-curing adhesive system (LC) and the other with a chemical curing system (CC). Separate light curing of adhesive and luting composite was carried out for LC whereas CC was cured in the absence of light polymerisation. A loading device was used to ensure adhesive cementation was carried out under standardized pressure of 6 N [34]. The details of the luting materials used are listed in Table 2. The cementation surfaces of CAD/CAM composites were sandblasted (aluminium oxide powder, 50 µm, 1.5 bar (BS and CS), 2.0 bar (LU)), whereas the surfaces of the hybrid ceramic and lithium disilicate ceramics were etched with 5%-hydrofluoric acid (60 s (VE), 20 s (EM)). After cementation, all test specimens were stored in distilled water at 37 °C for 24 h (ISO/TC 11,405:2003).

### 2.2. Mouth-motion-simulation

The fatigue testing of specimens was performed by a mouth-motion-simulator (prematecF1000, wl-tec GmbH, Wertheim, Germany). The simulator consists of two parts: the power source (magnet) and the measurement device (load cell with strain gauge). For testing, the specimens were embedded with core build-up composite (LuxaCore Z-dual, DMG) in special sample holders made of aluminium and polyether ketone (PEAK). The compressive cyclic loading was applied uniaxial in the central fossa with a linear increase and decrease between 50 and 500 N (2 Hz) for 1 million cycles in distilled water at 37 °C. This cycling simulates a clinical service of four years [35]. The load was applied with a semi-sphere shaped stainless steel antagonist (R1, SD Mechantronik GmbH, Feldkirchen, Germany) with a radius of 3.18 mm, which is comparable to the natural cusp of a human tooth (2–4 mm) [36].

### 2.3. Analysis of fatigue damage

After cyclic loading test specimens were stored in .5% aqueous fuchsin solution (C.I. 42510, Carl Roth GmbH + Co KG, Karlsruhe, Germany, Batch no: 276244301) for 24 h at room temperature to

**Table 1.** Milling-blocks and polishing information (provided by manufacturer).

| Code | Manufacturer | Block name (batch no.)/ color | Polishing system (manufacturer) |
|---|---|---|---|
| EM | Ivoclar Vivadent (Ellwangen, Germany) | IPS e.max CAD (V16780)/ A2 | OptraFine F+P (Ivoclar Vivadent) |
| VE | VITA Zahnfabrik (Bad Säckingen, Germany) | Vita Enamic (56063)/ 2M2 | Vita Enamic Polishing Set technical (VITA Zahnfabrik) |
| LU | 3M ESPE (St.Paul, MN, USA) | Lava Ultimate (N763596/A2 | Renfert all-in-one (Renfert, Hilzingen, Germany) |
| BC | Coltene (Altstätten, Switzerland) | Brilliant Crios (H16204)/ A2 | Diatech Polishers (Coltene) |
| CS | GC (Tokyo, Japan) | Cerasmart (1412101)/A2 | Diapolisher Paste (GC) |

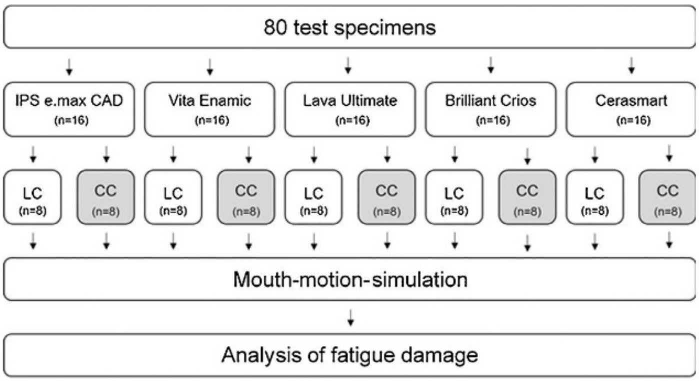

**Fig. 2.** Flow scheme of the investigation.

**Table 2.** Luting systems (provided by manufacturer).

| Code | Curing mode | Manufacturer | Pre-treatment of bonding surface (batch-no.; expiration date) | Adhesive (batch-no.; expiration date) | Luting composite (batch-no.; expiration date) |
|---|---|---|---|---|---|
| EM | LC | Ivoclar Vivadent | Adhese Universal (V42577; 10/2018) | | Variolink Esthetic DC (V37519; 03/2019) |
| | CC | | Monobond Plus (V12120; 03/2018) | Multilink Primer A + B (V21528; 09/2017) | Multilink Automix (V08514; 01/2018) |
| VE | LC | VITA Zahnfabrik | Vitasil (45040; 01/2018) | Vita A.R.T. Bond (G78662; A: 2018/04 B: 2018/01 Bond: 2017/12) | Vita Duo Cement (H11243A/ H11243; 07/2018) |
| | CC | Kuraray (Okayama, Japan) | Clearfil Ceramic Primer Plus (7N0018; 03/2019) | ED Primer II (A: 370029 B:3E0029; 02/2018) | Panavia F 2.0 (380129/ 2P0028; 11/2018 + 07/2018) |
| LU | LC | 3M ESPE | Scotchbond Universal (625559; 02/2018) | | Rely X Ultimate (623858; 09/2017) |
| | CC | | | | |
| BC | LC | Coltene | One Coat 7 Universal (G84296; 01/2018) | | DuoCem (H13220; 01/2018) |
| | CC | | One Coat 7 Universal (G84296; 01/2018) | One Coat 7 Universal (G84296; 01/2018) + One Coat 7.0 Activator (H19891; 08/2018) | |
| CS | LC | GC | G-Multi Primer (1607131; 07/2018) | G-Premio Bond (1607141; 07/2018) | G-Cem LinkForce (1607061; 07/2018) |
| | CC | | | G-Premio Bond (1607141; 07/2018) + G-Premio Bond DCA (1604041; 04/2018) | |

stain possible microcracks. Then, the specimen (crowns) were cleansed in distilled water and sectioned mesio-distally into four slices (IsoMet1000, Buehler, IL, USA). For exact positioning of the specimens in the sample holder, a dot marking had been implemented in the crown design.

For each slice, the area free of microcracking was determined at sixteen measurement points per specimen with a digital microscope. The percentage (arithmetic mean) of the area without microcracking was calculated (Smartzoom 5, Version 1.1, Zeiss, Jena, Germany). In addition to *cone* cracks, some specimens exhibited *radial* cracks. Therefore, the number of measurement points that showed at least one radial crack were counted.

The statistical analysis was performed using SPSS Statistics (Version 24, IBM, Armonk, NY, USA). The data of the area without microcracking was subjected to a two-factorial analysis (ANOVA). First, data was verified for normal distribution of residuals, variance homogeneity and independence. Data were tested for normal distribution by Shapiro–Wilk-Test and Komogorov–Smirnov with Lilliefors-Test. A variance homogeneity (Levene Test) was there. Neither in curing mode itself (LC or CC), nor in the interaction between the curing modes and CAD/CAM materials was a statistical difference shown. Therefore, only the CAD/CAM material itself was subjected to Tukey's test with a level of significance of $p < .05$.

## 3. Results

All specimens survived mouth-motion-simulation and no catastrophic failure occured. However, all CAD/CAM crowns

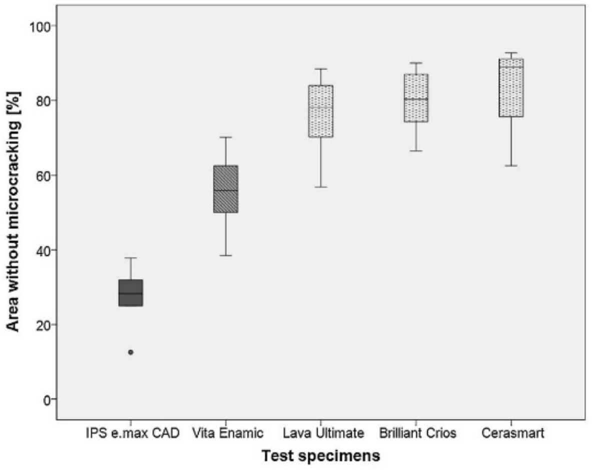

**Fig. 3.** Boxplots of all specimens (different pattern show significant difference p < .05).

showed fatigue damage under the OCA. The analysis of damage revealed three different types: *Cone cracks* starting from the surface, an OCA with *quasiplastic deformation* and *radial cracks* starting from the cementation interface. The pairwise comparison of EM to all other materials showed a significantly smaller area without microcracks. The same applies to VE specimens. All CAD/CAM composite groups (LU, BC and CS) showed the greatest area without any damage (Fig. 3). In addition to the damage under the OCA, EM and VE showed radial cracks at the cementation surface in both curing modes (LC and CC), whereas LU, BS and CS only had a few radial cracks if they were chemically cured (Fig. 4). Figure 5 shows a typical example for each CAD/CAM material where cone cracks and radial cracks are displayed.

The null hypothesis that PCMs and lithium disilicate ceramics show similar fatigue damage after loading was rejected. However, there was a significant difference between the CAD/CAM composites and the PICN, as well.

## 4. Discussion

In the present study the crowns were luted to human molars to better simulate the clinical situation [6]. Through CAD/CAM-milling of the test teeth, a high standardization of identical preparation and bonding to natural substrate was ensured [13]. The number of loading cycles applied, the direction of loading, the size of the antagonists and the dye penetration test was selected in accordance to comparable studies [32,35–38]. However, to simulate higher masticatory forces (e.g., bruxism), a higher maximum cyclic load (500 N) was used. In simulating mouth-motion, the presence of water is important because of *chemically assisted crack growth* [17]. Therefore, all specimens were tested in distilled water to better simulate the clinical situation. For analyzation of crack propagation some studies just recorded the occurrence of cracks [32,39,40]. Shembish et al. measured the length of the cracks, whereas Wendler et al. analyzed the area without cracks [38,41]. Latter method was also used in the current study.

All crowns – regardless of the material – showed fatigue damage after mouth-motion-simulation. While loading specimens in a mouth-motion-simulator, compressive stress is located under the OCA and tensile stress is concentrated at the inner side of the restoration at the cementation interface (Fig. 5) [42]. Shembish et al. investigated anatomically shaped monolithic crowns on resin dies after cyclic loading and showed cone cracks starting from the OCA for leucite ceramics and CAD/CAM composite [38]. In addition to loading, microcracks may also be initiated during the manufacturing process. Curran et al. investigated lithium disilicate ceramics, PICN and CAD/CAM composite after milling and showed that composite materials are less sensitive to damage than lithium disilicate ceramics [43].

In the present study, all specimens were either etched with hydrofluoric acid (EM and VE) or sandblasted with aluminium oxide powder (LU, BC, CS) according to their instructions for use. Radial cracks started from the cementation interface [15]. Particularly EM and VE showed radial cracks regardless of the curing mode (CC and LC), whereas all CAD/CAM composites exhibited no radial cracks for the LC groups and only a few radial cracks for the CC groups. Another study showed higher bond strength for light-cured luting systems of CAD/CAM composites compared to solely chemical curing, which may explain the absence of radial cracks in the light-cured LU, BC and CS [44]. Thus, besides the manufacturing process the conditioning of the cementation interface and the luting system may have an influence on the occurrence of radial cracks. This was also reported for zirconia [14].

With regard to fracture load, Okada et al. showed comparable data for lithium disilicate ceramics and CAD/CAM composites in a single load set-up, whereas Zierden et al. investigated fracture loads after cyclic loading and showed higher loads for CAD/CAM composites compared to ceramics [3,30]. The current study did not investigate fracture load, but analysed fatigue damage after cyclic loading. The lithium disilicate ceramics showed significantly higher damage compared to the CAD/CAM composites and PICN. This results was anticipated; due to their polymers phase, PICN material are more elastic than ceramics and may absorb repeated loading better [6].

Studies investigating the fatigue behavior of CAD/CAM materials showed that PICN has a higher damage tolerance compared to lithium disilicate ceramics [45]. This can be explained by the different microstructure and the R (resistance)-curve behavior of materials. EM exhibited direct crack propagation resulting in a smooth fracture surface, whereas VE fracture surface is rougher which may related to crack deflection at polymer phase, that makes the VE resistant to crack propagation [19,45]. In this study VE showed a significantly higher area without microcracks compared to EM. So, it is hypothesized that the cracks in VE were deflected because of the R-curve behavior of the polymer phase.

The CAD/CAM composites showed the largest area without microcracks. That relates to the theory that crack propagation starts at flaws [45]. Ankyu et al. reported a higher Weilbull modulus for LU compared to EM due to flaws and voids in the microstructure [46].

Even though ceramics are brittle materials, they nevertheless show a plastic deformation under the OCA, which means that they can also absorb energy. However, in ceramics, this material property is extremely limited [8]. Zhang et al. showed three different damage modalities for porcelain-veneered zirconia crowns: plastic deformation, cone and radial cracks [18]. Wang et al. described the same damage modalities for veneered lithium disilicate and zirconia crowns [9]. According to our findings, PCMs show damage modalities comparable to lithium disilicate but with a smaller area of fatigue damage.

In addition to mouth-motion-testing, numerical methods, such as finite element method (FEM), are increasingly used to analyse stress areas in restorations [5,9]. As CAD/CAM composites have a lower elastic modulus compared to ceramics a different stress distribution can be shown [11]. Using FEM, Duan et al. calculated a stress concentration under the OCA and at the cementation interface for IPS e.max CAD. In comparison, Lava Ultimate showed stress concentration only under the OCA [12]. This may explain the radial cracks in the EM group, which were also described by Chen et al. for IPS e.max CAD as well [47].

In accordance with other data, the present study detected the most damage in the OCA for the CAD/CAM composites, as well as in

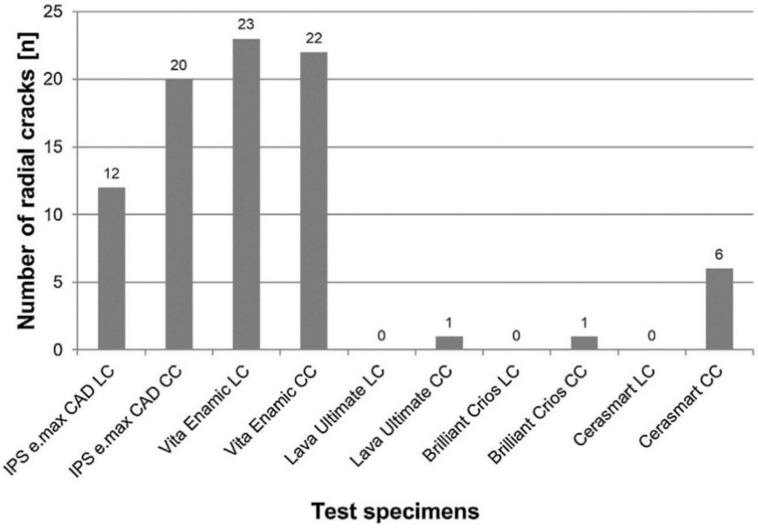

**Fig. 4.** Number of measurement points with minimum one radial crack [n].

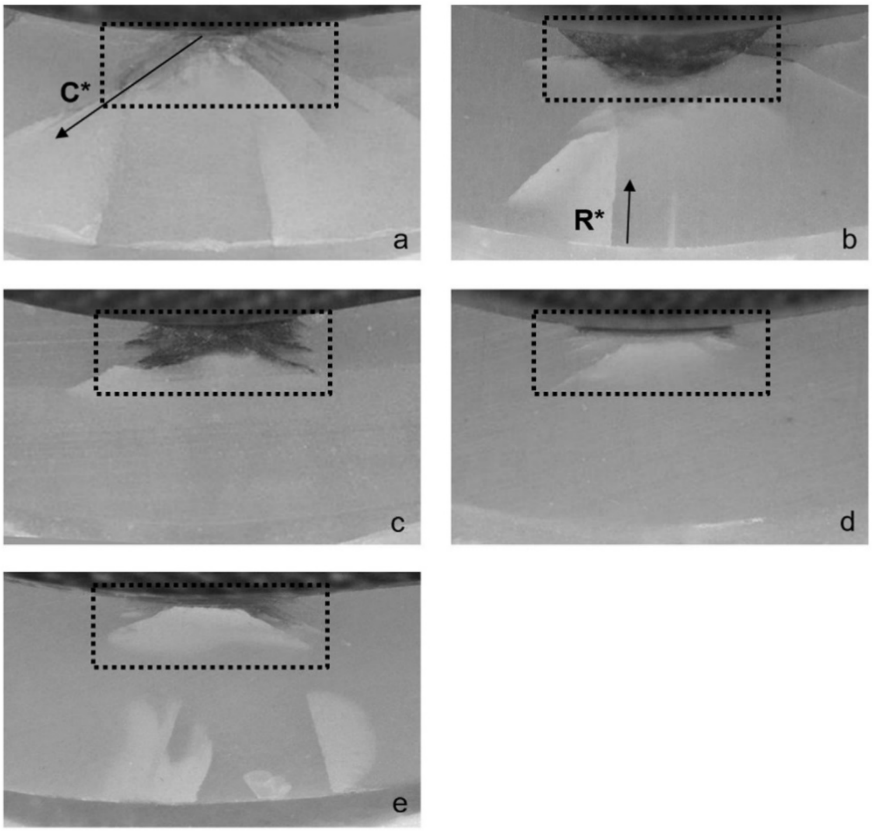

**Fig. 5.** Example of a measurement point with microcracks: EM (a), VE (b), LU (c), BC (d), CS (e); C* = example of a cone crack with direction of crack propagation, R* = example of a radial crack with direction of crack propagation, box = OCA.

the periphery for EM and VE (Fig. 5) [31,47,48]. Furthermore, Chen et al. described that ceramics compensate with high stress distribution through transfer energy in outer areas, which is also in agreement with our observations [47].

Homaei et al. showed with FEM high tensile stress in the OCA causing cone cracks. For EM a maximum stress of approximately 81 MPa and for VE of 35 MPa was described [49]. In this study we did not calculate the stress concentration but we found a

significantly higher damage for EM compared to VE. This may indicate that the polymer phase of VE absorbs more crack energy compared to EM and is in good accordance to Coldea et al. [21].

Although this study was designed as an in-vivo close set-up with human teeth and mouth-motion simulation, the results originated from laboratory test. Thus, further investigations – especially clinical studies – are required, to investigate the clinical performance of new CAD/CAM materials.

## 5. Conclusion

In this in vitro set-up new monolithic CAD/CAM materials such as CAD/CAM composites and PICN (PCM) reveal damage modes comparable to lithium disilicate ceramics after mouth-motion simulation. Even under simulated higher masticatory forces CAD/CAM composites showed the greatest damage free area, followed by PICN and lithium disilicate, especially if a light cured luting system was used. Nevertheless, in-vitro data has to be interpreted with care, when it comes to the clinical application.

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## 7.8 Publikation 5

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Original Article

# Monitoring fatigue damage in different CAD/CAM materials: A new approach with optical coherence tomography

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**Abstract**

*Purpose:* To investigate fatigue damage over time, monolithic posterior computer-aided-designed/computer-aided-manufactured (CAD/CAM) crowns were artificially aged in a mouth-motion-simulator, and damage was monitored with optical coherence tomography (OCT).
*Methods:* Forty-eight crowns were milled of six different CAD/CAM-materials (n=8), including 3Y-TZP (Lava Plus,'3Y'), 4Y-PSZ (Pritidentamultidisc,'4Y'), 5Y-PSZ (Prettauanterior,'5Y'), zirconia-reinforced lithium silicate (CeltraDuo,'ZLS'), hybrid ceramic (Vita Enamic,'VE'), and resin composite (BrilliantCrios,'COM'), and were adhesively luted on CAD/CAM-milled human molars. Specimens were artificially aged in a mouth-motion-simulator (50-500N, 2Hz, 37°C) for a period of 1 million cycles. Before loading and every 250,000 cycles, the specimens were investigated with spectral domain (SD)-OCT (RS-3000). The maximum vertical and horizontal damage were measured with imaging-processing-software (ImageJ). After testing, the specimens were sliced and analysed via light microscope (Zeiss) to compare the new OCT method with the established light microscope method. Data were subjected to ANCOVA and 2x4-ANOVA.
*Results:* No failure occurred during mouth-motion-simulation. However, all specimens (except for 3Y and 4Y) showed fatigue damage. There was a significant difference in the maximum damage between the CAD/CAM-materials ($p<.05$). ZLS exhibited the highest damage, followed by VE, COM and 5Y. While damage associated with 5Y was initially noticed after 750,000 cycles, all other materials already showed crack formation after 250,000 cycles. Furthermore, a linear increase in damage over time was noticed in all materials. Due to the shallow light penetration of OCT, damage in the outer area could only be visualized with light microscope.
*Conclusions:* OCT is feasible for monitoring fatigue damage over time within different CAD/CAM-materials, particularly for subsurface damages.

***Keywords:*** *CAD/CAM materials, Microcracks, Fatigue damage, Optical coherence tomography, Non-destructive method, Monolithic dental crowns*

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## 1. Introduction

Today, several tooth-coloured CAD/CAM materials are available for monolithic posterior fixed dental prosthesis (FDP) [1]. They are homogenous, highly standardized industrial products with improved material properties compared to manually fabricated conventional restorations [2, 3]. Moreover, they do not have the oft-described problem of chipping fractures and show superior fracture resistance compared to veneered FDPs [1, 4, 5]. However, the mechanical properties, including fatigue behaviour under loading,[6] differ between the high-strength zirconia, the brittle glass ceramic and the elastic resin composite [7-9].

In general, zirconia is classified by the concentration of yttrium, which determines the translucency [10]. Earlier formulations, such as 3 mol% yttria zirconias (3Y-TZP), exhibit a high strength but reduced aesthetics compared to glass ceramics [4, 11] .Therefore, new zirconia formulations with more translucent 5 mol% yttria cubic zirconia (5Y-PSZ), were developed. However, the flexural strength of 5Y-PSZ is only half of 3Y-TZP. For that reason, the 4 mol% yttria cubic zirconia (4Y-PSZ) should combine the mechanical properties strength and aesthetic with a lower translucency and higher strength compared to 5Y-PSZ, which still accomplish the aesthetic demands [10, 12]. In contrast to the high-strength zirconia, glass ceramics are more brittle materials with higher aesthetic properties[13]. Nevertheless, Rauch et al. showed good clinical outcome for posterior monolithic restorations made of lithium disilicate ceramics IPS e.max CAD (Ivoclar Vivadent) [14]. Besides the thoroughly investigated lithium disilicate ceramic, in recent years new zirconia-reinforced lithium silicate ceramics were developed for CAD/CAM fabrication of FDPs, which show comparable mechanical properties to lithium disilicate ceramics [15, 16].

