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Übereinstimmung von CAD/CAM-rekonstruierten und natürlichen Zahnoberflächen im Hinblick auf okklusale Morphologie, Okklusion und Ästhetik

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Ich erkläre hiermit an Eides statt,

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München,

Inhaltsverzeichnis

1 Abkürzungsverzeichnis

CAD	Computer-aided-design
CAM	Computer-aided-manufacturing
ZrO_2	Zirkoniumdioxid
Al_2O_3	Aluminiumoxid

2 Publikationsliste

Englischsprachige Originalarbeiten

Kollmuss M, Jakob FM, Kirchner HG, Ilie N, Hickel R, Huth KC (2013) Comparison of biogenerically reconstructed and waxed-up complete occlusal surfaces with respect to the original tooth morphology (2013). *Clin Oral Invest* 17: 851-857.

Kollmuss M, Kist S, Obermeier K, Pelka AK, Hickel R, Huth KC (2014) Antimicrobial effect of gaseous and aqueous ozone on caries pathogen microorganisms grown in biofilms. *Am J Dent* 27: 134-138.

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Posterpräsentationen auf Kongressen

Kollmuss M, Jakob FM, Kirchner HG, Ilie N, Hickel R, Huth KC (2012) Abweichung biogenerischer Rekonstruktionen bzw. Wax-Ups von Kauflächen im Vergleich zum Originalzahn. 26. Jahrestagung der Deutschen Gesellschaft für Zahnerhaltung (DGZ), Dresden, *DZZ* 67: D30-D31.

Huth KC, Broos K, Kist S, Hickel R, **Kollmuss M** (2015) Cytotoxicity and regenerative potential of three different tricalcium silicate-based cements. 25th Congress of the International Association of Paediatric Dentistry (IAPD), Glasgow 1-4 July 2015, Abstract Book Volume 25-Suppl. 1, p. 184 # PR08-1.25.

3 Einleitung

3.1 Entwicklung der CAD/CAM-Technologie in der Zahnmedizin

D P p „C p “ (CAD) „C p manufacturing (CAM) hat in vielen Bereichen der Technik Einzug gehalten. Dabei wird am Computer ein digitales Modell des gewünschten Werkstücks erstellt und im Anschluss mit Hilfe eines additiven oder subtraktiven Fertigungsverfahrens hergestellt. In diesem Zusammenhang muss auch der B „R p P yp “ zeiteffiziente Fertigung von individuellen und somit nicht serienmäßig produzierten Formen ermöglicht. Dabei kommen hochmoderne digitale Erfassungssysteme für Oberflächen, basierend auf Laser- oder Streifenlichtscannern zum Einsatz.

Mit dieser Entwicklung haben sich auch in einigen Feldern der Medizin und Zahnmedizin vielfältige Anwendungsmöglichkeiten von CAD/CAM-Techniken ergeben (Miyazaki *et al.*, 2009). Durch den Einsatz von Diamant- und Hartmetallschleifkörpern können nun subtraktiv Materialien verarbeitet werden, deren Anwendung mit konventionellen Fertigungsmethoden bisher nicht, oder nur unter sehr großem Aufwand möglich war. Das beste Beispiel hierfür sind hochfeste Oxidkeramiken wie Zirkoniumoxid (ZrO_2) oder Aluminiumoxid (Al_2O_3). Diese hervorragend biokompatiblen Materialien haben ein breites Einsatzspektrum in der Medizin, angefangen bei Prothesen zum endoprothetischen Ersatz der großen Gelenke bis hin zur Kronenversorgung an einem einzelnen Zahn (Agustín-Panadero *et al.*, 2014).

Bereits Ende der 1980-er Jahre begann dazu an der Universität Zürich unter der Leitung von Prof. Mörmann die Entwicklung eines kompakten Systems zur digitalen Erfassung von präparierten Zähnen, einer darauf basierenden Konstruktion einer individuell passenden Restauration und eine anschließende

subtraktive Fertigung des Werkstücks aus einem Keramikblock (Mörmann und Brandestini, 1989).
D „C R C- y “ Firma Sirona (Bensheim, Deutschland) vermarktete System ist bis heute das erfolgreichste CAD/CAM-System in der Zahnheilkunde mit einer weltweiten Verbreitung.

