Aus der Poliklinik für Zahnärztliche Prothetik
Klinik der Ludwig-Maximilians-Universität München

Direktor: Prof. Dr. med. dent. Daniel Edelhoff

In-vivo-Verschleißverhalten von Restaurationen aus CAD/CAM-Komposit versus Lithium-Disilikat-Keramik bei Patienten nach prothetischer Gesamtrehabilitation

Dissertation
zum Erwerb des Doktorgrades der Zahnmedizin
an der Medizinischen Fakultät der
Ludwig-Maximilians-Universität zu München

vorgelegt von
Gintare Burian

aus
Klaipeda

2023

Mit Genehmigung der Medizinischen Fakultät der
Ludwig-Maximilians-Universität zu München

Berichterstatter:	Prof. Dr. med. dent. Jan-Frederik Güth
Mitberichterstatter:	apl. Prof. Dr. med. dent. Karin Huth
	Priv. Doz. Dr. rer. nat. Uwe Baumert
Mitbetreuung durch den promovierten Mitarbeiter:	Priv. Doz. Dr. med. dent. Christine Keul
Dekan:	Prof. Dr. med. Thomas Gudermann
Tag der mündlichen Prüfung:	06.02.2023

Inhaltsverzeichnis

Publikationsliste

Güth JF, Erdelt K, Keul C, Burian G, Schweiger J, Edelhoff D. In vivo wear of CAD-CAM composite versus lithium disilicate full coverage first-molar restorations: a pilot study over 2 years. *Clin Oral Invest* 24, 4301–4311 (2020)

(**https://doi.org/10.1007/s00784-020-03294-5**)

IF 2020: 3.573

Burian G, Erdelt K, Schweiger J, Keul C, Edelhoff D, Güth JF. In-vivo-wear in composite and ceramic full mouth rehabilitations over 3 years. Sci Rep. 2021 Jul 7;11(1):14056.

(https://doi.org/10.1038/s41598-021-93425-z)

IF 2020: 5.133

1 Einleitung

Der nicht-kariogene Verlust von Zahnhartsubstanz stellt eine zunehmende Herausforderung für die zahnmedizinischen Versorgung weltweit dar [1]. Dies spiegelt sich unter anderem in der zunehmenden Zahl an Publikationen über die letzten Jahrzehnte wider [2]. Hinsichtlich der Altersverteilung ist zu beobachten, dass bei einem Großteil an älteren Patienten auch zunehmend jüngere Menschen unter einem Verlust der Zahnhartsubstanz leiden [3, 4].

Die Zähne sind einer Vielzahl von Faktoren ausgesetzt, die über eine Lebensspanne zu einem sukzessiven Verlust an Zahnhartsubstanz führen, unter anderem chemische und physikalische Faktoren [5]. Chemische Noxen führen zur Erosion, die aufgrund der pH-Wertverschiebung eine Demineralisation des Zahnschmelzes und später auch des Dentins auslöst [6]. Zu physikalischen Ursachen gehören Abrasion und Attrition. Als Abrasion bezeichnet man ein Verschleißmuster, das durch Interaktion zwischen Zähnen und Fremdkörpern entsteht, während Attrition durch Zahn-Zahn-Kontakt bedingt ist [7]. Die beschriebenen Verschleißmechanismen zeigen Wechselwirkungen sowie einen potenzierenden Effekt, der letztendlich zu einem zunehmendem Verlust an Zahnhartsubstanz führt [7]. Der alterskorrelierte, pathologisch erhöhte Verlust an Zahnhartsubstanz äußert sich in erhöhter Zahnempfindlichkeit, sowie funktionellen und ästhetischen Beeinträchtigungen, die sich negativ auf die dentale Funktionalität und die Lebensqualität auswirken [8].

Die steigende Prävalenz von Abrasions- und Erosionsgebissen stellt Kliniker vor große Herausforderungen, da diese meist eine komplexe prothetische Rehabilitation erfordern [9]. Die zeitintensive Wiederherstellung der Kaufunktion und der Ästhetik erfordert ein hohe Patienten-Compliance und ist meist mit hohen Behandlungskosten verbunden [10]. Um einen pathologischen Zahnverschleiß in der Frühphase zu erkennen, in der es noch möglich ist mittels minimal-invasiver Methoden funktionelle und strukturelle Beschwerden zu behandeln, erfordert neue Strategien für die Diagnose und das Therapiemonitoring [11].

Verschiedene Konzepte zur Behandlung von generalisiertem Zahnverschleiß sind in Literatur vorgestellt worden [9, 12]. Eines davon ist der Einsatz von CAD/CAM-Kompositen, welcher eine interessante Alternative zur Keramikrestauration darstellt [13, 14]. Aufgrund ihrer standardisierten Fertigung und reproduzierbaren Materialeigenschaften scheinen kunststoffbasierte CAD/CAM-Materialien den direkten Kompositrestaurationen überlegen zu sein [15]. CAD/CAM-Polymere haben auch gegenüber Glaskeramiken mehrere Vorteile: Sie sind nicht nur einfacher und kostengünstiger zu verarbeiten, sondern ermöglichen auch eine leichtere Reparatur und die Möglichkeit der Herstellung dünner Restaurationen bei minimal-invasivem Behandlungskonzept [13, 16]. Allerdings haben sie im Vergleich zu Keramiken meist mindere mechanische Eigenschaften, wie zum Beispiel die Verschleißraten, welche für eine Langzeitstabilität der Restaurationen von großer Bedeutung sind [17, 18]. Die spärliche Datenlage zu klinischen Verschleißraten von CAD/CAM-Kompositen bei Patienten nach prothetischer Gesamtrehabilitation war der Grund für die Durchführung beider Arbeiten.

Es gibt viele Möglichkeiten zur klinischen Verschleißmessung von Zahnhartsubstanz oder Restaurationsmaterialen [19]. Sie lassen sich in direkte und indirekte Methoden einteilen. Direkte Methoden umfassen die visuelle, qualitative Evaluation der Zahnhartsubstanz- bzw. des Restaurationsmaterials. In der Literatur finden sich verschiedene Bewertungssysteme, mit dem Ziel eine Standardisierung sowie eine gewisse Praktikabilität mit Hinblick auf die zahnärztliche Praxis einzuführen [20]. Die bekanntesten Systeme zur Bewertung des Zahnhartsubstanzverlustes sind der Eccles Index [21], Tooth Wear Index (TWI) [22], Lussi index [23] und Basic Erosive Wear Examination (BEWE) [24]. Diese subjektiven Bewertungen können als semiquantitative Verfahren angesehen werden, sind jedoch in ihrer Aussagekraft eingeschränkt, da sie stark vom Untersucher abhängig sind und keine Quantifizierung des Substanzverlustes erlauben [25, 26]. Nichtsdestotrotz, werden diese einfachen und schnellen Bewertungssysteme häufig in epidemiologischen Studien eingesetzt [3].

Indirekte Methoden zur objektiven Quantifizierung von Verschleißraten von Zahnhartsubstanz oder Restaurationen sind kostspielig, zeitaufwendig und technisch anspruchsvoll. Für die Verschleißmessungen werden hauptsächlich präzise Gipsmodelle verwendet, die mittels Tast- oder Laserprofilometrie mit optischen 3-D Scannern digitalisiert werden [27-29]. Daraus ergibt sich eine Punktewolke mit x-, y-, z- Koordinaten, die dann zu einem 3D-Datennetz rekonstruiert wird [27, 30]. Die Verschleißparameter werden dann durch eine sequenzielle, digitale Datenüberlagerung über die Bereiche, in denen minimale bis keine Veränderungen detektiert werden durch die entsprechende Software berechnet. Gegenwärtig werden in der Literatur verschiedene Protokolle mit unterschiedlichen Verfahren zur Herstellung von Gipsmodellen, Scanner- oder Softwareeigenschaften und -Einstellungen sowie Auswertungsmethoden beschrieben [19].

Ziel der vorliegenden Dissertation waren die Verschleißraten von Lithium-Disilikat-Keramik und CAD/CAM-gefertigten Komposit Restaurationen bei Patienten nach vollständiger, bimaxillärer, prothetischer Rehabilitation zu quantifizieren. Die vorliegende Arbeit beschäftigt sich dabei mit folgenden beiden Themenkomplexen, die jeweils in einer Publikation abgebildet sind:

1. Dem Vergleich der Verschleißraten zwischen Lithium-Disilikat-Keramik- und CAD/CAM-gefertigten Kompositrestaurationen des 1. Molars nach 2 Jahren.
2. Dem Vergleich der Verschleißraten zwischen Lithium-Disilikat-Keramik- und CAD/CAM-gefertigten Kompositrestaurationen zwischen Prämolaren und Molaren Restaurationen nach 3 Jahren.

Die vorgestellten Arbeiten wurden in der Poliklinik für Zahnärztliche Prothetik durchgeführt. Die Konzeption der Studie erfolgte in Zusammenarbeit mit Prof. Dr. med. dent. Jan-Frederik Güth, Prof. Dr. med. dent. Daniel Edelhoff und PD Dr. med. dent. Christine Keul. Die gesamte Datenauswertung wurde nach Einarbeitung durch Dr. Kurt Erdelt von mir eigenständig durchgeführt. Die statistische Auswertung erfolgte nach Anleitung durch Dr. Kurt Erdelt durch mich. Die beiden vorgestellten Manuskripte wurden nach Anleitung durch Prof. Dr. med. dent. Jan-Frederik Güth selbständig verfasst.

2 Eigene Arbeiten

2.1 Originalarbeit: Güth JF, Erdelt K, Keul C, Burian G, Schweiger J, Edelhoff D. In vivo wear of CAD-CAM composite versus lithium disilicate full coverage first-molar restorations: a pilot study over 2 years. Clin Oral Invest 24, 4301–4311 (2020) (https://doi.org/10.1007/s00784-020-03294-5) IF 2020: 3.573

Zusammenfassung

Ziel: Das Ziel der vorliegenden Arbeit war es die Verschleißraten antagonistischer Restaurationen aus einem experimentellen CAD/CAM-Komposit und Lithium-Disilikat-Keramik bei Patienten mit rekonstruierter vertikaler Dimension der Okklusion (VDO) nach generalisiertem Verlust der Zahnhartsubstanz quantifiziert und verglichen.

Material und Methode: Zwölf Patienten wurden mit Restaurationen entweder aus CAD/CAM-Komposit oder Lithium-Disilikat-Keramik rehabilitiert. Für die Verschleißuntersuchung wurden die Restaurationen des 1. Molaren (n = 48) ausgewählt. Bei jährlichen Kontrollterminen wurden Polyetherabformungen genommen und die resultierenden Gipsmodelle unter Verwendung eines Laborscanners digitalisiert. Die durchschnittliche Beobachtungsdauer betrug 371 Tage für den ersten und 769 Tage für den zweiten Kontrolltermin. Die resultierenden Datensätze (n = 96) wurden durch Überlagerung von 3D-Datensätzen mit einer iterativen Best-Fit-Methode analysiert. Basierend auf den Überlagerungsdaten wurden die Verschleißraten der okklusalen Kontaktflächen berechnet.

Ergebnisse: Bei antagonistischen Restaurationen aus CAD/CAM-Komposit (COMP) lag die durchschnittliche Verschleißrate bei 24,8 ± 13,3 µm/Monat, bei Lithium-Disilikat-Keramik (LS2) bei 9,5 ± 4,3 µm/Monat im ersten Jahr mit signifikanten Unterschieden ($p < 0.0001$) zwischen den beiden Materialien. Im zweiten Jahr nahmen die monatlichen Verschleißraten für beide Materialien signifikant ab: COMP (16,2 ± 10,7 µm/Monat) und LS2 (5,5 ± 3,3 µm/Monat). Der statistische Vergleich der Tragezeit zeigte signifikante Unterschiede für beide Materialien: COMP $p < 0.037$ und LS2 $p < 0.001$.

Eine logarithmische Anpassung (COMP R2 = 0.081; LS2 R2 = 0.038) der Daten wurde berechnet, um den Verschleißverlauf abzuschätzen.

Schlussfolgerung: Bei Patienten mit rekonstruierter VDO zeigen Restaurationen aus Lithium-Disilikat-Keramik niedrigere Verschleißraten als die aus experimentellem CAD/CAM-Komposit. Im Falle einer Gesamtsanierung des Gebisses sind CAD/CAM-Kompositrestaurationen im kaulasttragenden Bereich aufgrund ihrer okklusalen Verschleißraten kritisch zu sehen. Jedoch sollte bei der Auswahl eines Restaurationsmaterials nicht nur die funktionelle okklusale Stabilität berücksichtigt werden, sondern auch die Möglichkeit einer minimal-invasiven, ggf. präparationfreien Behandlung unter maximalem Erhalt der natürlichen Zahnhartsubstanz in Betracht gezogen werden.

Clinical Oral Investigations (2020) 24:4301–4311
https://doi.org/10.1007/s00784-020-03294-5

ORIGINAL ARTICLE

Check for updates

In vivo wear of CAD-CAM composite versus lithium disilicate full coverage first-molar restorations: a pilot study over 2 years

Jan-Frederik Güth [1] · Kurt Erdelt [1] · Christine Keul [1] · Gintare Burian [1] · Josef Schweiger [1] · Daniel Edelhoff [1]

Received: 19 August 2019 / Accepted: 17 April 2020 / Published online: 12 May 2020

Abstract

Objectives To present a digital approach to measure and compare material wear behavior of antagonistic first molar restorations made of an experimental CAD/CAM composite (COMP) and lithium disilicate ceramic (LS2) in patients with reconstructed vertical dimension of occlusion (VDO) after generalized hard tissue loss.

Methods A total of 12 patients underwent complete full jaw rehabilitation with full occlusal coverage restorations made either of COMP or LS2. The first molar restorations ($n = 48$) were chosen for wear examination. At annual recall appointments, polyether impressions were taken, and resulting plaster casts were digitalized using a laboratory scanner. Mean observation period was 371 days for first and 769 days for second year. The resulting 96 datasets were analyzed by superimposition of 3-D datasets using an iterative best-fit method. Based on the superimposition data, the wear rates of the occlusal contact areas (OCAs) were calculated.

Results For antagonistic restorations made of COMP, the average wear rate was 24.8 ± 13.3 μm/month, while for LS2, it was 9.5 ± 4.3 μm/month in first year, with significant differences ($p < 0.0001$) between the materials. In second year, monthly wear rates decreased significantly for both materials: COMP (16.2 ± 10.7 μm/month) and LS2 (5.5 ± 3.3 μm/month). Statistical comparison between wear time showed significant differences for both materials: COMP $p < 0.037$ and LS2 $p < 0.001$. A logarithmic fit (COMP $R^2 = 0.081$; LS2 $R^2 = 0.038$) of the data was calculated to estimate the wear progression.

Significance In patients with reconstructed VDO, restorations made of LS2 show a more stable wear behavior than ones out of experimental CAD/CAM composite. In cases of complete rehabilitation, load bearing CAD/CAM-composite restorations should be critically considered for application due to their occlusal wear behavior. However, when choosing a restorative material, not only the functional occlusal stability should be taken into account but also the prospect of minimally invasive treatment with maximum preservation of natural tooth structures.

Keywords Abrasion · Wear · Dental materials · CAD/CAM composite · Lithium disilicate · Wear behavior

Introduction

Tooth wear is a condition of growing concern these days. Loss of dental hard tissue has a multifactorial etiology. Basically, there are three main reasons which lead to worn dentition (erosion/bio corrosion, abrasion, and attrition), and previous studies showed that these wear mechanisms show mutual interactions [1, 2]. Possible consequences of an accelerated loss of hard

✉ Jan-Frederik Güth
jan_frederik.gueth@med.uni-muenchen.de

Kurt Erdelt
kurt.erdelt@med.uni-muenchen.de

Christine Keul
christine.keul@med.uni-muenchen.de

Gintare Burian
gintare.burian@med.uni-muenchen.de

Josef Schweiger
josef.schweiger@med.uni-muenchen.de

Daniel Edelhoff
daniel.edelhoff@med.uni-muenchen.de

[1] Department of Prosthetic Dentistry, University Hospital, LMU Munich, Goethestrasse 70, 80336 Munich, Germany

tissue can be a reduced vertical dimension of occlusion (VDO), an increased tooth sensitivity, and changes in esthetics and function. The rising prevalence and incidence of this complex condition forces dentists to develop new strategies for diagnosis, patient monitoring, and treatment in order to react as early and effectively as possible, using minimal invasive methods [3, 4].

CAD/CAM polymers, also termed high-performance polymers (HPP), have been introduced to the market as an alternative to ceramics [5, 6]. Polymerized following industrial standards and processed by subtractive methods using CAD/CAM technology, the mechanical properties of these materials are considered to be superior to those of direct polymers [7]. However, the possible applications of CAD/CAM polymers clearly depend on their individual chemical composition, as the individual parameters significantly influence their mechanical properties [8]. Today, these CAD/CAM polymers on the basis of highly cross-linked PMMA resins or filled composites are offered by numerous manufacturers. They attract interest in different fields in dentistry and allow numerous novel treatment options [9, 10].

Currently, CAD/CAM polymers on the basis on PMMA are used as long-term temporary restorations during extended pretreatment phases of up to 2 years [11]. Their material properties allow ultra-thin restoration designs, which dispense extensive tooth preparation and lead to significant dental hard tissue preservation [12, 13]. However, the prospective transition to definitive ceramic restorations requires the clinician to prepare the teeth to ensure an adequate occlusal thickness and an appropriate edge design for the restorations [14]. Inevitably, this may lead to an additional loss of tooth structure.

Keeping this in mind, CAD/CAM polymers on the basis of highly filled composites might constitute a new definitive treatment approach without or with only minimal hard tissue loss. These polymers harbor favorable grinding/milling properties, and due to low modulus of elasticity, it results in higher edge stability, so that these polymers can be used in thinner designs than ceramic materials [10]. Some manufacturers have been offering similar materials for several years now and recommend their application as definitive restorations under clinical conditions. So far, no clinical data have been available on the long-term behavior of these restorations. The main limitation is that clinical research presents many challenges as patient recruitment, funding, and extended time to accumulate some reliable data on clinical restoration changes. Many different 3-D measuring techniques were used in the past, to provide quantitative data on dental materials wear [15, 16]. These comparable methods were used in previous studies mostly reporting on the wear of single posterior composite crowns to be around 40 μm/year [17, 18]. The difference to the present study is that single crowns located within a tooth row were evaluated, but not a full arch reconstruction was conducted out of composite material. It can be assumed that in the previous studies the single crowns were protected by adjacent structures, which could result in comparable wear to adjacent structures. Whereas when a full mouth reconstruction is carried out, the wear behavior of the CAD/CAM polymers might be different especially if, as in the present study, they are to be used to maintain the reconstructed vertical dimension of occlusion (VDO).

The purpose of this clinical pilot study was (1) to present, apply, and evaluate a digital method for measuring wear in a clinical setting and (2) to assess the wear behavior of two restorative materials in patients with a reconstructed VDO after a generalized loss of tooth structure. In this study, an experimental CAD/CAM composite was compared with a lithium disilicate ceramic regarding longitudinal abrasion characteristic over 2 years. The null hypothesis of the study was that the restorations made of the experimental CAD/CAM composite exhibit similar wear rates as restorations made of lithium disilicate ceramic.