In 2011, a new class of materials called resin composites was introduced [17]. Meanwhile, several products are available. Chemically they are industrial cured composites containing of ceramic particles embedded in dimethacrylate resin [15, 18]. These materials are characterized by a low elastic modulus and fracture strength compared to ceramics [15]. Furthermore, a hybrid ceramic containing of a porous feldspathic ceramic network penetrated with polymers was developed.This aims to combine the mechanical properties of ceramics and polymers [15, 19]. Studies showed a reduced fracture strength and

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brittleness for the hybrid ceramic compared to glass ceramics [18].

The majority of failures occur due to repeatable subcritical loading [20]. Fatigue damage occurs under the occlusal contact area (OCA) and includes three phases: crack nucleation, crack propagation and partial or total failure [6, 21, 22]. Traditional methods for the investigation of fatigue damage are destructive, such as slicing specimens and analysing them under a light microscope or scanning electron microscope (SEM). These methods only allow for investigation after testing [23-25]. The progression of cracks can also be recorded by a high-speed video camera [26, 27]. However, for tooth-coloured materials, only the surface damage can be monitored/detected, not the inner damage.

Another method is analysis with optical coherence tomography (OCT), which is a non-invasive approach that is approved for imaging of biological microstructures in micrometre resolution [7, 28-30]. OCT was originally developed as a diagnostic tool in ophthalmology. However, currently, other medical disciplines such as dermatology, cardiology and neurology use this real-time imaging method for clinical application [31]. Furthermore, studies have shown that the application of OCT in dentistry is feasible for monitoring of composite filling material [30], visualization of polymerization [32], caries diagnosis [33], tooth fracture [33], control of marginal sealing of fillings [33] and periodontal tissue [34]. However, there are only a few studies that have used OCT for investigations in the prosthodontic field [7, 29, 35]. To the authors' knowledge, there is only one study that has investigated damage to glass ceramic before and after fatigue loading with OCT [7]. However, there has yet to be a study that has monitored fatigue damage over time in different CAD/CAM materials.

Therefore, the aim of this study was to monitor fatigue damage in six different CAD/CAM materials before and after loadings of 250,000, 500,000, 750,000 and 1,000,000 cycles with OCT in vitro. Ultimately, the specimens were sliced and analysed with a digital light microscope to compare the new OCT method with the established light microscope method. Artificial ageing of the monolithic crowns was simulated by cyclic loading with masticatory forces up to 500 N. The null hypothesis was that there would be no difference between the CAD/CAM materials with regard to fatigue damage.

## 2. Materials and methods

### 2.1. Manufacturing of test specimens

Forty-eight monolithic posterior CAD/CAM crowns were milled from six types of restoration materials (n=8 per group) and were adhesively luted on CAD/CAM-milled human teeth. Caries-free and undamaged human third molars, which were extracted for therapeutic reasons, were anonymously collected in consent with the patients and the local ethics committee (Ref. no. 143/09). There was a maximum period of six months between tooth extraction and usage of teeth in this study. For disinfection, the teeth were carefully cleaned before storage in 0.5% chloramine-T trihydrate solution (Lysoform, Berlin, Germany) for seven days followed by distilled water according to ISO/TS 11405. [36] The teeth were CAD/CAM-milled under permanent water cooling in a numerical control milling machine (CNC) (Mikron HSM 400, GF Machining Solutions, Geneva, Switzerland) to ensure identical tooth preparation with a dentin surface [37]. Therefore, a Standard Tessellation Language (STL) dataset was designed with CAD software (Service Release 12, McNeel Europe, Barcelona, Spain) according to the following parameters: a height of 4.0 mm, a mesio-distal width of 9.5 mm, a bucco-oral width of 7.5 mm, a convergence angle of 6° and a 1.0 mm chamfer with 30° angle [6].

For manufacturing the crowns, a corresponding STL dataset was designed (Version 2.8.8.5, Dental System, 3Shape, Copenhagen, Denmark), with an occlusal-layer thickness of 1.5 mm, a cervical thickness of 1.0 mm, a cement gap of 80 µm and a parameter of fit of 15 µm. Additionally, one marking point each on the mesial and buccal axial wall was implemented in the crown design to ensure exact position in the mouth-motion-simulator and the OCT (Fig. 1). Six different CAD/CAM-materials were used for crown manufacturing: 3Y-TZP zirconium dioxide ('3Y', Lava Plus, 3M Espe, St. Paul, MN, USA), 4Y-PSZ zirconium dioxide ('4Y', Priti multidisc ZrO2 extra translucent, Pritidenta, Leinfelden-Echterdingen, Germany), 5Y-PSZ zirconium dioxide ('5Y', Prettau anterior, Zirkonzahn, Bruneck, Italy), zirconia-reinforced lithium silicate ('ZLS', Celtra Duo, Dentsply Sirona, Hanau, Germany), polymer-infiltrated ceramic network (PICN) hybrid ceramic ('VE', Vita Enamic, Vita Zahnfabrik, Bad Säckingen, Germany) and resin composite ('COM', Brilliant Crios, Coltene, Altstätten, Switzerland) (Table 1). The crowns were milled according to the STL crown dataset in CNC machines optimized for the specific requirements of the different materials (3Y, 4Y, 5Y: Cybaman Replikator, Cybaman Technologies, Cheshire, UK; ZLS, VE, BC: Mikron MILL S400U, GF Machining Solutions, Geneva, Switzerland). Before manually polishing with the recommended polishing system (Table 1), the integrity of each single crown was controlled under a digital optical light microscope (Smartzoom 5, Zeiss, Jena, Germany). After polishing, the ZLS crowns were crystallized and the zirconium dioxide crowns (3Y, 4Y, 5Y) sintered according the manufacturer's instructions (Table 1). The cementation surfaces of the 3Y, 4Y, 5Y and COM crowns were blasted with aluminium oxide powder, and the surfaces of the ZLS and VE crowns were etched with 5%-hydrofluoric acid. All teeth were etched with 35% phosphoric acid for 15 s (Etchant Gel S Kit, Coltene, Altstätten, Switzerland). Afterwards, the crowns were adhesively luted on CAD/CAM-milled human molars according to the manufacturer's information under a standardized pressure of 6 N [38]. A light-curing unit (Bluephase, Ivoclar Vivadent, Schaan, Liechtenstein) were used for polymerization of adhesive and luting systems. The light intensity was checked before application (>800 mW/cm²). In Table 1, detailed information on the luting materials is listed. Before mouth-motion-simulation, all specimens were stored in distilled water at 37°C for 24 h according to ISO/TC. For fatigue testing, each specimen was embedded with core-built-up composite (LuxaCore Z-dual, DMG, Germany) in a special sample holder made of aluminium and polyether ketone (PEAK).

### 2.2. Mouth-motion-simulation

Fatigue testing of specimens was simulated in a mouth-motion-simulator (prematecF1000, wl-tec GmbH, Wertheim, Germany) with compressive, cyclic loading between 50 and 500 N (2 Hz) in the central fossa of the crowns [6, 37]. The specimens were tested in distilled water at 37 ± 2°C in uniaxial direction under constant contact with a semi-spherical stainless steel antagonist (R1, SD Mechantronik GmbH, Feldkirchen, Germany, ) with a diameter of 3.18 mm and an elastic modulus of 200 GPa [39]. For each specimen a new antagonist was used. In total, a clinical service of four years was simulated [40].

### 2.3. Monitoring of fatigue damage with optical coherence tomography

For monitoring of the six CAD/CAM-materials over time, a commercial spectral domain (SD)-OCT (RS-3000, NIDEK Co., LTD., Gamagori, Aichi, Japan), with the corresponding software NAVIS-EX (Vers. 1.5.1.2, NIDEK Co., LTD., Gamagori, Aichi, Japan), was used for image acquisition to detect fatigue damage. All OCT images were captured using a central wavelength of 880 nm and an axial and transverse optical resolution of 7 and 20 µm [41, 42]. For standardized positioning of the test specimens in the OCT, a cubic sample holder of PEAK was manufactured. A 3D-printed platform with a goniometer (GNL18/M, Thorlabs InC., Newton, New Jersey, USA) was mounted in front of the OCT, which allowed for exact positioning of the test specimen in the cubic sample holder (Fig. 2). This ensured a perpendicular aligning of the central OCT beam to the occlusal surface of the crowns. Before testing (T0) and after every 250,000 cycles (T1-

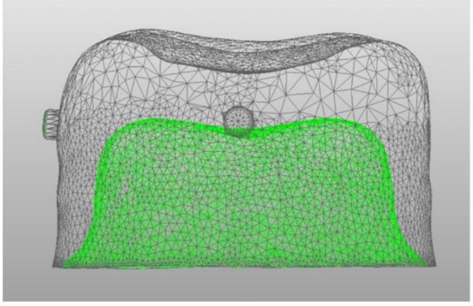

**Fig. 1.** STL data set of the crown with one marking point each on the mesial and buccal axial wall.

**Table 1.** CAD/CAM-materials, manufacturing information and luting systems (provided by manufacturer).

| Code | CAD/CAM Material | Product Name (Manufacturer/ Batch No.) | Polishing System (Manufacturer / Batch No.) | Pre-treatment of cementation surface | Crystallisation/ Sintering Program according to manufacturer's instruction | Pre-treatment of bonding surface (Manufacturer/ Batch No.) | Adhesive (Manufacturer/ Batch No.) | Luting System (Manufacturer/ Batch No.) | material specific refractive index (n) |
|---|---|---|---|---|---|---|---|---|---|
| 3Y | 3 mol% Y2O3-tetragonal zirconia polycrystal (3Y-TZP) | Lava Plus (3M Espe, St. Paul, MN, USA/ 4638621) | Zirconia polisher with integrated diamond particles (Komet Dental/ Gebr. Brasseler GmbH & Co. KG, Lemgo, Germany/ 960762), Fugupol Zirkopol (Feguramed, Buchen, Germany/ 069) | blasting with aluminium oxide powder (50 µm, 2 bar) | Austromat 3001 (Program: room-800°C (20°C/min), 800°C-1450°C (10°C/min), 1450°C (120 min), 1450°C-800°C (15°C/min), 800-250°C (20°C/min), 250°C-room), Dekema, Freilassing, Germany | Scotchbond Universal (3M Espe/ 90121A) | | RelyX Ultimate (3M Espe/ 4801246) | 2.11 |
| 4Y | 4 mol% Y2O3-partially stabilized zirconia (4Y-PSZ) | Priti multidisc ZrO2 extra translucent (Pritidenta, Leinfelden-Echterdingen, Germany/ W1048 18 ET) | | blasting with aluminium oxide powder (50 µm, 1 bar) | Austromat 3001 (Program: room-1450°C (10°C/min), 1450°C (120 min), 1450°C-room (10°C/min)), Dekema | | | | 1.85 |
| 5Y | 5 mol% Y2O3-partially stabilized zirconia (5Y-PSZ) | Prettau anterior (Zirkonzahn, Bruneck, Italy/ ZB4150D) | | blasting with aluminium oxide powder (110 µm, 3.5 bar) | Austromat 3001 (Program: room-1450°C (10°C/min), 1450°C (120 min), 1450°C-room (10°C/min)), Dekema | | | | 1.91 |
| ZLS | zirconia-reinforced lithium silicate glass ceramic | Celtra Duo (Dentsply Sirona, Hanau, Germany/ 16004940) | | 5%-hydrofluoric acid (30 s) | Programat EP3000 (Program: B 500°C, S 3:30 min, 500°C-820°C (60°C/min),T1 820°C (1 min), 820°C-750°C (3 min), 750°C-50°C), Ivoclar Vivadent, Schaan, Lichtenstein) | Calibra Silan (Dentsply Sirona/ 00006181) | Prime&Bond active (Dentsply Sirona/ 60667340) | Calibra Ceram (Dentsply Sirona/ 00003574) | 1.55 |
| VE | polymer-infiltrated ceramic network (PICN) | Vita Enamic (Vita Zahnfabrik, Bad Säckingen, Germany/ 75840) | Vita Enamic Polishing Set technical (Vita Zahnfabrik/ E76470) | 5%-hydrofluoric acid (60 s) | / | Vita Adiva (Vita Zahnfabrik/ E51810255A) | Vita Adiva T-Bond I/II (Vita Zahnfabrik/ I:E51802824, II: E5610984A) | Vita Adiva F-Cem (Vita Zahnfabrik/ E71809758) | 1.51 |
| COM | CAD/CAM composite | Brilliant Crios (Coltene, Altstätten, Switzerland/ J02758) | DIATECH Finishing & Polishing Kit (Coltene/ 424330) | blasting with aluminium oxide powder (50 µm, 1.5 bar) | / | One Coat 7 Universal (Coltene/ J08515) | | DuoCem (Coltene/ I94771) | 1.51 |

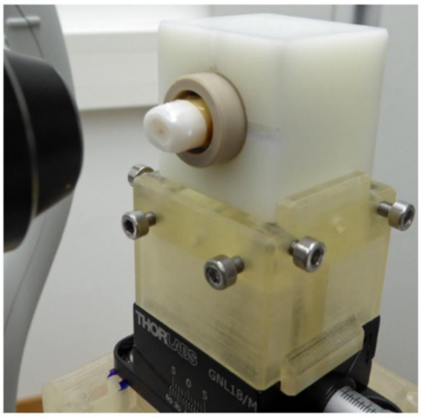

**Fig. 2.** 3D-printed platform with a goniometer for exact positioning of the test specimen in front of the OCT.

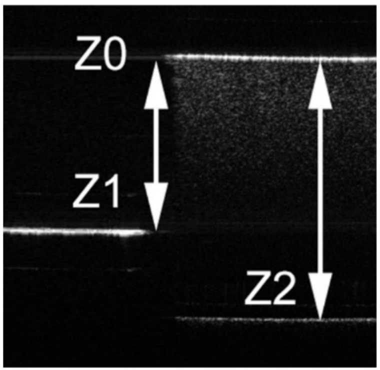

**Fig. 4.** Example for measurement of the material specific refractive index (n=(Z2-Z0)/(Z1-Z0)) [45].

T4) (Fig. 3), the specimens were examined for fatigue damage with the non-destructive OCT method. In the application 'Macula Map', eight greyscale images (B-scans) were taken per specimen in mesio-distal direction. For investigation of fatigue damage, the raw OCT data were imported into the imaging processing software ImageJ (ver.1.52f, Wayne Rasband, NIH, USA) [29, 43, 44]. The vertical and horizontal maximum damage was measured in pixel distance,[29] converted into millimetres (pixel size: 5.7 µm (vertical)/18 µm (horizontal)) and divided by the material-specific refractive index (n=(Z2-Z0)/(Z1-Z0)) (Table 1), which was measured and calculated for each of the six CAD/CAM materials, as described by Oguro et al. (Fig. 4) [45]. Finally, the arithmetic mean of all values was calculated for each specimen. Analyses were performed by one experienced operator (M.S.).

### *2.4. Analysis of fatigue damage with light microscope*

After mouth-motion-simulation and investigation with OCT, all specimens were dyed in .5% aqueous fuchsin solution (C.I. 42510, Carl Roth GmbH + Co KG, Karlsruhe, Germany, batch no: 276244301) for 24 hours at room temperature to stain possible microcracks. After carefully cleaning under running distilled water, the specimens were sectioned mesio-distally into four slices (IsoMet1000, Buehler, IL, USA) under constant water cooling. A special sample holder allowed for exact positioning for slicing. This ensured the investigation of identical measurement points (2x4 slices) in the OCT and the light microscope. Vertical and horizontal fatigue damage were analysed under the digital light microscope with the corresponding software (Smartzoom 5, version 1.1), and the arithmetic mean for each specimen was calculated.

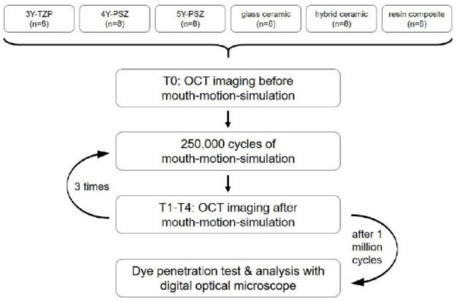

**Fig. 3.** Flow scheme of the investigation.

### *2.5. Statistical analysis*

For statistical analysis, SPSS (Version 25, IBM, Armonk, NY, USA) was used. The data obtained from the OCT were submitted to an analysis of covariance (ANCOVA), with the factor 'number of cycles' as a covariate and four levels of 'CAD/CAM material'. The variance heterogeneity from factor 'CAD/CAM material' was modelled using the MIXED procedure. Furthermore, the data from the OCT (T4) and microscope were subjected to a 2x4-ANOVA method. The variance heterogeneity was also modelled with the MIXED procedure. Due to the risk for alpha-error accumulation, p values were corrected with the Bonferroni method. The level of significance was set at $\alpha$=.05.

## 3. Results

All specimens survived mouth-motion-simulation, and no partial or total failure occurred. The 3Y and 4Y specimens did not show any damage at all. As in all other CAD/CAM materials, fatigue damage in the form of microcracks under the OCA was observed.

The statistical analysis showed significant differences between the four CAD/CAM materials in vertical and horizontal directions ($p<.05$) (Fig. 5 and 6, Table 2). Zirconia-reinforced lithium silicate exhibited the highest damage, followed by hybrid ceramic, resin composite and 5Y-PSZ. While damage to 5Y-PSZ was initially noticed after 750,000 cycles, all other materials already showed crack formation after 250,000 cycles. A linear increase in damage was noticed in all materials (except for 3Y and 4Y) (Table 2). Therefore, the null hypothesis had to be partially rejected.

The area of damage was higher under the microscope compared to OCT. Between the OCT images (T4) and the microscope, a significant difference was shown for the zirconia-reinforced lithium silicate and hybrid ceramic specimens (Fig. 7 and 8). Figure 9 depicts a typical example of measuring points for all six CAD/CAM materials analysed with OCT and microscope.

## 4. Discussion

For simulation of a clinical set-up, CAD/CAM-milled human teeth were used for the investigation. Compared to manually prepared human teeth that have been used in other studies,[46-48], this method

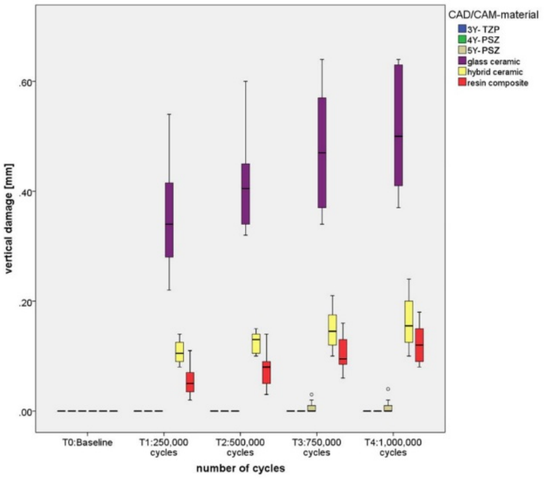

**Fig. 5.** Boxplots of the vertical damage investigated with OCT.

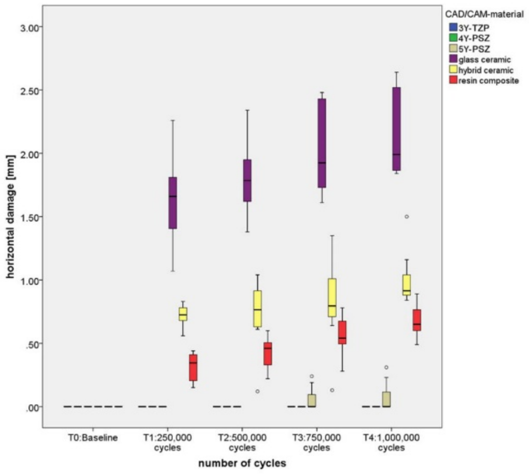

**Fig. 6.** Boxplots of the horizontal damage investigated with OCT.

**Table 2.** Analysis of covariance (ANCOVA) with number of cycles as covariate and four levels of CAD/CAM material.

| | Vertical Damage | | | | Horizontal Damage | | | |
|---|---|---|---|---|---|---|---|---|
| Parameter | Estimate | p-Value | 95% Confidence Interval | | Estimate | p-Value | 95% Confidence Interval | |
| | | | Lower Bound | Upper Bound | | | Lower Bound | Upper Bound |
| 5Y * number of cycles | .001 | .855 | -.013 | .016 | .014 | .813 | -.109 | .136 |
| zirconia-reinforced lithium silicate * number of cycles | .053 | .002 | .021 | .086 | .179 | .002 | .072 | .285 |
| hybrid ceramic * number of cycles | .019 | .001 | .008 | .029 | .094 | .027 | .011 | .176 |
| resin composite* number of cycles | .023 | .000 | .013 | .034 | .122 | .000 | .080 | .164 |
| 5Y | -.029 | .298 | -.086 | .028 | -.176 | .413 | -.621 | .268 |
| zirconia-reinforced lithium silicate | .273 | .000 | .179 | .367 | 1.271 | .000 | .960 | 1.582 |
| hybrid ceramic | .057 | .006 | .017 | .097 | .392 | .003 | .142 | .641 |
| resin composite | .000a | / | / | / | .000 | / | / | / |
| number of cycles | .000 a | / | / | / | .000 | / | / | / |

a. This parameter was set to zero because it is redundant.

allows for identical tooth preparation while using natural substrates[6, 37].Therefore, the CAD/CAM-crowns were milled according to one single STL dataset, which ensured the same testing conditions for each specimen. Nevertheless, it must be observed that the composition and microstructure of natural tissues still differs [49].

Furthermore, studies have shown better fracture and bond strength for adhesive luting compared to conventional cementation [24, 50]. As such, the specimens were adhesively luted using the manufacturer's recommended luting system.