Im Laufe der Jahre wurde das System immer weiter entwickelt: Insbesondere in den Bereichen der Aufnahmeeinheit und der Rekonstruktionssoftware wurde ein großer Fortschritt hin zu einer immer genaueren Erfassung und präziseren Rekonstruktion erreicht. Wichtige Punkte hierbei waren die Einführung der dritten Generation des CEREC-Systems mit einer Blaulicht-Kamera zur Erfassung der intraoralen Strukturen (CEREC BlueCam). Diese neue Kamera zeigte hervorragende Parameter hinsichtlich Präzision und Genauigkeit der Erfassung. Das aktuellste System basiert nicht mehr auf dem Prinzip einer Fotokamera, sondern auf einer Videoaufnahme des zu scannenden Bereichs, was A ö („C R C O “) (Wiedhahn *et al.*, 2012).

Ein Meilenstein in der Rekonstruktion der verloren gegangenen Zahnhartsubstanz war die Einführung des „ Z “ Prof. Mehl im Jahr 2005 (Mehl *et al.*, 2005). Dieses Zahnmodell verwendet die verbliebene Zahnhartsubstanz und kann anhand eines mathematischen Algorithmus daraus die verloren gegangene Substanz rekonstruieren. Dabei fließen sowohl Parameter des präparierten Zahnes, als auch die der Nachbarzähne und Antagonisten mit ein.

3.2 Erfolgskriterien einer CAD/CAM gefertigten Restauration

Für CAD/CAM gefertigte Restaurationen gelten prinzipiell die gleichen Standards und Erfolgskriterien wie für konventionell gefertigte Restaurationen. Das Ziel einer jeden zahnärztlichen restaurativen Maßnahme ist die Wiederherstellung von Funktion und Ästhetik im betroffenen Bereich. Zudem treten wirtschaftliche Parameter hinzu, wie eine angemessene Zeit für eventuell nötige Anpassungen. Als herausragender Parameter der Funktion ist die Rekonstruktion der okklusalen Kontaktverhältnisse zu bezeichnen (Türp *et al.*, 2008). Diese Kontakte, sowohl statische als auch dynamische, sind das Hauptkriterium, ob der Zahnersatz die Funktion eines natürlichen Kauvorgangs ermöglichen kann. Hierbei soll als allgemein anerkanntes Konzept ein maximaler, gleichmäßig verteilter Vielpunktkontakt erreicht werden. Dynamische Kontakte sind bei festsitzenden Versorgungen, von Ausnahmen abgesehen, nicht erwünscht. Dies garantiert eine sichere Abstützung der Okklusion durch die Restauration sowie eine Vermeidung von Hindernissen bei Bewegungen des dynamischen Kauvorgangs. Als Erfolgsparameter kann also die Anzahl der statischen Kontaktpunkte nach Entfernen aller störenden dynamischen Kontakte gelten.

In den meisten Fällen ist eine möglichst exakte Rekonstruktion der ursprünglichen Zahnhartsubstanz der sicherste Weg, um stabile okklusale Verhältnisse der Restauration zu gewährleisten. Somit sollte sich das Oberflächenrelief der Restauration im nicht funktionsgestörten Gebiss, möglichst wahrheitsgetreu an der Oberfläche der ursprünglichen, natürlichen Zahnhartsubstanz orientieren. Dabei sind bereits verschiedene Methoden beschrieben worden, die hauptsächlich auf der Auswertung des linearen Abstandes zwischen der Restauration und der damit überlagerten Originaloberfläche des Zahnes beruhen (Richter und Mehl, 2006). In den beiden dieser Dissertation zugrunde liegenden Publikationen wird zusätzlich ein neues Modell vorgestellt, welches auf der Betrachtung des Volumens zwischen den beiden Oberflächen basiert. Dies hat sich als eine alternative, exakte Methode zur Erfassung der Abweichung der Restauration von der Ausgangssituation erwiesen.

Ein weiterer wichtiger Punkt bei der Rekonstruktion einer natürlichen Kaufläche im Rahmen einer prothetischen Versorgung ist die Ästhetik. Diese spielt im

Seitenzahnbereich für den Patienten oft nur eine geringe Rolle, allerdings wird die Gesamtqualität einer prothetischen Arbeit von Zahnarzt und Zahntechniker auch nach diesem subjektiven Parameter beurteilt. Dabei muss jedoch betont werden, dass die Bewertung der Ästhetik stets großen inter-individuellen Schwankungen unterliegt. Aus diesem Grund sollten bei Untersuchungen dieses Punkts immer zwei unabhängige Bewerter herangezogen werden.