Materials and methods

Patients

The study was performed in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) after approval by the Ethics Committee of the university hospital of LMU Munich (012-12; 541-12).

A total of 12 (7 males, 5 females; mean age, 36.3 ± 9.4 years) patients with changes in the vertical dimension of occlusion (VDO) due to loss of hard tissues were included in the study. In all patients, restoring the vertical dimension of occlusion with full arch antagonistic restorations in both jaws was indicated (no-prep occlusal veneers, partial crowns, or full crowns). Canine-guided occlusion through rehabilitation was achieved in every patient. The following inclusion criteria for study participation were defined:

- Age above 18 years and under 70 years.
- Appropriate, at least average oral hygiene.
- Extended decrease of the vertical dimension of occlusion (VDO) due to attritional, abrasive, erosive, or pathological damage to the tooth structure.
- Indication for a minimum of 12 restorations in antagonistic jaws.
- Healthy/treated periodontal tissues (at most grade 1 tooth mobility).
- Pregnant and breastfeeding women were excluded from the study.

All patients participating in the study were informed about the background of the study and the risks associated with it and gave their informed consent.

The patients were divided into two groups:

1) Group COMP included 6 patients, who received adhesively bonded CAD/CAM restorations (n = 168) made of experimental, industrially polymerized composite blocks.
2) Group LS2 consisted of 6 patients, who received monolithic ceramic restorations (n = 168), as control group.

The wear rate was determined based on the first molar restorations (COMP $n = 24$; LS2 $n = 24$) in the maxilla and mandible. Measurements were performed after first and second year for each first molar which resulted in 96 post control datasets. An overview of the study process is shown in Fig. 1.

Treatment and laboratory procedures

The experimental composite material (Ivoclar Vivadent, Schaan, Liechtenstein) consisted of 22% V_f matrix (dimethacrylate) and 78% V_f filler (barium glass fillers, 15%; ytterbium trifluoride, 9%; mixed oxides, 44%; silicon oxides, 3%; copolymers, 7%). The material used in this study exhibited the manufacturer's properties which were as follows: flexural strength = 167 MPa, modulus of elasticity = 11.4 GPa, Vickers hardness = 915 MPa, and water absorption after 7 days = 28 μg/mm^3.

Mechanical properties of used lithium disilicate ceramic (IPS e.max Press, Ivoclar Vivadent, Schaan, Liechtenstein) according to manufacturer are as follows: flexural strength = 400 ± 40 MPa, modulus of elasticity = 95 ± 5 GPa, and Vickers hardness = 5900 ± 100 MPa (https://www.ivoclarvivadent.com/en/p/laboratory-professional/products/all-ceramics/ips-emax-technicians/ips-emax-press).

The clinical procedure in both groups was conducted corresponding to the state of the art in current adhesive (minimally invasive) restorations. Necessary core build-ups were made with direct low viscosity (Tetric EvoFlow, Ivoclar Vivadent, Schaan, Liechtenstein) and/or high-viscosity composites (Tetric EvoCeram, Ivoclar Vivadent, Schaan, Liechtenstein) and a multi-step adhesive system (Syntac, Ivoclar Vivadent, Schaan, Liechtenstein). Impressions were taken with polyether (Permadyne/Impregum Penta, 3 M, Seefeld, Germany) by an individualized Rimlock tray. Fabrication of the restorations was completed in a dental laboratory by an experienced dental technician.

COMP restorations were designed and manufactured using the Cerec system (CEREC InLab V3.86, Dentsply Sirona, Bensheim, Germany), with the following settings: proximal contacts strength = 75 μm, occlusal contact strength = 25 μm, and adhesive gap = 20 μm. Before placing the composite restorations, the inner surfaces were prepared using modified Rocatec procedure (Rocatec soft 30 μm; 1 bar; nozzle distance, 2 cm; 5s blast time per unit) and conditioned with Monobond Plus (Ivoclar Vivadent, Schaan, Liechtenstein).

LS2 restorations were fabricated using the press technique. The inner surfaces of the lithium disilicate restorations were etched with 5% hydrofluoric acid (IPS Ceramic Etching Gel, Ivoclar Vivadent, Schaan, Liechtenstein) for 20 s, rinsed with air/water spray for 60 s, and cleaned in ultrasonic bath for next 60 s. Then, silan coupling agent as part of Monobond Plus (Ivoclar Vivadent, Schaan, Liechtenstein) was applied for 60 s.

Adhesive bonding in both groups was performed with Total Etch & Rinse technique using Syntac (Ivoclar Vivadent, Schaan, Liechtenstein) in combination with the Variolink II (Ivoclar Vivadent, Schaan, Liechtenstein) and light curing, following the manufacturer's instructions. If necessary, occlusal adjustments in static and dynamic occlusion were performed with ball-shaped diamond finishing bur (8801 314 018, Komet Dental, Lemgo, Germany) and water spray application. Finally, the adjusted occlusal areas were polished

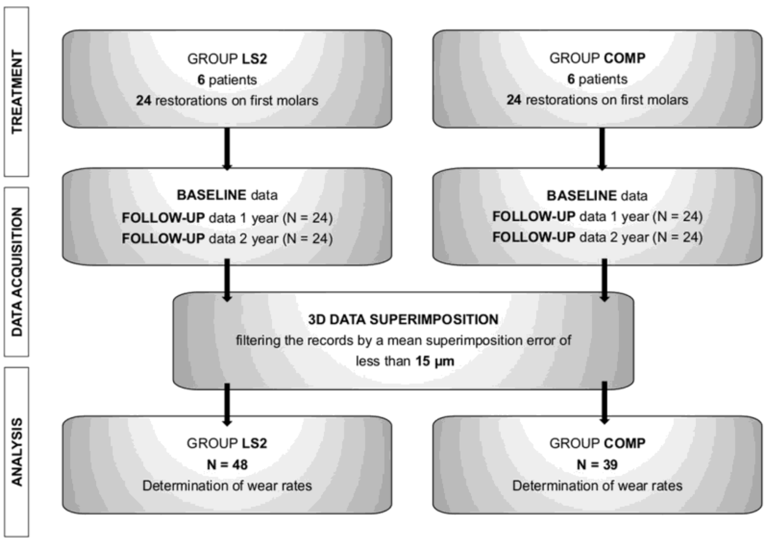

Fig. 1 Overview of the study design and procedure

by adequate polishing sets (Composite: Set 4312A, Ceramic: 4313B, Komet Dental, Lemgo, Germany).

Baseline and follow-up

To investigate the wear behavior of the restorations in both groups, dental impressions with a polyether impression material (Impregum Penta, 3M Espe, Seefeld, Germany) were taken after adhesive bonding and occlusal adjustments of the restorations (baseline). The impressions were poured between 24 and 48 h with type IV dental stone (Plurastone, Pluradent, Offenbach, Germany). The resulting plaster casts were stored at room temperature 21 °C ± 1 °C. All gypsum models were scanned with a laboratory scanner (D810, 3Shape, Copenhagen, Denmark). All follow-up recalls were performed by the same experienced clinician at approximate 12-month interval after clinical loading. Mean observation period in both groups was 371 ± 106 days (first year) and 769 ± 102 days (second year).

Processing of datasets

The resulting STL datasets at baseline and follow-up recalls were imported into the Geomagic Qualify 2012 surface matching analytical software (Geomagic Inc., Morrisville, NC, USA). As a first step, the individual restored first molars of the digital models were isolated and stored as separate datasets in order to facilitate a restoration-related analysis. The data points below the tooth equator were eliminated. Subsequently, the recall data were superimposed with the baseline data, initially highlighting the entire restauration surface of the reference dataset and the follow-up dataset using a best-fit method. The result of this overlay was visually evaluated and the average overlay error determined. Next best-fit alignment was conducted only over those surfaces in which the deviation was less than the overlay error. This procedure was iterated until the overlay error no longer decreased. Only datasets with an overlay error of less than 15 µm were further processed (COMP $n = 39$; L2S $n = 48$). Figure 2 illustrates an example of the procedure. The error of the superimposition was documented for each specimen individually.

This iterative approach allowed to delineate those areas of the restorations that showed signs of wear. After completion of the superimposition, the differences between the datasets were visualized by color-coded pictures which reproduced wear caused by the antagonist restoration. Only areas in which wear could be detected (blue color coding) were selected for further wear analysis. The distance data was exported and stored as individual result files (.csv). Figure 3 shows an example of the wear behavior based on color-coded representation.

Wear evaluation

The resulted files were imported into a statistics program SPSS (version 25, IBM, Armonk, NY, USA) and prepared for further analysis of wear. Subsequently, the average wear depth and the maximum wear depth were calculated perpendicular to the surface of the restoration. To ensure comparability of data in spite of different times in situ, wear was calculated by dividing the values by the number of wear days. Afterwards, the average wear rate per month and the average maximum wear rate per month were determined for the material groups. Furthermore, the data were analyzed for significant differences between the groups of materials (Mann-Whitney *U* test). The *p* value was set at 0.05.

Results

Superimposition error results

A prerequisite for further analysis was a superimposition error between baseline and follow-up datasets less than 15 µm after data overlay (Fig. 4). It turned out that the follow-up data for the experimental CAD/CAM composite caused larger superimposition errors in overlaying process than lithium disilicate. The group COMP exhibited a mean overlay error of 11.9 ± 4 µm after first-year follow-up, compared with 9.3 ± 2 µm in the group LS2. Furthermore, second-year follow-up datasets results confirmed increased superimposition errors in both groups. Group COMP showed an overlay error of 14.6 ±

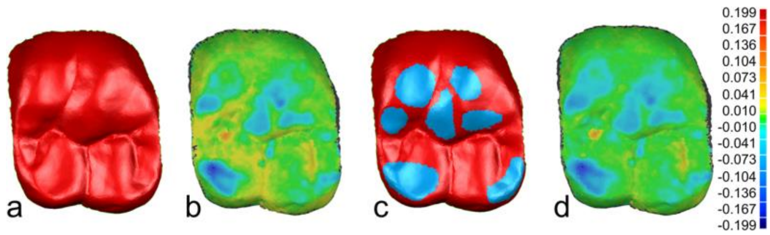

Fig. 2 Example of the iterative approach to the overlay of baseline and follow-up datasets: **a** overlay over the entire occlusal surface; **b** color-coded representation of the differences between baseline and follow-up data after the first overlay; **c** exclusion of areas with antagonistic wear, to achieve fitting of the areas that are not changing; **d** color-coded representation of the differences between baseline and follow-up data after superimposing and exclusion of the worn surfaces. This procedure was iterated until the overlay error no longer changed

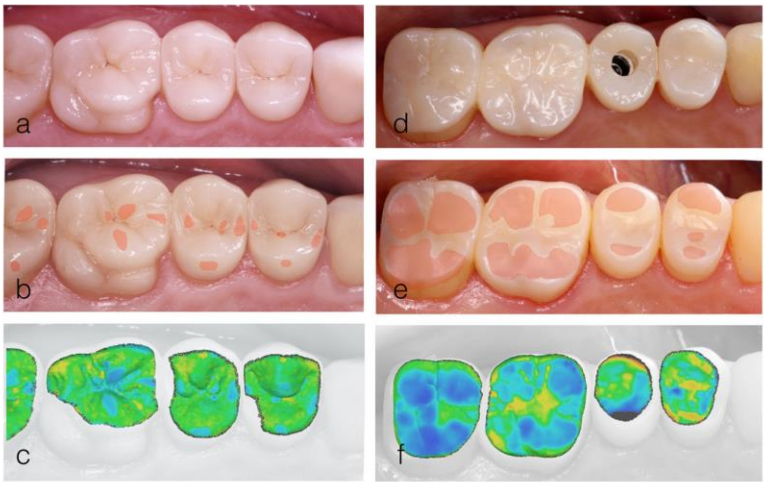

Fig. 3 Color-coded representation of the abrasion behavior: **a** clinical photograph taken at baseline after restoration with lithium disilicate ceramics, **b** clinical photograph taken at the 24-month follow-up (worn surfaces were later marked in red), **c** color-coded representation of the deviations following data overlay, **d** clinical photograph at baseline after restoration with an experimental CAD/CAM composite, **e** clinical photograph taken at the 12-month follow-up (worn surfaces were later marked in red)

7 μm, which was significantly higher in relation to first-year values. As a consequence, more datasets had to be excluded in second year. Group LS2 remained near constant with mean superimposition error of 9.4 ± 1 μm. Filtering out the datasets with overlay errors less than 15 μm, the number of analyzed records was reduced to 39 in group COMP. All lithium disilicate ceramics fulfilled these criteria, and 48 records were included for further analysis.

Average wear rates per month

The values for the wear rates per month in first and second year after placement for COMP and L2S are shown in Table 1. Table 2 shows results of wear rates per year. The Kolmogorov-Smirnov test showed that no normal distribution of values was present; thus, the Mann-Whitney *U* test was used for statistical comparison between materials and wear time.

Analyzing first-year data showed statistically significant differences ($p < 0.001$) between COMP (24.8 ± 13.3 μm/month) and LS2 (9.5 ± 4.3 μm/month). Second-year data showed decreased wear rates per month for both materials, still with significant differences ($p < 0.001$): COMP (16.2 ± 10.7 μm/month) and LS2 (5.5 ± 3.3 μm/month). Statistical comparison of wear between first and second year showed significant differences for both materials: COMP $p < 0.037$ and LS2 $p < 0.001$. The results are shown in Fig. 5.

Maximum wear rates per month

The values for the maximum depth of wear per month in first and second year are shown in Table 3 and Fig. 6. The Kolmogorov-Smirnov test showed that no normal distribution of values was present; thus, the Mann-Whitney *U* test was used for statistical comparison between materials and wear time. The average maximum wear rate across all restorations made of the experimental CAD/CAM composite was 76 ± 42.9 μm/month which was significantly different ($p < 0.001$) from the average maximum wear rates of 36.1 ± 22.6 μm/month for restorations made of lithium disilicate ceramics in first year. In second year, exhibited maximum wear rates decreased for both materials: COMP 45 ± 23.3 μm/month and LS2 19.9 ± 14.3 μm/month; these results still showed significant differences ($p < 0.001$). Figure 6 shows the corresponding box plots.

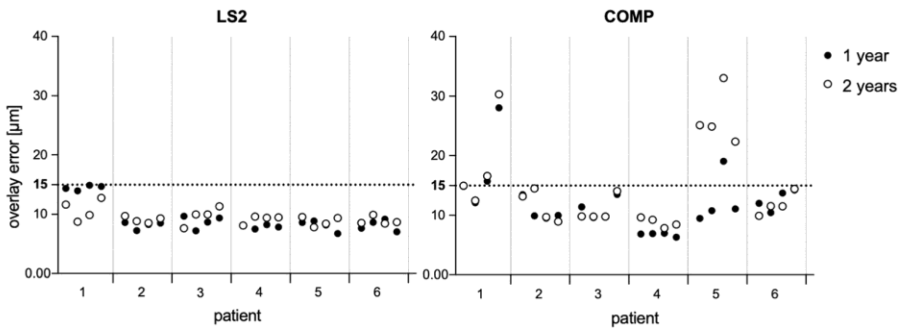

Fig. 4 Overlay error of each molar specimen in accordance with individual patients

Table 1 Average wear rates per month [μm]

	Time	N	Mean	SD	Median	95% CI	IQR
LS2	1 year	24	9.46	4.31	8.67	7.63/11.28	4.56
	2 years	24	5.47	3.29	4.44	4.08/6.86	2.84
COMP	1 year	21	24.76	13.32	24.92	18.69/30.82	24.50
	2 years	18	16.23	10.72	13.61	10.89/21.56	12.97

Wear in time axis

The progress of total wear over time for each specimen is shown in Fig. 7. The following graph demonstrates continuous increase of wear for both materials. Based on the previous statements, the statistically significant decrease of wear rates per month over time confirms that abrasion shows a time dependency. The highest overall loss of restorative material occurred during the first year of use, whereas between the first and second year, the amount of wear decreases. Curve fitting was calculated and adjusted with SPSS to analyze time dependence of wear.

Two assumptions were made for curve fitting: (1) At starting point, when restorations were placed, no wear had occurred yet. (2) The total wear increases with time. Based on these two assumptions, only linear and logarithmic functions are possible. However, a linear function does not fulfill assumption one, because it does not cross the y-axis at zero. Therefore, linear increase of wear rates must be rejected. Logarithmic function (COMP $R^2 = 0.081$; L2S $R^2 = 0.038$) showed the best fit to these data points, as the function starts almost at zero and increases continuously.

Discussion

The present clinical pilot study compared the wear behavior of antagonistic monolithic restorations made of two materials: experimental CAD/CAM composites and lithium disilicate ceramics. To our best knowledge, the present study is the first so far to compare wear of CAD/CAM composite versus CAD/CAM composite with lithium disilicate versus lithium disilicate in vivo conditions [19]. The results showed significant differences in wear progress between these two materials in patients that received full mouth rehabilitation. Restorations made of the experimental CAD/CAM composite exhibited higher wear rates than those made of lithium disilicate ceramics. The null hypothesis must therefore be rejected.

Table 2 Mean wear rates per year [μm]

	Time	N	Mean	SD
LS2	1 year	24	113.52	51.72
	2 years	24	65.64	39.48
COMP	1 year	21	297.12	159.84
	2 years	18	194.76	128.64

The average wear rates per month were higher in first year compared with the follow-up values in both groups. It should be taken into consideration that these wear rates will decrease every year as a possible consequence of the formation of the occlusion wear facets.

While the wear area increases, the applied forces are distributed onto a larger area. This reduces the forces per area and might the reason that wear rates are highest initially after placing the restorations, as restorations are adjusting to each other. Longitudinal studies are still needed to confirm our expectations on this wear behavior in vivo for extended follow-up intervals. As well, the possibility of non-contact area wear of composites, that is caused by failure of composite components, cannot be refused [20]. This might influence the accuracy of the superimposition and might even lead to higher overall wear in the composite group, which even more supports the findings of this study.

Quantitative wear measurement acquired in this study's clinical setting was assessed using a new iterative approach. Measurements were performed on entire occlusal surface on every first molar, using plaster casts after conventional impression. To minimize potential errors of this workflow, the overlay and analysis were performed for each molar individually, to gain a certain independence of adjacent structures. This made it possible to eliminate at least the influence of overall distortions of impressions and manufacture of plaster casts that could influence the results [21]. In addition, the superimposition process was iterated until the overlay error was no longer changed by further superimposition. In this way, the best fit of baseline and follow-up data over the areas that had not been exposed to any antagonistic wear could be achieved.