For artificial ageing, the specimens were loaded in water to simulate intraoral conditions considering the chemical-assisted crack growth [2, 51]. Because chewing is not a single static loading, cyclic fatigue tests provide more reliable information on mechanical properties compared to static tests [2, 21]. Thus, the specimens were loaded in a mouth-motion-simulator, with a linear increase and decrease between 50 and 500 N. Other studies have used lower forces, between 50 and 80 N,[2, 46] but monolithic materials, especially polymer-based ones, are discussed for patients with higher masticatory forces (e.g., bruxism), where loads up to 800 N are described [25]. For analysis of damage, different methods are described in the literature. A common technique for the investigation of cracks is the fractography [52]. With this method, the crack origin, development and failure load can be explored by analysing the fracture pattern [53]. However, a monitoring of crack propagation is only possible in transparent materials and for analysis,

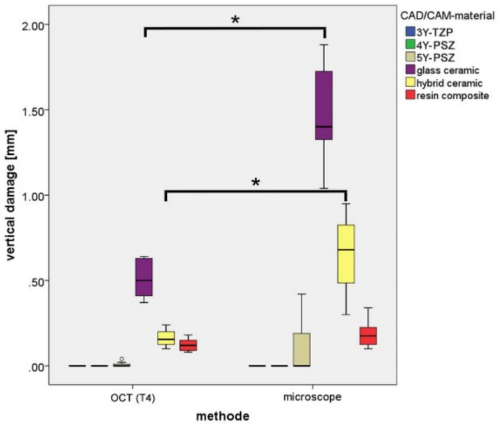

**Fig. 7.** Comparison of OCT (T4) and microscope–vertical damage (*show significant difference p< .05).

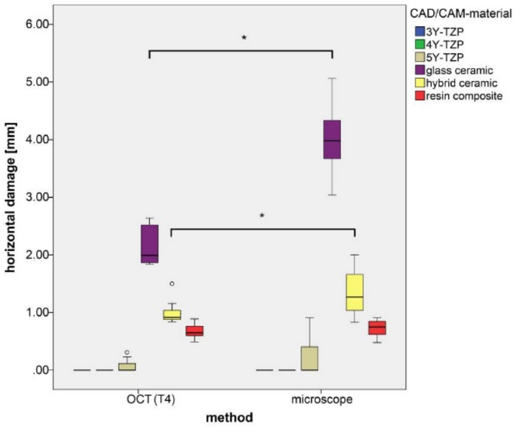

**Fig. 8.** Comparison of OCT (T4) and microscope–horizontal damage (*show significant difference p< .05).

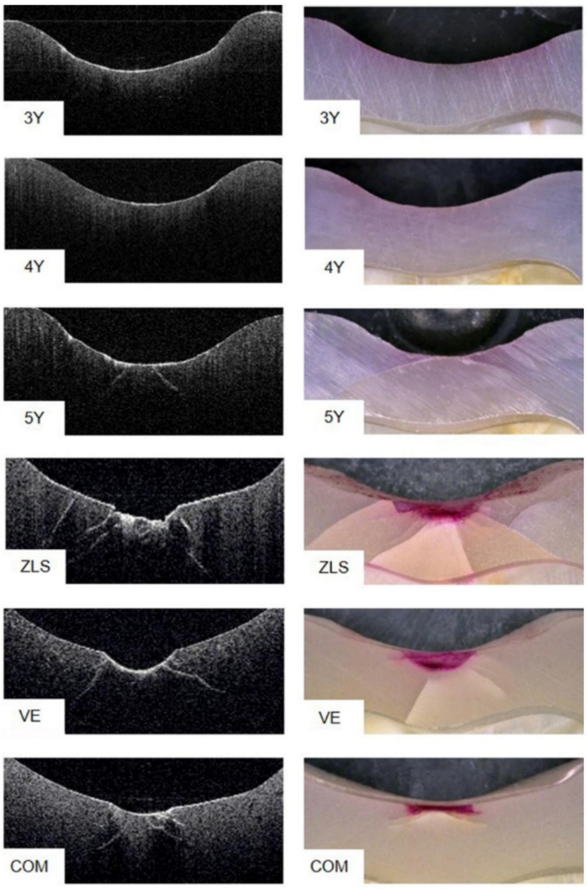

**Fig. 9.** Example of measurement points with fatigue damage after 1 million cycles: OCT T4 (left), microscope (right).

specimens have to be destroyed. Therefore, this method was not applicable for the present study. In many studies only the occurrence of cracks, the type of crack or the applied load until fracture is described [7, 25, 54, 55]. The investigation of crack development and progression is difficult, because devices like video cameras only record cracks in transparent materials or on the specimens' surface [27]. Some authors have measured the area without damage by slicing the specimen [6, 56], whereas Shembish et al. measured the crack length. As this study investigated specimens at different points over time, the area of damage in vertical and horizontal directions were measured rather than single crack length. Some CAD/CAM materials, such as VE showed a loss of substance besides crack propagation. Therefore, it might be interesting to analyse the surface abrasion as well and calculate the volume loss over time.

Yazigi et al. showed that the OCT method is suitable for revealing crack formation in glass ceramics [7]. In this study, cracks were also found in zirconium dioxide, hybrid ceramic and resin composite; thus, this method might be applicable for different kinds of restoration materials. De Oliveira et al. showed higher resolution images for SD-OCT compared to swept source (SS)-OCT [44]. Therefore, in this study a SD-OCT was used to image crack propagation. Because the OCT method is a new approach for monitoring fatigue damage in restorations, the specimens were additionally analysed under a digital light microscope. The latter required the destructive method of slicing the specimens, so only the OCT images from T4 were compared to light microscope. The results showed higher vertical and horizontal damage for the microscope method compared to OCT, but only the zirconia-reinforced lithium silicate and hybrid ceramic, which had the highest damage of all the tested materials, showed significant differences. For one thing, this finding may be explained by the shallow light penetration of the OCT. Depending on the material and wavelength of the OCT, the depth of penetration varies between 1 and 3 mm [29, 44]. Hence, subsurface damage directly under the OCA can be shown with OCT, whereas outer cracks cannot be captured. Then, again, sectioning of specimens involves the risk of cracks forming during cutting [44]. Thus, crack propagation may continue during slicing as well, which might caused artifacts in the specimens.

The OCT images showed a bright cluster on the surface of the specimens. This phenomenon reflects an increase in signal intensity on the interface between the air and CAD/CAM material [32].

The first crack nucleation originates at the surface, with subsurface microcracks at the loading point [2, 57, 58]. Homaei et al. calculated with FEM analysis the maximum stress concentration under the contact point in the OCA for hybrid ceramic and glass ceramic [20]. Indeed, initial flaws occurred during the first 250,000 cycles in the resin composite, hybrid ceramic and zirconia-reinforced lithium silicate. By contrast, crack initiation began in 5Y-PSZ between 500,000 and 750,000 cycles. Giertmühlen et al. investigated 5Y-PSZ as well and showed a significantly higher initial fracture strength compared to post-fatigue testing [59]. 5Y-PSZ contains tetragonal zirconia polycrystals as well as cubic zirconia to improve the aesthetic, but it only has half the flexural strength of 3Y-TZP [10, 12].

However, 5Y-PSZ showed the least vertical and horizontal damage compared to zirconia-reinforced lithium silicate, hybrid ceramic and resin composite. Rosentritt et al. investigated the loadings until failure and found a higher number of cycles until failure for resin composite and a lower number of fracture pieces compared to hybrid ceramic [2]. In this study, the specimens were not loaded until failure, but the hybrid ceramic showed a significantly higher area of fatigue damage compared to resin composite, which might lead to earlier failure. Besides, the hybrid ceramic specimen showed less damage compared to zirconia-reinforced lithium silicate. Choi et al. described a different stress distribution and fracture mechanism for the hybrid ceramic compared to glass ceramic, which can readily be explained by a plastic deformation of the polymer phase that may absorb acting force as described in the literature [1, 60]. Thus, this might be an explanation why the polymer containing specimens showed less damage compared to zirconia-reinforced lithium silicate.

It is discussed if a lithium silicate ceramic as a reference for the glass ceramic materials shows less damage compared to the zirconia-reinforced lithium silicate used in the present study. In the literature comparable strength values between zirconia-reinforced lithium silicate and lithium disilicate ceramic are described. Nevertheless, a higher range of measured strength values for zirconia-reinforced lithium silicate were observed [15, 61]. Probably the lithium disilicate ceramic shows a less scattering of damage.

Nevertheless, all CAD/CAM materials (except for 3Y-TZP and 4Y-PSZ) showed a linear increase in damage over time. Furthermore, a significant difference between the restoration materials was shown. This finding is consistent with the literature [6].

For further investigation, clinical studies are required. However, for resin composite and hybrid ceramic, long-term clinical data are not yet available. Thus, data from the laboratory are important, such as dynamic fatigue tests, to better understand the behaviour of new CAD/CAM materials [2]. In this regard, OCT may be a perspective for clinical practice as well, because it is a non-invasive approach that does not use radiation.

## 5. Conclusion

Within the limitations of an in vitro study, this investigation showed the possibility of monitoring fatigue damage with OCT over time. The highest vertical and horizontal damage were observed for the zirconia-reinforced lithium silicate, followed by the hybrid ceramic, resin composite and 5Y-PSZ, whereas 4Y-PSZ and 3Y-TZP did not show damage. Although, different materials were tested, comparable fatigue and a linear increase in damage were found. Nevertheless, in outer areas, microcracks were not captured with OCT.

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## Conflicts of interests

There are no conflicts of interests related to this study.

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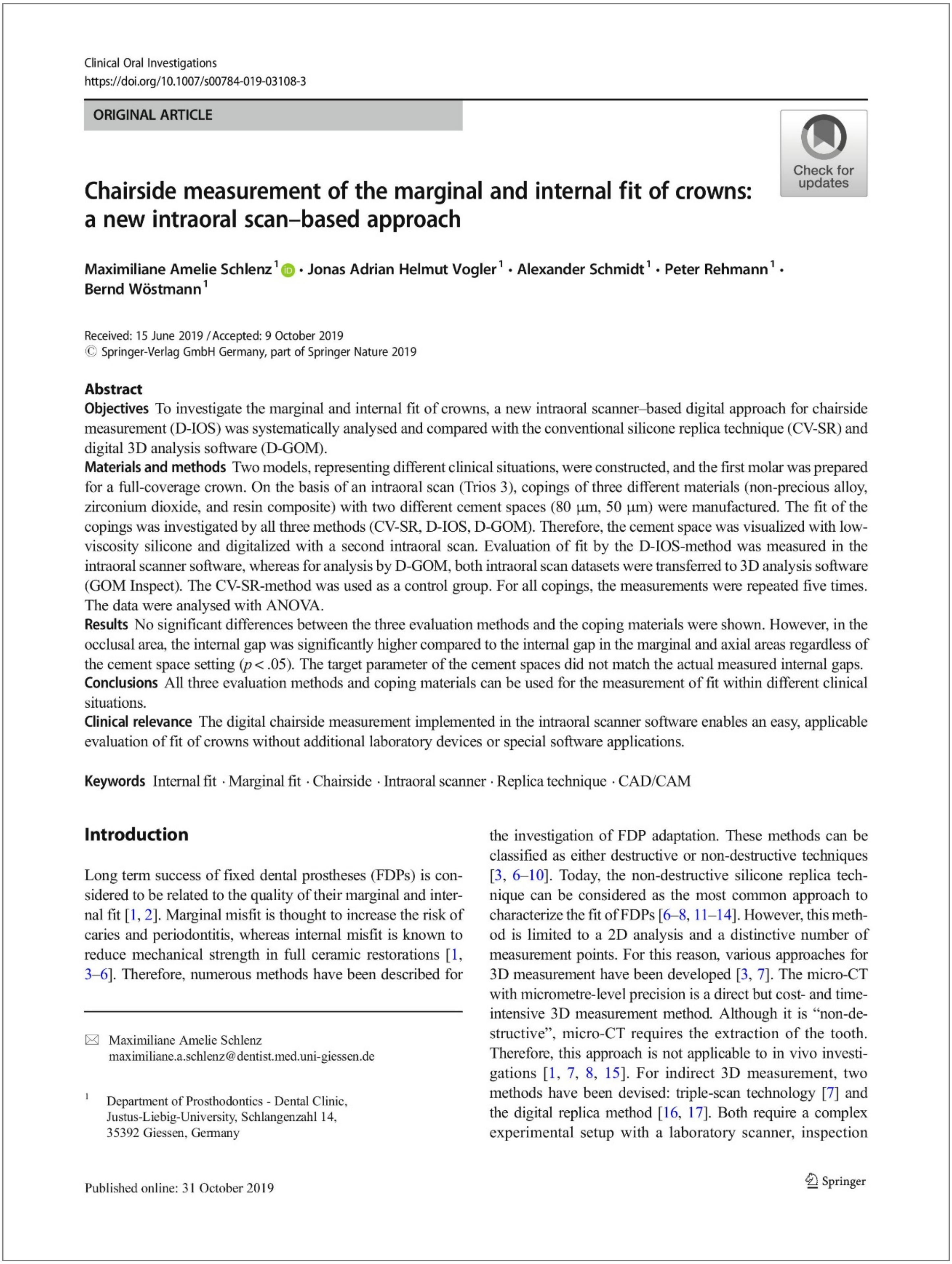
## 7.9 Publikation 6



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ORIGINAL ARTICLE

# Chairside measurement of the marginal and internal fit of crowns: a new intraoral scan–based approach

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## Abstract

**Objectives** To investigate the marginal and internal fit of crowns, a new intraoral scanner–based digital approach for chairside measurement (D-IOS) was systematically analysed and compared with the conventional silicone replica technique (CV-SR) and digital 3D analysis software (D-GOM).

**Materials and methods** Two models, representing different clinical situations, were constructed, and the first molar was prepared for a full-coverage crown. On the basis of an intraoral scan (Trios 3), copings of three different materials (non-precious alloy, zirconium dioxide, and resin composite) with two different cement spaces (80 μm, 50 μm) were manufactured. The fit of the copings was investigated by all three methods (CV-SR, D-IOS, D-GOM). Therefore, the cement space was visualized with low-viscosity silicone and digitalized with a second intraoral scan. Evaluation of fit by the D-IOS-method was measured in the intraoral scanner software, whereas for analysis by D-GOM, both intraoral scan datasets were transferred to 3D analysis software (GOM Inspect). The CV-SR-method was used as a control group. For all copings, the measurements were repeated five times. The data were analysed with ANOVA.

**Results** No significant differences between the three evaluation methods and the coping materials were shown. However, in the occlusal area, the internal gap was significantly higher compared to the internal gap in the marginal and axial areas regardless of the cement space setting ($p < .05$). The target parameter of the cement spaces did not match the actual measured internal gaps.

**Conclusions** All three evaluation methods and coping materials can be used for the measurement of fit within different clinical situations.

**Clinical relevance** The digital chairside measurement implemented in the intraoral scanner software enables an easy, applicable evaluation of fit of crowns without additional laboratory devices or special software applications.

**Keywords** Internal fit · Marginal fit · Chairside · Intraoral scanner · Replica technique · CAD/CAM

## Introduction

Long term success of fixed dental prostheses (FDPs) is considered to be related to the quality of their marginal and internal fit [1, 2]. Marginal misfit is thought to increase the risk of caries and periodontitis, whereas internal misfit is known to reduce mechanical strength in full ceramic restorations [1, 3–6]. Therefore, numerous methods have been described for the investigation of FDP adaptation. These methods can be classified as either destructive or non-destructive techniques [3, 6–10]. Today, the non-destructive silicone replica technique can be considered as the most common approach to characterize the fit of FDPs [6–8, 11–14]. However, this method is limited to a 2D analysis and a distinctive number of measurement points. For this reason, various approaches for 3D measurement have been developed [3, 7]. The micro-CT with micrometre-level precision is a direct but cost- and time-intensive 3D measurement method. Although it is "non-destructive", micro-CT requires the extraction of the tooth. Therefore, this approach is not applicable to in vivo investigations [1, 7, 8, 15]. For indirect 3D measurement, two methods have been devised: triple-scan technology [7] and the digital replica method [16, 17]. Both require a complex experimental setup with a laboratory scanner, inspection

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software and expert skills [6, 7, 16–18]. A novel approach to facilitate 3D measurement may be based on an intraoral scanner (IOS). Zimmermann et al. recently described a measurement method with the software OraCheck (Cyfex, Zurich, Switzerland) that can be implemented in the Cerec System (Dentsply Sirona, Bensheim, Germany) [19]. However, to the best of our knowledge, no systematic evaluation has been described that compares this method to established conventional approaches, specifically the silicone replica technique.

Thus, the aim of this study was to develop a new IOS-based digital approach (D-IOS) for simple, cost-effective and precise assessment of the fit of full crowns suitable for application in patients and to investigate its reliability in a laboratory setting. This systematic investigation aimed to compare the results of the new D-IOS method to the conventional silicone replica technique (CV-SR) [20] and a modified digital replica method (D-GOM) [6] in two different clinical situations: FDP with mesial and distal adjacent teeth (A) and FDP on the terminal tooth with only mesial adjacent teeth (B). To represent the numerous available materials and cement space settings, three different typical materials (non-precious-alloy (NPA), zirconium-dioxide (ZIR), and resin composite (COM)) were used for the production of simplified crowns (copings) with a cement space of 50 μm and 80 μm. The following null hypotheses were tested:

I) The three evaluation methods (D-IOS, CV-SR, and D-GOM) show no statistically significant differences for the marginal and internal fit measurement.
II) There are no significant differences among the three coping materials (COM, ZIR, and NPA) for the marginal and internal fit.
III) The two selected parameters of 50 μm and 80 μm for the cement spaces are not related to the size of the measured internal fit.

## Materials and methods

### Preparation of test models

For the investigation of different clinical situations, two test models (A and B) were constructed. Therefore, caries-free, undamaged human teeth, which were extracted for therapeutic reasons in consensus with approval of the patients and the approval of the local ethics committee (Reg. No. 143/09), were embedded in acrylic resin and mounted on a carrier plate (Fig. 1). In both models, the left first upper molar (FDI 26) was prepared under constant water cooling for a full-coverage crown with a reduction of 1.5 mm, a circumferential chamfer line of 1 mm, a convergence angle of 5–10°, and a preparation height of 4 mm [21]. All edges were rounded. Model A represented a clinical situation with mesial and distal adjacent teeth (FDI 25 and 27) (Fig. 2a), whereas model B displayed a preparation of the terminal tooth with only mesial adjacent teeth (FDI 24 and 25) (Fig. 2b). Four grooves on the models (mesial, distal, oral, and buccal) served as reference points for identical positioning and standardized evaluation of measurement points (Fig. 1).

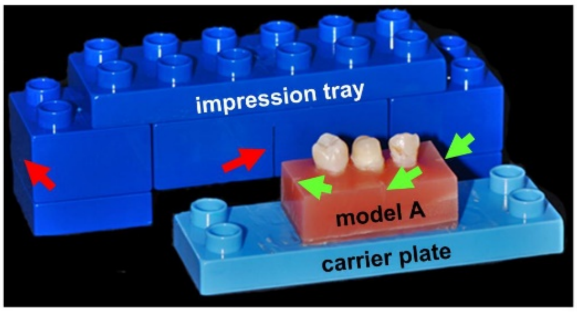

**Fig. 1** Simulation of a clinical situation with two adjacent teeth and a prepared first molar (model A) mounted on a carrier plate (patrix) with referent marks (green arrows). The impression tray (matrix) has corresponding markings (red arrow) for a reproducible, standardized setting

### Manufacturing of copings

Both models A and B were digitally scanned with an intraoral scanner (IOS, Trios3, version 1.18.2.10, 3Shape, Copenhagen, Denmark) according to a scanning protocol based on the manufacturer's instructions. Before usage, the IOS was calibrated using the respective calibration device. The datasets obtained were used for designing the copings in CAD software (version 17.2.1, dental system, 3Shape). The copings were milled from a solid block of non-precious alloy (NPA), zirconium dioxide (ZIR), and resin composite (COM) on a respective 5-axis milling machine (NPA: Datron D5, Datron AG, Mühltal, Germany; ZIR: FinoCAM CA, Fino GmbH; COM: FinoCAM W, Fino GmbH) (Fig. 3). The parameters of the copings were set to a 600 μm layer thickness with a 200 μm edge reinforcement [11, 12]. For all materials, one coping with a cement gap (down to 0.5 mm above the margin line [16]) of 50 μm and another with 80 μm were manufactured. The zirconia copings were sintered in a calibrated dental ceramic oven (Austromat μSiC, Dekema, Freilassing, Germany) according to the manufacturer's instructions (room–800 °C, 40 min; 800–1450 °C, 65 min; 1450 °C, 120 min; 1450–800 °C, 45 min; 800–250 °C, 30 min; 250 °C–room).