3.3 Fertigungsprozesse für vollkeramische Restaurationen

In letzter Zeit haben sich drei konkurrierende Herstellungsverfahren für vollkeramische Einzelzahnrestaurationen herauskristallisiert. Das seit langer Zeit mit großem Erfolg eingesetzte klassische zahntechnische Verfahren des Pressens einer Keramikrestauration mit Hilfe einer Lost-Wax-Form wird zunehmend von computergestützten Verfahren abgelöst, die einerseits rein
„ “ Z p A
Hilfe des zahntechnischen Labors verwirklicht werden.

3.3.1 Lost-Wax-Pressverfahren

Bei diesem klassischen zahntechnischen Verfahren wird, ähnlich wie bei einer metallischen Restauration, zuerst ein exaktes Modell des Werkstücks aus Wachs modelliert und in eine feuerfeste Einbettmasse eingebettet. Nun wird durch Erhitzen der Muffel das Wachs verbrannt, wodurch ein Hohlraum und somit eine Negativ-Form des Werkstücks entsteht im Kern der Muffel. In diesen Hohlraum wird nun unter hohem Druck eine zähflüssige, erhitzte Keramikmasse gepresst. Dabei kommen industriell gefertigte Keramik-Rohlinge zum Einsatz. Somit wird durch Druck und Hitze eine Umformung des Keramik-Rohlings erreicht. Die entstandene Restauration kann nun weiter angepasst, ausgearbeitet und finalisiert werden (Kern *et al.*, 2015)

Allerdings können mit diesem Verfahren nur Keramiken verarbeitet werden, deren Grundmatrix Siliziumoxid ist. Diese Keramiken sind auch als Glaskeramiken bekannt. Der Glasanteil sorgt für eine amorphe Struktur des

Werkstoffs und ermöglicht einen Schmelzpunkt, der technisch mit vertretbarem Aufwand erreichbar ist. Somit ist es nicht möglich mit dem Lost-Wax-Pressverfahren Oxidkeramiken, die keinerlei Anteile von Siliziumoxid enthalten, zu verarbeiten. Dazu zählen die mittlerweile ebenfalls weit verbreiteten Oxidkeramiken wie Zirkoniumdioxid und Aluminiumoxid. Diese Einschränkung der Materialauswahl ist ein entscheidender Nachteil dieses Verfahrens. Nichtsdestotrotz kommt das Verfahren der Lost-Wax-Presstechnik noch in großem Stile zum Einsatz, da hier im Vergleich nur geringe Investitionskosten entstehen. So muss ein zahntechnisches Labor lediglich in einen Pressofen investieren und kann auf den Kauf eines CAD-CAM-Systems im Bereich mehrerer Zehntausend Euro verzichten.

3.3.2 „Chairside“-Fertigung in der Zahnarztpraxis

Bereits im Jahr 1985 stellte Prof. Werner Mörmann mit der Firma Sirona zusammen ein System vor, welches die Kombination dreier Komponenten vereinte (Mörmann und Brandestini, 1989). Eine Kamera zur intraoralen Erfassung der Präparation, ein Computer zur Konstruktion der Restauration und eine Schleifeinheit zur Fertigstellung der Restauration. D „C R C®“ bekannte System ist seit nun fast drei Jahrzehnten auf dem Markt etabliert und weit verbreitet. Es ermöglicht dem Zahnarzt, unabhängig vom zahntechnischen Labor, vollkeramische Restaurationen in seiner Praxis herzustellen und, abhängig vom verwendeten Material, sogar in der gleichen Sitzung am Patienten einzugliedern.

Die neueste Generation des CEREC-Systems basiert auf einer Videokamera ("CEREC-Omnicam") zur intraoralen Erfassung der Präparation und einer weiter entwickelten Schleifeinheit (CEREC in.lab MC XL), auf der auch größere Werkstücke, wie dreigliedrige Brücken, problemlos gefertigt werden können.

Das CEREC-System ist insbesondere geeignet, mehrflächige Inlay-Restaurationen herzustellen, da die hier verwendeten Materialien wie IPS Empress, eine Leucit-verstärkte Glaskeramik, keiner aufwendigen Nachvergütung bedürfen. Sie können somit direkt nach der Politur der Restauration am Patienten eingegliedert werden. Andere Materialien, insbesondere die Gruppe der Lithium-Silikatkeramiken, deren Hauptvertreter IPS e.max ist, benötigen hingegen nach der CAM-Fertigung einen Kristiallisationsbrand. Hierfür ist wiederum ein Keramikofen von Nöten, was den Einsatz in der zahnärztlichen Praxis ohne Praxislabor erschwert.