For the quantitative measurement of vertical height loss of antagonistic restorations, mean superimposition error of 15 μm was determined as the standard deviation error between the data records. In vitro studies, the standard deviation of superimposition has been described to be between 5 and 10 μm [22]. Against that data, capturing under clinical conditions seems to be more error prone and present higher variations; therefore, higher standard deviations up to 15 μm had to be accepted. On the other side, data bellow tolerance of 15 μm were excluded in this study to receive most reliable data. Based on individual bite forces and masticatory movements, every investigated specimen exhibited different pattern of abrasion. DeLong et.al reported that the estimation of superimposition for samples of clinical studies usually fluctuate from 10 to 20 μm per point; they considered the superimposition of less than 10 μm to be an excellent fit, whereas a value of more than 50 μm indicates a poor fit [15]. This goes in line with other clinical investigations in measuring wear, where

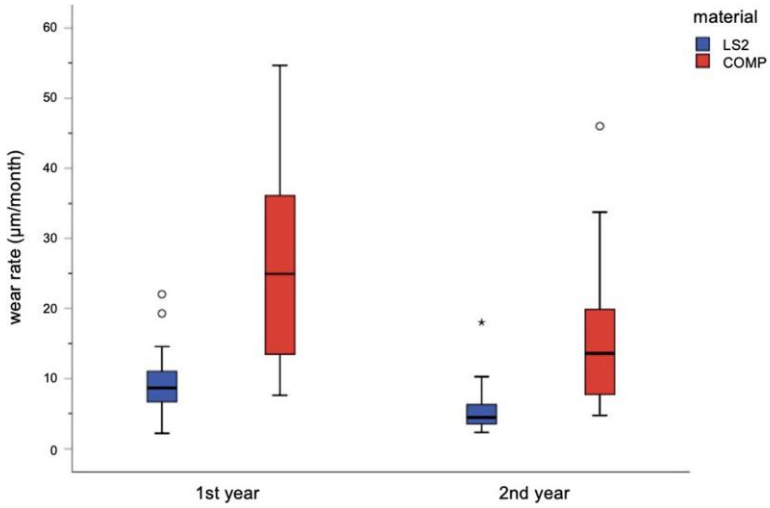

Fig. 5 Mean wear rates (µm/month). Boxplots illustrate median and IQR values. Circles represent the outliers

workflow inaccuracy in the range of 15–20 µm was considered acceptable [18, 23–26]. Schmid-Schwap et al. [27] even set the limit at 30 µm for standard deviation/workflow inaccuracies for molars as reasonable, as they are more difficult to superimpose. However, this was stated for the wear of methacrylate artificial teeth. In presented study, composite restorations showed higher superimposition errors which may be caused by non-antagonistic wear which is more pronounced on composite than lithium disilicate ceramic [28].

Wear can be quantified using depth, area, and volume. The connection and correlation of these parameters are explained excellent by DeLong et al. [29]. However, the methodology of wear measurements under clinical conditions is currently intensively discussed [30–34]. In this clinical study, the parameter of vertical height loss measured perpendicular to working surface was applied. The calculation of volume changes under clinical conditions seems to be very error prone. Most critical point is to define area for volume calculation, between exposed and non-exposed area of wear. In contrast, the reproducibility and comparability of these measurements were restricted, due to high failure rate on assessing thin margins and different surface areas, what made this data unusable. Furthermore, previous studies already elucidated the advantage of measuring vertical height loss compared with

Table 3 Maximum wear rates per month [µm]

	Time	N	Mean	SD	Median	95% CI	IQR
LS2	1 year	24	36.13	22.55	31.99	26.61/45.65	12.09
	2 years	24	19.88	14.33	15.66	13.83/25.93	7.24
COMP	1 year	21	76.03	42.91	72.32	56.50/95.56	58.37
	2 years	18	45.06	23.27	38.86	33.49/56.63	23.50

volumetric wear measurement. The main advantage is the possibility of a direct quantification of wear and eliminating the influence of surface size [27, 31]. A combination of vertical height loss and surfaces measurement was desirable; however, surface measurement underlay the same trouble as volumetric measurements.

According to the biomimetics concept, the wear behavior of dental restorations should ideally resemble physiologic tooth enamel. However, clinical data on the wear behavior of natural teeth is rare and varies widely. In the few existing studies, the wear rates for natural enamel were found to be about 10–40 µm/year [35–37]. The parameter that was comparable with the measurements reported in the literature seems to be the mean wear rate per year. However, the results of clinical trials showed considerable fluctuations [30]. The wear rates differed significantly between different research groups; Etman et al. [38] stated wear of 148 µm after first year for lithium disilicate glass-ceramic posterior crowns, whereas Kramer et al. [39] determined it as 78 µm after 4 year for ceramic inlays made of lithium disilicate. Only very few studies investigated wear of posterior composite crowns in vivo and reported wear to be around 40 µm/year, which is considerably lower than values found in this study [17, 18]. Although there is an abundance of clinical data on the wear characteristics of direct composite restorations, literature shows a considerable variation in results from 50 to 200 µm per year [30, 40, 41]. It must be taken into account that these studies compared wear rates with opposing enamel as an antagonist. Besides that, direct composite resin restorations of class I/II are protected by enamel which limits the conclusions drawn in regard of biomechanical loading. Additionally, not only antagonistic situation but also the clinical environment in which the restorations are placed seems to play a role for wear rates, and it is clear that wear rates might differ for single restoration against different antagonists. In the present study,

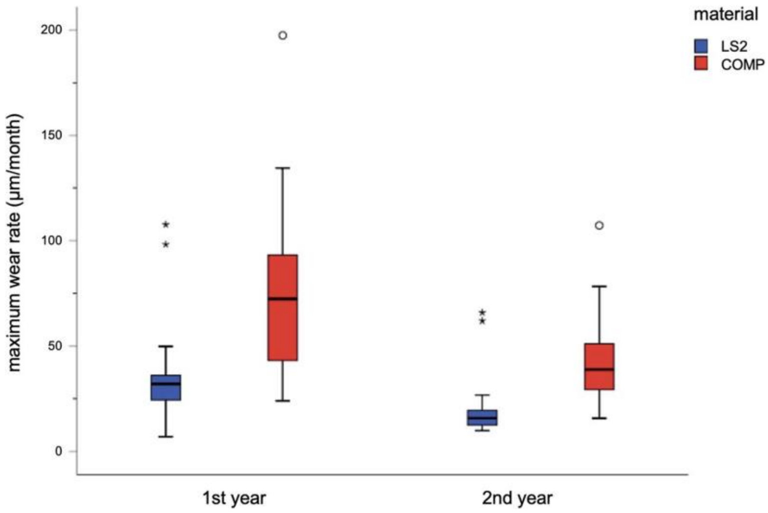

Fig. 6 Maximum wear rates (μm/month). Boxplots illustrate median and IQR values. Circles represent the outliers

the patients received full mouth rehabilitation using either CAD/CAM composite or lithium disilicate. In this clinical constellation, restorations are not protected by adjacent structures like enamel or crowns from other materials with lower wear rates. This means that the restorations in this study are subjected to complete bite forces and have to carry the full occlusal load either by opposing composite or ceramic. There is still no reliable data on wear rates in clinical cases of posterior restorations in cases of complete rehabilitation. Therefore, it is challenging to validate the credibility of our results. In this pilot study, wear was measured only on first molars. Further analysis applying the same methodology would also be considerable to make a distinction between premolars and molars, as some studies confirmed wear was more pronounced on molars than premolars [42, 43].

The analysis of the wear behavior of restorative materials and tooth structure in clinical cases poses two main problems for scientists and clinicians: taking exact and reproducible impressions and finding an adequate valid and reliable method for analysis of wear. Distortions or impression tolerances are two among other potential factors impairing the resulting cast quality [21, 44]. Moreover, the scanning process itself is prone to further inaccuracies, affecting the measurement results [45]. To avoid errors due to plaster cast fabrication, it is possible to scan impressions directly; however, undercuts and steep tooth geometries seem to limit this approach [46]. Also from the point of accuracy, there seems no significant advantage due to digitizing a conventional impression directly compared using the poured plaster model [47]. A considerable change of this step in the workflow would be the use of intraoral scanner for digital impressions. However, in vivo studies validated that conventional precision impression materials, like polyether used in this study, still show higher precision for full-dental arch impression compared with current intraoral scanners systems [47, 48]. To exclude any influence of global distortion and inaccuracies of data acquisition, the present analysis is based on single tooth areas after sectioning the virtual dataset. Against this background, an application of intraoral scanner seems to be reasonable for further studies. Another limitation of the present pilot study was the relatively small cohort size. However, after an accumulated number of 87 numbers of datasets, significant differences between the groups of

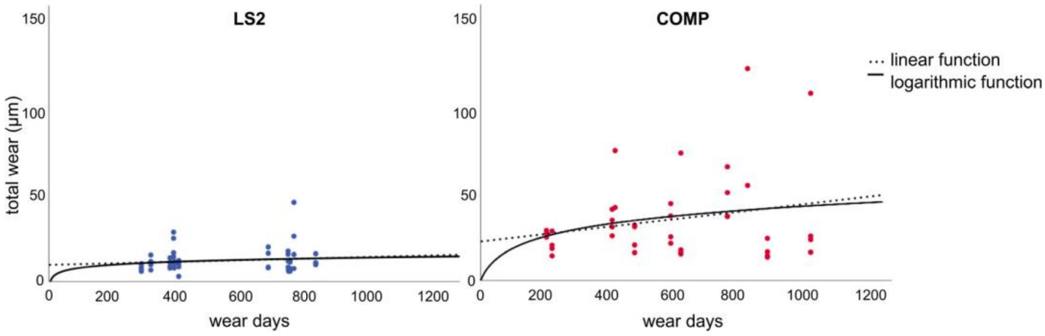

Fig. 7 Wear over time axis of each individual specimen

materials could already be detected. Also, it can be presumed that our patients showed parafunctional behavior after altering the VDO, which could lead to increased wear of material during the first year. But so far, there is no evidence based on well-controlled clinical trials regarding this correlation [49]. However, based on the results for both types of restorations and assuming functionally active patients, an additional protective splint (night guard) may be recommended to be used at least overnight to prevent repeated early loss of vertical dimension.

To estimate the annual loss of vertical dimension, the average wear rates need be doubled because wear takes place in both jaws. Nevertheless, potential dental compensation has to be considered when this conclusion is drawn [50]. This would mean a total loss of height of 49.5 μm/month in the posterior region for restorations made of the experimental CAD/CAM composite and 18.9 μm/month for restorations made of lithium disilicate ceramics in first year after placement. Based on the assumption of logarithmic wear model, this trend might be reduced over following years in function. However, this hypothesis has to be proven in further studies. Seen from this point of view, restorations made of lithium disilicate ceramic seem to offer a more stable prognosis in terms of wear and prevention in the long run.

On the other hand, CAD/CAM composite restorations also have some advantages. These include the minimal invasiveness due to the better properties of CAD/CAM composite and higher flexibility of the material compared with ceramics [51]. The characteristics of the polymeric material and the superior edge stability facilitate procedures with very thin layers of the material and with little depth of preparation margins—or even without any preparation at all—which seems advantageous in terms of maximum tooth conservation. Moreover, CAD/CAM composite restorations have been associated with a more favorable wear behavior on the antagonistic enamel, which seen from a biomimetic point of view should be preferable as tooth structures will be preserved [52].

In summary, it can be concluded that in patients with a generalized loss of tooth substance, partial coverage restorations made of monolithic lithium disilicate ceramics to reconstruct the VDO showed lower wear rates than similar restorations made of an experimental CAD/CAM composite. Further studies are necessary to show whether these results are also valid for different clinical environments and settings, as well as for natural enamel antagonists.

Conclusion

Within the limitations of the present experiment, the following could be concluded. (1) COMP wore significant more than L2S (16.2 ± 10.7 μm/month vs 5.5 ± 3.3 μm/month, p = 0.001) after 2 years, and (2) wear versus time decreased following a logarithmic behavior. In cases of complete rehabilitation, load bearing CAD/CAM-composite restorations crowns should be critically considered for application due to their occlusal wear behavior.

Funding information Open Access funding provided by Projekt DEAL. The study was supported by a grant of Ivoclar Vivadent. The funding source had no influence in the collection, analysis, and interpretation of data, in writing the report, and the decision to submit the article for publication.

Compliance with ethical standards

Conflict of interest The authors Güth JF, Schweiger J, and Edelhoff D receive study grants and honoraria for scientific lectures from the sponsoring company. The authors Erdelt K, Burian G, and Keul CK declare no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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

References

1. Lussi A, Carvalho TS (2014) Erosive tooth wear: a multifactorial condition of growing concern and increasing knowledge. Monogr Oral Sci 25:1–15
2. Lussi A (2006) Dental erosion : from diagnosis to therapy. Monographs in oral science. Karger, Basel xii, 219 p
3. Loomans B, Opdam N, Attin T, Bartlett D, Edelhoff D, Frankenberger R, Benic G, Ramseyer S, Wetselaar P, Sterenborg B, Hickel R, Pallesen U, Mehta S, Banerji S, Lussi A, Wilson N (2017) Severe tooth wear: European consensus statement on management guidelines. J Adhes Dent 19(2):111–119
4. Wetselaar P, Lobbezoo F (2016) The tooth wear evaluation system: a modular clinical guideline for the diagnosis and management planning of worn dentitions. J Oral Rehabil 43(1):69–80
5. Magne P (2006) Composite resins and bonded porcelain: the postamalgam era? J Calif Dent Assoc 34(2):135–147
6. Güth JF et al (2012) Treatment concept with CAD/CAM-fabricated high-density polymer temporary restorations. J Esthet Restor Dent 24(5):310–318

7. Mainjot AK, Dupont NM, Oudkerk JC, Dewael TY, Sadoun MJ (2016) From artisanal to CAD-CAM blocks: state of the art of indirect composites. J Dent Res 95(5):487–495
8. Stawarczyk B, Özcan M, Trottmann A, Schmutz F, Roos M, Hämmerle C (2013) Two-body wear rate of CAD/CAM resin blocks and their enamel antagonists. J Prosthet Dent 109(5):325–332
9. Güth JF et al (2016) CAD/CAM polymer vs direct composite resin core buildups for endodontically treated molars without ferrule. Oper Dent 41(1):53–63
10. Schlichting LH, Maia HP, Baratieri LN, Magne P (2011) Novel-design ultra-thin CAD/CAM composite resin and ceramic occlusal veneers for the treatment of severe dental erosion. J Prosthet Dent 105(4):217–226
11. Edelhoff D, Liebermann A, Beuer F, Stimmelmayr M, Güth JF (2016) Minimally invasive treatment options in fixed prosthodontics. Quintessence Int 47(3):207–216
12. Schlichting LH, Resende TH, Reis KR, Magne P (2016) Simplified treatment of severe dental erosion with ultrathin CAD-CAM composite occlusal veneers and anterior bilaminar veneers. J Prosthet Dent 116(4):474–482
13. Johnson AC, Versluis A, Tantbirojn D, Ahuja S (2014) Fracture strength of CAD/CAM composite and composite-ceramic occlusal veneers. J Prosthodont Res 58(2):107–114
14. Lawn BR, Pajares A, Zhang Y, Deng Y, Polack MA, Lloyd IK, Rekow ED, Thompson VP (2004) Materials design in the performance of all-ceramic crowns. Biomaterials 25(14):2885–2892
15. DeLong R, Pintado M, Douglas WH (1985) Measurement of change in surface contour by computer graphics. Dent Mater 1(1): 27–30
16. Mehl A, Gloger W, Kunzelmann KH, Hickel R (1997) A new optical 3-D device for the detection of wear. J Dent Res 76(11): 1799–1807
17. Ohlmann B et al (2008) Wear of posterior metal-free polymer crowns after 2 years. J Oral Rehabil 35(10):782–788
18. Zenthofer A et al (2013) Wear of metal-free resin composite crowns after three years in service. Dent Mater J 32(5):787–792
19. D'Arcangelo C, Vanini L, Rondoni GD, Vadini M, de Angelis F (2018) Wear evaluation of prosthetic materials opposing themselves. Oper Dent 43(1):38–50
20. Bayne SC, Taylor DF, Heymann HO (1992) Protection hypothesis for composite wear. Dent Mater 8(5):305–309
21. Christensen GJ (2008) The challenge to conventional impressions. J Am Dent Assoc 139(3):347–349
22. Heintze SD, Cavalleri A, Forjanic M, Zellweger G, Rousson V (2008) Wear of ceramic and antagonist–a systematic evaluation of influencing factors in vitro. Dent Mater 24(4):433–449
23. Soderholm KJ et al (2001) Clinical wear performance of eight experimental dental composites over three years determined by two measuring methods. Eur J Oral Sci 109(4):273–281
24. Rodriguez JM, Austin RS, Bartlett DW (2012) In vivo measurements of tooth wear over 12 months. Caries Res 46(1):9–15
25. Rodriguez JM, Austin RS, Bartlett DW (2012) A method to evaluate profilometric tooth wear measurements. Dent Mater 28(3):245–251
26. Palaniappan S, Bharadwaj D, Mattar DL, Peumans M, van Meerbeek B, Lambrechts P (2009) Three-year randomized clinical trial to evaluate the clinical performance and wear of a nanocomposite versus a hybrid composite. Dent Mater 25(11):1302–1314
27. Schmid-Schwap M, Rousson V, Vornwagner K, Heintze SD (2009) Wear of two artificial tooth materials in vivo: a 12-month pilot study. J Prosthet Dent 102(2):104–114
28. Mayworm CD, Camargo SS Jr, Bastian FL (2008) Influence of artificial saliva on abrasive wear and microhardness of dental composites filled with nanoparticles. J Dent 36(9):703–710
29. DeLong R (2006) Intra-oral restorative materials wear: rethinking the current approaches: how to measure wear. Dent Mater 22(8):702–711
30. Wulfman C, Koenig V, Mainjot AK (2018) Wear measurement of dental tissues and materials in clinical studies: a systematic review. Dent Mater 34(6):825–850
31. Stober T, Heuschmid N, Zellweger G, Rousson V, Rues S, Heintze SD (2014) Comparability of clinical wear measurements by optical 3D laser scanning in two different centers. Dent Mater 30(5):499–506
32. Lohbauer U, Reich S (2017) Antagonist wear of monolithic zirconia crowns after 2 years. Clin Oral Investig 21(4):1165–1172
33. Esquivel-Upshaw JF, Kim MJ, Hsu SM, Abdulhameed N, Jenkins R, Neal D, Ren F, Clark AE (2018) Randomized clinical study of wear of enamel antagonists against polished monolithic zirconia crowns. J Dent 68:19–27
34. Heintze SD, Reichl FX, Hickel R (2019) Wear of dental materials: clinical significance and laboratory wear simulation methods -a review. Dent Mater J 38(3):343–353
35. Lambrechts P, Braem M, Vuylsteke-Wauters M, Vanherle G (1989) Quantitative in vivo wear of human enamel. J Dent Res 68(12): 1752–1754
36. Molnar S, McKee JK, Molnar IM, Przybeck TR (1983) Tooth wear rates among contemporary Australian aborigines. J Dent Res 62(5): 562–565
37. Bartlett DW, Blunt L, Smith BG (1997) Measurement of tooth wear in patients with palatal erosion. Br Dent J 182(5):179–184
38. Etman MK, Woolford M, Dunne S (2008) Quantitative measurement of tooth and ceramic wear: in vivo study. Int J Prosthodont 21(3):245–252
39. Kramer N et al (2006) Antagonist enamel wears more than ceramic inlays. J Dent Res 85(12):1097–1100
40. Pesun IJ, Olson AK, Hodges JS, Anderson GC (2000) In vivo evaluation of the surface of posterior resin composite restorations: a pilot study. J Prosthet Dent 84(3):353–359
41. Palaniappan S, Elsen L, Lijnen I, Peumans M, van Meerbeek B, Lambrechts P (2010) Three-year randomised clinical trial to evaluate the clinical performance, quantitative and qualitative wear patterns of hybrid composite restorations. Clin Oral Investig 14(4): 441–458
42. Mundhe K, Jain V, Pruthi G, Shah N (2015) Clinical study to evaluate the wear of natural enamel antagonist to zirconia and metal ceramic crowns. J Prosthet Dent 114(3):358–363
43. Loomans BAC, Kreulen CM, Huijs-Visser HECE, Sterenborg BAMM, Bronkhorst EM, Huysmans MCDNJM, Opdam NJM (2018) Clinical performance of full rehabilitations with direct composite in severe tooth wear patients: 3.5 years results. J Dent 70:97–103
44. Güth JF et al (2016) A new method for the evaluation of the accuracy of full-arch digital impressions in vitro. Clin Oral Investig 20(7):1487–1494
45. Gonzalez de Villaumbrosia P et al (2016) In vitro comparison of the accuracy (trueness and precision) of six extraoral dental scanners with different scanning technologies. J Prosthet Dent 116(4):543–550 e1
46. Bosniac P, Rehmann P, Wostmann B (2018) Comparison of an indirect impression scanning system and two direct intraoral scanning systems in vivo. Clin Oral Investig
47. Ender A, Attin T, Mehl A (2016) In vivo precision of conventional and digital methods of obtaining complete-arch dental impressions. J Prosthet Dent 115(3):313–320
48. Guth JF et al (2017) Accuracy of five intraoral scanners compared to indirect digitalization. Clin Oral Investig 21(5):1445–1455
49. Moreno-Hay I, Okeson JP (2015) Does altering the occlusal vertical dimension produce temporomandibular disorders? A literature review. J Oral Rehabil 42(11):875–882
50. Berry DC, Poole DF (1976) Attrition: possible mechanisms of compensation. J Oral Rehabil 3(3):201–206
51. Magne P, Schlichting LH, Maia HP, Baratieri LN (2010) In vitro fatigue resistance of CAD/CAM composite resin and ceramic posterior occlusal veneers. J Prosthet Dent 104(3):149–157