### Analysis of fit

The measurement of fit was carried out at 16 measurement points, at which the positions were standardized and transferable to all three evaluation methods (Fig. 4) [20]: conventional

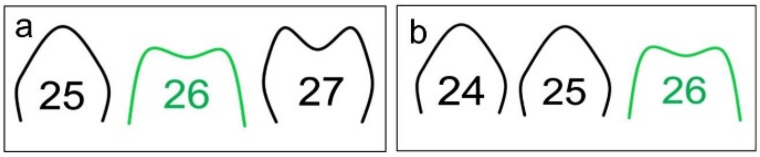

**Fig. 2** Schematic drawing of model A with mesial and distal adjacent teeth (**a**) and model B with only mesial adjacent teeth (**b**)

silicone replica technique (CV-SR), digital analysis with IOS software (D-IOS), and digital analysis with 3D software (D-GOM). First, the cement space was visualized with low-viscosity silicone [16]. Therefore, the copings were isolated with powder spray (CEREC Optispray, Dentsply Sirona, Bensheim, Germany), filled with silicone, and seated on the prepared tooth (detailed information about the materials used in this study is listed in Table 1). A loading device ensured a constant load of 20 N for standardized testing conditions [17, 20]. After 10 min, the copings were carefully removed, and the intact remnant of the silicone replica on the prepared tooth was controlled. A second scan of the model (with the silicone replica on the prepared tooth) was accomplished with the intraoral scanner for the two digital evaluation methods. Then, an over impression was taken to collect the silicone replica for the conventional evaluation method. For this process, a one-step heavy body wash impression protocol with a high-viscosity green-coloured and a low-viscosity pink-coloured vinyl polysiloxane silicone was used in combination with modified interlocking plastic bricks (Unico Plus, Simba Dickie Group, Fürth, Germany) that served as an impression tray. The plastic bricks allowed for the exact positioning of the model on the carrier plate (Fig. 1) [20]. After 10 min of setting time, the impression was removed from the model, and the impression was filled with low-viscosity yellow-coloured vinyl polysiloxane silicone. Each specimen was sectioned in the mesio-distal and oral-buccal direction with a razor blade. For standardized sectioning, four grooves (mesial, distal, oral, and buccal) were prepared in the impression tray (Fig. 1) [20]. According to these grooves, all specimens were sectioned

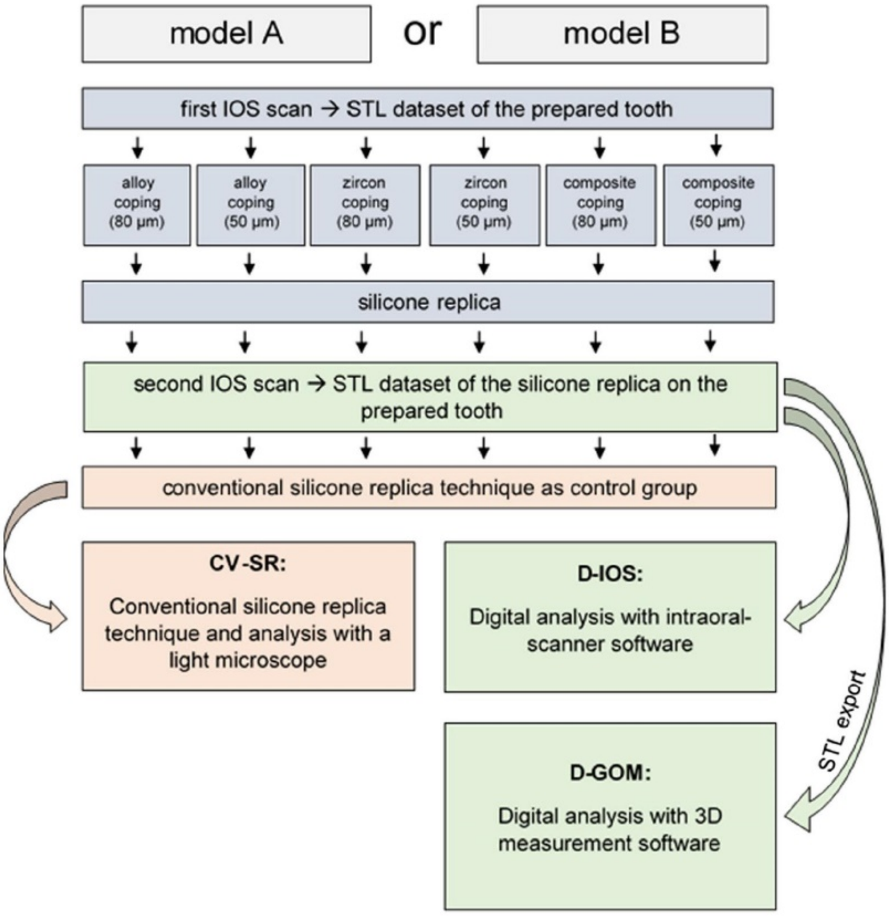

**Fig. 3** Flow scheme of the investigation

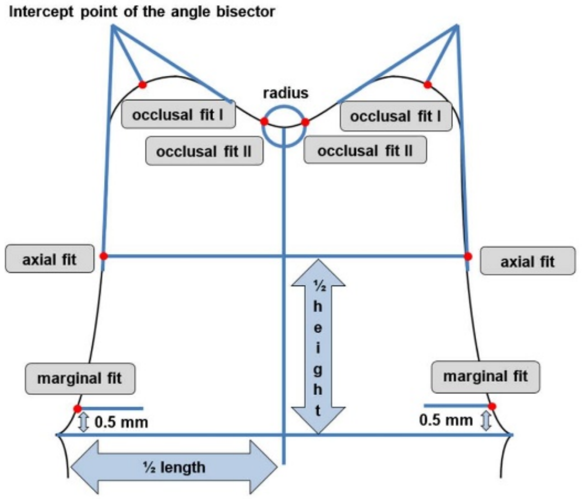

**Fig. 4** Schematic drawing of measurement points for highly standardized evaluation

reproducibly in the same plane. The grooves in the impression tray matched the reference marks on the model, so the sectioning planes of the digital methods (D-IOS and D-GOM) were identical to those of the conventional method (CV-SR).

**Table 1** Materials used in the study (information provided by the manufacturer)

| Material | Colour | Product name (Batch no.) | Manufacturer |
|---|---|---|---|
| Powder spray | Blue | Cerec Optispray (S50868) | Dentsply Sirona (Bensheim, Germany) |
| Addition-curing silicone | Blue | Fit Test C&B (1841465) | Voco (Cuxhaven, Germany) |
| Vinyl polyether silicone | Yellow | EXA'lence Extra Light Body (1806261) | GC (Tokyo, Japan) |
| Vinyl polyether silicone | Pink | EXA'lence Light Body (1806221) | |
| Vinyl polyether silicone | Green | EXA'lence Putty (1711091) | |
| Resin composite block | A2 | LuxaCam Composite (784249) | DMG (Hamburg, Germany) |
| Zirconium dioxide | – | Lava Plus (4525742) | 3M (St. Paul, MN, USA) |
| Non-precious alloy (> 10 wt% cobalt, chrome, 1–10 wt% tungsten, silicon, manganese, iron, 0.1–1 wt% carbon) | – | Finoframe CoCr (K10627) | Fino (Bad Bocklet, Germany) |

For the analogue measurement by the CV-SR method, a light microscope (Smartzoom 5, PlanApo D 1.6x/0.1 FWD 36 mm, Zeiss, Jena, Germany) with the corresponding measurement software was used (Smartzoom 5, version 1.1, Zeiss), whereas for analysis by D-IOS, the two intraoral scans (with and without a silicone replica) were automatically superimposed over the adjacent non-prepared teeth in the IOS software using the new monitoring and measurement function. For evaluation by D-GOM, the two intraoral scan datasets were exported as standard tessellation language (STL) datasets and analysed in 3D analysis software (GOM Inspect 3D, version V8 SR1, GOM GmbH, Braunschweig, Germany). For superimposition over the adjacent teeth, the best-fit algorithm was used. Measurements of all three evaluation methods were repeated five times for each coping. Figure 5 shows an example of a mesio-distal cutting plane with measurement points for all evaluation methods.

The statistical analysis was performed using SPSS Statistics (version 25, IBM, Armonk, NY, USA). The data were subjected to a $2 \times 3 \times 3$-ANOVA method with factors of material and position. The three-way interaction, the interactions of material by the evaluation method, and the interaction method by position were very weak and clearly. Therefore, the interaction of material by position is interpreted. Pairwise comparisons of margins are reported for the three coping materials (COM, ZIR, and NPA) analysed for every level of position of internal fit (marginal, axial, and occlusal). Inspection of model residuals did not show serious deviations from a normal distribution. The procedure MIXED was used to allow for heterogeneity of variances. Due to the risk for alpha-error accumulation, $p$ values were corrected with the Bonferroni method. The level of significance was $p < .05$.

## Results

All evaluation methods could be carried out on the two models, A and B, which simulated different clinical situations. The results obtained for the internal fit are displayed in Fig. 6 and Table 2. There was no significant difference among the three evaluation methods, CV-SR, D-GOM, and D-IOS, regarding the measurement of fit, so the first null hypothesis could not be rejected. Among the three coping materials, COM, ZIR, and NPA, no significant difference was observed regarding the complete internal fit (Fig. 6, Table 2), whereas for the examination of the single measuring positions (marginal, axial, and occlusal fit), differences were shown (Fig. 7, Tables 3 and 4). All coping materials exhibited higher internal gaps for the occlusal measurement points compared to the

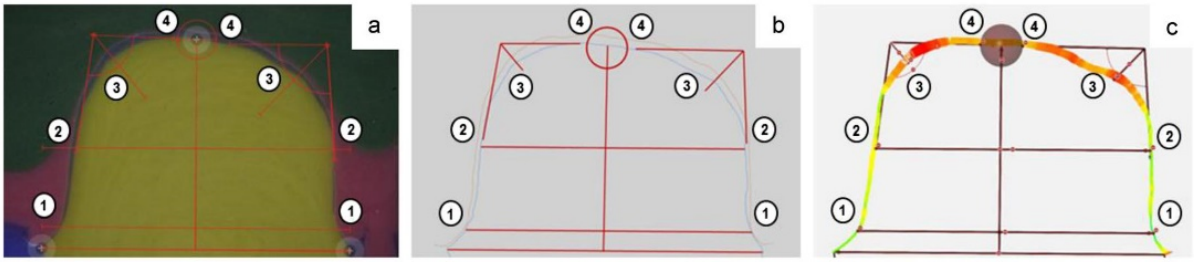

**Fig. 5** Example of specimens for measurement of fit: CV-SR (**a**), D-IOS (**b**), and D-GOM (**c**) (1 = marginal fit, 2 = axial fit, 3/4 = occlusal fit)

axial and marginal measurement points, so the second null hypothesis had to be partly rejected. In particular, NPA showed a significantly higher internal gap in the occlusal area compared to COM and ZIR. Furthermore, two different cement spaces (50 μm and 80 μm) were investigated. The data show that the target parameters of the cement space do not match the measured internal gaps. Only COM (50 μm) in model A showed a marginal fit of 48.9 ± 6.5 μm, which almost matches the target parameter of 50 μm. In particular, in the occlusal and marginal area the internal gap tended to be lower if the cement gap was set to 80 μm. The absolute discrepancy of the various material copings and measurement positions is displayed in Tables 3 and 4. Therefore, the third null hypothesis could not be rejected either.

## Discussion

The primary aim of this study was the systematical investigation of the new D-IOS method and the comparison of the measurement results to the conventional silicone replica technique (CV-SR) and the modified digital replica method (D-GOM). To compare the three evaluation methods, the measurement of fit was highly standardized with identical measurement points [20]. Therefore, it was abstained from analysing marginal discrepancies as the measuring points can hardly be standardized. So, in contrast to Praca et al. [20], the marginal fit was measured 0.5 mm above the preparation line, because one aspect of this study was the investigation if the target parameters of the cement space match the measured internal gaps. Other studies reported marginal discrepancy including over-extension and under-extension as describes by Holmes et al. [22]. With that method, various types of marginal misfit can be described. However, a definition of identical measurement points for a standardized comparison of the investigation method is not possible.

For the investigation of different clinical situations, two models (A and B) were manufactured. Therefore, human teeth were used for an in vivo close setup [2, 20]. Other studies investigating marginal and internal fit used artificial teeth made of acrylic [4, 7, 10, 16], gypsum [6], zirconia [5, 15], or metal [16–18] materials. The copings were milled from zirconium dioxide (ZIR) [1], non-precious alloy (NPA) [1], and resin composite (COM) [8] to reflect the variety of

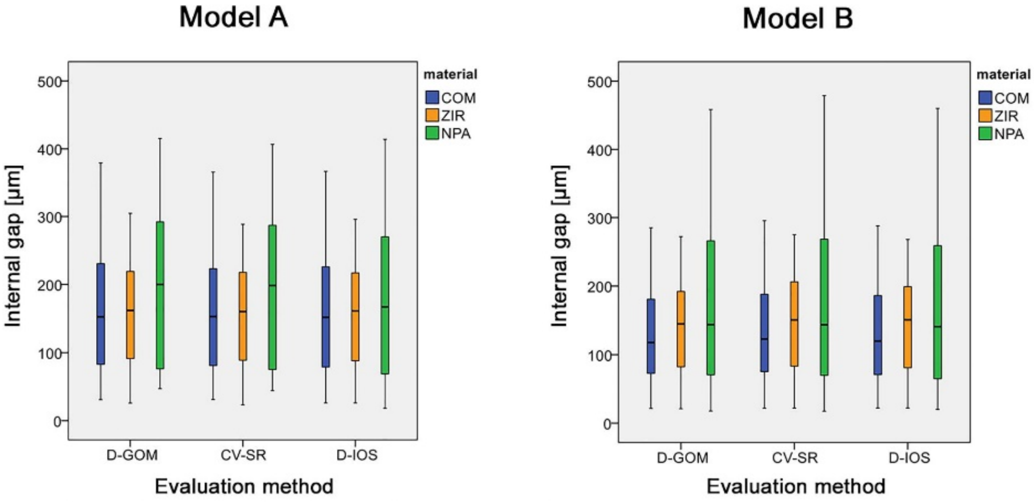

**Fig. 6** Boxplots of evaluation methods and coping materials for models A and B

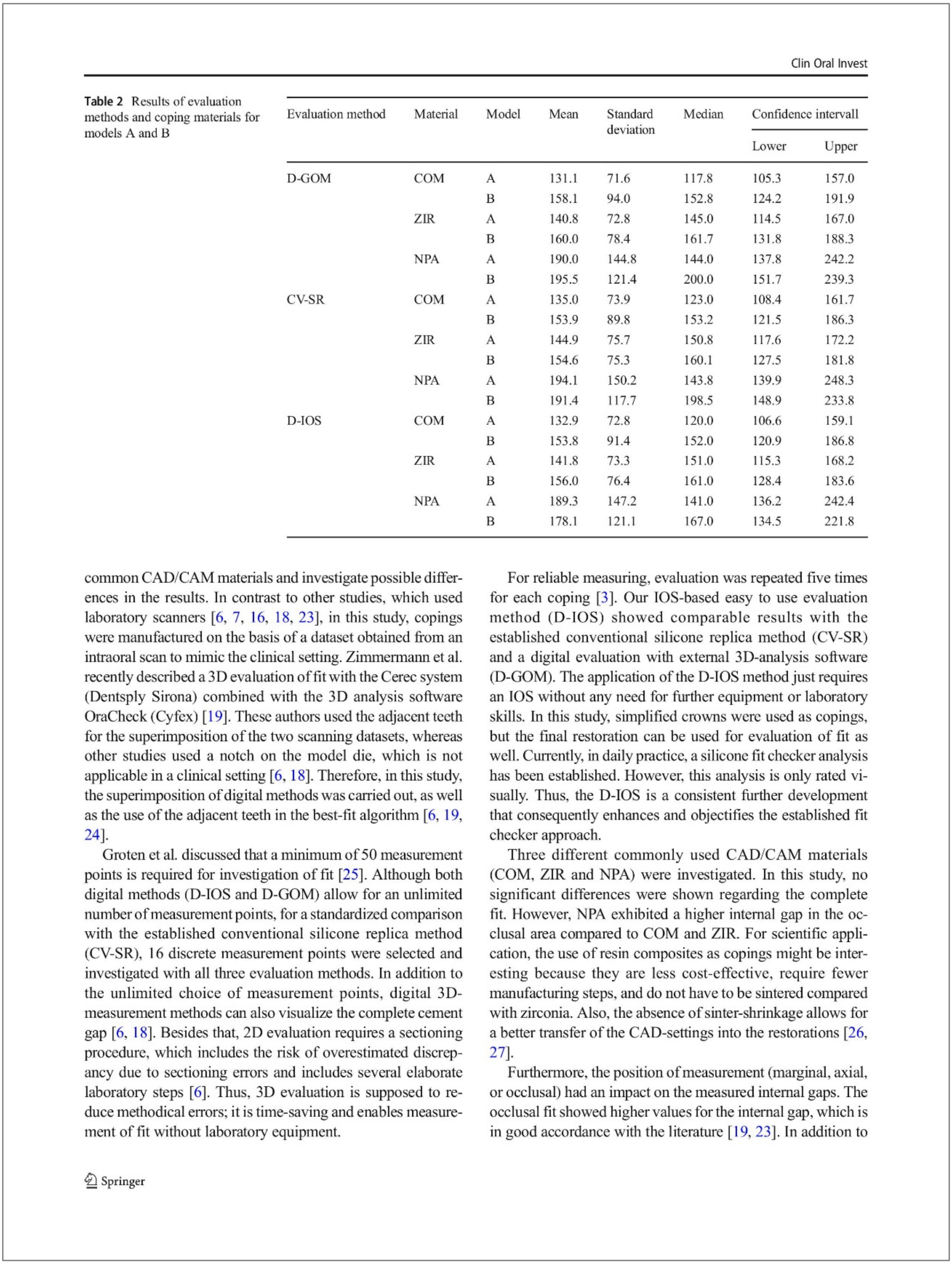

**Table 2** Results of evaluation methods and coping materials for models A and B

| Evaluation method | Material | Model | Mean | Standard deviation | Median | Confidence intervall | |
|---|---|---|---|---|---|---|---|
| | | | | | | Lower | Upper |
| D-GOM | COM | A | 131.1 | 71.6 | 117.8 | 105.3 | 157.0 |
| | | B | 158.1 | 94.0 | 152.8 | 124.2 | 191.9 |
| | ZIR | A | 140.8 | 72.8 | 145.0 | 114.5 | 167.0 |
| | | B | 160.0 | 78.4 | 161.7 | 131.8 | 188.3 |
| | NPA | A | 190.0 | 144.8 | 144.0 | 137.8 | 242.2 |
| | | B | 195.5 | 121.4 | 200.0 | 151.7 | 239.3 |
| CV-SR | COM | A | 135.0 | 73.9 | 123.0 | 108.4 | 161.7 |
| | | B | 153.9 | 89.8 | 153.2 | 121.5 | 186.3 |
| | ZIR | A | 144.9 | 75.7 | 150.8 | 117.6 | 172.2 |
| | | B | 154.6 | 75.3 | 160.1 | 127.5 | 181.8 |
| | NPA | A | 194.1 | 150.2 | 143.8 | 139.9 | 248.3 |
| | | B | 191.4 | 117.7 | 198.5 | 148.9 | 233.8 |
| D-IOS | COM | A | 132.9 | 72.8 | 120.0 | 106.6 | 159.1 |
| | | B | 153.8 | 91.4 | 152.0 | 120.9 | 186.8 |
| | ZIR | A | 141.8 | 73.3 | 151.0 | 115.3 | 168.2 |
| | | B | 156.0 | 76.4 | 161.0 | 128.4 | 183.6 |
| | NPA | A | 189.3 | 147.2 | 141.0 | 136.2 | 242.4 |
| | | B | 178.1 | 121.1 | 167.0 | 134.5 | 221.8 |

common CAD/CAM materials and investigate possible differences in the results. In contrast to other studies, which used laboratory scanners [6, 7, 16, 18, 23], in this study, copings were manufactured on the basis of a dataset obtained from an intraoral scan to mimic the clinical setting. Zimmermann et al. recently described a 3D evaluation of fit with the Cerec system (Dentsply Sirona) combined with the 3D analysis software OraCheck (Cyfex) [19]. These authors used the adjacent teeth for the superimposition of the two scanning datasets, whereas other studies used a notch on the model die, which is not applicable in a clinical setting [6, 18]. Therefore, in this study, the superimposition of digital methods was carried out, as well as the use of the adjacent teeth in the best-fit algorithm [6, 19, 24].

Groten et al. discussed that a minimum of 50 measurement points is required for investigation of fit [25]. Although both digital methods (D-IOS and D-GOM) allow for an unlimited number of measurement points, for a standardized comparison with the established conventional silicone replica method (CV-SR), 16 discrete measurement points were selected and investigated with all three evaluation methods. In addition to the unlimited choice of measurement points, digital 3D-measurement methods can also visualize the complete cement gap [6, 18]. Besides that, 2D evaluation requires a sectioning procedure, which includes the risk of overestimated discrepancy due to sectioning errors and includes several elaborate laboratory steps [6]. Thus, 3D evaluation is supposed to reduce methodical errors; it is time-saving and enables measurement of fit without laboratory equipment.

For reliable measuring, evaluation was repeated five times for each coping [3]. Our IOS-based easy to use evaluation method (D-IOS) showed comparable results with the established conventional silicone replica method (CV-SR) and a digital evaluation with external 3D-analysis software (D-GOM). The application of the D-IOS method just requires an IOS without any need for further equipment or laboratory skills. In this study, simplified crowns were used as copings, but the final restoration can be used for evaluation of fit as well. Currently, in daily practice, a silicone fit checker analysis has been established. However, this analysis is only rated visually. Thus, the D-IOS is a consistent further development that consequently enhances and objectifies the established fit checker approach.

Three different commonly used CAD/CAM materials (COM, ZIR and NPA) were investigated. In this study, no significant differences were shown regarding the complete fit. However, NPA exhibited a higher internal gap in the occlusal area compared to COM and ZIR. For scientific application, the use of resin composites as copings might be interesting because they are less cost-effective, require fewer manufacturing steps, and do not have to be sintered compared with zirconia. Also, the absence of sinter-shrinkage allows for a better transfer of the CAD-settings into the restorations [26, 27].