3.3.3 CAD/CAM-Fertigung im zahntechnischen Labor

Eine weitere Möglichkeit ist die Fertigung von vollkeramischen Restaurationen im zahntechnischen Labor. Dabei wird die konventionelle Abformung mit einem scanbaren Gips ausgegossen und anschließend in einem Laborscanner digitalisiert. Dabei können Laser- sowie Streifenlicht-basierte Systeme zum Einsatz kommen. Nun kann mit Hilfe einer Rekonstruktionssoftware die gewünschte Restauration konstruiert werden. Dabei sind diese Software-Systeme, im Gegensatz zum CEREC-System, in der Lage fast jede Art von Zahnersatz bis hin zur 14-gliedrigen Brücke oder Modellgussgerüsten zu konstruieren. Dabei wird bei diesen Software-Systemen der Rekonstruktion eines harmonischen Okklusionskonzepts große Bedeutung beigemessen.
Anschließend erfolgt die Fertigung des Werkstücks aus einer nahezu beliebig erweiterbaren Palette von Materialien: Neben den schon angesprochenen Glaskeramiken können sowohl hochfeste Oxidkeramiken, Metalle und Kunststoffe verwendet werden, die auch in entsprechender Größe als Ronden lieferbar sind, um auch größere Restaurationen zu verwirklichen. Die Infrastruktur eines zahntechnischen Labors ermöglicht im Anschluss eine an das Material angepasste Nachvergütung und Individualisierung.

4 Ziele dieser Arbeit

All diese verschiedenen Fertigungsarten stehen in direkter Konkurrenz zueinander. Es existieren zahlreiche Untersuchungen zu den einzelnen Verfahren, jedoch erstaunlich wenige, welche die einzelnen Verfahren direkt miteinander vergleichen. Um herauszufinden, was die Vor- und Nachteile der verschiedenen Fertigungsstrategien sind, ist es aber von größter Wichtigkeit vergleichende Untersuchungen durchzuführen.

Diese Arbeit legt ihren Schwerpunkt auf die Untersuchung der Ähnlichkeit der rekonstruierten Restauration zur ursprünglichen, natürlichen Zahnhartsubstanz. Ferner stehen Parameter, welche die Okklusion und Ästhetik betreffen im Fokus.

Die erste Studie sollte an klassischen Teilkronenpräparationen mit Verlust der kompletten Kaufläche, die Rekonstruktionsmöglichkeit mittels der CEREC-Software (V3.8) untersuchen. Als Vergleich kommen von einem erfahrenen Zahntechnikermeister aufgewachste Kauflächen zum Einsatz. Zudem erfolgte ein Vergleich zwischen dem Datensatz der rekonstruierten Restauration und einem Scan der fertig geschliffenen Restauration, um eventuelle Änderungen und Ungenauigkeiten des Fertigungsprozesses zu evaluieren.

Die zweite Studie beschäftigt sich mit dem Vergleich des Endproduktes von drei verschiedenen Fertigungsprozessen: einem Chairside-Ansatz, einem CAD/CAM-Verfahren im zahntechnischen Labor und einem klassischen Pressverfahren. Die fertigen Restaurationen wurden erneut eingescannt und mit der ursprünglichen Zahnoberfläche verglichen. Zusätzlich erfolgte eine Bewertung der Okklusion und Ästhetik sowie eine Messung der Zeit, die nötig war, um eine eventuelle Bisserhöhung nach Fertigung im Artikulator einzuschleifen.

Diese beiden Studien bieten einen Vergleich zwischen den etablierten Fertigungsstrategien und lassen somit Schlüsse über eventuelle Stärken und Schwächen der einzelnen Verfahren zu.

5 Deutsche Zusammenfassung

Ziel der beiden Publikationen war es, zum einen die Möglichkeiten der Rekonstruktion von Kauflächen mittels verschiedener Strategien im Hinblick auf die ursprüngliche Morphologie zu untersuchen. Zum anderen sollten Okklusionsparameter und eine ästhetische Bewertung des Endergebnisses erfolgen. Diese Arbeit liefert somit einen Beitrag zur Einordnung unterschiedlicher CAD/CAM-Systeme hinsichtlich ihrer Vor- und Nachteile im Einsatz bei der Fertigung von vollkeramischen Einzelzahnrestaurationen.