52. Stawarczyk B, Liebermann A, Eichberger M, Güth JF (2015) Evaluation of mechanical and optical behavior of current esthetic dental restorative CAD/CAM composites. J Mech Behav Biomed Mater 55:1–11

2.2 Originalarbeit: Burian G, Erdelt K, Schweiger J, Keul C, Edelhoff D, Güth JF. In-vivo-wear in composite and ceramic full mouth rehabilitations over 3 years. Sci Rep. 2021 Jul 7;11(1):14056. (https://doi.org/10.1038/s41598-021-93425-z) IF 2020: 5.133

Zusammenfassung

Ziel: Das Ziel dieser Studie war die Quantifizierung und der Vergleich der Verschleißraten von Prämolaren (PM) und Molaren (M) Restaurationen aus Lithium-Disilikat-Keramik (LS2) und einem experimentellen CAD/CAM-Komposit (COMP) im Rahmen einer komplexen prothetischen Gesamtrehabilitation von Abrasionsgebiss mit Veränderungen in der Vertikaldimension der Okklusion (VDO).

Material und Methode: Zwölf Patienten mit pathologisch erhöhtem Zahnverschleiß wurden prothetisch mit antagonistischen Restaurationen rehabilitiert. Dazu wurde entweder eine Lithium-Disilikat-Keramik (n = 6 Patienten, n = 16 posteriore Restaurationen/ Patient; N = 96 Restaurationen/ Jahr) oder ein experimentelles CAD/CAM-Komposit (n = 6 Patienten, n = 16 posteriore Restaurationen/ Patient; N = 96 Restaurationen/ Jahr) verwendet. Die Daten wurden im Rahmen der jährlichen Kontrolluntersuchung erhoben (350 ± 86d; 755 ± 92d; 1102 ± 97d). Jeder jährliche Recalldatensatz von Prämolar- und Molarenrestaurationen (N = 192) wurde einzeln mit dem entsprechenden Basisdatensatz unter Verwendung einer iterativen Best-Fit-Methode überlagert und verglichen. Der mittlere vertikale Verlust der okklusalen Kontaktbereiche (OCAs) wurde für jede Restauration und für jede Recallzeit berechnet.

Ergebnisse: Für LS2-Restaurationen betrug die mittlere Verschleißrate pro Monat für das erste Jahr 7,5 ± 3,4 µm (PM), 7,8 ± 2,0 µm (M), für das zweite Jahr 3,8 ± 1,6 µm (PM), 4,4 ± 1,5 µm (M), für das dritte Jahr 2,8 ± 1,3 µm (PM), 3,4 ± 1,7 µm (M). Bei COMP-Restaurationen betrug die mittlere Abnutzungsrate pro Monat für das erste Jahr 15,5 ± 8,9 µm (PM), 28,5 ± 20,2 µm (M), für das zweite Jahr 9,2 ± 5,9 µm (PM), 16,7 ± 14,9 µm (M) und für das dritte Jahr 8,6 ± 5,3 µm (PM), 9,5 ± 8,0 µm (M). Drei COMP-Restaurationen versagten nach zwei Jahren und wurden daher in den 3-Jahres-Ergebnissen nicht berücksichtigt. Die Verschleißraten in der LS2-Gruppe zeigten signifikanten

Unterschiede zwischen Prämolaren- und Molarenrestaurationen (p = 0,041; p = 0,023; p = 0,045). Die Verschleißraten in der COMP-Gruppe zeigten nur in den ersten beiden Jahren signifikante Unterschiede zwischen Prämolaren und Molaren (p < 0,0001; p = 0,0027).

Schlussfolgerung: COMP-Restaurationen zeigten im Vergleich zu LS2 deutlich höhere Verschleißraten. Die präsentierten Ergebnisse legen nahe, dass mit zunehmender Zeit in situ die monatlichen Verschleißraten für beide Materialien im Laufe der Zeit abnehmen. Auf Basis dieses begrenzten Datensatzes zeigen sowohl LS2- als auch COMP-Restaurationen nach 3 Jahren Nachbeobachtung angemessene klinische Verschleißraten. Der Verschleiß von COMP-Restaurationen war höher, bei einer jedoch weniger invasiven, prothetischen Behandlung. Zahnärzte sollten bei Patienten mit ausgeprägtem Zahnhartsubstanzverlust ein ausgewogenes Verhältnis zwischen notwendiger Invasivität der Präparation und langfristiger okklusaler Stabilität wählen.

www.nature.com/scientificreports

scientific reports

Check for updates

OPEN

In-vivo-wear in composite and ceramic full mouth rehabilitations over 3 years

Gintare Burian[1], Kurt Erdelt[1], Josef Schweiger[1], Christine Keul[1], Daniel Edelhoff[1] & Jan-Frederik Güth[2]✉

The aim of this study was to quantify and to compare the wear rates of premolar (PM) and molar (M) restorations of lithium disilicate ceramic (LS2) and an experimental CAD/CAM polymer (COMP) in cases of complex rehabilitations with changes in vertical dimension of occlusion (VDO). Twelve patients with severe tooth wear underwent prosthetic rehabilitation, restoring the VDO with antagonistic occlusal coverage restorations either out of LS2 (n = 6 patients, n = 16 posterior restorations/patient; N = 96 restorations/year) or COMP (n = 6 patients; n = 16 posterior restorations/patient; N = 96 restorations/year). Data was obtained by digitalization of plaster casts with a laboratory scanner at annual recalls (350 ± 86 days; 755 ± 92 days; 1102 ± 97 days). Each annual recall dataset of premolar and molar restorations (N = 192) was overlaid individually with the corresponding baseline dataset using an iterative best-fit method. Mean vertical loss of the occlusal contact areas (OCAs) was calculated for each restoration and recall time. For LS2 restorations, the mean wear rate per month over 1 year was 7.5 ± 3.4 µm (PM), 7.8 ± 2.0 µm (M), over 2 years 3.8 ± 1.6 µm (PM), 4.4 ± 1.5 µm (M), over 3 years 2.8 ± 1.3 µm (PM), 3.4 ± 1.7 µm (M). For COMP restorations, the mean wear rate per month over 1 year was 15.5 ± 8.9 µm (PM), 28.5 ± 20.2 µm (M), over 2 years 9.2 ± 5.9 µm (PM), 16.7 ± 14.9 µm (M), over 3 years 8.6 ± 5.3 µm (PM), 9.5 ± 8.0 µm (M). Three COMP restorations fractured after two years and therefore were not considered in the 3-year results. The wear rates in the LS2 group showed significant differences between premolars and molars restorations (p = 0.041; p = 0.023; p = 0.045). The wear rates in COMP group differed significantly between premolars and molars only in the first two years (p < 0.0001; p = 0.007). COMP restorations show much higher wear rates compared to LS2. The presented results suggest that with increasing time in situ, the monthly wear rates for both materials decreased over time. On the basis of this limited dataset, both LS2 and COMP restorations show reasonable clinical wear rates after 3 years follow-up. Wear of COMP restorations was higher, however prosthodontic treatment was less invasive. LS2 showed less wear, yet tooth preparation was necessary. Clinicians should balance well between necessary preparation invasiveness and long-term occlusal stability in patients with worn dentitions.

The availability of in vivo data on the wear behavior of tooth-colored monolithic dental materials in cases of complete rehabilitation is limited. Loss of dental hard tissue due to tooth wear is a well described clinical problem with an increasing prevalence in dental practice[1,2]. In general, tooth wear is a result of different mechanisms: interaction with exogenous materials/ three body wear (abrasion), tooth-to-tooth contact/ two body wear (attrition) or chemical dissolution of hard tissues (erosion)[3,4]. These wear mechanisms often act sequentially or in synchrony, which can lead to accelerated excessive tooth wear at relatively young age. This condition poses several complications as changes in vertical dimension of occlusion (VDO) with possible functional impairment, increased tooth sensitivity and reduced esthetics[4]. At this point severe tooth wear affects people's quality of life[5].

The multifactorial conditions of tooth wear implicate restorative challenges for clinicians, as a complex holistic rehabilitation is required, including occlusal adjustment e.g.[6]. New solutions are needed which are in line with state-of-the-art minimally invasive dentistry[7]. Due to CAD/CAM technology, multiple polymers with advantageous features have been introduced to the dental market. These CAD/CAM polymers, manufactured under industrial standards, show superior mechanical properties to those of direct polymers and have even

[1]Department of Prosthetic Dentistry, University Hospital, Ludwig-Maximilians-University Munich, Goethestrasse 70, 80336 Munich, Germany. [2]Department of Prosthodontics, Goethe University, Center for Dentistry and Oral Medicine (Carolinum), Theodor-Stern-Kai 7, 60596 Frankfurt am Main, Germany. ✉email: gueth@med.uni-frankfurt.de

been considered as an alternative to glass–ceramic[8–10]. Multiple advantages of CAD/CAM composites have been already observed in different in vitro studies: a high fatigue resistance, an antagonistic friendly behavior and appropriate optical properties[11,12]. Consequently, they were implemented in different fields of prosthetic dentistry[13,14]. Especially in challenging cases of worn dentition, CAD/CAM-fabricated polymer restorations allow to comply with the aims of minimal invasive dentistry and biomimetic approaches[15].

Both, glass ceramics and composite resins are applied and reported as restorative materials for treatment of severe tooth wear[6,16,17]. In respective clinical cases, material thickness plays an important role, as for patients with already advanced hard tissue loss a maximal preservation of the remaining tooth substance is desired[18]. CAD/CAM-based polymer materials are easier and cheaper to manufacture and due to their standardized production show reproducible material properties compared to direct polymer. However, they show inferior mechanical properties, as material hardness and wear resistance, compared to ceramics[19]. Therefore, the question is whether CAD/CAM polymers are worth considering as an appropriate material for long-term prosthetic rehabilitation of severe worn dentition.

Nevertheless, about the wear behavior and wear rates of these dental materials used for treatments of severe worn dentition over a longer period of time, too little is known. In consideration of this limited data availability on in vivo wear performance in cases of complete rehabilitation with increased VDO, the evaluation of wear rates for CAD/CAM polymers and pressed lithium disilicate ceramics, over 3 years, was the aim of the present investigation. A further aim of the study was to assess the differences between wear performance of premolar and molar restorations. The first hypothesis states that restorations made of lithium disilicate ceramic would show lower wear rates than CAD/CAM polymers. Secondly, the wear rates of restorations would be greater in molars than premolars.

Materials and methods

Study cohort. This non-blinded, non-randomized study was performed according to the Declaration of Helsinki after approval by the Ethics Committee of Ludwig Maximilian University of Munich (012–12; 541–12). All subjects were informed about the background of the study, the risks associated with it and gave written informed consent before participation in the study.

12 patients (7 males, 5 females, age: mean 36.3 ± 9.4 years) with changes in the vertical dimension of occlusion (VDO) due to severe tooth wear were recruited. Inclusion criteria for this study were as follows: exposed dentin; decreased vertical dimension of occlusion due to loss of dental hard tissue; indication for at least 12 restorations in upper and lower jaws; age between 18 and 70 years; proper oral hygiene; healthy/ treated periodontal tissues (tooth mobility no more than grade I). Exclusion criteria were pregnancy or lactation. Craniomandibular disorders were not explicitly excluded. However, patients underwent a splint therapy previous to the definitive restorative treatment to functionally evaluate the new vertical dimension and bite position.

All patients underwent full-mouth rehabilitation restoring the vertical dimension of occlusion with antagonistic full coverage restorations from the same material. The concept of canine protected centric occlusion could be implemented in every patient.

The patients were divided into two equal groups: group LS2 included 6 patients, who received a full mouth restoration of the upper and lower jaw with adhesively bonded monolithic ceramic restorations [per patient: n = 28, n (premolar) = 8, n (molar) = 8], group COMP consisted of 6 patients, who received a full mouth restoration of the upper and lower jaw with adhesively bonded CAD/CAM restorations [per patient: n = 28, n (premolar) = 8, n (molar) = 8], made of experimental composite blocks, polymerized under standardized industrial conditions.

The wear rates were evaluated using posterior restorations in the maxilla and mandible (LS2: n = 96; COMP: n = 96).

Treatment and laboratory procedures. In this clinical trial all procedures were performed according to current principles of minimally invasive dentistry. If needed, damaged teeth were restored using direct low-viscosity (Tetric EvoFlow, Ivoclar Vivadent, Schaan, Liechtenstein) and/or high-viscosity composites (Tetric EvoCeram, Ivoclar Vivadent, Schaan, Liechtenstein) and a multi-step adhesive system (Syntac, Ivoclar Vivadent, Schaan, Liechtenstein). Subsequently, tooth preparations were performed according to the material guidelines to receive either LS2 or COMP restorations. The required minimum thickness for restorations made of the lithium disilicate ceramic had been defined as 1.0 mm, the experimental CAD/CAM-composite blanks allowed minimum layer of 0.3 mm in circular area and 1.0 mm in occlusal load bearing zone. Polyether material (Permadyne/Impregum Penta, 3 M, Seefeld, Germany) was used for impressions with individualized rim-lock trays.

Dental restorations were manufactured in a dental laboratory by an experienced dental technician. Press technique was chosen for fabrication of LS2 restorations, instead of CAD/CAM technique, due to similar materials properties and better esthetics. LS2 restorations were fabricated and glazed afterwards. Applied lithium disilicate ceramic (IPS e.max Press, Ivoclar Vivadent, Schaan, Liechtenstein) exhibited following mechanical properties (according to manufacturer): flexural strength = 400 ± 40 MPa, modulus of elasticity = 95 ± 5GPa, Vickers hardness = 5,900 ± 100 MPa. COMP restorations were fabricated using the CEREC system (CEREC InLab V3.86, Dentsply Sirona, Bensheim, Germany). CEREC settings were defined as follows: proximal contact strength = 75 µm, occlusal contacts strength = 25 µm, adhesive gap = 20 µm. Manufacturer reported about composition of the experimental CAD/CAM composite material (Ivoclar Vivadent, Schaan, Liechtenstein), which consisted of 22% V_f matrix (dimethacrylate) and 78% V_f filler (barium glass fillers, 15%; ytterbium trifluoride, 9%; mixed oxides, 44%; silicon oxides, 3; copolymers, 7%). The material showed mechanical properties as follows: flexural strength = 167 MPa, modulus of elasticity = 11.4GPa, Vickers hardness = 915 MPa and water absorption after 7 days = 28 µg/mm^3.

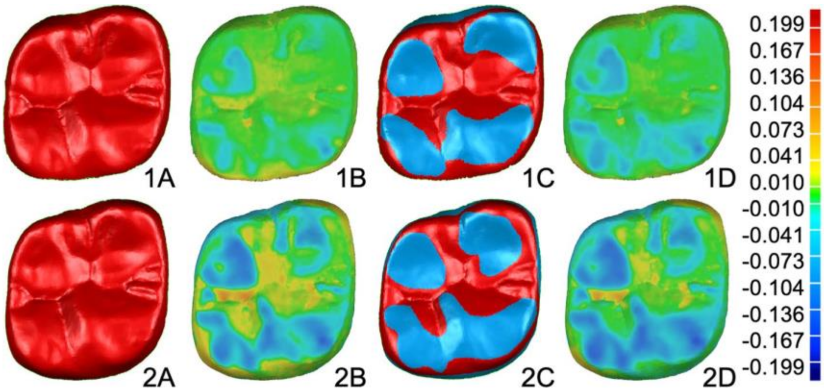

Figure 1. Color-coded superimposition procedure and the wear progression of first molar CAD/CAM composite restoration (Patient 6) in the first (1) and third (2) year. (**1A**/**2A**) pre-alignment over the full occlusal area; (**1B**/**2B**) differences between baseline and recall dataset after the pre-alignment; (**1C**/**2C**) iterative selection of areas, which were not exposed to wear, for further alignment of the data; (**1D**/**2D**) visualization of wear areas after the final data alignment.