Furthermore, the position of measurement (marginal, axial, or occlusal) had an impact on the measured internal gaps. The occlusal fit showed higher values for the internal gap, which is in good accordance with the literature [19, 23]. In addition to

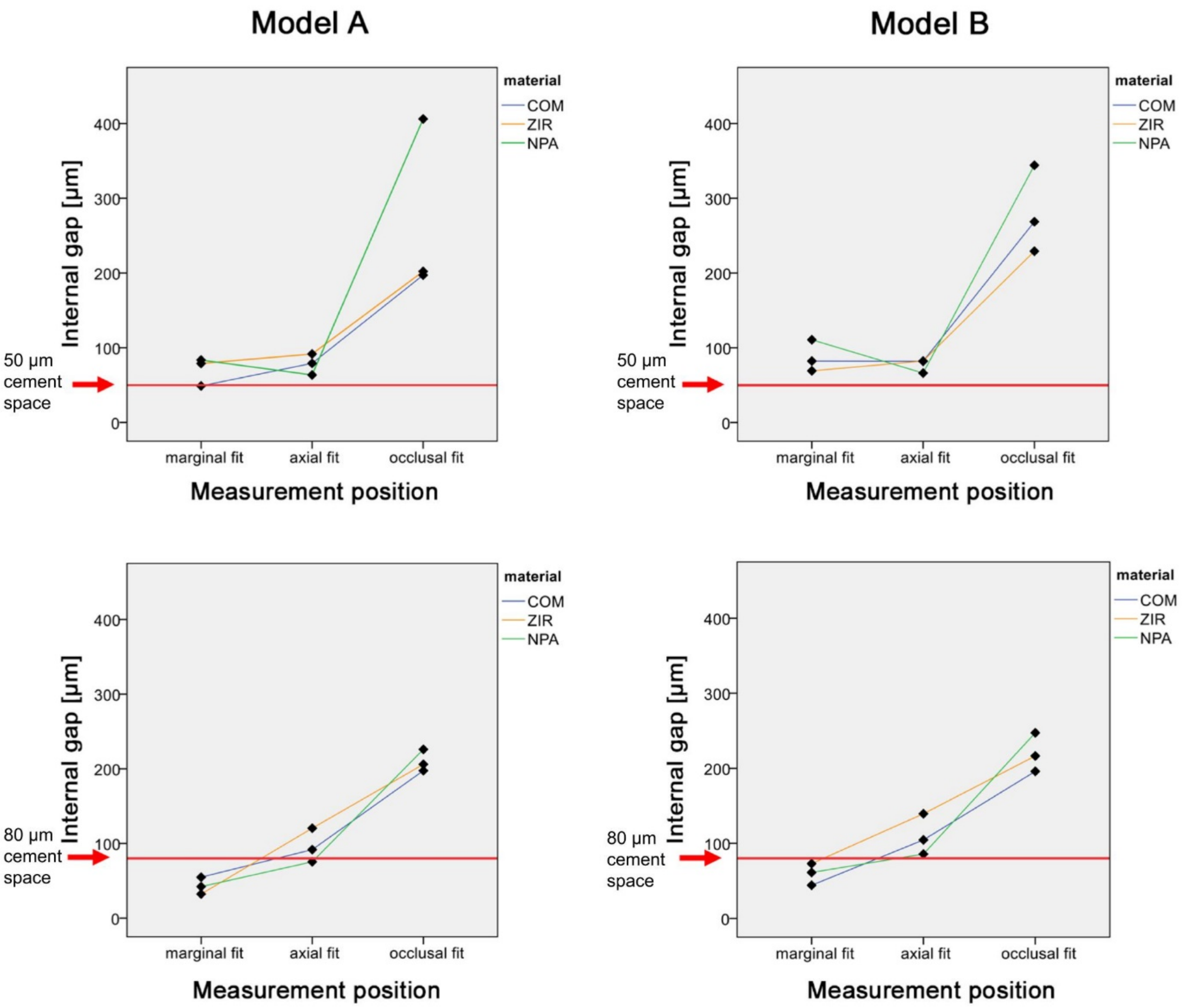

**Fig. 7** Line charts of interaction between the position of fit and coping material for models A and B with 50 µm and 80 µm cement space

the fitting accuracy, Boitelle et al. investigated zirconia crowns and revealed that none of the setting parameters (marginal, 20 µm; axial, 70 µm; and occlusal, 100 µm) were able to reproduce the actual measured internal gap [23], which corresponds to the findings in the present study. Hmaidouch et al. described that crowns with a cement space setting of

**Table 3** Model A: results of internal fit measurement (pooled data for the three evaluation methods)

| Position | Cement space | Internal gap (mean (SD) [µm]) | | | Internal gap - cement space = absolute discrepancy (mean (SD) [µm]) | | |
|---|---|---|---|---|---|---|---|
| | | COM | ZIR | NPA | COM | ZIR | NPA |
| Marginal fit ($n = 20$) | 50 µm | 48.9 (6.5) | 79 (2.5) $^{a}$ | 83.6 (.4) $^{a}$ | 13.7 (5.2) | 29 (2.4) $^{a}$ | 33.6 (.4) $^{a}$ |
| | 80 µm | 54.8 (11.3) $^{a}$ | 32.3 (.2) $^{a}$ | 42.2 (5) $^{a}$ | − 36.2 (5.9) $^{a}$ | − 47.7 (.2) $^{a}$ | − 37.8 (5) $^{a}$ |
| Axial fit ($n = 20$) | 50 µm | 79.2 (.2) $^{a}$ | 91.7 (4.2) $^{a}$ | 63.6 (4.4) | 29.2 (.2) $^{a}$ | 41.7 (4.2) $^{a}$ | 14.8 (4.4) |
| | 80 µm | 91.8 (2.3) $^{a}$ | 120.4 (7.3) $^{b}$ | 75.5 (.8) | 12.7 (.3) $^{a}$ | 40.9 (7.9) $^{b}$ | 9.6 (3.5) $^{a}$ |
| Occlusal fit ($n = 40$) | 50 µm | 197.2 (.8) $^{a}$ | 202.6 (10) $^{a}$ | 406.1 (10.6) | 147.2 (.8) $^{a}$ | 152.2 (10) $^{a}$ | 356.1 (10.6) |
| | 80 µm | 197.5 (1.7) $^{a}$ | 206 (4.7) $^{a}$ | 226 (.5) | 117.5 (1.7) $^{a}$ | 126 (4.7) $^{a}$ | 146 (.5) |

The same letter (a, b) denotes no significant difference

**Table 4** Model B: results of internal fit measurement (pooled data for the three evaluation methods)

| Position | Cement space | Internal gap (mean (SD) [µm]) | | | Internal gap - cement space = absolute discrepancy (mean (SD) [µm]) | | |
|---|---|---|---|---|---|---|---|
| | | COM | ZIR | NPA | COM | ZIR | NPA |
| Marginal fit ($n = 20$) | 50 µm | 82.3 (7.4) $^{a,b}$ | 69.2 (.4) $^{b}$ | 110.7 (8) $^{a}$ | 32.3 (5.8) $^{a,b}$ | 27.6 (.5) $^{a}$ | 60.7 (7) $^{b}$ |
| | 80 µm | 44.2 (.3) $^{b}$ | 73 (6.6) $^{a}$ | 61.2 (6.1) $^{a,b}$ | − 35.8 (4.2) $^{b}$ | − 17.6 (.4) $^{a,b}$ | − 20.4 (4.1) $^{b}$ |
| Axial fit ($n = 20$) | 50 µm | 81.9 (.4) $^{a}$ | 82.2 (5.7) $^{a,b}$ | 66.2 (4.7) $^{b}$ | 32.9 (.6) $^{a,b}$ | 44.8 (4) $^{a}$ | 20.4 (4.3) $^{b}$ |
| | 80 µm | 104.6 (.2) | 139.5 (8.1) | 85.7 (6) | 24.6 (.2) $^{a}$ | 59.5 (8.1) $^{b}$ | 25.7 (6.9) $^{a}$ |
| Occlusal fit ($n = 40$) | 50 µm | 268.6 (9.7) | 229.2 (.6) | 344.2 (9.1) | 218.6 (9.7) | 179.2 (.6) | 294.2 (9.1) |
| | 80 µm | 195.9 (.3) | 216.4 (5.3) | 247.3 (5) | 115.9 (.3) | 136.4 (5.3) | 167.3 (5) |

The same letter (a, b) denotes no significant difference

100 µm showed better marginal and internal fit compared with those with a cement space setting of 50 µm [28]. In this study, copings with a cement space setting of 80 µm showed, especially in the occlusal area, less absolute discrepancy between the setting parameters and the actual internal gaps compared with the cement space setting of 50 µm. Praca et al. explained the decision for a cement space setting of 80 µm because they did not have to adjust the fit after milling [20].

In the literature, a marginal opening of less than 120 µm is described as clinically acceptable [1–3, 7, 8], which is in good accordance with the findings in the present study. Zimmermann et al. showed comparable results for the investigation of the axial, marginal, and occlusal fit of endocrowns milled from a composite resin with a cement space setting of 80 µm [29]. For all three coping materials, higher internal gaps were shown for the occlusal fit compared to the marginal and axial fit. May et al. discussed that the marginal fit of the restoration is often the point of interest, but the internal fit is important as well, especially for ceramic restorations. That study showed a doubled fracture load for the occlusal space of 50 µm compared with that of 500 µm [30]. Rezende et al. described an increase in the stress concentration in crowns with thicker cement space [5].

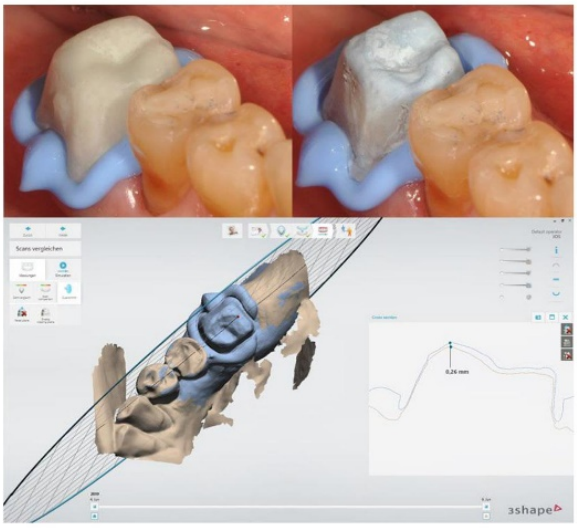

**Fig. 8** Single clinical pilot case with COM coping set on a prepared tooth

The limitation of this study is the laboratory set-up. A clinical environment, such as saliva, preparation geometries, and subgingival margins might influence the reliability of the intraoral scan datasets. Therefore, further clinical investigation is required. Nevertheless, a single pilot case with a COM coping (Fig. 8) showed comparable results among all three evaluation methods (D-IOS, D-GOM, and CV-SR). Furthermore, with this method, two adjacent teeth without preparation are required for superimposition of STL datasets. Whether this method is also applicable to 3-unit or 4-unit restorations needs further investigation.

For daily practice, automatic software evaluation might be helpful to improve the quality of FDPs, especially with ceramic restoration.

## Conclusion

The digital chairside measurement implemented in the intraoral scanner software enables an easy, applicable control of the fit of crowns without additional laboratory devices or special software applications and shows comparable results to the established conventional silicone replica technique and external 3D analysis software. For clinical studies using copings, resin composite materials may be an alternative, as they showed comparable fit to zirconia and reduced laboratory costs.

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## Compliance with ethical standards

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

**Ethical approval** The use of human teeth was approved by the local ethics committee.

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

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## 7.10 Publikation 7

International Journal of
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*Article*

# New Intraoral Scanner-Based Chairside Measurement Method to Investigate the Internal Fit of Crowns: A Clinical Trial

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**Abstract:** To measure the internal fit of the computer-aided designed/computer-aided manufactured (CAD/CAM) crowns, a new scanner-based chairside approach was investigated in patients, and the results were compared to the established silicone replica technique and a digital laboratory replica method. Thirty full-coverage crown preparations were included. Based on a digital impression with an intraoral scanner (IOS, Trios 3), three CAD/CAM measurement copings ('COM', resin composite; 'ZIR', zirconium dioxide; 'NPA', non-precious alloy) were fabricated for each tooth preparation. The internal fit of the measurement copings was analyzed with three different evaluation methods: IOS-based digital approach (D-IOS), digital replica method with laboratory software (D-GOM), and conventional silicone replica technique (CV-SR). The congruence between the determined target parameter of the 80-µm cement space and the actual measured internal gap was investigated. Statistical analysis was performed by ANOVA ($p$-value $< 0.05$). No significant difference was determined between the three evaluation methods. However, significant differences were observed for the three coping materials ($p$-value $< 0.05$), the single measurement position (marginal, axial, and occlusal fit) ($p$-value $< 0.05$), and the interaction between the coping material and the measurement position ($p$-value $< 0.05$). COM revealed the smallest internal gap, followed by ZIR and NPA. Regardless of the coping material, the occlusal gap was higher than the axial and marginal gaps. Furthermore, only the internal gaps of the marginal area almost matched the target parameter of 80-µm for the cement space. D-IOS is effective for measuring internal fit of single crowns in different clinical settings.

**Keywords:** CAD-CAM; internal fit; chairside; intraoral scanner; replica technique; dental crowns

## 1. Introduction

In light of the increasing digitalization of dentistry, especially with regard to intraoral scanning, the exact determination of the internal fit of fixed dental prostheses (FDPs) is of interest [1–3]. Misfit in the marginal area might lead to secondary caries or periodontitis, whereas, a large internal gap in the occlusal area can affect the boding and mechanical strength of ceramic restorations [1,4–9]. Besides intraoral scanning, further development in computer-aided design/computer-aided manufacturing (CAD/CAM) technologies offers a growing range of materials manufactured in various workflows [3,10–12]. Thus, there is a high demand for an easily applicable method for the analysis of the internal fit of FDPs. Preferably, there should be a chairside method in the dental office without the need of an elaborate laboratory setup and expert knowledge.

Most evaluation methods described cannot be applied in patients without tooth extraction [13–15]. Thus, the indirect conventional silicone replica is still the most common approach in studies investigating the internal fit of FDPs in patients [16–20]. Though, this method is limited to two-dimensional analysis with a small number of measurement points. To overcome these limitations, three-dimensional approaches such as micro-CT [1], triple-scan technology [21], digital replica method [22,23], and optical coherence tomography [13] have been developed in recent years. However, micro-CT is not clinically applicable because of the need for radiography [1,21,24,25]. Furthermore, artifacts of metallic restorations might influence the analysis [13]. In contrast, the triple-scan technology and digital replica method are clinically applicable but require a complex experimental setup and expert skills [7,21–23,26]. Some studies have investigated the internal fit of FDPs using coherence tomography. This method seems to be promising in several areas of dentistry, but has limitations regarding material selection and requires a separate complex device that is not yet available for use in dentistry [13,27].

Recently, Zimmermann et al. developed a new three-dimensional approach based on an intraoral scanner (IOS) Cerec Omnicam (Dentsply Sirona, Bensheim, Germany) with the software OraCheck (Cyfex, Zurich, Switzerland) in a laboratory setup [28]. In a previous laboratory study, we systematically investigated a novel IOS-based evaluation method with the IOS Trios 3 (3Shape, Copenhagen, Denmark). The results were in good accordance compared to a digital replica method and the well-established analog silicone replica method [29]. However, in a clinical environment, saliva, various preparation geometries, or subgingival margins might affect the reliability of the approach. To the best of our knowledge, no systematic clinical evaluation has been described yet, comparing established methods with the new IOS-based approach in patients.

Hence, the aim of this clinical trial was to evaluate three different evaluation methods: the new IOS-based digital approach (D-IOS) [29], a digital replica method with laboratory software (D-GOM) [7] and the conventional silicone replica technique (CV-SR) [30]. Taking into account different CAD/CAM materials, resin composite (COM), zirconium dioxide (ZIR), and non-precious alloy (NPA) were used as measurement copings. In the present study, the following null hypothesis was tested: there is no statistically significant difference between the evaluation methods (CV-SR, D-GOM, D-IOS) or the materials (COM, ZIR, NPA) and the target parameter of 80-μm cement space matches the actual measured internal gap.

## 2. Materials and Methods

Altogether 30 preparations in 20 patients (12 females, 8 males; age 35–87 years) were included in the present study. Treatment was performed at the Department of Prosthodontics of the Justus Liebig University Giessen (Germany) from April to November 2019. Only asymptomatic teeth that required a full-coverage preparation (crowns, bridges, or telescopic crowns) were included. Teeth with undistinguishable finish lines or inability to keep the preparation dry for impression taking were excluded. All subjects gave their informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki. The protocol was approved by the Ethics Committee of the Justus Liebig University Giessen (Ref. no. 267/13) and registered in the German Clinical Trial Register (DRKS00017049). One single operator (J.V.) performed all the experiments. The flow scheme in Figure 1 presents the study setup.

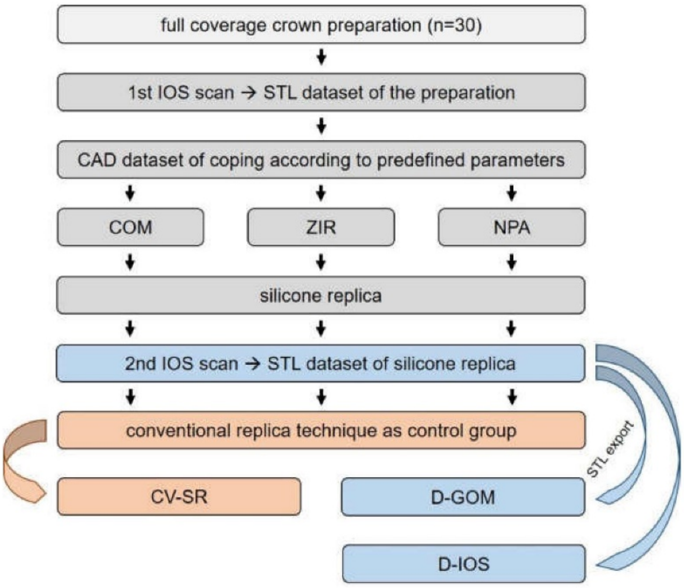

**Figure 1.** Flow scheme of the clinical trial.

On the first appointment, preliminary treatment of the teeth, that is caries excavation or core-built up (OptiBond FL, Kerr, Bieberach, Germany; Rebilda LC, Voco, Cuxhaven, Germany), was performed if required. Teeth were prepared under constant water cooling with a chamfer line and round edges according to the preparation guidelines for full-coverage crowns using diamond burs [31]. For subgingival finish lines, the double-cord technique (Medi-Kord, La Maison Dentaire SA, Balzers, Lichtenstein) was used to retract the gingiva [32]. During impression taking, lips and cheeks were retracted with Optragate (Ivoclar Vivadent, Schaan, Lichtenstein). For digital impressions, the IOS Trios 3 (version 1.18.2.10, 3Shape, Copenhagen, Denmark) was used. Before usage, the IOS was calibrated with the respective calibration device [33]. Furthermore, a predefined scanning path was observed, beginning with the occlusal/oral surface and ending with the buccal surface [34]. Only the preparation and the adjacent teeth were scanned to obtain a higher accuracy of the scan data set. After digital impression taking, a provisional restoration (Luxatemp, DMG, Hamburg, Germany) was manufactured and temporarily cemented (Temp-Bond, Kerr, Biberach, Germany).

In the dental laboratory, measurement copings (representing the restorations) were designed using CAD software (version 17.2.1, dental system, 3Shape, Copenhagen, Denmark) according to the following parameters: 600-µm layer thickness [35,36], 200-µm edge reinforcement [35,36] and 80-µm cement gap [30]. Copings were milled from a blank of non-precious alloy (NPA), zirconium dioxide (ZIR), and resin composite (COM) on a 5-axis milling machine (A: Datron D5, Datron AG, Mühltal, Germany; Z: FinoCAM CA, Fino GmbH; P: FinoCAM W, Fino GmbH). Subsequently, all copings were manually polished according to the manufacturer's instructions, and zirconia copings were additionally sintered in a calibrated dental ceramic oven (Austromat µSiC, Dekema, Freilassing, Germany) (room–800 °C, 40 min; 800–1450 °C, 65 min; 1450 °C, 120 min; 1450–800 °C, 45 min; 800–250 °C, 30 min; 250 °C–room)[29].

On the second appointment, the internal fit of the measurement copings was investigated with one conventional (CV-SR) and two digital (D-GOM and D-IOS) methods. First, the provisional restoration was removed, and the prepared tooth was carefully cleaned. Then, copings were isolated with powder spray (CEREC Optispray, Dentsply Sirona, Bensheim, Germany) to visualize the cement space [22], filled with low-viscosity addition-curing silicone blue-colored (Fit Test C&B, Voco, Cuxhaven, Germany) and seated under a constant pressure of 20 N [23,30] on the prepared tooth. Copings were carefully removed after a setting time of 10 min, and the remaining silicone replica on the prepared tooth was inspected. Before taking a second digital impression with IOS Trios 3 (capturing the silicone replica on the prepared tooth), cheeks and lips were retracted with Optragate and the teeth were gently air-dried. Subsequently, an over impression was taken for the CV-SR method. Therefore, an impression tray (Inlay Tray, Detax, Ettlingen, Germany) was filled with a high-viscosity green-colored and low-viscosity pink-colored vinyl polyether silicone to pick up the blue-colored silicone replica on the prepared tooth. After a setting time of 10 min, the impression was removed and filled with low-viscosity yellow-colored vinyl polyether silicone. This completed the trials on patients who subsequently received their regularly planned restoration. The materials used in this study are listed in Table 1.

**Table 1.** Materials used in this study (information provided by the manufacturer).

| Material | Product Name (Batch No.) | Manufacturer |
|---|---|---|
| Powder spray | CEREC Optispray (S50868) | Dentsply Sirona (Bensheim, Germany) |
| Low-viscosity addition-curing silicone | Fit Test C&B (1841465) | Voco (Cuxhaven, Germany) |
| Low-viscosity vinyl polyether silicone | EXA'lence Extra Light Body (1806261) | GC (Tokyo, Japan) |
| Low-viscosity vinyl polyether silicone | EXA'lence Light Body (1806221) | |
| High-viscosity vinyl polyether silicone | EXA'lence Putty (1711091) | |
| Resin composite block | LuxaCam Composite (784249) | DMG (Hamburg, Germany) |
| 3Y-TZP zirconium dioxide | Lava Plus (4525742) | 3M (St.Paul, MN, USA) |
| Non-precious alloy (>10 wt% cobalt, chrome, 1–10 wt% tungsten, silicon, manganese, iron, 0.1–1 wt% carbon) | Finoframe CoCr (K10627) | Fino (Bad Bocklet, Germany) |

To ensure a standardized measurement setup for the evaluation of all three methods, each specimen was digitally (D-GOM and D-IOS) or manually sectioned (CV-SR) in the mesio-distal and oral-buccal direction, and the internal fit was determined at 16 predefined measurement points per tooth (Figure 2), and a total of 4320 measurements were performed. For standardized sectioning, the mesio-distal plane was defined in the direction of the central fissure of the adjacent teeth parallel to the axis of the prepared tooth. The oral-buccal plane was defined perpendicularly through the mesio-distal plane in the direction of the tooth axis and through the center of the prepared tooth. The silicone specimens (CV-SR) were sectioned with a razor blade, and the internal fit was analyzed with a light microscope (Smartzoom 5, PlanApo D 1.6x/ 0.1 FWD 36 mm, Zeiss, Jena, Germany) using the respective measurement software (Smartzoom 5, version 1.1, Zeiss). For further digital analysis with three-dimensional laboratory software (D-GOM), standard tessellation language (STL) data sets of the first and second digital impressions were exported from the IOS. Subsequently, both datasets were imported to three-dimensional analysis software (GOM Inspect 3D, version V8 SR1, GOM GmbH, Braunschweig, Germany) and superimposed over the adjacent teeth, using the iterative-closed-point (ICP) technique. With the D-IOS methods, both scans were automatically aligned, and the internal fit was directly analyzed with the new monitoring and measurement function of the IOS. This procedure was applied to all 30 specimens using three different coping materials and three evaluation methods. Figure 3 shows an example of the analysis of the internal fit for all three evaluation methods (CV-SR, D-GOM, D-IOS).