Zum Einsatz kam hierbei ein neues Verfahren, welches auf der Untersuchung der Volumina zwischen der rekonstruierten und der ursprünglichen Oberfläche beruhte. Dabei ergaben sich für die biogenerische CEREC-Rekonstruktion in beiden Studien geringere Abweichungen zwischen den beiden Oberflächen als bei den anderen Herstellungsarten. Dies ist bei genauerer Betrachtung der zugrunde liegenden Technik auch nicht verwunderlich, da sich diese Software ausschließlich auf die restliche Zahnhartsubstanz der Präparation und der Nachbarzähne und Antagonisten stützt. Alle anderen Software-Systeme greifen stets auf eine implementierte Datenbank von Zahnformen zurück und passen die hinterlegten Formen an die entsprechende Situation an. Trotzdem lieferten sowohl die im Labor CAD/CAM-gefertigten, als auch die konventionell gepressten Restaurationen klinisch brauchbare Ergebnisse, die sich entsprechend ihrer Indikation verwenden lassen.

Allerdings schneiden die Software-Systeme, die im zahntechnischen Labor zum Einsatz kommen, besser ab, wenn technische Parameter, wie die Anzahl der okklusalen Kontaktpunkte, untersucht werden. So zeigte sich bei den CAD/CAM-gefertigten Kronen aus dem zahntechnischen Labor die größte Anzahl von okklusalen Kontakten. Ein Grund hierfür ist sicherlich in dem deutlich weiteren Einsatzgebiet dieser Systeme zu suchen, die insbesondere auch für die Rekonstruktion kompletter Zahnreihen geeignet sind, wo ein individuelles Okklusionskonzept eine herausragende Rolle spielt.

Im Bereich der Ästhetik stellt nach wie vor die in Handarbeit aufgewachste Restauration den Goldstandard dar. Allerdings ist solch eine ästhetische Bewertung schwierig einzuordnen, da sie stets eine Meinung des Betrachters darstellt. Dies erklärt auch die inter-individuell sehr verschiedenen Bewertungen der Restaurationen. Trotzdem erreichte die Gruppe der konventionell im Lost-Wax-Verfahren hergestellten Restaurationen beiden Untersuchern stets die höchsten Bewertungen.

Abschließend kann als Fazit dieser Untersuchungen stehen, dass die CAD/CAM-Technik aufgrund ihrer eingangs erwähnten Vorteile im Bereich der Materialauswahl aus der modernen Zahnmedizin nicht mehr wegzudenken ist. Dabei können in allen untersuchten Gesichtspunkten im Vergleich zur konventionellen Fertigung mindestens gleichwertige, wenn nicht bessere Ergebnisse erzielt werden. Die rasanten Fortschritte, sowohl im Bereich des Maschinenbaus auf der einen, als auch im Bereich der Softwareentwicklung, lassen gespannt in die Zukunft blicken. Aktuellste Entwicklungen im Bereich des 3D-Drucks kommen bereits kommerziell zum Einsatz, beispielsweise für die Fertigung von Meistermodellen.

Allerdings sollte trotz allen Fortschritts stets eine kritische Hinterfragung und Untersuchung neuer Methoden erfolgen, damit den Qualitätsansprüchen der Zahnmedizin und Zahntechnik Rechnung getragen werden kann.

6 Englische Zusammenfassung

The aim of both publications was to investigate the reconstruction possibilities for occlusal surfaces by different strategies in regard to the original morphology. Further, the number of occlusal contacts and an aesthetic grading of the final restoration were performed. Therefore, this investigation was to classify different CAD/CAM-systems regarding their pros and cons in manufacturing of all ceramic single tooth restorations.

We used a new approach for the determination of the quality of the occlusal surface. Thus, we measured the volume between the surfaces of the reconstructed and the original tooth surface. Thereby, the biogeneric CEREC-reconstruction was superior to the other methods in both studies. When looking closer on the technique on which this tool is based, this result is not remarkable, as this software exclusively takes the tooth substance of the preparation, the adjacent and the antagonist teeth into account. All other software systems access deposited databases of tooth morphologies and modify them to the actual situation. Although, the computer assisted from the dental laboratory, as well as the conventional pressed restorations lead to clinical acceptable results that could be used within the clinical indication.