If occlusal adjustments were necessary, most could be carried out during the try-in phase, that re-firing or polishing could be done under laboratory conditions. Before luting of the restorations, the following pretreatment methods were applied:

- For the LS2 group: Etching of inner surfaces with 5% hydrofluoric acid (IPS Ceramic Etching Gel, Ivoclar Vivadent, Schann, Liechtenstein) for 20 s, rinsed with air/water spray for 60 s, cleaned in ultrasonic bath for 5 min. 60 s, air dried and silanizated for 60 s using Monobond Plus (Ivoclar Vivadent, Schaan, Liechtenstein).
- For the COMP group: tribochemical silica-coating of the inner surfaces using a modified Rocatec procedure (Rocatec soft 30 µm; 1 bar; nozzle distance: 2 cm; 5 s blast time per unit) and conditioning the restorations with Monobond Plus (Ivoclar Vivadent, Schann, Liechtenstein)

Tooth conditioning for adhesive bonding was identical for both groups, using Total Etch & Rinse technique and Syntac (Ivoclar Vivadent, Schaan, Liechtenstein). Variolink II (Ivoclar Vivadent, Schaan, Liechtenstein) was used as luting composite. Luting curing was performed following manufacturer's instructions. Variolink II was polymerized for at least 3 times 20 s (vestibular—occlusal, lingual) starting with the proximal margins with a LED curing light [Bluephase Style, Ivoclar Vivadent, Schaan, Liechtenstein (light intensity 1.100mW/cm^2 ± 10%; wavelength range 385–515 nm)], which was calibrated frequently by a radiometer (Bluephase Meter II, Ivoclar Vivadent, Schaan, Liechtenstein). If occlusal corrections were necessary after placement, restorations were carried out with corresponding diamond burs and polishers (ball shaped diamond finishing bur: 8801 314 018; polishing sets: Composite: Set 4312A, Ceramic: 4313B; Komet Dental, Lemgo, Germany). No occlusal splint was applied after the final treatment.

Data acquisition of baseline and follow-up records. To acquire baseline and follow-up data, dental impressions with a polyether impressions material (Impregum Penta; 3 M, Seefeld, Germany) were taken after placement of restorations (baseline) and annual recall appointments (follow-up). Mean monitoring time in both groups was 350 ± 86 days (1st year), 755 ± 92 days (2nd year), 1102 ± 97 days (3rd year). All impressions were casted between 24 and 48 h with type 4 dental stone (Plurastone; Pluradent, Offenbach, Germany). Resulting plaster casts were digitalized with a laboratory scanner (D810; 3Shape, Copenhagen, Denmark) and exported to standard tessellation language (STL) file format.

Processing of datasets. Geomagic Qualify software (2012.1.2, Geomagic Inc., Morrisville, NC, USA) was used to compare resulting baseline and follow-up STL datasets. To receive independent data of each specimen every posterior restoration was segmented and stored as individual dataset, resulting in 192 (LS2 n = 96; COMP n = 96) baseline and 570 (LS2 n = 288; COMP n = 282) follow-up records. Three molar restorations in COMP group (patient 5) were excluded from further analysis due to mechanical failure of restorations after two years. Every recall dataset was superimposed with the equivalent baseline record. At the beginning the entire surface matching was performed using best-fit method, resulting superimposition was visually estimated and next best-fit matching was executed only over surface areas with no signs of wear (Fig. 1). This iterative procedure was conducted until superimposition error remained stable. The overlay error of each specimen was listed separately. A superimposition error of more than 15 µm was determined as exclusion criteria for further data processing, as the influence of impressioning, model fabrication, scanning, and superimposition was considered too high for reliable data analysis. Due to this, the amount of data in LS2 group was reduced from 288 to 279, in COMP

Material	Time [year]	n	Premolar	n	Molar
LS2	1	46	6.8 ± 1.8	45	8.3 ± 1.8
	2	48	7.5 ± 1.9	47	9.1 ± 1.7
	3	47	8.2 ± 2.1	46	10.9 ± 2.1
COMP	1	47	9.9 ± 2.1	48	11.7 ± 2.5
	2	47	10.8 ± 2.1	39	12.0 ± 2.2
	3	45	11.9 ± 2.3	32	13.0 ± 1.7

Table 1. Mean values ± standard deviation (µm) of superimposition error between baseline und follow-up datasets.

group from 282 to 258. It must be noted that out of 33 data sets, which dropped out, 8 were premolar and 25 molar restorations (Table 1).

Subsequently to the overlay procedure, remained datasets underwent wear calculation perpendicular to the surface of the restoration, results were exported and saved separately for each specimen as a result record (.csv). Calculation of mean wear rates per month was chosen for further analysis.

Statistical analyses. The obtained data was transferred into a statistical program SPSS (version 25, IBM, Armonk, NY, USA) for further processing. The figures were generated using GraphPad Prism (version 8.4.2., GraphPad Software Inc., La Jolla, CA, USA). To guarantee best possible comparability of our results despite varying recall appointments and performed data filtering due to superimposition error, wear values were computed by dividing the results by the number of days in situ. Subsequently, the mean wear rate per month was calculated for both groups. Normality of data distribution of all groups was analyzed using Kolmogorov–Smirnov test. The Kruskal–Wallis test was used to analyze data interaction between variables, following the Wilcoxon signed-rank test or pairwise comparison with Mann–Whitney U test, which were applied to evaluate statistically significant differences between groups. In cases of multiple comparisons Bonferroni correction was used. The significance level was set at 0.05. The mean and median vertical loss was calculated, and outliers were eliminated by SPSS software. This elimination implicated decrease of follow-up data sets in both groups, in LS2 group from 279 to 253, in COMP group from 257 to 241.

Results

Measurements of superimposition error. Mean superimposition error was calculated according to material, time and tooth group. Differences between mean values were found regarding every characteristic. The COMP group showed enlarged errors trough matching process compared to the LS2 group. Premolars were easier to superimpose than molars in both groups. The differences regarding follow-up time were found. Higher superimposition errors were found with advancing age of restauration in situ (Table 1; Fig. 2).

Measurements of wear rates. 75% of data groups were not normally distributed. Therefore, non-parametric tests were applied to evaluate differences between the test groups. Calculated wear rates are shown in Tables 2 and 3 . Boxplots are given in Fig. 3. Wear rates decreased over time, therefore significant differences were found between different time intervals (LS2 PM 1–2 years $p < 0.0001$, 1–3 years $p < 0.0001$, 2–3 years $p = 0.033$; LS2 M 1–2 years $p < 0.0001$, 1–3 years $p < 0.0001$, 2–3 years $p = 0.013$; COMP PM 1–2 years $p < 0.0001$, 1–3 years $p < 0.001$, COMP M 1–2 years $p = 0.002$, 1–3 years $p < 0.0001$; 2–3 years $= 0.037$). No differences in PM wear rates of 2–3 years interval in COMP group were detected ($p = 1.000$). When comparing the premolar and molar wear rates significant differences in LS2 group were identified (1 year $p = 0.041$; 2 years $p = 0.023$; 3 years $p = 0.045$). The premolar and molar wear rates in COMP groups showed significant differences during one and two years of observation (1 years $p = 0.0001$; 2 years $p = 0.007$), over 3 years no significant differences were found (3 years $p = 0. 862$). Statistical comparison of wear rates between LS2 and COMP showed significant differences (1 years years: PM $p < 0.0001$, M $p < 0.0001$; 2 years: PM $p < 0.0001$, M < 0.0001; 3 years: PM $p < 0.0001$, M < 0.0001).

Discussion

The aim of this clinical study was to compare different materials' wear rates in patients after full mouth prosthetic rehabilitation with full occlusal coverage restorations due to severe tooth wear. Additional target was to compare differences between premolar and molar wear rates regarding the materials used. The first hypothesis was confirmed, as the wear rates of CAD/CAM composite restorations were significant higher compared to lithium disilicate. The second hypothesis must be partly rejected. The CAD/CAM composite group showed increased wear in the molar region in first two years. At 3 years, no significant differences were found, however this might be due to the fact that fewer restorations could be included after 3 years. Restorations made of lithium disilicate ceramic showed significant differences between premolar and molar wear rates with advancing age of restorations in situ. Much higher wear rates in both groups over first year confirm specific running-in wear in initial phase after placement of restorations[20].

Wear is considered as a dynamic and multilayered process, which emerges by surfaces interaction with exogenous materials and/or under teeth contact, what results in continuous loss of the tooth structure or restorative material[21]. Nevertheless, different restorative materials show different wear mechanisms. While ceramic wear

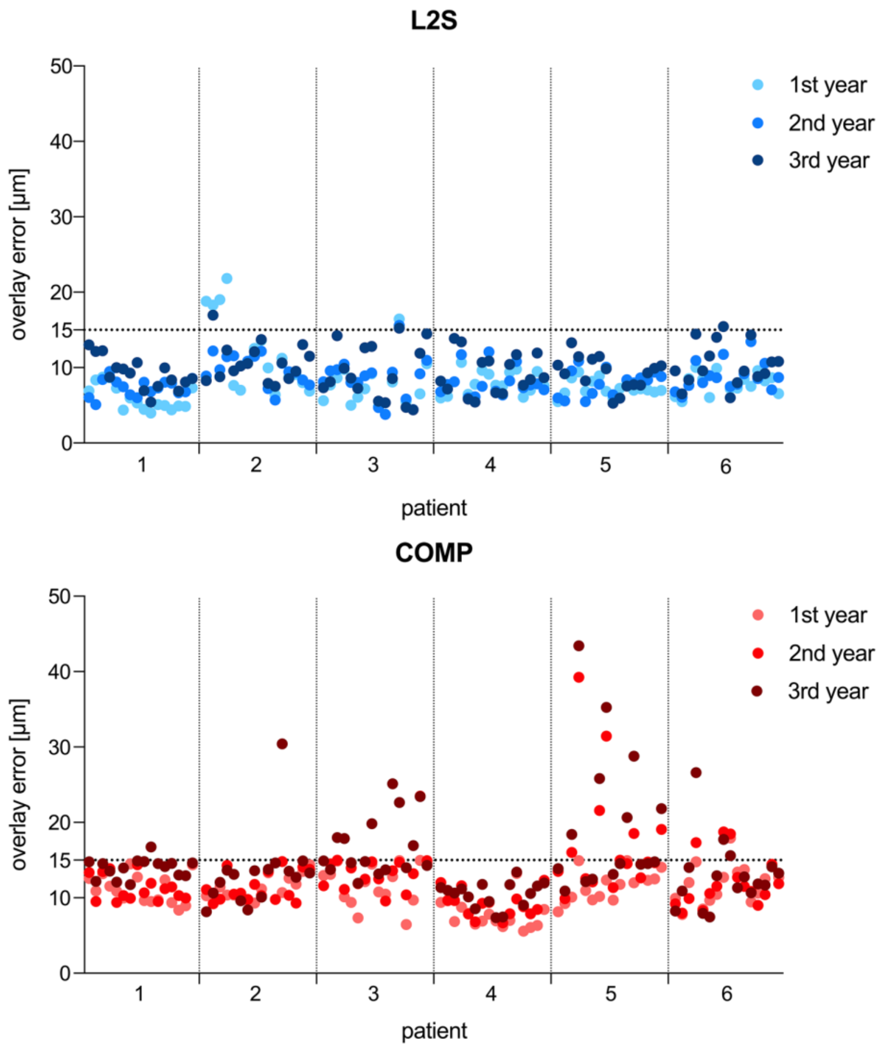

Figure 2. Visualized superimposition error (µm) of each specimen and individual patient. Superimposition error under 15 µm was defined as the requirement for further data analysis.

occurs by progressing microfracture process, composite restorations abrade by adhesion wear, which follows plastic deformation of the material[22,23]. Multiple in vitro investigations on lithium disilicate ceramics, as well as on CAD/CAM composites, provided clinical acceptable mechanical properties with tolerable wear behavior on opposing enamel[10,12,24]. However, the used methods for in vitro wear quantification differ from methods used in clinical trials, which complicates comparability[25,26]. Therefore, it is of great necessity to perform in vivo studies on materials wear performance, especially in cases of complete occlusal treatment with bite elevation. The primary goals of these complex therapies are to improve aesthetics, prevent further hard tissue loss and reestablish functional occlusion. However, the main focus in treatment with raise in VDO should always remain in creating harmony in the masticatory system through stable occlusion, which is important for long-term results. In line with this, material wear behavior in these cases plays a major role, as any disharmony in wear may result in adaptive responses like increased functional activity, which results in excessive wear of restorations. Therefore, there is a need to study occlusal wear in cases of full mouth rehabilitations. On the contrary, all clinical trials face numerous challenges, as patient recruitment and retention, funding, and possible clinical complications.

To date, different opinions on VDO alteration and possible consequences exist in the literature[27]. Several authors described possible complications during implementation of bite elevation, like increase of bite forces, hyperactivity of masticatory muscles, temporomandibular disorders and phonetic limitations[28–31]. At the same time, numerous case reports of successful treatment of severe worn dentition with VDO alteration are published in literature[32,33]. This comes to the point, that the increased restorations wear was not considered or defined as a potential complication, which unfortunately is difficult to assess through clinical examination.

	Patient	Sex	Age [year]	Time [year]	n	Premolar	n	Molar
LS2	1	Female	37	1	7	6.7 ± 2.1	7	6.7 ± 1.3
				2	8	5.3 ± 1.7	7	3.8 ± 0.5
				3	8	3.3 ± 1.3	8	2.8 ± 0.9
	2	Female	40	1	4	10.4 ± 5.1	5	9.3 ± 1.0
				2	7	5.2 ± 1.4	8	4.7 ± 1.2
				3	7	4.2 ± 1.6	6	3.9 ± 1.0
	3	Male	32	1	7	5.4 ± 0.7	7	8.2 ± 2.7
				2	7	3.3 ± 1.4	7	5.3 ± 1.3
				3	8	2.2 ± 0.9	6	3.2 ± 0.5
	4	Male	40	1	8	8.9 ± 2.9	6	8.6 ± 5.5
				2	6	3.2 ± 1.0	8	3.3 ± 0.9
				3	7	2.2 ± 0.5	7	2.8 ± 0.7
	5	Male	20	1	7	5.1 ± 1.1	7	6.4 ± 2.3
				2	8	2.6 ± 0.7	8	4.7 ± 1.4
				3	6	2.0 ± 0.7	8	2.8 ± 0.8
	6	Male	31	1	6	9.6 ± 5.0	7	7.9 ± 1.7
				2	8	3.1 ± 0.8	8	4.7 ± 2.3
				3	7	2.7 ± 1.2	7	5.1 ± 3.3
COMP	1	Female	44	1	7	11.7 ± 3.3	8	12.4 ± 5.5
				2	8	6.8 ± 2.4	8	5.5 ± 1.5
				3	7	6.4 ± 2.3	8	5.0 ± 1.3
	2	Female	38	1	7	7.9 ± 1.8	7	12.8 ± 3.3
				2	8	4.6 ± 1.4	7	8.4 ± 2.1
				3	7	3.6 ± 0.8	6	5.7 ± 1.8
	3	Female	38	1	7	13.8 ± 8.9	8	48.2 ± 21.6
				2	7	11.0 ± 6.8	7	40.4 ± 16.6
				3	6	11.8 ± 4.2	2	31.6 ± 7.2
	4	Male	51	1	6	10.9 ± 1.0	8	20.7 ± 9.8
				2	8	6.2 ± 1.2	8	13.0 ± 5.5
				3	7	5.2 ± 0.8	8	6.7 ± 2.3
	5	Male	47	1	7	28.0 ± 7.0	8	47.8 ± 22.8
				2	8	18.1 ± 5.9	2	28.1 ± 3.1
				3	7	17.6 ± 2.3	1	25.9
	6	Male	18	1	7	19.9 ± 8.0	8	26.8 ± 9.0
				2	7	8.9 ± 3.0	4	13.5 ± 1.7
				3	6	7.2 ± 1.0	6	13.0 ± 6.0

Table 2. Mean values ± standard deviation (μm/month) of wear rates of premolar and molar restorations for individual patient, respectively.

Material	Time [year]	n	Premolar		n	Molar	
			Mean (SD)	Median (IQR)		Mean (SD)	Median (IQR)
LS2	1	39	90 (40.8)	73.2 (40.8)	39	93.6 (24)	97.2 (33.6)
	2	44	45.6 (19.2)	39.6 (25.2)	46	52.8 (18)	49.2 (20.4)
	3	43	33.6 (15.6)	31.2 (25.2)	42	40.8 (20.4)	37.2 (16.8)
COMP	1	41	186 (107)	140 (162)	47	342 (242)	253 (276)
	2	46	110 (70.8)	81.6 (78.1)	36	200 (179)	133 (185)
	3	40	103 (63.6)	75.6 (105)	31	114 (96)	76.8 (51.6)

Table 3. Wear rates (μm/year) for premolar and molar restorations.

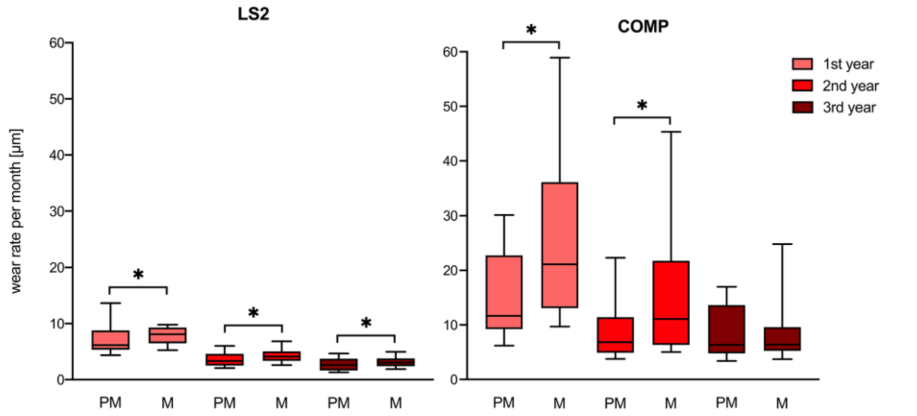

Figure 3. Boxplots illustrate median and IQR values of wear rates (µm/month) for premolar (PM) and molar (M) restorations. Comparison within teeth group (premolar vs molar)—Mann–Whitney U test [*Statistically significant differences].

The biomimetic approach in last decade inspired clinicians and scientists to search and to implement restorative materials with comparable wear behavior as of natural tooth enamel[34, 35]. Lambrechts et al.[36] determined enamel wear as 15 µm/year for premolars and 29 µm/year for molars, which is still held as clinical standard for comparison until this day. Clinical studies on wear of lithium disilicate glazed press core ceramic with opposing enamel reported mean vertical loss between 30 and 40 µm per year[37, 38], which does not differ much from findings of full coverage composite crowns with values around 44 µm per year[39]. However, these results are ascertained in functional harmonious occlusion, where a maximum of three restorations were placed. In this context it may be suggested that the crowns may be protected by the adjacent structures, which resulted in comparable wear rates to enamel. So one could conclude, if composite restorations are protected by adjacent teeth and established anterior/canine guidance, composite might be the alternative of choice if the antagonist is enamel. This implication further complicates possible comparison with obtained data in this study, as results show strong distinction, with wear rates of lithium disilicate ceramic around 90 µm in first year, with significant differences between premolar and molar restorations. In contrast to these results, CAD/CAM polymer shows significant higher wear rates, with a mean vertical loss of 186 µm in premolar region, and 342 µm in molar region during the first year. However, it must be noted, that in this study, full occlusal load had to be absorbed by the tested restorations. Therefore, use of occlusal splint could be recommended for minimizing the wear progression.

It can be assumed, that some patients possibly showed increased functional activity, which not only resulted in higher restorations wear, but also showed significant differences in material wear (Table 2). Varieties of wear rates of the posterior region can also reflect varying masticatory forces from tooth to tooth, accordingly to Ferrario et al.[40]. This could explain increased wear on molar restorations in the CAD/CAM polymer group. The differing mechanical properties compared to lithium disilicate ceramic might lead to the observed wear differences between molars and premolars. However, for interpretation, one must keep in mind, that every imbalance in occlusion, could be adjusted by dentoalveolar compensation through possible extrusion of worn teeth[41, 42].