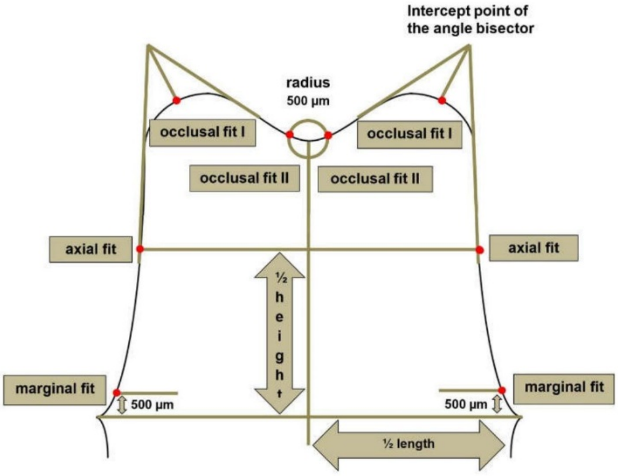

**Figure 2.** Schematic drawing of the measurement points.

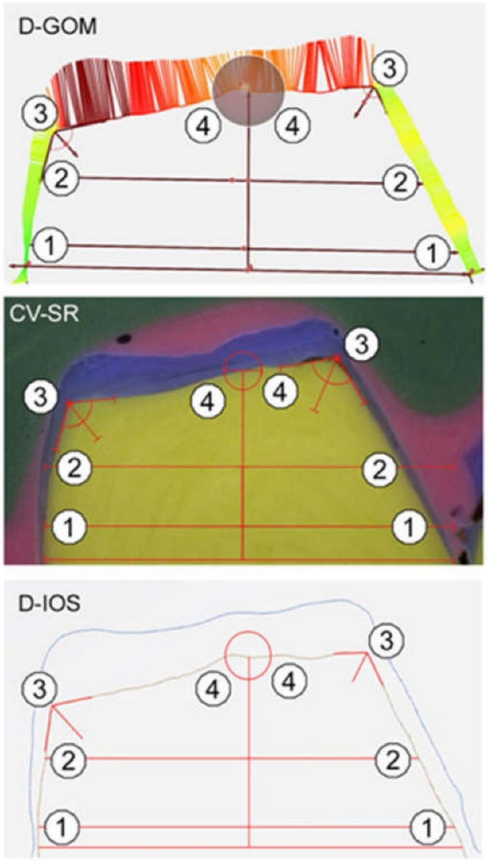

**Figure 3.** Example of the three evaluation methods (D-GOM = digital replica method with laboratory software, CV-SR = conventional silicone replica technique and D-IOS = IOS-based digital approach): 1 = marginal fit, 2 = axial Figure 3. = occlusal fit.

Statistical analysis was performed using SPSS version 25 (IBM Corporation, Armonk, NY, USA). 2×3×3-ANOVA with factor materials and positions was calculated. Knowing that the interaction between the evaluation method and the position was very weak, only the interaction between the materials by position was interpreted. Furthermore, pairwise comparisons of the three different coping materials (COM, ZIR, NPA) were tested for every level of position (marginal, axial, or occlusal fit). The model residuals did not indicate serious deviations from a normal distribution. To consider the heterogeneity of variances, the MIXED procedure was used, and due to an alpha-error accumulation, *p*-values were corrected (Bonferroni). The level of significance was set at *p*-value < 0.05.

## 3. Results

Altogether 30 prepared teeth distributed in 10 molars, 11 premolars, and 9 incisors were investigated. Almost half of the teeth (n = 14) showed a clinical situation with mesial and distal adjacent teeth, whereas the others (n = 16) represented a terminal preparation with only mesial adjacent teeth. All 90 CAD/CAM measurement copings were feasible to investigate the internal fit of single crowns, and no manual adjustment was required.

For the overall data, the results are displayed in Figure 4 and Table 2. No significant difference was observed between the three evaluation methods (CV-SR, D-GOM, D-IOS). Therefore, the first part of the null hypothesis could not be rejected. Furthermore, no significant difference was found among the tooth types and the clinical situation with mesial and distal or solely mesial adjacent teeth. However, significant differences were observed for the coping materials (*p*-value < 0.05), the single measurement position (marginal, axial, and occlusal fit) (*p*-value < 0.05), and the interaction between the coping material and the measurement position (*p*-value < 0.05) (Figure 5 and Tables 3 and 4). Thus, the second part of the null hypothesis had to be rejected. COM showed the smallest internal gap, followed by ZIR and NPA. Regardless of the coping material, the occlusal gap was higher compared to the axial and marginal gaps. Furthermore, only the internal gaps of the marginal area almost matched the target parameter of 80-µm for cement space (Figure 5 and Table 4). This implies that the third part of the null hypothesis was partly rejected.

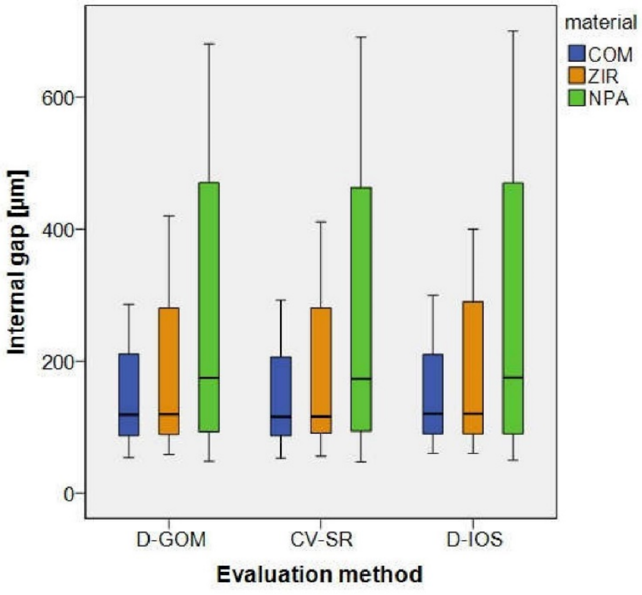

**Figure 4.** Boxplots of the three evaluation methods (D-GOM, CV-SR and D-IOS).

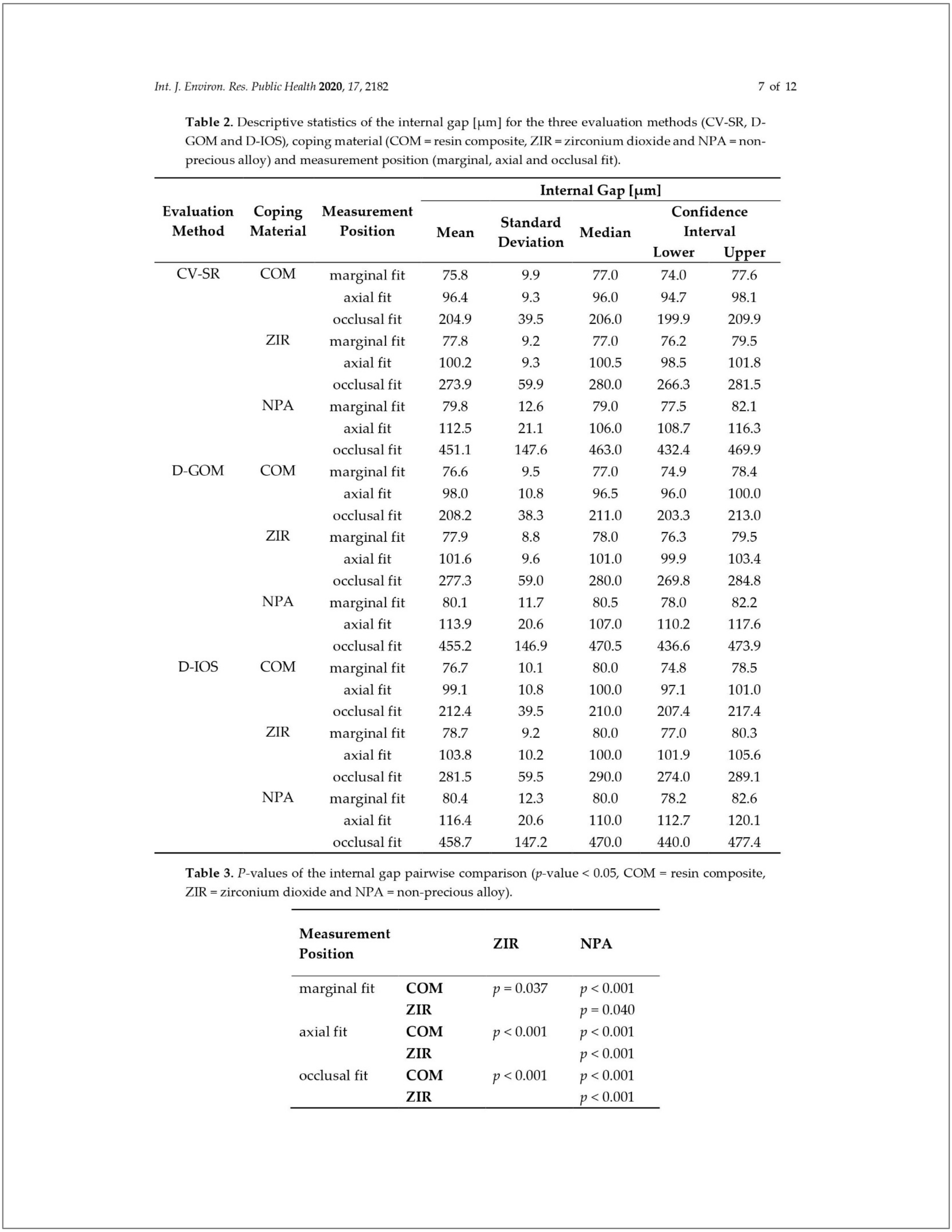

**Table 2.** Descriptive statistics of the internal gap [µm] for the three evaluation methods (CV-SR, D-GOM and D-IOS), coping material (COM = resin composite, ZIR = zirconium dioxide and NPA = non-precious alloy) and measurement position (marginal, axial and occlusal fit).

| Evaluation Method | Coping Material | Measurement Position | Internal Gap [µm] | | | | |
|---|---|---|---|---|---|---|---|
| | | | Mean | Standard Deviation | Median | Confidence Interval | |
| | | | | | | Lower | Upper |
| CV-SR | COM | marginal fit | 75.8 | 9.9 | 77.0 | 74.0 | 77.6 |
| | | axial fit | 96.4 | 9.3 | 96.0 | 94.7 | 98.1 |
| | | occlusal fit | 204.9 | 39.5 | 206.0 | 199.9 | 209.9 |
| | ZIR | marginal fit | 77.8 | 9.2 | 77.0 | 76.2 | 79.5 |
| | | axial fit | 100.2 | 9.3 | 100.5 | 98.5 | 101.8 |
| | | occlusal fit | 273.9 | 59.9 | 280.0 | 266.3 | 281.5 |
| | NPA | marginal fit | 79.8 | 12.6 | 79.0 | 77.5 | 82.1 |
| | | axial fit | 112.5 | 21.1 | 106.0 | 108.7 | 116.3 |
| | | occlusal fit | 451.1 | 147.6 | 463.0 | 432.4 | 469.9 |
| D-GOM | COM | marginal fit | 76.6 | 9.5 | 77.0 | 74.9 | 78.4 |
| | | axial fit | 98.0 | 10.8 | 96.5 | 96.0 | 100.0 |
| | | occlusal fit | 208.2 | 38.3 | 211.0 | 203.3 | 213.0 |
| | ZIR | marginal fit | 77.9 | 8.8 | 78.0 | 76.3 | 79.5 |
| | | axial fit | 101.6 | 9.6 | 101.0 | 99.9 | 103.4 |
| | | occlusal fit | 277.3 | 59.0 | 280.0 | 269.8 | 284.8 |
| | NPA | marginal fit | 80.1 | 11.7 | 80.5 | 78.0 | 82.2 |
| | | axial fit | 113.9 | 20.6 | 107.0 | 110.2 | 117.6 |
| | | occlusal fit | 455.2 | 146.9 | 470.5 | 436.6 | 473.9 |
| D-IOS | COM | marginal fit | 76.7 | 10.1 | 80.0 | 74.8 | 78.5 |
| | | axial fit | 99.1 | 10.8 | 100.0 | 97.1 | 101.0 |
| | | occlusal fit | 212.4 | 39.5 | 210.0 | 207.4 | 217.4 |
| | ZIR | marginal fit | 78.7 | 9.2 | 80.0 | 77.0 | 80.3 |
| | | axial fit | 103.8 | 10.2 | 100.0 | 101.9 | 105.6 |
| | | occlusal fit | 281.5 | 59.5 | 290.0 | 274.0 | 289.1 |
| | NPA | marginal fit | 80.4 | 12.3 | 80.0 | 78.2 | 82.6 |
| | | axial fit | 116.4 | 20.6 | 110.0 | 112.7 | 120.1 |
| | | occlusal fit | 458.7 | 147.2 | 470.0 | 440.0 | 477.4 |

**Table 3.** *P*-values of the internal gap pairwise comparison ($p$-value < 0.05, COM = resin composite, ZIR = zirconium dioxide and NPA = non-precious alloy).

| Measurement Position | | ZIR | NPA |
|---|---|---|---|
| marginal fit | **COM** | $p = 0.037$ | $p < 0.001$ |
| | **ZIR** | | $p = 0.040$ |
| axial fit | **COM** | $p < 0.001$ | $p < 0.001$ |
| | **ZIR** | | $p < 0.001$ |
| occlusal fit | **COM** | $p < 0.001$ | $p < 0.001$ |
| | **ZIR** | | $p < 0.001$ |

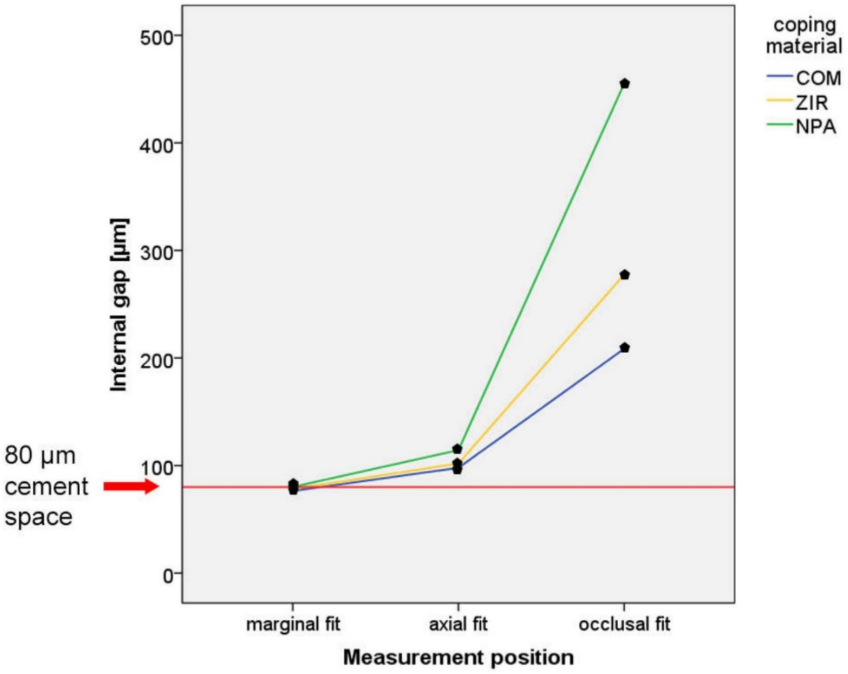

**Figure 5.** Line chart of interaction between the coping material and measurement position.

**Table 4.** Results of internal fit measurement (pooled data for the three evaluation methods, COM = resin composite, ZIR = zirconium dioxide and NPA = non-precious alloy).

| Measurement Position | Internal Gap (mean (SD) [µm]) | | | Internal Gap – Cement Space = Absolute Discrepancy (Mean (SD) [µm]) | | |
|---|---|---|---|---|---|---|
| | COM | ZIR | NPA | COM | ZIR | NPA |
| marginal fit (n = 120) | 76.4 (0.5) | 78.1 (0.5) | 80.1 (0.6) | −3.6 (0.5) | −1.9 (0.5) | 0.1 (0.6) |
| axial fit (n = 120) | 97.8 (0.6) | 101.8 (0.5) | 114.3 (1.1) | 17.8 (0.6) | 21.8 (0.5) | 34.3 (1.1) |
| occlusal fit (n = 240) | 208.5 (1.5) | 277.6 (2.2) | 455.0 (5.5) | 128.5 (1.5) | 197.6 (2.2) | 375.0 (5.5) |

## 4. Discussion

All three evaluation methods (D-GOM, D-IOS, and CV-SR) were applicable for the investigation of the internal gaps in different patient situations. Even though teeth of different types (incisor, premolar, molar), sizes, and shapes were prepared manually, a standardized preparation protocol according to published guidelines was observed [31]. During the investigation, the same hardware and software of IOS and GOM Inspect were used, and no update was deployed. Only one experienced operator investigated the internal fit with all three evaluation methods to ensure standardized testing conditions. This is also a strength of this study (standardization) as well as the main weakness (operator related bias). In order to reduce this risk of bias, the evaluations were carried out at different times.

In addition to the investigation of different evaluation methods for the analysis of internal fit, different coping materials were tested as well. The three CAD/CAM materials used in this study represent the principally used restorative material groups (polymers, ceramics, and alloys) for FDPs in dentistry today. However, most studies analyzed only one material [22,23,26,28] or compared two material groups (e.g., ceramics and polymers [37,38] or ceramics and alloys [39,40]) to each other.

Furthermore, because Hasanzade et al. described that manual post-processing leads to a significantly higher internal gap, in this study, measurement copings were not manually adjusted [41]. In the literature, a target parameter for the cement space between 30–500 μm is described [9,22,39,42]. However, an internal gap as small as possible is recommended, but should be implementable as well. Due to the fact that the results of another laboratory study showed a better congruence between the target parameter and the actual measured internal gap for 80-μm compared to 50-μm [29], the cement space was set at 80-μm [6,43].

For the analysis of both digital evaluation methods (D-IOS and D-GOM), STL datasets were superimposed over the adjacent teeth with best-fit alignment. Mennito et al. described that superimposition over hard tissue shows significantly better alignment compared to soft tissue [44]. Zimmermann et al. [28] also used adjacent teeth for superimposition, whereas Lee [7] used a notch in the virtual die for alignment, which is not applicable for investigation in patients. O'Toole et al. [45] investigated different alignment procedures and showed significantly lower alignment errors for reference alignment compared to best-fit alignment. In the oral cavity, there is no reference structure, so some studies used additional reference aids [46,47]. However, this is not applicable for measurement in daily practice without expert skills or a complex laboratory setup.

Although the number of measurement points is not limited for both digital methods (D-GOM and D-IOS) in this study, 16 measurement points per specimen distributed to marginal, axial, and occlusal positions were selected to allow comparison with the conventional silicone replica method (CV-SR); this procedure is well described in the literature [13,20,30]. However, a comparison with other studies is often difficult because of the different setups regarding coping materials, measurement positions, and methods [4,13].

The results of this clinical study did not show a significant difference between the three evaluation methods (D-IOS, D-GOM, and CV-SR) regarding the internal fit. Rudolph et al. investigated a digital replica method with laboratory software, which is comparable to D-GOM in this study [48]. They did not find a significant difference between the conventional silicone replica technique and their digital replica method, which is in good accordance with our results. Mai et al. also compared their computer-aided replica method to the conventional silicone replica technique and did not report a significant difference [26].

Bosniac et al. [35] investigated the marginal fit of single crowns with caraTrios (3Shape), a preceding IOS of the Trios 3 used in this study. They described significantly higher misfit for molars compared to all other tooth types and explained the findings with limited accessibility in the posterior region due to the size of the handpiece. In this study, no significant difference in tooth type was found. In recent years, the handpieces of the Trios IOS were constructed smaller, which enables easier scanning in the oral cavity.

Huang et al. [39] also investigated the internal fit of single crowns for different tooth types and found no significant differences. Furthermore, they showed significantly higher accuracy for non-precious alloys compared to ceramics for the marginal and axial measurement positions. These findings are in contrast to those of Pimienta et al. [1] and the results of our study, where NPA showed the highest internal gap compared to ZIR and COM. However, regarding occlusal positions, Huang et al. [39] also described significantly higher internal gaps for non-precious alloys, which agrees with our findings.

Rezende et al. described a significant discrepancy between the target parameter of the cement space and the actual measured internal gap [6]. In this study, only the internal fit in the marginal measurement position almost matched the predefined 80-μm. This might be explained by the milling radius correction of the CAM strategy. Zimmermann et al. showed a significant difference in the accuracy of fit for ceramic crowns milled by different CAM strategies [49]. Today, digital preparation analysis (e.g., prepCheck, Dentsply Sirona) enables chairside control of the preparation and a real-time correction. Future software developments may also display the required milling radius for better internal fit of CAD/CAM-fabricated restorations. This can improve the internal fit of CAD/CAM restorations and reduce failure. Furthermore, new CAD/CAM materials and workflows (e.g., polyaryletherketones (PAEKs), 3D printing) will be available in the near future [11,12], which require an adjustment of milling or printing parameters. The chairside control of the internal fit gives dentists an easily applicable tool for their own quality management and development of new workflows.

The chairside analysis of the internal fit with D-IOS allows a feasible inspection of the restoration in the dental office without expert skills or laboratory equipment. This study showed that the evaluation method could be applied to different CAD/CAM materials. Overall, further studies should investigate the applicability of D-IOS in various dental offices with different operators. Furthermore, only single crown preparations were analyzed, but the digital analysis of inlays, partial crowns, and bridges is conceivable as well. In the future, improvements of the current IOS systems should include automatic matching and artificial intelligence features to analyze the internal fit. This would decisively help to accelerate the evaluation process and extend its application in dental offices.