Nevertheless, the laboratory CAD-Software was superior regarding technical parameters such as the number of occlusal contacts achieved. Thus, the restorations made by the laboratory CAD software showed the highest number of occlusal contacts. One reason for this may be the wide field of indications in which these systems can be used as they are able to reconstruct complete rows of teeth where an individual occlusion concept is an outstanding challenge.

Regarding the aesthetic of restorations, the conventional fabrication was still the gold standard. However, such an aesthetic grading is a subjective rating with remarkable inter-individual differences. Thus, an overall interpretation of these results is difficult. Nevertheless, the restorations from the restorations from the conventional lost-wax-group reached the highest aesthetic scores within both examiners.

Concluding, this investigations proof, that CAD/CAM-techniques are an essential part of modern dentistry, as they offer the handling of a broad spectrum of materials. In all investigated parameters, the CAD/CAM-techniques lead to equal or even superior results than the conventional techniques. The accelerated progress in engineering as well as on software development promise great developments in the future. Most actual trends in CAD/CAM such as 3D-printing are already commercially used.

Nevertheless, all these new promising techniques should be handled carefully and well-designed studies have to be carried out to guarantee constant high quality standards in dentistry and dental technology.

7 Veröffentlichung I

Comparison of biogenerically reconstructed and waxed up complete occlusal surfaces with respect to the original tooth morphology

2013

Maximilian Kollmuss, Franz Michael Jakob, Hans-Georg Kirchner, Nicoleta Ilie, Reinhard Hickel und Karin Christine Huth

Clinical Oral Investigations 17: 851-857

ABSTRACT

Objectives: Recently, it has become possible to reconstruct complete occlusal surfaces using the biogeneric tooth model. This study aimed to mathematically assess and compare the morphologic agreement between original morphology and CAD-reconstructed, waxed-up, and CAM partial crowns.

Materials and Methods: Thirty-nine intact first permanent molars (39 participants) were included. Impressions, bite registrations and 3 gypsum replicas were made. Preparations for CAD/CAM partial crowns were performed and scanned. The restorations were biogenerically reconstructed (CEREC® v3.80) and milled. Wax-ups of these preparations were scanned as well as the milled restorations and original teeth. Discrepancies were evaluated by matching the scans with the original morphologies (Match3D, output: volume/area, z-difference) and by contact patterns. The discrepancies were compared between CAD-reconstructions and either wax-ups or milled restorations (paired t-test, $\alpha=0.025$ for 2 multiple tests).

Results: The mean differences between natural tooth morphology (triangular stabilisation 71,8%) and biogeneric reconstructions, wax-ups, and milled restorations (triangular stabilisation 87,2%) were: 184±36µm (volume/area), 187±41µm (z-difference); 263±40µm (volume/area), 269±45µm (z-difference); and 182±40µm (volume/area), 184±41µm (z-difference). Differences associated with biogeneric reconstructions were significantly less than of those of wax-ups (volume/area and z-difference, $p<0.0001$), but not significantly different than those of milled restorations ($p=0.423$ (volume/area), $p=0.110$ (z-difference)).

Conclusions: CAD software enables a closer reconstruction of teeth than do wax-ups, even when no cusps remain. The milling device is precise enough to transfer CAD into the final restoration.

Clinical Relevance: This study shows that state of the art CAD/CAM can effectively produce natural tooth morphology and may be ideal for fixed partial dentures.

INTRODUCTION

When restoring the occlusal surfaces of posterior teeth, clinicians largely agree that the task involves both harmonic intercuspidation and the restoration of natural looking morphology [1]. For indirect gold and pressed ceramic restorations, this aim is primarily addressed by the dental technician who waxes up the missing tooth parts by using an articulator. In contrast, computer-aided designed and manufactured (CAD/CAM) restorations accomplish this goal via different software systems and manual modifications.