When interpreting the results of this study, several methodical limitations need to be considered. The limitations of the workflow and process accuracy (impression, casting, scanning) that lead to the underlying data needs to be mentioned and are intensively discussed in a previous article applying the same methodology[43]. Also, the data of experimental CAD/CAM composite should be treated with caution due to its composition and properties. Therefore, it is of importance to mention that the findings of this study might not be transferrable to other CAD/CAM composites that are accessible on the dental market with varying characteristics, which can lead to differing wear rates as assessed in this clinical study. This study had a comparable but small patient cohort, which confined possible investigation of age and gender dependency correlation on wear. Secondly, the evaluation of masticatory bite forces and actual VDO increase would have allowed to provide an insight in potential interdependency with the abrasion of the materials. Thirdly, although, the comparatively high standard deviations of our data are inevitable, it is impossible to build homogenous patient groups regarding individual wear patterns and Table 2 shows these inherent differences of patients. Additionally, ongoing vertical loss of restorations over time does not represent a linear progression with constant rate, but rather a logarithmic one. In this regard, it can be concluded that the measured wear rates per month are not a constant value, as well as wear rates per year. Further, we decided to use press technique, instead of CAD/CAM, for fabrication of ceramic restorations, due to similar mechanical characteristics however slightly better optical properties[44]. Lastly, it's not possible to evaluate total wear of the restorations over the years, due to the loss of follow-up data after filtering procedure, especially of those patients, who showed higher wear rates in the composite group. This loss of the data is due to formation of enlarged occlusal contact areas and possible deformation if restorations over time, which complicates superimposition procedure as only surface areas with no changes and signs of wear can be used.

Complex rehabilitation with alteration of vertical dimension of occlusion (VDO) remains a major challenge for clinicians. Restorations made of lithium disilicate ceramic show more stable and evenly distributed wear rates compared to CAD/CAM polymer in cases with VDO alignment. Nevertheless, there is still a need for longitudinal clinical studies with larger cohorts, to provide better prediction on wear behavior of dental materials and to clarify clinical outcomes of used treatments as well as reference data of natural teeth. Decoding patient's individual abrasion pattern would allow more personalized dentistry by selecting the most suitable material for a complex rehabilitation. The biggest concern is that despite all the recent innovations and considerable advantages of indirect composite resins, their suitability for complex restorative treatments of generalized tooth wear might be questionable in the long run, considering the wear behavior especially in the load bearing zone.

Conclusion

Significant differences in COMP group in first two years between premolar and molar wear rates were assessed. Significant differences of premolar and molar wear rates in LS2 group were found, respectively, in the yearly investigations. Wear of COMP restorations was higher, than LS2, however the restorative procedure was less invasive. Clinicians should balance well between necessary preparation invasiveness and long-term occlusal stability in patients with worn dentition.

Received: 6 April 2021; Accepted: 17 June 2021
Published online: 07 July 2021

References

1. Salas, M. M., Nascimento, G. G., Huysmans, M. C. & Demarco, F. F. Estimated prevalence of erosive tooth wear in permanent teeth of children and adolescents: An epidemiological systematic review and meta-regression analysis. *J. Dent.* **43**, 42–50. https://doi.org/10.1016/j.jdent.2014.10.012 (2015).
2. Van't Spijker, A. *et al.* Prevalence of tooth wear in adults. *Int. J. Prosthodont.* **22**, 35–42 (2009).
3. Shellis, R. P. & Addy, M. The interactions between attrition, abrasion and erosion in tooth wear. *Monogr. Oral. Sci.* **25**, 32–45. https://doi.org/10.1159/000359936 (2014).
4. Lussi, A. in *Dental Erosion From Diagnosis to Therapy*. vol 20 *Interaction between Attrition, Abrasion and Erosion in Tooth wear* (ed Lussi A) Ch. 3, (2006).
5. Li, M. H. & Bernabe, E. Tooth wear and quality of life among adults in the United Kingdom. *J. Dent.* **55**, 48–53. https://doi.org/10.1016/j.jdent.2016.09.013 (2016).
6. Muts, E. J., van Pelt, H., Edelhoff, D., Krejci, I. & Cune, M. Tooth wear: A systematic review of treatment options. *J. Prosthet. Dent.* **112**, 752–759. https://doi.org/10.1016/j.prosdent.2014.01.018 (2014).
7. Loomans, B. *et al.* Severe tooth wear: european consensus statement on management guidelines. *J. Adhes. Dent.* **19**, 111–119. https://doi.org/10.3290/j.jad.a38102 (2017).
8. Mainjot, A. K., Dupont, N. M., Oudkerk, J. C., Dewael, T. Y. & Sadoun, M. J. From Artisanal to CAD-CAM blocks: State of the art of indirect composites. *J. Dent. Res.* **95**, 487–495. https://doi.org/10.1177/0022034516634286 (2016).
9. Alt, V., Hannig, M., Wostmann, B. & Balkenhol, M. Fracture strength of temporary fixed partial dentures: CAD/CAM versus directly fabricated restorations. *Dent. Mater.* **27**, 339–347. https://doi.org/10.1016/j.dental.2010.11.012 (2011).
10. Stawarczyk, B. *et al.* Two-body wear rate of CAD/CAM resin blocks and their enamel antagonists. *J. Prosthet. Dent.* **109**, 325–332. https://doi.org/10.1016/S0022-3913(13)60309-1 (2013).
11. Magne, P., Schlichting, L. H., Maia, H. P. & Baratieri, L. N. In vitro fatigue resistance of CAD/CAM composite resin and ceramic posterior occlusal veneers. *J. Prosthet. Dent.* **104**, 149–157. https://doi.org/10.1016/S0022-3913(10)60111-4 (2010).
12. Stawarczyk, B., Liebermann, A., Eichberger, M. & Guth, J. F. Evaluation of mechanical and optical behavior of current esthetic dental restorative CAD/CAM composites. *J. Mech. Behav. Biomed. Mater.* **55**, 1–11. https://doi.org/10.1016/j.jmbbm.2015.10.004 (2015).
13. Guth, J. F., Edelhoff, D., Goldberg, J. & Magne, P. CAD/CAM polymer vs direct composite resin core buildups for endodontically treated molars without ferrule. *Oper. Dent.* **41**, 53–63. https://doi.org/10.2341/14-256-L (2016).
14. Yilmaz, B. CAD-CAM high-density polymer implant-supported fixed diagnostic prostheses. *J. Prosthet. Dent.* **119**, 688–692. https://doi.org/10.1016/j.prosdent.2017.06.022 (2018).
15. Guth, J. F., Almeida, E. S. J. S., Ramberger, M., Beuer, F. & Edelhoff, D. Treatment concept with CAD/CAM-fabricated high-density polymer temporary restorations. *J. Esthet. Restor. Dent.* **24**, 310–318. https://doi.org/10.1111/j.1708-8240.2011.00497.x (2012).
16. Vailati, F., Vaglio, G. & Belser, U. C. Full-mouth minimally invasive adhesive rehabilitation to treat severe dental erosion: A case report. *J. Adhes. Dent.* **14**, 83–92. https://doi.org/10.3290/j.jad.a21852 (2012).
17. Edelhoff, D. *et al.* Interdisciplinary full-mouth rehabilitation for redefining esthetics, function, and orofacial harmony. *J. Esthet. Restor. Dent.* **31**, 179–189. https://doi.org/10.1111/jerd.12455 (2019).
18. Hamburger, J. T., Opdam, N. J., Bronkhorst, E. M. & Huysmans, M. C. Indirect restorations for severe tooth wear: Fracture risk and layer thickness. *J. Dent.* **42**, 413–418. https://doi.org/10.1016/j.jdent.2013.10.003 (2014).
19. Lawson, N. C., Bansal, R. & Burgess, J. O. Wear, strength, modulus and hardness of CAD/CAM restorative materials. *Dent. Mater.* **32**, e275–e283. https://doi.org/10.1016/j.dental.2016.08.222 (2016).
20. Barkmeier, W. W., Latta, M. A., Erickson, R. L. & Lambrechts, P. Comparison of laboratory and clinical wear rates of resin composites. *Quintessence Int.* **35**, 269–274 (2004).
21. Mair, L. H., Stolarski, T. A., Vowles, R. W. & Lloyd, C. H. Wear: Mechanisms, manifestations and measurement: Report of a workshop. *J. Dent.* **24**, 141–148 (1996).
22. Wang, Y. & Hsu, S. M. Wear and wear transition mechanisms of ceramics. *Wear* **195**, 112–122. https://doi.org/10.1016/0043-1648(95)06800-7 (1996).
23. Ilie, N. *et al.* Academy of dental materials guidance-resin composites: Part I-mechanical properties. *Dent. Mater.* **33**, 880–894. https://doi.org/10.1016/j.dental.2017.04.013 (2017).
24. Zandparsa, R., El Huni, R. M., Hirayama, H. & Johnson, M. I. Effect of different dental ceramic systems on the wear of human enamel: An in vitro study. *J. Prosthet. Dent.* **115**, 230–237. https://doi.org/10.1016/j.prosdent.2015.09.005 (2016).
25. Heintze, S. D. How to qualify and validate wear simulation devices and methods. *Dent. Mater.* **22**, 712–734. https://doi.org/10.1016/j.dental.2006.02.002 (2006).
26. Heintze, S. D., Faouzi, M., Rousson, V. & Ozcan, M. Correlation of wear in vivo and six laboratory wear methods. *Dent. Mater.* **28**, 961–973. https://doi.org/10.1016/j.dental.2012.04.006 (2012).
27. Abduo, J. Safety of increasing vertical dimension of occlusion: A systematic review. *Quintessence Int.* **43**, 369–380 (2012).
28. Kois, J. C. & Phillips, K. M. Occlusal vertical dimension: Alteration concerns. *Compend.Contin. Educ. Dent.* **18**, 1169–1174 (1997) (**Quiz 1180**).
29. Burnett, C. A. & Clifford, T. J. A preliminary investigation into the effect of increased occlusal vertical dimension on mandibular movement during speech. *J. Dent.* **20**, 221–224 (1992).

30. Ormianer, Z. & Gross, M. A 2-year follow-up of mandibular posture following an increase in occlusal vertical dimension beyond the clinical rest position with fixed restorations. *J. Oral. Rehabil.* **25**, 877–883 (1998).
31. Christensen, J. Effect of occlusion-raising procedures on the chewing system. *Dent. Pract. Dent. Rec.* **20**, 233–238 (1970).
32. Edelhoff, D. *et al.* CAD/CAM-generated high-density polymer restorations for the pretreatment of complex cases: A case report. *Quintessence Int.* **43**, 457–467 (2012).
33. Edelhoff, D. & Brix, O. All-ceramic restorations in different indications: A case series. *J. Am. Dent. Assoc.* **142**(Suppl 2), 14S-19S. https://doi.org/10.14219/jada.archive.2011.0338 (2011).
34. Lambrechts, P., Vanherle, G., Vuylsteke, M. & Davidson, C. L. Quantitative evaluation of the wear resistance of posterior dental restorations: A new three-dimensional measuring technique. *J. Dent.* **12**, 252–267 (1984).
35. Hmaidouch, R. & Weigl, P. Tooth wear against ceramic crowns in posterior region: A systematic literature review. *Int. J. Oral. Sci.* **5**, 183–190. https://doi.org/10.1038/ijos.2013.73 (2013).
36. Lambrechts, P., Braem, M., Vuylsteke-Wauters, M. & Vanherle, G. Quantitative in vivo wear of human enamel. *J. Dent. Res.* **68**, 1752–1754. https://doi.org/10.1177/00220345890680120601 (1989).
37. Suputtamongkol, K., Anusavice, K. J., Suchatlampong, C., Sithiamnuai, P. & Tulapornchai, C. Clinical performance and wear characteristics of veneered lithia-disilicate-based ceramic crowns. *Dent. Mater.* **24**, 667–673. https://doi.org/10.1016/j.dental.2007.06.033 (2008).
38. Esquivel-Upshaw, J. F. *et al.* Three years in vivo wear: core-ceramic, veneers, and enamel antagonists. *Dent. Mater.* **28**, 615–621. https://doi.org/10.1016/j.dental.2012.02.001 (2012).
39. Ohlmann, B. *et al.* Clinical wear of posterior metal-free polymer crowns: One-year results from a randomized clinical trial. *J. Dent.* **35**, 246–252. https://doi.org/10.1016/j.jdent.2006.09.001 (2007).
40. Ferrario, V. F., Sforza, C., Serrao, G., Dellavia, C. & Tartaglia, G. M. Single tooth bite forces in healthy young adults. *J. Oral Rehabil.* **31**, 18–22 (2004).
41. Berry, D. C. & Poole, D. F. Attrition: Possible mechanisms of compensation. *J. Oral. Rehabil.* **3**, 201–206 (1976).
42. Murphy, T. Compensatory mechanisms in facial height adjustment to functional tooth attrition. *Aust. Dent. J.* **4**, 312–323. https://doi.org/10.1111/j.1834-7819.1959.tb03727.x (1959).
43. Guth, J. F. *et al.* In vivo wear of CAD-CAM composite versus lithium disilicate full coverage first-molar restorations: A pilot study over 2 years. *Clin. Oral Investig.* **24**, 4301–4311. https://doi.org/10.1007/s00784-020-03294-5 (2020).
44. Vasiliu, R. D., Porojan, S. D., Birdeanu, M. I. & Porojan, L. Effect of thermocycling, surface treatments and microstructure on the optical properties and roughness of CAD-CAM and heat-pressed glass ceramics. *Materials* https://doi.org/10.3390/ma13020381 (2020).

Acknowledgements
This work was supported by a research-grant of Ivoclar Vivadent (Schaan, Liechtenstein).

Author contributions
G.B.: data post-processing, statistical analysis, drafting of manuscript K.E.: concept of study design, methodology, statistical analysis, critical revision of manuscript J.S.: technical fabrication, critical revision of manuscript C.K.: concept of study design, critical revision of manuscript D.E.: concept of study design, data acquisition, treatments, critical revision of manuscript J-F.G.: concept of study design, treatments, methodology, data acquisition, drafting of manuscript.

Funding
Open Access funding enabled and organized by Projekt DEAL.

Competing interests
The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to J.-F.G.

3 Diskussion

3.1 In-vivo-Verschleißmessung von ersten Molarrestaurationen aus CAD/CAM-Komposit und Lithium-Disilikat-Keramik: eine Pilotstudie über 2 Jahre

In dieser klinischen Studie wurden die Verschleißraten von antagonistischen monolithischen ersten Molarenrestaurationen aus zwei unterschiedlichen Materialien verglichen: einem experimentellen CAD/CAM-Komposit und einer Lithium-Disilikat-Keramik. Die Ergebnisse zeigten, dass es einen signifikanten Unterschied der Verschleißraten dieser beiden Materialien bei Patienten gab, die eine komplexe Gesamtrehabilitation mit Bisshebung erhielten. Die Restaurationen aus dem experimentellen CAD/CAM-Komposit zeigten höhere Verschleißraten als die aus Lithium-Disilikat-Keramik.

Die Verschleißraten waren im ersten Jahr im Vergleich zu den zwei Jahreswerten in beiden Gruppen höher. Dabei ist zu berücksichtigen, dass diese Verschleißraten als mögliche Folge der Bildung größerer Verschleißfacetten von Jahr zu Jahr abnehmen. Mit zunehmender Verschleißfläche verteilt sich die einwirkende Kraft auf eine größere Fläche, dadurch wird die Kraft pro Flächeneinheit reduziert, was der Grund für die hohen Verschleißraten im ersten Jahr sein könnte. Auch die Möglichkeit eines kontaktlosen Verschleißes von Kompositen, der durch das Versagen von Kompositkomponenten verursacht wird, kann nicht ausgeschlossen werden [31]. Dies könnte die Genauigkeit der Überlagerung beeinflussen und sogar zu einem höheren Gesamtverschleiß in der CAD/CAM-Kompositgruppe führen.

Die quantitative Verschleißmessungen in dieser Studie wurden mit einer iterativen Methode ausgewertet. Die gesamte Kaufläche jedes ersten Molaren wurde vermessen, unter Verwendung von Gipsmodellen, die nach konventioneller Präzisionsabformung erstellt wurden. Um mögliche Fehler in diesem Arbeitsablauf zu minimieren, wurde jeder Molar separat überlagert und analysiert, um eine gewisse Unabhängigkeit von Nachbarstrukturen zu erlangen. Dadurch konnte der Einfluss von Verzerrungen der Abformungen und der Gipsmodelle, die die Ergebnisse beeinflussen könnten, minimiert werden [32]. Außerdem wurde der Überlagerungsprozess so lange durchgeführt, bis der Überlagerungsfehler durch weitere Überlagerung nicht mehr verändert wurde. Auf diese Weise konnte der Best-Fit von Baseline- und Follow-up-Daten über die Bereiche erreicht werden, die keiner antagonistischen Abnutzung ausgesetzt waren.

Als Standardabweichungsfehler zwischen den Datensätzen für die quantitative Messung des vertikalen Höhenverlustes antagonistischer Restaurationen wurde ein Überlagerungsfehler von 15 µm festgelegt. In in-vitro-Studien wurden als Standardabweichung der Überlagerung zwischen 5 und 10 µm beschrieben [33]. Demgegenüber scheint die Erfassung unter klinischen Bedingungen fehleranfälliger zu sein und größere Schwankungen aufzuweisen, daher mussten höhere Standardabweichungen bis 15 µm in Kauf genommen werden. Die Datensätze mit einem Überlagerungsfehler von über 15 µm wurden ausgeschlossen, um zuverlässige Daten zu erhalten. DeLong et.al. berichteten, dass die Schätzung der Überlagerung für Proben klinischer Studien in der Regel zwischen 10 und 20 µm pro Punkt schwankt. Sie hielten eine Überlagerung von weniger als 10 µm für einen exzellenten Fit, während ein Wert von mehr als 50 µm einen schlechten Fit anzeigte [34]. Dies steht im Einklang mit anderen klinischen Untersuchungen zur Verschleißmessungen, bei denen Workflow-Ungenauigkeiten im Bereich von 15–20 µm als akzeptabel angesehen wurden [29, 35-38]. Schmid-Schwapet et al. [39] setzten die Grenze für Workflow-Ungenauigkeiten für Molaren sogar auf 30 µm, da diese schwieriger zu überlagern sind. Dies wurde jedoch für den Verschleiß von Methacrylat-Kunststoffzähnen angegeben. In der vorgestellten Studie zeigten Kompositrestaurationen höhere Überlagerungsfehler, die durch nicht-antagonistischen Verschleiß verursacht werden können, der bei Kompositen stärker ausgeprägt ist als bei Lithium-Disilikat-Keramiken [40].