## 5. Conclusions

The new intraoral scanner-based chairside measurement method is applicable for the analysis of the internal fit of single crowns in different clinical settings and did not show significant differences compared to the conventional silicone replica method and the digital replica method with laboratory software.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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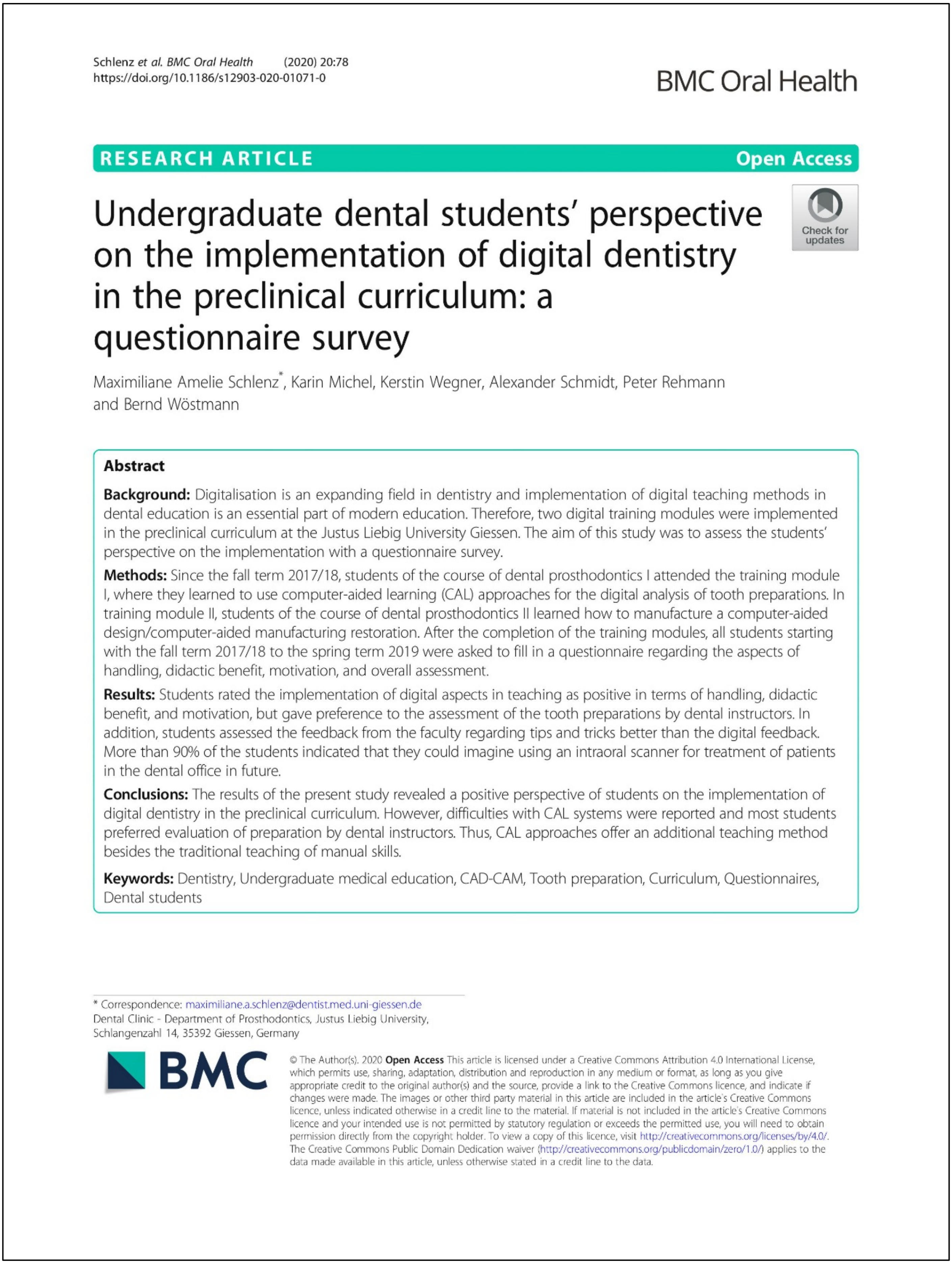
## 7.11 Publikation 8



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RESEARCH ARTICLE Open Access

# Undergraduate dental students' perspective on the implementation of digital dentistry in the preclinical curriculum: a questionnaire survey

Maximiliane Amelie Schlenz*, Karin Michel, Kerstin Wegner, Alexander Schmidt, Peter Rehmann and Bernd Wöstmann

## Abstract

**Background:** Digitalisation is an expanding field in dentistry and implementation of digital teaching methods in dental education is an essential part of modern education. Therefore, two digital training modules were implemented in the preclinical curriculum at the Justus Liebig University Giessen. The aim of this study was to assess the students' perspective on the implementation with a questionnaire survey.

**Methods:** Since the fall term 2017/18, students of the course of dental prosthodontics I attended the training module I, where they learned to use computer-aided learning (CAL) approaches for the digital analysis of tooth preparations. In training module II, students of the course of dental prosthodontics II learned how to manufacture a computer-aided design/computer-aided manufacturing restoration. After the completion of the training modules, all students starting with the fall term 2017/18 to the spring term 2019 were asked to fill in a questionnaire regarding the aspects of handling, didactic benefit, motivation, and overall assessment.

**Results:** Students rated the implementation of digital aspects in teaching as positive in terms of handling, didactic benefit, and motivation, but gave preference to the assessment of the tooth preparations by dental instructors. In addition, students assessed the feedback from the faculty regarding tips and tricks better than the digital feedback. More than 90% of the students indicated that they could imagine using an intraoral scanner for treatment of patients in the dental office in future.

**Conclusions:** The results of the present study revealed a positive perspective of students on the implementation of digital dentistry in the preclinical curriculum. However, difficulties with CAL systems were reported and most students preferred evaluation of preparation by dental instructors. Thus, CAL approaches offer an additional teaching method besides the traditional teaching of manual skills.

**Keywords:** Dentistry, Undergraduate medical education, CAD-CAM, Tooth preparation, Curriculum, Questionnaires, Dental students

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## Background

Currently, digitalisation is an expanding field in dentistry, especially in terms of computer-aided design/computer-aided manufacturing (CAD/CAM) of dental restorations and appliances. For the fixed dental prostheses (FDPs), traditional manufacturing requires numerous manual steps by the dentist as well as by the dental laboratory. This process can be facilitated decisively using CAD/CAM technologies [1, 2]. Instead of conventional impressions with subsequent fabrication of plaster models, intraoral scanners can be used to digitise the intraoral situation. Subsequently, the restoration can be designed with CAD software and milled by computerised numerical control (CNC) machines. If necessary, models can also be fabricated using a CAD/CAM process. Due to the industrial manufacturing process, a standardised quality of the FDPs can be ensured and the production time with overall costs are reduced [2]. However, as for all technical innovations, high-quality training of users is necessary for successful implementation of CAD/CAM technologies in daily patient care [1, 3]. Thus, implementation of digital techniques and workflows is indispensable in contemporary education of dental students. However, publications in this field mostly reflect on the performance of CAL systems [3–8], whereas the view of the students is only sparsely analysed. Thus, this study is primarily focussed on the students' perspective.

In most universities, education of dental students is still solely focused on conventional teaching methods including traditional laboratory techniques such as waxing, casting, finishing, and tooth preparation exercises on the phantom head (simulation unit). Thus, the challenge was to implement new digital technologies such as the so-called computer-aided learning (CAL), without neglecting the training of manual skills, which are still important for dental treatment [5–7, 9, 10].

Since the fall term 2017/18, students of the Justus Liebig University Giessen were introduced to digital technologies in the preclinical curriculum. Students still perform their exercises on the phantom heads, but they also use the CAL software for additional support. Especially for students who prepare a tooth for the first time, it is difficult to understand and fulfil the preparation requirements. *Knight* suggested that it is important to have a precise idea of the final result for the training of manual skills [11]. Currently, CAL approaches can support traditional teaching methods [8]. Furthermore, students' awareness for tooth structure loss can be increased by using three-dimensional imaging of their own preparations and by superimposition of the images on the original tooth in the CAL software for the self-assessment process. This is especially important, as studies have shown that self-assessment increases the motivation to learn and supports lifelong learning [5, 12].

Students need an individual feedback on their performance to learn from their mistakes and to get a sense of their accomplishments [11]. Therefore, a high reliability of the evaluation process is essential. However, studies regarding the traditional evaluation of preparations according to the glance-and-grade principle have reported a low interrater (between different examiners) and intrarater (one examiner at different times) reliability [5, 13, 14]. Furthermore, students request an immediate feedback with objective assessment criteria and suggestions for improvement [12, 15]. Due to different staff member opinions, work experiences, and evaluation standards as well as lack of time, it is often difficult to provide immediate feedback for each student in everyday teaching. This may entail a lack of objectivity and disagreement between students and staff members [5, 12]. *Renne* et al. reported that students often perceive assessments as subjective and arbitrary [16]. This perception may lead to decreased self-awareness and may negatively influence students' performance [17]. Taken together, at the moment each university seems to develop an individual concept. General approaches – even country based – could not be identified in the literature.

Digital methods such as CAL are especially suitable in such situations, as they provide an objective and immediate feedback. They allow for an individual learning speed and are available when required by the students [1, 3, 6, 7, 9, 18]. Thus, the workload of the faculty staff is reduced in the long term [5]. However, such methods require high investment costs at the beginning and their implementation in the existing curriculum is time-consuming [6, 19, 20]..

At the Justus Liebig University Giessen, two training modules were implemented in the preclinical education. These modules consisted of students learning to analyse their preparations digitally (I) and to accomplish a complete CAD/CAM workflow for FDPs (II). Nevertheless, for the success of an educational concept, it is important to consider the students' perspective [5]. Therefore, the aim of this study was to evaluate students' opinions about these training modules through questionnaires.

## Methods

### Teaching concept

At the Justus Liebig University Giessen, faculties (dentists) of the Department of Prosthodontics supervise (MAS, KM, KW and AS) two classes of the preclinical curriculum: *course of dental prosthodontics I* (Ph1) in the third semester and *course of dental prosthodontics II* (Ph2) in the fifth semester. Students are allowed to use the preclinical laboratory during free practicing hours besides the official course lessons. The aim of the preclinical education is to learn the theoretical and the practical basics of prosthodontics, which students can apply to patients in the clinical curriculum later. This includes learning the correct preparation techniques for different types of FDPs and the complete workflow from preparation to impression making and manufacturing.

To implement digital dentistry in the existing curriculum, training modules for theoretical and practical knowledge transfer were implemented in both the preclinical prosthodontic courses since the fall term 2017/18 (Fig. 1). Students also had the opportunity to use a digital preparation analysis software (prepCheck, Dentsply Sirona, Bensheim, Germany) by themselves during the free practicing lessons. Thus, the preparation analysis was digitised and the digital workflow of the CAD/CAM manufactured FDPs was already taught in the preclinical curriculum.

### Training module I – digital preparation analysis

Students of the third semester (18 male, 73 female, 13 not specified) were introduced to the digital preparation analysis during a 45-min lecture. The main targets of preparation exercises such as training of manual skills and self-assessment were repeated and basic information on digital preparation analysis was provided. Subsequently, students watched a step-by-step video of prepCheck. The application of the software with intraoral scanning was demonstrated on the phantom head in small groups of a maximum of five students. In addition, students received a handout with all the steps of the preparation analysis and a guide for the interpretation of the prepCheck report.

In order to give students the opportunity to compare their own preparations to preset parameters and to the so-called *master preparation*, outstanding preparations of students from the preliminary dental exam of the summer semester 2017 were stored in the software.

The steps for the digital preparation analysis were as follows:

1. Intraoral scan: To perform the digital preparation analysis with prepCheck, students selected the tooth and the type of restoration (full crown in the present study) and scanned the preparation with the adjacent teeth, the antagonists, and the bite with the intraoral scanner (CEREC Omnicam, Dentsply Sirona, Bensheim, Germany). Subsequently, the model axis, the preparation margin, and the crown axis were defined. To analyse the preparation, the scanned data were imported into the prepCheck software.
2. Digital preparation analysis with master preparation: Students compared their preparations with the master preparation stored in the software (Fig. 2). The transparency of the three-dimensional student and master preparations could be modified using sliders. A colour scale on the student preparations showed the discrepancies between the two preparations. The deviations in millimetres were displayed in a legend.
3. Digital preparation analysis with parameters: Students compared their preparation to preset parameters regarding undercuts, preparation angle, occlusal and axial reduction, preparation margin, edges, surface texture, and the integrity of the adjacent teeth. Figure 3 shows an example of a student's preparation analysed according to the different parameters.
4. PrepCheck report: The prepCheck analyses were exported in the 'prepCheck report' as a portable document format file, which was saved on the preclinical computers. They were also given to the students on a universal serial bus stick. Students presented their prepCheck reports in groups of two to train their self-assessment skills. Subsequently, the listening student gave feedback on the evaluation according to the sandwich principle [21].

All students analysed a full crown preparation of an upper incisor and a lower molar (21 and 46 according to the Fédération Dentaire Internationale [FDI] nomenclature), which they had already prepared in the running course. During the two-day training module, faculties were available to answer questions and help students with the CAL system. Whenever the digital preparation

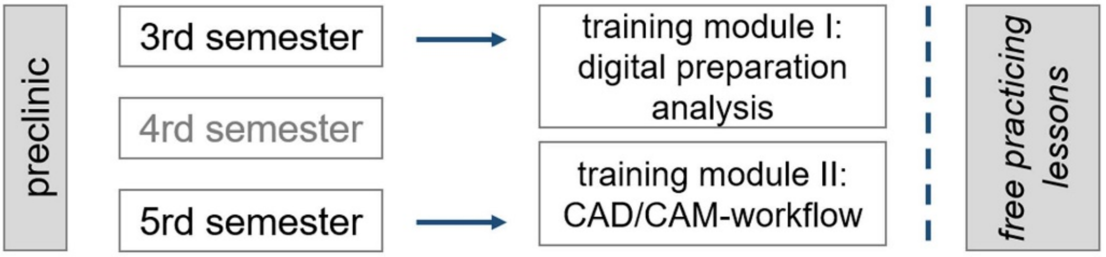


**Fig. 1** Teaching concept

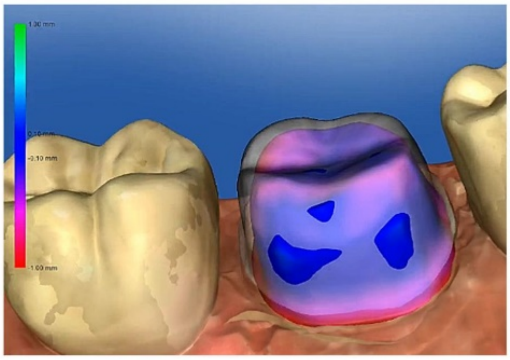


**Fig. 2** Digital preparation analysis with master preparation (colored = student preparation, white = master preparation)

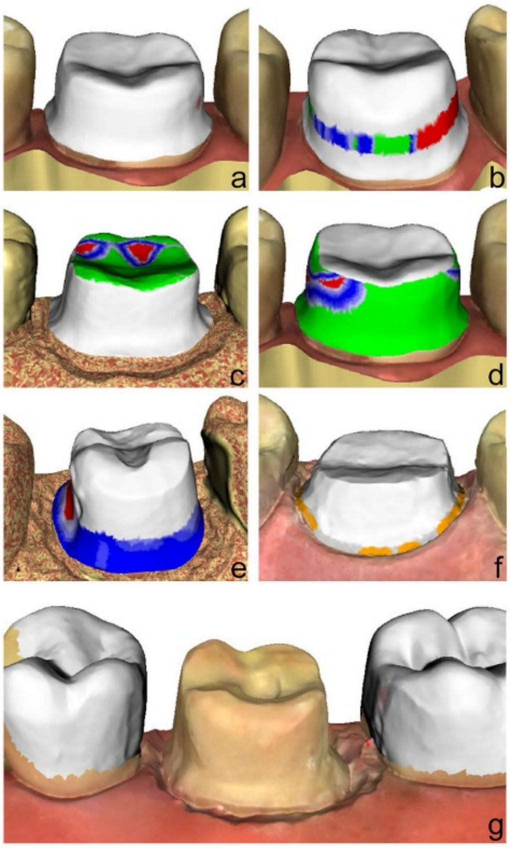


**Fig. 3** Digital preparation analysis with preset parameters (**a** = undercuts, **b** = preparation angle, **c** = occlusal reduction, **d** = axial reduction, **e** = preparation of margin line, **f** = surface of margin line, **g** = integrity of adjacent teeth)

analysis showed need for improvement in the preparations, students were encouraged to correct their preparations and analyse the results with prepCheck again.

### Training module II – CAD/CAM workflow

An intraoral scanner (CEREC Omnicam) and a CNC milling machine (MC XL, Dentsply Sirona, Germany) were used for manufacturing the FDPs.

During the two-day training module, students of the fifth semester (25 male, 68 female, 4 not specified) were taught how to fabricate a crown using a CAD/CAM workflow. The first day started with a 60-min lecture giving students an overview of the CAD/CAM technology and a revision of the digital preparation analysis with prepCheck. Students also learned the theoretical background of digital impression making. Finally, the application of the CEREC software and the CNC milling machine were presented in a 20-min demonstration in small groups of a maximum of five students. During the remaining course time, students started with the CAD/CAM workflow for producing a posterior crown (FDI 46).

On the second day, a 45-min lecture was presented on CAD/CAM materials and their handling requirements. Subsequently, students were given a 20-min demonstration in small groups of a maximum of five participants to show them how to check the accuracy of fit and polish the ceramic (Celtra Duo, Dentsply Sirona, Germany). The remaining course time was used to finish the CAD/CAM crown. In addition to the lectures and the demonstrations, students received a script with background information regarding the CAD/CAM workflow.

The steps for the application of the CAD/CAM workflow were as follows:

1. Intraoral scan: Students created a fictional patient in the CEREC software. After selecting the tooth, restoration type (full crown), and material (Celtra Duo), an intraoral scan of the preparation including adjacent teeth, the antagonists, and the bite was performed with the Omnicam. Subsequently, the model axis, the preparation margin, and the crown axis were defined.
2. Digital preparation analysis: An objective preparation analysis with prepCheck was performed to analyse the preparation. The preparation was corrected and scanned for a second time if necessary.
3. Computer-aided design: Digital modelling of the crown was performed in the CEREC software. Initially, the software proposed a model, which could be modified using different sliders. It was possible to apply or remove substance and smoothen the restoration surface with a 'digital wax knife'. The material-specific minimum layer

thickness was also displayed. The occlusal and the proximal contact points could also be faded in and out. The objective was that the students should present a crown model with correct contact points, a sufficient minimum layer thickness, and appropriate shape.

4. Computer-aided manufacturing: A ceramic CAD/CAM block was inserted in the milling machine. Data were transferred from the Omnicam to the milling unit via wireless local area network connection. After milling, the restoration was carefully removed. The sprue was cut off with a diamond grinding wheel at 8000–12,000 rpm and polished with a rubber wheel.
5. Checking the fit: The space between the prepared tooth and the restoration was simulated with a low-viscosity silicone (Fit Test C&B, Voco, Cuxhaven, Germany). The strength of the occlusal and the proximal contact points was checked with occlusion foil (Hanel, Coltene, Altstätten, Switzerland) and dental floss.
6. Finishing and polishing: The contact points were corrected with a diamond bur if necessary. Crowns were finished with a diamond polishing body (< 60 μm) under light pressure at 8000–12,000 rpm, ensuring that the restoration did not overheat, followed by high-gloss polishing with a Robinson brush wheel and polishing paste (Zirkopol, feguramed GmbH, Buchen, Germany) at 4000–8000 rpm.

### Questionnaire survey

Two paper-and-pencile questionnaires (questionnaire I regarding the digital preparation analysis (Ph1) and questionnaire II regarding the CAD/CAM workflow (Ph2) were designed in cooperation with the Teaching Evaluation Service Centre of the Justus Liebig University Giessen. The questionnaires contained evaluative statements regarding the handling, didactic benefit, motivation, and overall assessment of digital dentistry. Students could agree or disagree with the statements based on a five-point Likert scale (Fig. 4) [22]. In addition, students were asked whether they preferred the assessment of the preparations by the software or by a dentist (Ph1). They were also asked if they preferred using conventional or digital workflow for manufacturing the FDPs (Ph2). At the end of the questionnaires, students were asked to answer a binary question (yes/no) if they could imagine using digital applications in their dental office in future. An abstention was allowed for each statement and the questionnaires were evaluated anonymously. All students of the course of dental prosthodontics I in the third semester and the course of dental prosthodontics II (Ph2) in the fifth semester between the fall term 2017/18 and the spring term 2019 participated in this study. Questionnaires were distributed at the end of the training modules and collected

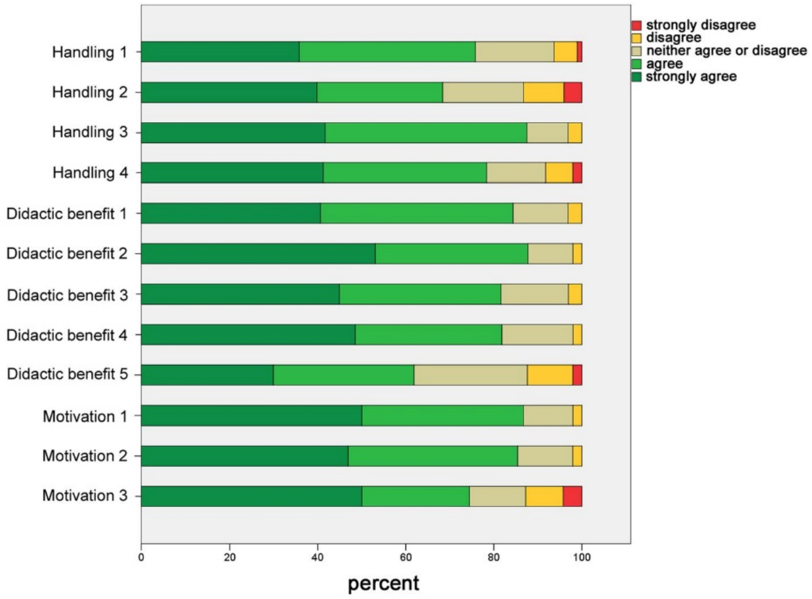


**Fig. 4** Depiction of the results of the questionnaire I – Digital preparation analysis regarding the aspects handling, didactic benefit and motivation

anonymously. The study was approved by the local ethics committee of the Justus Liebig University Giessen (Ref. no. 171/19).

Statistical analysis was performed using SPSS Statistics (version 24, IBM, Armonk, NY, USA). Median and percentiles were used to describe the data.