In the past, the occlusal designs of CAD/CAM manufactured crowns or inlays were a challenging and time-consuming process, which required a great deal of knowledge and experience related to CAD-software. In the past several years, many improved features with respect to occlusal design have been introduced. The first software systems were based on standard morphology, which needed individual adaptation [2-5], while newer systems use algorithms to adjust the occlusal surface to the bite registrations [6, 7]. A new approach involves the “ ” [8]. T on a mathematical description of teeth for which the information is obtained from a 3D-data library comprising several hundred scans of caries-free and intact occlusal surfaces [9]. It is possible to mathematically construct a missing surface of a tooth by analysing the remaining tooth substance (CEREC® v3.00) [10, 11]. This allows the design of partial crowns and inlays with fitting occlusal dimensions in an acceptable time frame [12]. A new software update (v3.80) [13] now provides, for the first time, the chance to reconstruct a complete occlusal surface, even when the whole original occlusal surface has been lost. The necessary data for the biogeneric reconstruction are then gathered either from the tooth distal to the restoration, the antagonist, a bite registration or the contra-lateral tooth in the same arch.

The present study aimed to assess the mathematical match between the original occlusal surface and the biogenerically reconstructed occlusal surface with

CAD, the occlusal surface waxed up by a dental technician and the CAM ceramic restoration. In addition, the contact point situation of the original teeth and the milled restoration was evaluated descriptively. The following working hypotheses were tested: 1) the biogeneric reconstruction matches the original tooth surface better than does the waxed up occlusal surface and 2) the biogeneric reconstruction matches the original tooth surface better than does the finally milled ceramic restoration because of compromised precision inherent in the milling process.

MATERIALS AND METHODS

Participants

The participants of this clinical study were selected from clinical students of dentistry at the Department of Restorative Dentistry, University of Munich. Participants were included when they had at least one quadrant with intact tooth morphologies without carious lesions and without missing teeth or spaces. Exclusion criteria were the presence of fillings, fissure sealants or unwillingness to participate in the study. Informed written consent was obtained from all participants. The study was granted approval by the Ethics Committee of the University of Munich (No. 022-10).

Models and preparation

If more than one quadrant met the inclusion criteria in an individual patient, only one quadrant was randomly selected by using a random selection program (SPSS, version 19, SPSS Inc., Chicago, IL, USA). A silicone impression (Aquasil, Dentsply DeTrey, Konstanz, Germany) was taken from the selected quadrant with a partial impression tray (Speiko, Münster, Germany). An alginate impression (Schuetz Dental, Rosbach, Germany) was taken from the antagonist quadrant. The impressions were poured out three times with type IV gypsum (MM Dental, Gummersbach, Germany). Saw-cut models were made from these gypsum replicas. To assign the gypsum replicas in the correct occlusal relation, two bite registrations were made. One registration was made with scannable material (CADbite, Ivoclar Vivadent, Schaan, Liechtenstein) for CAD reconstruction. The other registration was made with a silicone material (Futar D Fast, Kettenbach, Eschenburg, Germany) for use in a semi-adjustable articulator (Artex, AmmanGirrbach, Pforzheim, Germany). A quantification of occlusal contacts on the original gypsum cast was done with articulating paper. Additionally, it was evaluated if there was a triangular stabilisation on the