Der Verschleiß kann anhand der Tiefe, der Fläche und des Volumens quantifiziert werden. Der Zusammenhang und die Korrelation dieser Parameter wurde bereits von DeLong et al. beschrieben [30]. Die Methodik von Verschleißmessungen unter klinischen Bedingungen wird derzeit ebenfalls intensiv diskutiert [19, 41-44]. In dieser klinischen Studie wurde der vertikale Höhenverlust senkrecht zur

Arbeitsfläche gemessen. Die Berechnung von Volumenänderungen unter klinischen Bedingungen scheint sehr fehleranfällig zu sein. Der kritischste Punkt ist die Definition des Bereichs für die Volumenberechnung zwischen exponiertem und nicht exponiertem Verschleißbereich. Dagegen war die Reproduzierbarkeit und Vergleichbarkeit dieser Messungen durch die hohe Fehlerquote bei der Beurteilung dünner Ränder und unterschiedlicher Oberflächen eingeschränkt, was diese Daten unbrauchbar machte. Darüber hinaus haben frühere Studien bereits den Vorteil der Messung des vertikalen Höhenverlustes gegenüber der volumetrischen Verschleißmessung aufgezeigt. Der Hauptvorteil ist die Möglichkeit einer direkten Quantifizierung des Verschleißes und der Eliminierung des Einflusses der Oberflächengröße [39, 41]. Eine Kombination aus vertikalem Höhenverlust und Oberflächenmessung war wünschenswert, Oberflächenmessungen unterliegen jedoch denselben Schwierigkeiten wie volumetrische Messungen.

Nach dem Biomimetischen Konzept sollte das Verschleißverhalten von Zahnrestaurationen idealerweise mit dem von physiologischem Zahnschmelz vergleichbar sein. Klinische Daten zum Verschleißverhalten natürlicher Zähne sind jedoch rar und weisen eine hohe Varianz auf. In den wenigen vorliegenden Studien wurden Abnutzungsraten für natürlichen Schmelz von ca. 10–40 µm/Jahr beschrieben [45-47]. Die Ergebnisse klinischer Studien zeigten jedoch erhebliche Schwankungen [19]. Die Verschleißraten unterschieden sich signifikant zwischen verschiedenen Forschungsgruppen; Etman et al. [48] gaben für Lithium-Disilikat-Glaskeramik-Seitenzahnkronen einen Verschleiß von 148 µm nach dem ersten Jahr an, während Kramer et al. [49] diesen für Keramikinlays aus Lithium-Disilikat mit 78 µm nach 4 Jahren bezifferten. Nur sehr wenige Studien untersuchten den Verschleiß von Seitenzahn-Kompositkronen in vivo und gaben einen Verschleiß von ca. 40 µm/Jahr an, was deutlich unter den Werten der vorliegenden Studie liegt [35, 50]. Obwohl es viele klinische Daten zum Verschleißverhalten direkter Kompositrestaurationen gibt, zeigt die Literatur eine erhebliche Streuung der Ergebnisse von 50 bis 200 µm pro Jahr [19, 51, 52]. Dabei ist zu berücksichtigen, dass in diesen Studien die Verschleißraten mit dem gegenüberliegenden Schmelz als Antagonist verglichen wurden. Darüber hinaus sind direkte Kompositrestaurationen der Klasse I/II durch Schmelz geschützt, was die Aussagen zur biomechanischen Belastung und deren Verschleiß einschränkt. Darüber hinaus scheint nicht nur die antagonistische Situation, sondern auch die klinische Umgebung, in der die Restaurationen platziert werden, eine Rolle für die Abnutzungsraten zu spielen, und es ist klar, dass die Abnutzungsraten für einzelne Restaurationen gegenüber unterschiedlichen Antagonisten ebenfalls unterschiedlich ausfallen kann. In der vorliegenden Studie erhielten die Patienten eine vollständige Mundrehabilitation entweder mit CAD/CAM-Komposit oder Lithium-Disilikat-Keramik. In dieser klinischen Konstellation werden Restaurationen nicht durch angrenzende Strukturen wie Schmelz oder Kronen aus anderen Materialien mit geringerer Abnutzung geschützt. Das bedeutet, dass die Restaurationen in dieser Studie den vollen Bisskräften ausgesetzt sind und die volle okklusale Belastung entweder durch gegenüberliegendes Komposit oder Keramik tragen müssen. Zu den Abnutzungsraten von Seitenzahnrestaurationen in vivo bei einer kompletten Rehabilitation liegen noch keine belastbaren Daten vor. Die vorliegende Arbeit liefert damit erste Ergebnisse zu Verschleißmessungen an den ersten Molaren. Weitere longitudinale Studien wären sicher sinnvoll, die die Unterschiede zwischen Prämolaren und Molaren untersuchen, da einige Studien bereits vermuten ließen, dass der Verschleiß bei Molaren ausgeprägter ist als bei Prämolaren [53, 54].

Die Analyse des Verschleißverhaltens von Restaurationsmaterialien und Zahnhartsubstanz in klinischen Fällen stellt Wissenschaftler und Kliniker vor zwei Hauptprobleme. Zum einen ist es von übergeordneter Relevanz exakte und reproduzierbare Abformungen zu nehmen, zum anderen gilt es eine valide und reproduzierbare Methode zur Verschleißanalyse zu finden. Verzerrungen oder Abformungenauigkeiten sind zwei weitere potenzielle Faktoren, die die resultierende Modellqualität beeinträchtigen können [32, 55]. Außerdem ist der Scanvorgang selbst anfällig für weitere Ungenauigkeiten, die die Messergebnisse verzerren können [56]. Um Fehler bei der Modellherstellung zu vermeiden, besteht die Möglichkeit, Abformungen direkt einzuscannen, jedoch scheinen unter sich gehende Stellen und steile Zahngeometrien diesen Ansatz zu kompromittieren [57]. Insgesamt scheint die Digitalisierung einer konventionellen Abformung im direkten Vergleich mit dem gegossenen Gipsmodell bis dato hinsichtlich der Genauigkeit keinen signifikanten Vorteil zu bieten [58]. In-vivo-Studien haben gezeigt, dass konventionelle Präzisionsabformmaterialien, wie z.B. in dieser Studie verwendete Polyether, im Vergleich zu aktuellen Intraoralscannersystemen immer noch eine höhere Präzision für die Abformung des gesamten Zahnbogens aufweisen [58, 59]. Um den Einfluss globaler Verzerrungen und Ungenauigkeiten bei der Datenerfassung auszuschließen, basiert die vorliegende Analyse auf Einzelzahnbereichen nach Nachbearbeitung des digitalen Datensatzes. Es besteht jedoch noch sehr viel Potential in der digitalen Zahnheilkunde und die weitere wissenschaftliche Auseinandersetzung mit der Verwendung von Intraoralscannern im Rahmen von Querschnittsstudien sowie Longitudinalstudien ist ein vielversprechendes Gebiet.

Eine Einschränkung der vorliegenden Pilotstudie war die vergleichsweise kleine Kohorte. Etwas entkräften lässt sich diese Einschränkung durch die Tatsache, dass sich bereits bei einer Anzahl von 87 Datensätzen signifikante Unterschiede zwischen den beiden untersuchten Materialien zeigten. Basierend auf den Ergebnissen für beide Arten von Versorgungen und unter der Annahme funktionell aktiver Patienten kann jedoch in Bezug auf die klinische Anwendung empfohlen werden, mindestens über Nacht eine zusätzliche Schutzschiene zu verwenden, um die Verschleißraten von Restaurationen zu minimieren.

Um den Gesamtverlust der vertikalen Dimension abzuschätzen, müssen die Verschleißraten verdoppelt werden, da der Verschleiß in beide Kiefern stattgefunden hat. Hier muss jedoch ein möglicher dentoalveolärer Kompensationsmechanismen in Betracht gezogen werden [60]. Dies würde einen Gesamthöhenverlust von 49,5 µm/Monat im Seitenzahnbereich für Restaurationen aus dem experimentellen CAD/CAM-Komposit und 18,9 µm/Monat für Restaurationen aus Lithium-Disilikat-Keramik im ersten Jahr nach Eingliederung erklären. Basierend auf der Annahme eines logarithmischen Verschleißmodells würden diese Werte in den folgenden Jahren sinken. Diese Hypothese muss jedoch in weiteren longitudinalen Studien bewiesen werden. Unter diesen Gesichtspunkten scheinen Restaurationen aus Lithium-Disilikat-Keramik eine stabilere Prognose bezüglich Verschleißraten zu bieten.

Andererseits zeigen CAD/CAM-Kompositrestaurationen auch einige Vorteile. Die mechanischen Eigenschaften des CAD/CAM-Komposit ermöglichen die Herstellung von Restaurationen mit sehr dünnen Rändern, somit ist eine Behandlung mit nur minimaler, oder ganz ohne Präparation möglich [61]. Darüber hinaus sind CAD/CAM-Kompositrestaurationen mit einem günstigeren Verschleißverhalten am antagonistischen Schmelz assoziiert, was aus biomimetischer Sicht einen Vorteil bietet, da die Zahnstrukturen erhalten bleiben [62].

Zusammenfassend lässt sich feststellen, dass bei Patienten mit generalisiertem Zahnsubstanzverlust partielle Deckungsrestaurationen aus monolithischer Lithium-Disilikat-Keramik zur Rekonstruktion des VDO geringere Abnutzungsraten aufwiesen als vergleichbare Restaurationen aus einer experimentellen CAD/CAM-Komposit. Weitere Studien sind notwendig, um zu zeigen, ob diese Ergebnisse auch für verschiedene klinische Umgebungen und Settings sowie für natürliche Schmelzantagonisten gültig sind.

3.2 In-vivo-Verschleißmessung von Komposit- und Lithium-Disilikat-Keramikrestaurationen nach vollständiger prothetischer Rehabilitation über 3 Jahre

Das Ziel dieser klinischen Studie bestand darin, die Verschleißraten von CAD/CAM-Komposit- und Lithium-Disilikat-Keramikrestaurationen bei Patienten nach einer prothetischen Gesamtrehabilitation mit Anhebung der Vertikaldimension der Okklusion zu evaluieren und zu vergleichen. Ein weiteres Ziel war es, den Unterschied in der Verschleißrate zwischen Prämolaren- und Molarenrestaurationen in Bezug auf die verwendeten Materialien zu bewerten. Die Verschleißraten von CAD/CAM-Kompositrestaurationen waren signifikant höher im Vergleich zu Lithium-Disilikat-Keramikrestaurationen. Darüber hinaus konnten auch die Verschleißratenunterschiede zwischen verschiedenen Zahngruppen festgestellt werden. Die CAD/CAM-Komposit-Gruppe zeigte in den ersten beiden Jahren höhere Verschleißraten im Molarenbereich im Vergleich zu Prämolaren. Allerdings zeigte sich nach drei Jahren kein signifikanter Unterschied mehr. Dies könnte jedoch auch daran liegen, dass nach drei Jahren weniger Restaurationen zur Analyse aufgrund von hohen Überlagerungsfehlern herangezogen werden konnten. Auch bei Restaurationen aus Lithium-Disilikat-Keramik bestanden mit zunehmendem Alter signifikante Unterschiede zwischen Prämolaren- und Molarenverschleißraten. Die deutlich höheren Verschleißraten der beiden Gruppen im ersten Jahr können den initialen Verschleiß im Anfangsstadium nach dem Einsetzen der Restauration bestätigen [63].

Zahnverschleiß ist ein dynamischer und vielschichtiger Prozess, der durch Oberflächeninteraktion mit exogenen Materialien und/oder unter Zahnkontakt entsteht und zu einem kontinuierlichen Verlust der Zahnhartsubstanz oder des Restaurationsmaterials führt [64]. Dennoch zeigen unterschiedliche Restaurationsmaterialien auch unterschiedliche Verschleißmechanismen. Während keramischer Verschleiß durch fortschreitende Mikrofrakturprozesse entsteht, ist es bei Kompositrestaurationen eher ein adhäsiver Verschleiß, der durch plastische Verformung des Materials verursacht wird [65, 66]. Mehrere In-vitro-Studien an Lithium-Disilikat-Keramiken und CAD/CAM-Kompositen haben klinisch akzeptable mechanische Eigenschaften und angemessene Verschleißraten gezeigt [62, 67, 68].

Allerdings unterscheiden sich die Methoden zur In-vitro-Verschleißquantifizierung von denen in klinischen Studien, was die Vergleichbarkeit der auf diesem Wege ermittelten Daten erschwert [69, 70]. Daher ist die Durchführung von In-vivo-Studien zu Verschleißraten von Restaurationsmaterialien, insbesondere bei prothetischer Gesamtrekonstruktion mit Bisshebung, von großer Bedeutung. Die Ziele dieser komplexen Therapien sind die Verbesserung der Ästhetik, die Verhinderung eines weiteren Hartgewebeverlusts und die Wiederherstellung der Kaufunktion. Der wichtige Teil der Behandlung bei anspruchsvollen Fällen mit Veränderung der Vertikaldimension der Okklusion ist der Erhalt bzw. die Sicherstellung der Harmonie im Kausystem durch eine stabile Okklusion, die für langfristige Behandlungserfolg unerlässlich ist. Dementsprechend spielen die Verschleißraten des Materials in diesen Fällen eine wichtige Rolle, da eine Disharmonie des Verschleißes zu Anpassungsprozessen wie einer erhöhten funktionellen Aktivität führen kann, die wiederum zu einem übermäßigen Verschleiß von Restaurationen führt.

In der Literatur existieren bisher unterschiedliche Konzepte zur Änderungen der Vertikaldimension der Okklusion und mit assoziierten Komplikationen [71]. Mehrere Autoren beschrieben mögliche Komplikationen bei der Durchführung der Bisserhöhung, wie Steigerung der Bisskräfte, Hyperaktivität der Kaumuskulatur, Kiefergelenksbeschwerden und phonetische Einschränkungen [72-75]. Gleichzeitig sind in der Literatur zahlreiche Fallberichte zur erfolgreichen Behandlung des Abrasionsgebiss mit Veränderungen in Vertikaldimension publiziert [76, 77]. Allerdings wurden die erhöhten Verschleißraten der Restaurationen nicht als mögliche Komplikation betrachtet, was leider durch die klinische Untersuchung auch schwer zu beurteilen ist.

Der biomimetische Ansatz hat im letzten Jahrzehnt Kliniker und Wissenschaftler dazu bewegt, Restaurationsmaterialien mit zahnschmelzähnlichen Verschleißraten zu identifizieren und einzusetzen [78, 79]. Lambrechts *et.al* [45] berichten 15 µm/Jahr Schmelzverschleiß für Prämolaren und 29 µm/Jahr für Molaren. Diese Werte gelten bis heute als klinischer Vergleichsstandard. Klinische Studien zum Verschleiß von Lithium-Disilikat-Keramik mit antagonistischem Schmelz berichteten über einen mittleren vertikalen Verlust zwischen 30 und 40 µm pro Jahr [80, 81]. Dieser unterscheidet sich mit Werten um 44 µm pro Jahr nicht wesentlich von Kompositkronen [82]. Diese Ergebnisse gelten jedoch lediglich in funktionell harmonischer Okklusion. Kompositrestaurationen könnten eine prothetische Alternative sein, wenn es sich beim Antagonisten um einen natürlichen Zahn handelt und die Versorgungen durch benachbarte Zähne in der statischen Okklusion sowie eine etablierte Front-/Eckzahnführung geschützt sind. Jedoch zeigten sich in der durchgeführten Untersuchung nach Gesamtrehabilitation deutlich höhere Verschleißraten in CAD/CAM-Kompositrestaurationen mit einem mittleren vertikalen Verlust von 186 µm im Prämolarenbereich und 342 µm im Molarenbereich im ersten Jahr. Dabei muss jedoch beachtet werden, dass in dieser Studie die volle okklusale Belastung von den Restaurationen getragen werden musste. Daher kann die Verwendung einer Aufbissschiene zur Minimierung des Verschleißfortschritts empfohlen werden.

Die teils heterogenen Ergebnisse hinsichtlich der Verschleißraten, vor allem die hohe Schwankungsbreite in Komposit Gruppe, deuten darauf hin, dass die Kompositrestaurationen sensibler auf Parafunktionen und eine erhöhte funktionelle Aktivität reagieren. Übertagen auf die tägliche Praxis würde dieser Zusammenhang ein sorgfältiges Patientenscrenning und eine genaue Indikationsstellung erfordern um das individuell am besten geeignete Material zu verarbeiten. Darüber hinaus können die unterschiedlichen Abnutzungsraten im Seitenzahnbereich auch auf die physiologisch bedingt abweichenden Kaukräfte von Prämolaren und Molaren zurückzuführen sein, wie es u.a. Ferrario et al. in ihrer Arbeit zeigten [83]. Dies könnte den erhöhten Verschleiß bei Molarenrestaurationen in beiden Gruppen erklären. Bei der Interpretation muss jedoch berücksichtigt werden, dass jedes Ungleichgewicht in der Okklusion durch dentoalveoläre Kompensationsmechanismen wie vertikale oder horizontale Zahnbewegungen ausgeglichen werden könnte [60, 84].

Bei der Interpretation der Ergebnisse dieser Studie müssen einige methodische Limitationen berücksichtigt werden. Eingangs muss erwähnt werden, dass die Ergebnisse möglicherweise nicht auf andere auf dem Dentalmarkt erhältliche CAD/CAM-Komposite mit differierenden mechanischen

Eigenschaften übertragbar sind, was zu abweichenden Verschleißraten führen könnte. Zum anderen handelt es sich in der vorgestellten Studie um eine vergleichsweise kleine Patientenkohorte, die die Aussagekraft der Studie hinsichtlich verschiedener Altersgruppen einschränkt. Hinzukommend mussten einige Recalldaten aufgrund nicht tolerierbarer Überlagerungsfehler von weiteren Analysen ausgeschlossen werden, insbesondere bei den Patienten, die in der Kompositgruppe vergleichsweise hohe Verschleißraten aufwiesen. Dieser Datenverlust ist somit vermutlich auf die Bildung von vergrößerten okklusalen Kontaktflächen (Schneeschuh-Prinzip) und mögliche Verformungen bei Restaurationen im Laufe der Zeit zurückzuführen.

Die Durchführung von komplexen Rehabilitationen mit Veränderung der vertikalen Dimension bleibt eine große Herausforderung für Zahnärzte und Zahntechniker. Restaurationen aus Lithium-Disilikat-Keramik zeigen in diesen Fällen stabilere und gleichmäßiger verteilte Verschleißraten im Vergleich zu CAD/CAM-Kompositen. Dennoch besteht weiterhin der Bedarf an klinischen Longitudinalstudien mit größeren Kohorten, um das Verschleißverhalten von Restaurationsmaterialien besser vorhersagen zu können und klinische Ergebnisse der eingesetzten Restaurationen sowie Referenzdaten natürlicher Zähne zu klären. Die Entschlüsselung des individuellen Abrasionsmusters des Patienten würde eine personalisiertere Zahnmedizin ermöglichen, indem das am besten geeigneten Material für eine prothetische Versorgung ausgewählt werden könnte.