## Results

All students ($n = 104$) from the training module I (digital preparation analysis) and all students ($n = 97$) from the training module II (CAD/CAM workflow) answered the questionnaires. Nevertheless, due to the possibility of abstention, the number of valid answers per question ranged between 84.6 to 95.2% and 84.5 to 97.9% for modules I and II, respectively.

In general, students assessed the aspects of handling, didactic benefit, and motivation positively in both the questionnaires (Figs. 5 and 7, Tables 1 and 2). However, students from the training module I indicated difficulties with the scanning of the preparations (Table 1) and the understanding of the prepCheck report (Table 1). Furthermore, students stated that they preferred the evaluation of their preparations by the dentists instead of the software, especially regarding tips and feedback (Fig. 6, Table 1). Nevertheless, 86.2% of the students could imagine using the digital preparation analysis in their dental office in future.

Students from the training module II also reported difficulties while using the intraoral scanning handpiece (Table 2). In addition, digital modelling of the restoration was sometimes challenging (Table 2). Most of the students stated that they preferred the digital workflow to the conventional manufacturing of FDPs with respect to the aspects of time consumption, more tips/better feedback, easier handling, more enjoyable practicing experience, and greater fault tolerance (Fig. 7, Table 2). Among the students from module II, 96.8% of the students could imagine using an intraoral scanner in daily practice in future.

## Discussion

In recent years, the requirements of modern education have changed. *Welk* et al. described that 83.5% of the dental students at the University of Tennessee (USA) expected to be taught using the CAL approaches [23]. *Murbay* et al. recommended that in the current era of digital technology, modern teaching methods such as simulation trainers should be integrated into dental education, as is the standard in other businesses such as aviation or automobile traffic [4]. However, *Margaryan* et al. [24] advised against a radical shift from conventional teaching methods to digital technologies, as demanded by *Prensky* [25].

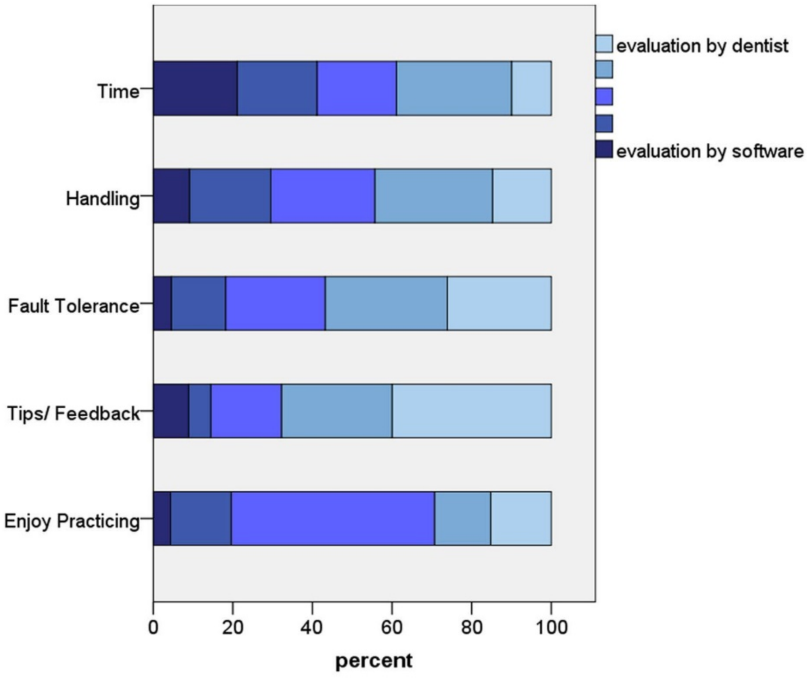


**Fig. 5** Depiction of the results of the questionnaire I – Digital preparation analysis regarding the aspects evaluation by dentist or software

**Table 1** Items and descriptive statistics of the questionnaire I (Digital preparation analysis)

| Item | Item description | 25th percentile | Median | 75th percentile | N |
|---|---|---|---|---|---|
| Handling 1[a] | The menu guidance of the intraoral scanner and prepCheck-software is easily comprehensible. | 4 | 4 | 5 | 95 |
| Handling 2[a] (rec.) | The scanning process with the intraoral scanner handpiece does not cause me any difficulties. | 3 | 4 | 5 | 98 |
| Handling 3[a] | The analysis of the preparation with prepCheck is feasible. | 4 | 4 | 5 | 96 |
| Handling 4[a] | After the demonstration and exercises in the trainings module, I feel confident to use prepCheck by myself. | 4 | 4 | 5 | 97 |
| Didactic benefit 1[a] | The workflow of the intraoral scanner and prepCheck software is clear and understandable. | 4 | 4 | 5 | 96 |
| Didactic benefit 2[a] | Seeing my preparation on the monitor and getting an objective analysis with prepCheck, trains my own judgement | 4 | 5 | 5 | 98 |
| Didactic benefit 3[a] | Using prepCheck is as well training of intraoral scanning. | 4 | 4 | 5 | 98 |
| Didactic benefit 4[a] | The prepCheck report is helpful to improve my own performance regarding preparation. | 4 | 4 | 5 | 99 |
| Didactic benefit 5[a] | The prepCheck report is easy to understand. | 3 | 4 | 5 | 97 |
| Motivation 1[a] | Using new technologies (e.g. prepCheck) motivates me. | 4 | 4.5 | 5 | 98 |
| Motivation 2[a] | Analyzing my own preparation with prepCheck motivates me. | 4 | 4 | 5 | 96 |
| Motivation 3[a] (rec.) | I do not think that prepCheck as an additional course component is a chore. | 3 | 4 | 5 | 94 |
| Overall assessment [b] | If you consider the following aspects of the assessment of your preparation, what type of assessment would you prefer (dentist or prepCheck)? (1 = dentist, 5 = prepCheck) | | | | |
| Overall assessment 1[b] | less time | 2 | 3 | 4 | 90 |
| Overall assessment 2[b] | easier handling | 2 | 3 | 4 | 88 |
| Overall assessment 3[b] | greater fault tolerance | 1 | 2 | 3 | 88 |
| Overall assessment 4[b] | more tips/ better feedback | 1 | 2 | 3 | 90 |
| Overall assessment 5[b] | enjoy practicing more | 2 | 3 | 3 | 92 |

N = number of valid answers (total: *N* = 104)

[a] type of answer: 1 = strongly disagree, 5 = strongly agree

[b] type of answer: 1 = evaluation by dentist, 5 = evaluation by prepCheck

rec: Handling 2 and Motivation 3 were recoded before the analysis of questionnaire, so that higher values also express a more positive assessment here

The concept for implementation of digital dentistry into our preclinical curriculum consisted of two training modules that enabled the CAL systems to be integrated into the existing curriculum without completely replacing the conventional teaching methods. This approach allows a step-by-step implementation, as recommended by *Welk* et al. [23] Furthermore, with single training modules the curriculum is more flexible to meet the needs of the students. *Margaryan* et al. described the high relevance of involving students in teaching and respecting their preferences of teaching methods to achieve the highest possible educational success [24]. Therefore, the training modules of the present study were evaluated using a Likert scale, which is a standard procedure for surveys in the field of medicine [26–28].

After the training modules, most of the students stated that they felt confident of using the digital preparation analysis by themselves or of manufacturing a chairside restoration using the CAD/CAM workflow. These results showed that the structure of the curriculum, consisting of lectures, demonstrations, and training of practical skills in small groups, seems to be comprehensible for the students. However, such a curriculum involves high staff costs, which is consistent with the experiences of other authors [6, 19].

However, it is controversial whether the digital learning systems improve students' self-assessment skills. *Wolgin* et al. stated that students often overestimate their own performance [5]. In the present study, students did not assess their own performance with and without the digital preparation analysis, as all students should benefit from the CAL approach. Nevertheless, to reflect on their own preparations and to train their self-assessment skills, students presented their preparation analysis reports to each other according to the sandwich principle [21].

**Table 2** Items and descriptive statistics of the questionnaire II (CAD/CAM-workflow)

| Item | Item description | 25th percentile | Median | 75th percentile | N |
|---|---|---|---|---|---|
| Handling 1[a] | The menu guidance of the intraoral scanner is easily comprehensible. | 4 | 4 | 5 | 93 |
| Handling 2[a] (rec.) | The scanning process with the intraoral scanner handpiece does not cause me any difficulties. | 3 | 4 | 4 | 94 |
| Handling 3[a] | The digital modelling of the restoration is good to perform. | 3 | 4 | 5 | 95 |
| Handling 4[a] | After the demonstration and exercises in the training module, I feel confident to perform the entire CAD/CAM workflow by myself. | 4 | 4 | 5 | 94 |
| Didactic benefit 1[a] | The workflow of the CAD/CAM workflow is clear and understandable. | 4 | 4 | 5 | 94 |
| Didactic benefit 2[a] | Seeing my preparation on the monitor trains my own judgement. | 4 | 5 | 5 | 95 |
| Didactic benefit 3[a] | By participating the training module, I acquired a good knowledge of the CAD/CAM workflow. | 4 | 5 | 5 | 93 |
| Motivation 1[a] | Using new technologies (e.g. intraoral scanning) motivates me. | 4 | 5 | 5 | 91 |
| Motivation 2[a] | The manufacturing of CAD/CAM restorations of my own preparation motivates me. | 4 | 5 | 5 | 92 |
| Motivation 3[a] (rec.) | I do not think that learning the CDA/CAM-workflow as an additional course component is a chore. | 4 | 5 | 5 | 92 |
| Overall assessment [b] | Which workflow do you prefer considering the following aspects? (1 = conventional, 5 = digital) | | | | |
| Overall assessment 1[b] | less time | 4 | 5 | 5 | 89 |
| Overall assessment 2[b] | easier handling | 3 | 4 | 4 | 92 |
| Overall assessment 3[b] | greater fault tolerance | 2 | 3 | 4 | 82 |
| Overall assessment 4[b] | more tips/ better feedback | 3 | 4 | 5 | 90 |
| Overall assessment 5[b] | enjoy practicing more | 3 | 4 | 4 | 86 |

N = number of valid answers (total: *N* = 97)

[a] type of answer: 1 = strongly disagree, 5 = strongly agree

[b] type of answer: 1 = conventional workflow, 5 = digital workflow,

rec: Handling 2 and Motivation 3 were recoded before the analysis of questionnaire, so that higher values also express a more positive assessment here

Based on the results of the questionnaires, it can be concluded that the aspect of motivation was rated very positively. *Mays* et al. stated that students who were involved in teaching showed more responsibility for achieving their own learning success [8]. Therefore, instead of using the preparation by a faculty as the master preparation, [6] students' best exam preparations were used in the present study. This should motivate the students and show them that it is possible to achieve preparations analogous to the master preparation with their level of education at the end of the preclinical course.

For effective education, a sufficient number of CAL approaches are required to enable students to learn digital dentistry, which is clearly an obstacle in the introduction of these techniques. In 2002, *Welk* et al. [29] started a survey of all German universities regarding the use of CAL learning systems in dental education. They revealed a positive attitude towards digital technologies with low implementation in the clinical education [29]. These findings were confirmed by a university survey conducted in 2010, where CAD/CAM technology was offered as an additional course component in student education at just one university in Germany [30].

Due to the prosthodontic nature of their course students evaluated only full crown preparations which is a clear limitation of this study. In the future, CAL approaches should also be implemented in restorative dentistry (i.e. inlay preparations) as described by *Wolgin* et al. [5] Furthermore, multi center approaches would be fruitful to better establish CAL methods in the undergraduate curriculum.

The results of the present study showed that most of the students could imagine using an intraoral scanner for patient treatment in the dental office in future. Studies have shown that students implement what they have learned during their studies in treatments performed in future [31]. Therefore, it should be the duty of the universities to impart theoretical knowledge and practical skills of digital dentistry to ensure modern treatment options for patients. However, this cannot be achieved in a cost-neutral way, especially with respect to the necessary investment costs and personnel costs.

## Conclusions

This study showed a positive perspective of students on the implementation of digital dentistry in the preclinical curriculum. However, difficulties with CAL systems were reported and most students preferred evaluation of preparation by dental instructors. Thus, CAL approaches cannot replace dental instructors but offer an additional teaching method besides the traditional teaching of manual skills.

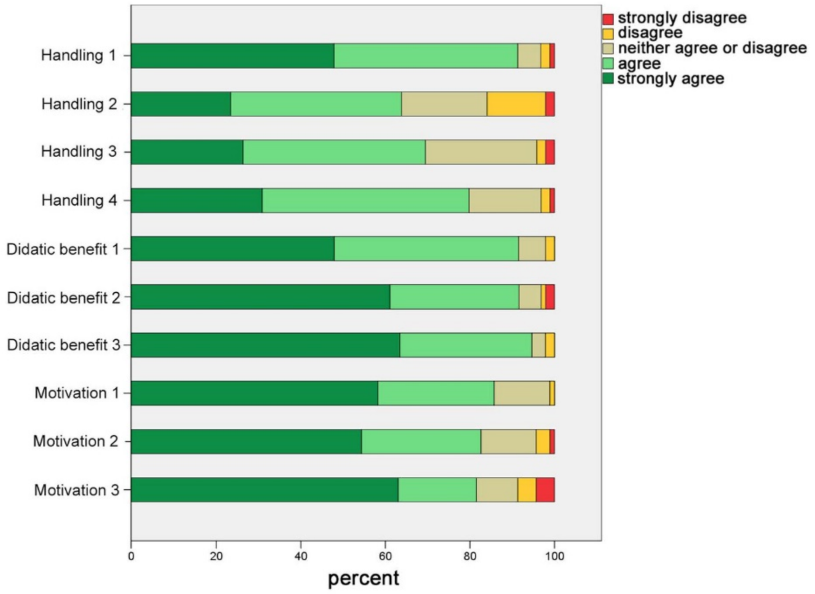


**Fig. 6** Depiction of the results of the questionnaire II – CAD/CAM-workflow regarding the aspects handling, didactic benefit and motivation

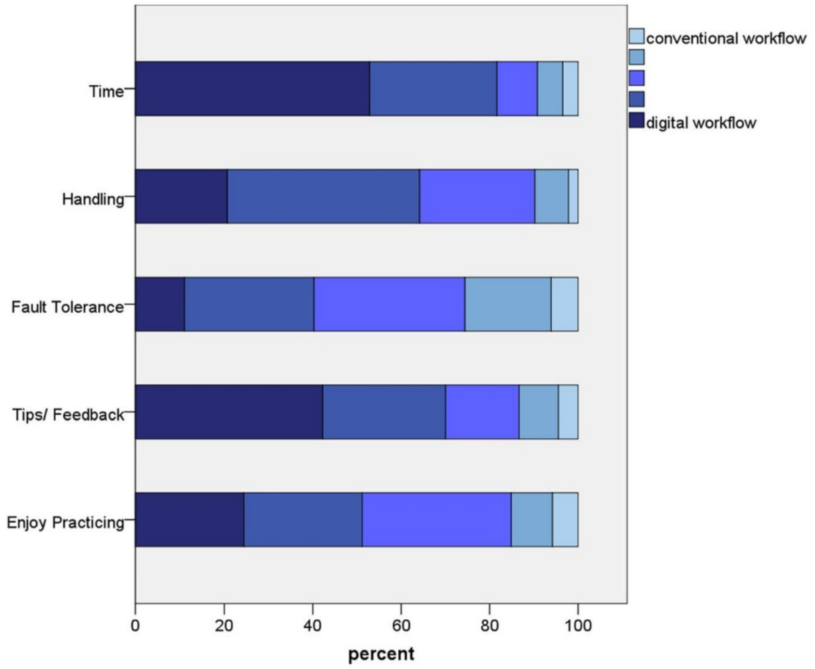
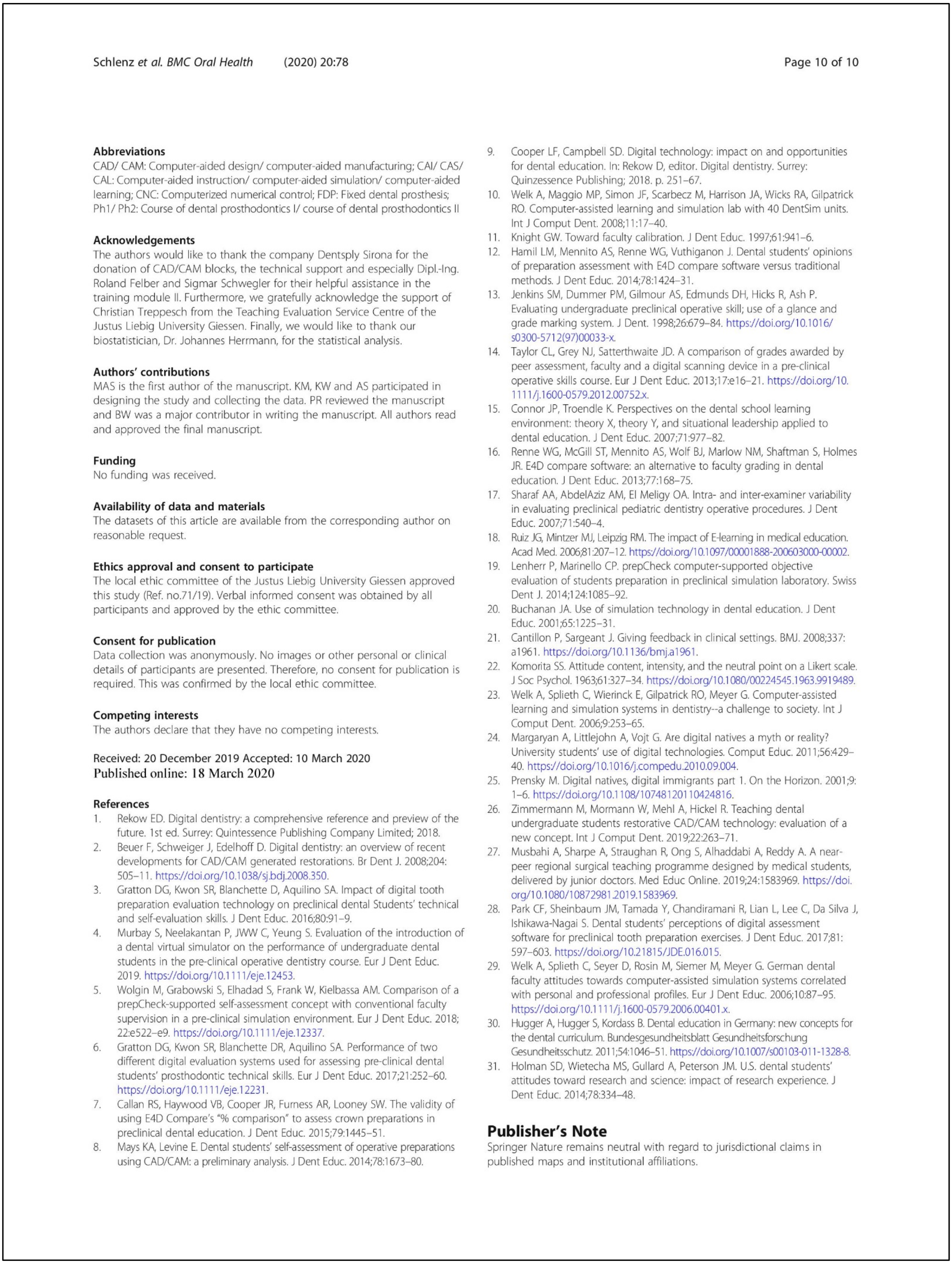


**Fig. 7** Depiction of the results of the questionnaire II – CAD/CAM-workflow regarding the aspects of using a conventional or digital workflow for manufacturing of FDPs



### Abbreviations

CAD/ CAM: Computer-aided design/ computer-aided manufacturing; CAI/ CAS/ CAL: Computer-aided instruction/ computer-aided simulation/ computer-aided learning; CNC: Computerized numerical control; FDP: Fixed dental prosthesis; Ph1/ Ph2: Course of dental prosthodontics I/ course of dental prosthodontics II

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### Authors' contributions

MAS is the first author of the manuscript. KM, KW and AS participated in designing the study and collecting the data. PR reviewed the manuscript and BW was a major contributor in writing the manuscript. All authors read and approved the final manuscript.

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### Availability of data and materials

The datasets of this article are available from the corresponding author on reasonable request.

### Ethics approval and consent to participate

The local ethic committee of the Justus Liebig University Giessen approved this study (Ref. no.71/19). Verbal informed consent was obtained by all participants and approved by the ethic committee.

### Consent for publication

Data collection was anonymously. No images or other personal or clinical details of participants are presented. Therefore, no consent for publication is required. This was confirmed by the local ethic committee.

### Competing interests

The authors declare that they have no competing interests.

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## Publisher's Note

# 8 Erklärung

„Hiermit erkläre ich, dass ich die vorliegende Arbeit bzw. die mir zuzuordnenden Teile im Rahmen einer kumulativen Habilitationsschrift, selbstständig und ohne unzulässige Hilfe oder Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Alle Textstellen, die wörtlich oder sinngemäß aus veröffentlichten oder nichtveröffentlichten Schriften entnommen sind, und alle Angaben, die auf mündlichen Auskünften beruhen, sind als solche kenntlich gemacht. Ich versichere, dass ich für die nach §2 (3) der Habilitationsordnung angeführten bereits veröffentlichten Originalarbeiten als Erst-oder Seniorautor fungiere, da ich den größten Teil der Daten selbst erhoben habe, für das Design der Arbeiten verantwortlich bin und die Manuskripte maßgeblich gestaltet habe. Für alle von mir erwähnten Untersuchungen habe ich die in der „Satzung der Justus-Liebig-Universität zur Sicherung guter wissenschaftlicher Praxis“ niedergelegten Grundsätze befolgt. Ich versichere, dass alle an der Finanzierung der Arbeiten beteiligten Geldgeber in den jeweiligen Publikationen genannt worden sind. Ich versichere außerdem, dass die vorgelegte Arbeit weder im Inland noch im Ausland in gleicher oder ähnlicher Weise einer anderen Prüfungsbehörde vorgelegt wurde oder Gegenstand eines anderen Prüfungsverfahrens war. Mit der Überprüfung meiner Arbeit durch eine Plagiatserkennungssoftware bzw. ein internetbasiertes Softwareprogramm erkläre ich mich einverstanden.“

Gießen, 29. September 2020 Dr. Maximiliane Schlenz

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