4 Zusammenfassung

Die Prävalenz des nicht kariogenen Zahnhartsubstanzverlustes steigt weltweit. Während die Behandlung von komplexen Fällen des Abrasionsgebisses meistens mit Keramikrestaurationen als Goldstandard durchgeführt wird, stellen innovative CAD/CAM-Komposite eine mögliche Alternative dar. Die klassische Behandlung mittels Lithium-Disilikat-Keramiken führt zu einem meist nicht unerheblichen Verlust an Zahnhartsubtanz durch die Präparation, was im Zuge eines minimal-invasiven Behandlungkonzepts berücksichtigt werden muss. Eine Rehabilitation mittels CAD/CAM-Kompositen bietet einen ökonomischen und minimalinvasiven Weg zur Behandlung des Abrasionsgebisses. Hier gibt es jedoch noch keine belastbaren klinischen Daten zum Abrasionsverhalten derartiger Restaurationen. Vor diesem Hintergrund war das Ziel der vorliegenden Arbeiten, die Verschleißraten einer Lithium-Disilikat-Keramik und einem CAD/CAM-Komposit, die Patienten im Zug einer prothetischer Gesamtrehabilitation eingesetzt wurden, zu quantifizieren und zu vergleichen.

Die CAD/CAM-Komposit Restaurationen zeigten deutlich höhere Verschleißraten als die Lithium-Disilikat-Keramik. In beiden untersuchten Gruppen wurden signifikante Unterschiede zwischen Prämolaren- und Molarenverschleißraten festgestellt, mit höheren Verschleißraten in der Molarengruppe. Insgesamt konnten die vorliegenden Arbeiten zeigen, dass eine Behandlung mit Restaurationen aus Lithium-Disilikat-Keramik und CAD/CAM-Kompositen innerhalb des untersuchten Zeitraums von 3 Jahren unbedenklich ist.

Darüber hinaus zeigen die erhobenen Daten, dass die Behandlung des Abrasionsgebisses mit CAD/CAM-Kompositen möglich ist. Allerdings scheint deren Verschleißverhalten anfälliger zu sein für patientenindividuelle Parameter. Jedoch sind noch weitere prospektiv angelegte Studien notwendig, um weitere Daten zu den untersuchten Restaurationen über einen längeren Zeitraum zu erhalten.

5 Literaturverzeichnis

1. Lussi, A. and T.S. Carvalho, *Erosive tooth wear: a multifactorial condition of growing concern and increasing knowledge.* Monogr Oral Sci, 2014. **25**: p. 1-15.

2. Schlueter, N. and B. Luka, *Erosive tooth wear - a review on global prevalence and on its prevalence in risk groups.* Br Dent J, 2018. **224**(5): p. 364-370.

3. Kreulen, C.M., et al., *Systematic review of the prevalence of tooth wear in children and adolescents.* Caries Res, 2010. **44**(2): p. 151-9.

4. Salas, M.M., et al., *Estimated prevalence of erosive tooth wear in permanent teeth of children and adolescents: an epidemiological systematic review and meta-regression analysis.* J Dent, 2015. **43**(1): p. 42-50.

5. Bartlett, D. and S. O'Toole, *Tooth wear and aging.* Aust Dent J, 2019. **64 Suppl 1**: p. S59-S62.

6. Lussi, A., et al., *Dental erosion--an overview with emphasis on chemical and histopathological aspects.* Caries Res, 2011. **45 Suppl 1**: p. 2-12.

7. Shellis, R.P. and M. Addy, *The interactions between attrition, abrasion and erosion in tooth wear.* Monogr Oral Sci, 2014. **25**: p. 32-45.

8. Papagianni, C.E., et al., *Oral health-related quality of life in patients with tooth wear.* J Oral Rehabil, 2013. **40**(3): p. 185-90.

9. Muts, E.J., et al., *Tooth wear: a systematic review of treatment options.* J Prosthet Dent, 2014. **112**(4): p. 752-9.

10. O'Toole, S., et al., *The treatment need and associated cost of erosive tooth wear rehabilitation - a service evaluation within an NHS dental hospital.* Br Dent J, 2018. **224**(12): p. 957-961.

11. Loomans, B., et al., *Severe Tooth Wear: European Consensus Statement on Management Guidelines.* J Adhes Dent, 2017. **19**(2): p. 111-119.

12. Mesko, M.E., et al., *Rehabilitation of severely worn teeth: A systematic review.* J Dent, 2016. **48**: p. 9-15.

13. Schlichting, L.H., et al., *Novel-design ultra-thin CAD/CAM composite resin and ceramic occlusal veneers for the treatment of severe dental erosion.* J Prosthet Dent, 2011. **105**(4): p. 217-26.

14. Guth, J.F., et al., *Treatment concept with CAD/CAM-fabricated high-density polymer temporary restorations.* J Esthet Restor Dent, 2012. **24**(5): p. 310-8.

15. Alt, V., et al., *Fracture strength of temporary fixed partial dentures: CAD/CAM versus directly fabricated restorations.* Dent Mater, 2011. **27**(4): p. 339-47.

16. Ruse, N.D. and M.J. Sadoun, *Resin-composite blocks for dental CAD/CAM applications.* J Dent Res, 2014. **93**(12): p. 1232-4.

17. Zhi, L., T. Bortolotto, and I. Krejci, *Comparative in vitro wear resistance of CAD/CAM composite resin and ceramic materials.* J Prosthet Dent, 2016. **115**(2): p. 199-202.

18. Lawson, N.C., R. Bansal, and J.O. Burgess, *Wear, strength, modulus and hardness of CAD/CAM restorative materials.* Dent Mater, 2016. **32**(11): p. e275-e283.

19. Wulfman, C., V. Koenig, and A.K. Mainjot, *Wear measurement of dental tissues and materials in clinical studies: A systematic review.* Dent Mater, 2018. **34**(6): p. 825-850.

20. Wetselaar, P., A. Faris, and F. Lobbezoo, *A plea for the development of an universally accepted modular tooth wear evaluation system.* BMC Oral Health, 2016. **16**(1): p. 115.

21. Eccles, J.D., *Dental erosion of nonindustrial origin. A clinical survey and classification.* J Prosthet Dent, 1979. **42**(6): p. 649-53.

22. Smith, B.G. and J.K. Knight, *An index for measuring the wear of teeth.* Br Dent J, 1984. **156**(12): p. 435-8.

23. Lussi, A., et al., *Dental erosion in a population of Swiss adults.* Community Dent Oral Epidemiol, 1991. **19**(5): p. 286-90.

24. Bartlett, D., C. Ganss, and A. Lussi, *Basic Erosive Wear Examination (BEWE): a new scoring system for scientific and clinical needs.* Clin Oral Investig, 2008. **12 Suppl 1**: p. S65-8.

25. Perry, R., et al., *Composite restoration wear analysis: conventional methods vs. three-dimensional laser digitizer.* J Am Dent Assoc, 2000. **131**(10): p. 1472-7.

26. Peters, M.C., et al., *Comparison of two measurement techniques for clinical wear.* J Dent, 1999. **27**(7): p. 479-85.

27. Mehl, A., et al., *A new optical 3-D device for the detection of wear.* J Dent Res, 1997. **76**(11): p. 1799-807.

28. Chadwick, R.G., et al., *Development of a novel system for assessing tooth and restoration wear.* J Dent, 1997. **25**(1): p. 41-7.

29. Rodriguez, J.M., R.S. Austin, and D.W. Bartlett, *A method to evaluate profilometric tooth wear measurements.* Dent Mater, 2012. **28**(3): p. 245-51.

30. DeLong, R., *Intra-oral restorative materials wear: rethinking the current approaches: how to measure wear.* Dent Mater, 2006. **22**(8): p. 702-11.

31. Bayne, S.C., D.F. Taylor, and H.O. Heymann, *Protection hypothesis for composite wear.* Dent Mater, 1992. **8**(5): p. 305-9.

32. Christensen, G.J., *The challenge to conventional impressions.* J Am Dent Assoc, 2008. **139**(3): p. 347-9.

33. Heintze, S.D., et al., *Wear of ceramic and antagonist--a systematic evaluation of influencing factors in vitro.* Dent Mater, 2008. **24**(4): p. 433-49.

34. DeLong, R., M. Pintado, and W.H. Douglas, *Measurement of change in surface contour by computer graphics.* Dent Mater, 1985. **1**(1): p. 27-30.

35. Zenthofer, A., et al., *Wear of metal-free resin composite crowns after three years in service.* Dent Mater J, 2013. **32**(5): p. 787-92.

36. Soderholm, K.J., et al., *Clinical wear performance of eight experimental dental composites over three years determined by two measuring methods.* Eur J Oral Sci, 2001. **109**(4): p. 273-81.

37. Rodriguez, J.M., R.S. Austin, and D.W. Bartlett, *In vivo measurements of tooth wear over 12 months.* Caries Res, 2012. **46**(1): p. 9-15.

38. Palaniappan, S., et al., *Three-year randomized clinical trial to evaluate the clinical performance and wear of a nanocomposite versus a hybrid composite.* Dent Mater, 2009. **25**(11): p. 1302-14.

39. Schmid-Schwap, M., et al., *Wear of two artificial tooth materials in vivo: a 12-month pilot study.* J Prosthet Dent, 2009. **102**(2): p. 104-14.

40. Mayworm, C.D., S.S. Camargo, Jr., and F.L. Bastian, *Influence of artificial saliva on abrasive wear and microhardness of dental composites filled with nanoparticles.* J Dent, 2008. **36**(9): p. 703-10.

41. Stober, T., et al., *Comparability of clinical wear measurements by optical 3D laser scanning in two different centers.* Dent Mater, 2014. **30**(5): p. 499-506.

42. Lohbauer, U. and S. Reich, *Antagonist wear of monolithic zirconia crowns after 2 years.* Clin Oral Investig, 2017. **21**(4): p. 1165-1172.

43. Esquivel-Upshaw, J.F., et al., *Randomized clinical study of wear of enamel antagonists against polished monolithic zirconia crowns.* J Dent, 2018. **68**: p. 19-27.

44. Heintze, S.D., F.X. Reichl, and R. Hickel, *Wear of dental materials: Clinical significance and laboratory wear simulation methods -A review.* Dent Mater J, 2019. **38**(3): p. 343-353.

45. Lambrechts, P., et al., *Quantitative in vivo wear of human enamel.* J Dent Res, 1989. **68**(12): p. 1752-4.

46. Bartlett, D.W., L. Blunt, and B.G. Smith, *Measurement of tooth wear in patients with palatal erosion.* Br Dent J, 1997. **182**(5): p. 179-84.

47. Molnar, S., et al., *Tooth wear rates among contemporary Australian Aborigines.* J Dent Res, 1983. **62**(5): p. 562-5.

48. Etman, M.K., M. Woolford, and S. Dunne, *Quantitative measurement of tooth and ceramic wear: in vivo study.* Int J Prosthodont, 2008. **21**(3): p. 245-52.

49. Kramer, N., et al., *Antagonist enamel wears more than ceramic inlays.* J Dent Res, 2006. **85**(12): p. 1097-100.

50. Ohlmann, B., et al., *Wear of posterior metal-free polymer crowns after 2 years.* J Oral Rehabil, 2008. **35**(10): p. 782-8.

51. Pesun, I.J., et al., *In vivo evaluation of the surface of posterior resin composite restorations: a pilot study.* J Prosthet Dent, 2000. **84**(3): p. 353-9.

52. Palaniappan, S., et al., *Three-year randomised clinical trial to evaluate the clinical performance, quantitative and qualitative wear patterns of hybrid composite restorations.* Clin Oral Investig, 2010. **14**(4): p. 441-58.

53. Mundhe, K., et al., *Clinical study to evaluate the wear of natural enamel antagonist to zirconia and metal ceramic crowns.* J Prosthet Dent, 2015. **114**(3): p. 358-63.

54. Loomans, B.A.C., et al., *Clinical performance of full rehabilitations with direct composite in severe tooth wear patients: 3.5 Years results.* J Dent, 2018. **70**: p. 97-103.

55. Guth, J.F., et al., *A new method for the evaluation of the accuracy of full-arch digital impressions in vitro.* Clin Oral Investig, 2016. **20**(7): p. 1487-94.

56. Gonzalez de Villaumbrosia, P., et al., *In vitro comparison of the accuracy (trueness and precision) of six extraoral dental scanners with different scanning technologies.* J Prosthet Dent, 2016. **116**(4): p. 543-550 e1.

57. Bosniac, P., P. Rehmann, and B. Wostmann, *Comparison of an indirect impression scanning system and two direct intraoral scanning systems in vivo.* Clin Oral Investig, 2018.

58. Ender, A., T. Attin, and A. Mehl, *In vivo precision of conventional and digital methods of obtaining complete-arch dental impressions.* J Prosthet Dent, 2016. **115**(3): p. 313-20.

59. Guth, J.F., et al., *Accuracy of five intraoral scanners compared to indirect digitalization.* Clin Oral Investig, 2017. **21**(5): p. 1445-1455.

60. Berry, D.C. and D.F. Poole, *Attrition: possible mechanisms of compensation.* J Oral Rehabil, 1976. **3**(3): p. 201-6.

61. Magne, P., et al., *In vitro fatigue resistance of CAD/CAM composite resin and ceramic posterior occlusal veneers.* J Prosthet Dent, 2010. **104**(3): p. 149-57.

62. Stawarczyk, B., et al., *Evaluation of mechanical and optical behavior of current esthetic dental restorative CAD/CAM composites.* J Mech Behav Biomed Mater, 2015. **55**: p. 1-11.

63. Barkmeier, W.W., et al., *Comparison of laboratory and clinical wear rates of resin composites.* Quintessence Int, 2004. **35**(4): p. 269-74.

64. Mair, L.H., et al., *Wear: mechanisms, manifestations and measurement. Report of a workshop.* J Dent, 1996. **24**(1-2): p. 141-8.

65. Wang, Y. and S.M. Hsu, *Wear and wear transition mechanisms of ceramics.* Wear, 1996. **Volume 195**(Issues 1–2): p. Pages 112-122.

66. Ilie, N., et al., *Academy of Dental Materials guidance-Resin composites: Part I-Mechanical properties.* Dent Mater, 2017. **33**(8): p. 880-894.

67. Stawarczyk, B., et al., *Two-body wear rate of CAD/CAM resin blocks and their enamel antagonists.* J Prosthet Dent, 2013. **109**(5): p. 325-32.

68. Zandparsa, R., et al., *Effect of different dental ceramic systems on the wear of human enamel: An in vitro study.* J Prosthet Dent, 2016. **115**(2): p. 230-7.

69. Heintze, S.D., *How to qualify and validate wear simulation devices and methods.* Dent Mater, 2006. **22**(8): p. 712-34.

70. Heintze, S.D., et al., *Correlation of wear in vivo and six laboratory wear methods.* Dent Mater, 2012. **28**(9): p. 961-73.

71. Abduo, J., *Safety of increasing vertical dimension of occlusion: a systematic review.* Quintessence Int, 2012. **43**(5): p. 369-80.

72. Kois, J.C. and K.M. Phillips, *Occlusal vertical dimension: alteration concerns.* Compend Contin Educ Dent, 1997. **18**(12): p. 1169-74, 1176-7; quiz 1180.

73. Burnett, C.A. and T.J. Clifford, *A preliminary investigation into the effect of increased occlusal vertical dimension on mandibular movement during speech.* J Dent, 1992. **20**(4): p. 221-4.

74. Ormianer, Z. and M. Gross, *A 2-year follow-up of mandibular posture following an increase in occlusal vertical dimension beyond the clinical rest position with fixed restorations.* J Oral Rehabil, 1998. **25**(11): p. 877-83.

75. Christensen, J., *Effect of occlusion-raising procedures on the chewing system.* Dent Pract Dent Rec, 1970. **20**(7): p. 233-8.

76. Edelhoff, D., et al., *CAD/CAM-generated high-density polymer restorations for the pretreatment of complex cases: a case report.* Quintessence Int, 2012. **43**(6): p. 457-67.

77. Edelhoff, D. and O. Brix, *All-ceramic restorations in different indications: a case series.* J Am Dent Assoc, 2011. **142 Suppl 2**: p. 14S-9S.

78. Lambrechts, P., et al., *Quantitative evaluation of the wear resistance of posterior dental restorations: a new three-dimensional measuring technique.* J Dent, 1984. **12**(3): p. 252-67.

79. Hmaidouch, R. and P. Weigl, *Tooth wear against ceramic crowns in posterior region: a systematic literature review.* Int J Oral Sci, 2013. **5**(4): p. 183-90.

80. Suputtamongkol, K., et al., *Clinical performance and wear characteristics of veneered lithia-disilicate-based ceramic crowns.* Dent Mater, 2008. **24**(5): p. 667-73.

81. Esquivel-Upshaw, J.F., et al., *Three years in vivo wear: core-ceramic, veneers, and enamel antagonists.* Dent Mater, 2012. **28**(6): p. 615-21.

82. Ohlmann, B., et al., *Clinical wear of posterior metal-free polymer crowns. One-year results from a randomized clinical trial.* J Dent, 2007. **35**(3): p. 246-52.

83. Ferrario, V.F., et al., *Single tooth bite forces in healthy young adults.* J Oral Rehabil, 2004. **31**(1): p. 18-22.

84. Murphy, T., *Compensatory mechanisms in facial height adjustment to functional tooth attrition.* Australian Dental Journal, 1959. **4**(5): p. 312-323.

Danksagung

Allen, die diese Arbeit ermöglicht haben und mich unterschützt haben, möchte ich gerne danken:

Mein besonderer Dank gilt Herrn Prof. Dr. med. dent. Jan-Frederik Güth, nicht nur für die Bereitstellung des Dissertationsthemas, sondern auch für die großartige persönliche Betreuung.

Herrn Prof. Dr. med. dent. Daniel Edelhoff gilt ein herzlicher Dank für die Bereitstellung der Patientendaten und Unterstützung bei der Entstehung beider Publikationen.

Darüber hinaus möchte ich mich bei Frau PD Dr. med. dent. Christine Keul für die Unterstützung bei der Erstellung der Manuskripte bedanken.

Bei Dr. Dipl.-Ing. Kurt Erdelt möchte ich mich für die Hilfestellung bei der Datenanalyse und der statistischen Auswertung bedanken.

Ein besonderer Dank gilt meiner Familie, die mich immer unterstützte und meinen beruflichen Werdegang erst ermöglicht haben.

Eidesstattliche Versicherung

Ich, Gintare Burian, geboren am 16.02.1993 in Klaipeda, erkläre hiermit an Eides statt, dass ich die vorliegende Dissertation mit dem Titel:

In-vivo-Verschleißverhalten von Restaurationen aus CAD/CAM-Komposit versus Lithium-Disilikat-Keramik bei Patienten nach prothetischer Gesamtrehabilitation

selbständig verfasst, mich außer der angegebenen keiner weiteren Hilfsmittel bedient und alle Erkenntnisse, die aus dem Schrifttum ganz oder annähernd übernommen sind, als solche kenntlich gemacht und nach ihrer Herkunft unter Bezeichnung der Fundstelle einzeln nachgewiesen habe.

Ich erkläre des Weiteren, dass die hier vorgelegte Dissertation nicht in gleicher oder in ähnlicher Form bei einer anderen Stelle zur Erlangung eines akademischen Grades eingereicht wurde.

München, 6.2.2023	Gintare Burian
______________________	______________________
Ort, Datum	Unterschrift