respective teeth of the quadrant. The overall workflow is shown in Figure 1. All
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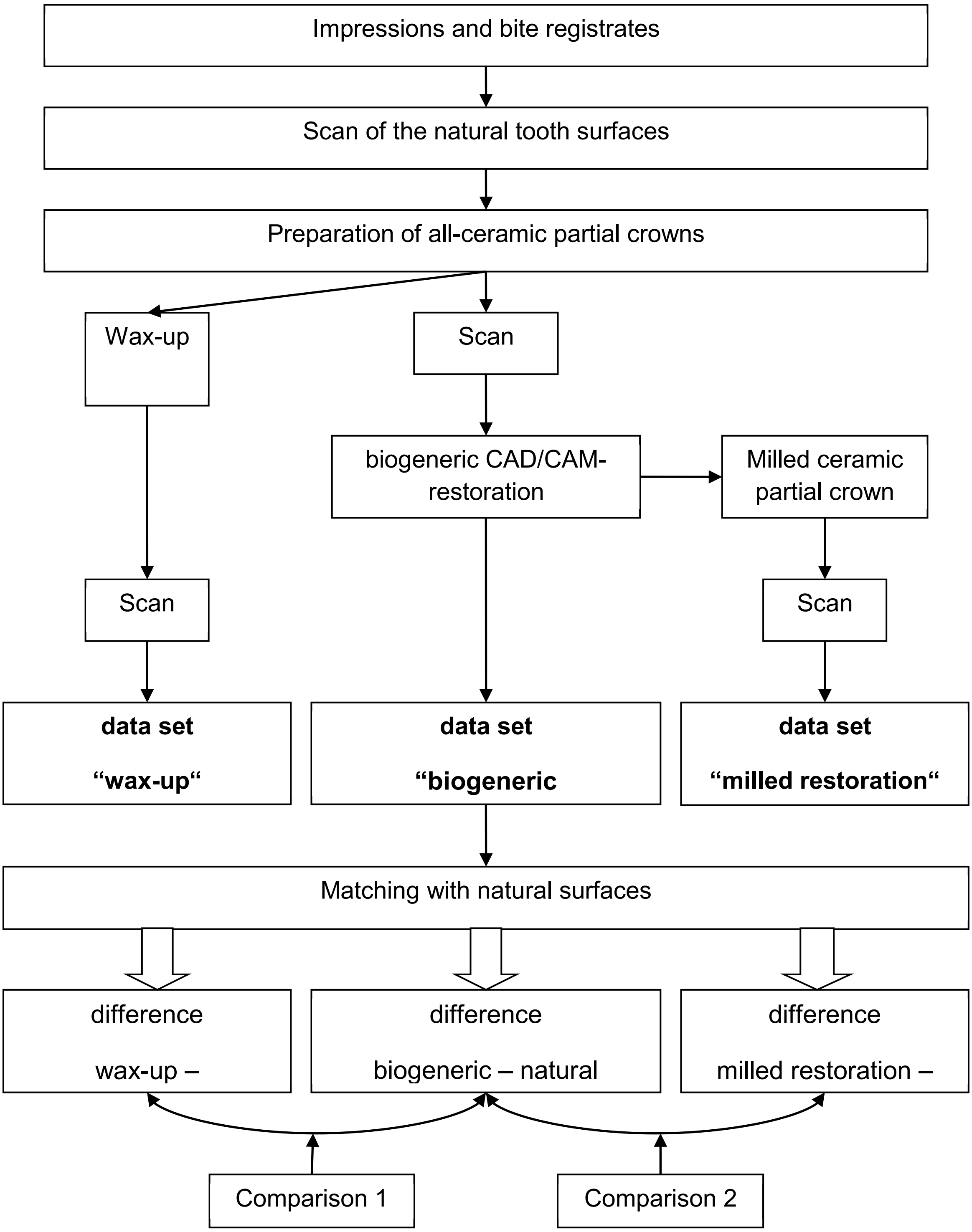


Fig. 1: Study workflow from the impressions to the data sets

The first molar of each quadrant was selected for preparation. The preparations for the all-ceramic partial crowns were performed by 39 students in their first clinical year after two weeks of full-time training in cavity preparations for CAD/CAM restorations. Each student performed one preparation. The preparations were done according to recommendations specific to CAD/CAM restorations [14]. Among other criteria, we specifically verified a minimum tooth removal of 1.5 mm in the occlusal and 2.0 mm in the proximal dimensions. To date, all cusps were removed. The preparation margin on the oral and buccal surface was set at the equator of the tooth. On the proximal surfaces the contact point was removed, avoiding subgingival preparation margins. During preparation we looked at the insertion axis of the planned restoration to be perpendicular to the occlusal surface plane and the equatorial line of the respective tooth and the distal adjacent tooth. Further, we looked at the preparation margin to include an angle of 90° in order to avoid any fractures of the ceramic restoration [14]. The preparation criteria were confirmed by a dentist with clinical expertise in CAD/CAM restorations.

Scanning and reconstruction procedures

The preparations were scanned by the same experienced dentist with CEREC® Bluecam (Sirona, Bensheim, Germany) according to the following protocol: the prepared tooth as well as the adjacent mesial and distal teeth were scanned as best as possible perpendicular to the occlusal plane. In addition, the scanning device was tilted 15° mesial, distal, oral or buccal to the described angle scanning all four sides in order to catch any undercuts of the scanned teeth.

Subsequently, the bite registration (CADbite) was trimmed as not to cover the adjacent teeth and placed on the preparation and scanned perpendicularly to the occlusal plane of the tooth. The result was an exact virtual 3D-model of the preparation, including the mesially and distally adjacent original teeth and the occlusal shapes of the antagonist teeth (CEREC® v3.80). The unprepared tooth morphology from the second replica was scanned using the same protocol and the replica were mounted in an articulator by another bite registrate.

The 3D-model was virtually trimmed and the preparation margin was determined by the automatic preparation margin detector of the software. The margin was visually checked and manually corrected if necessary. The minimum occlusal

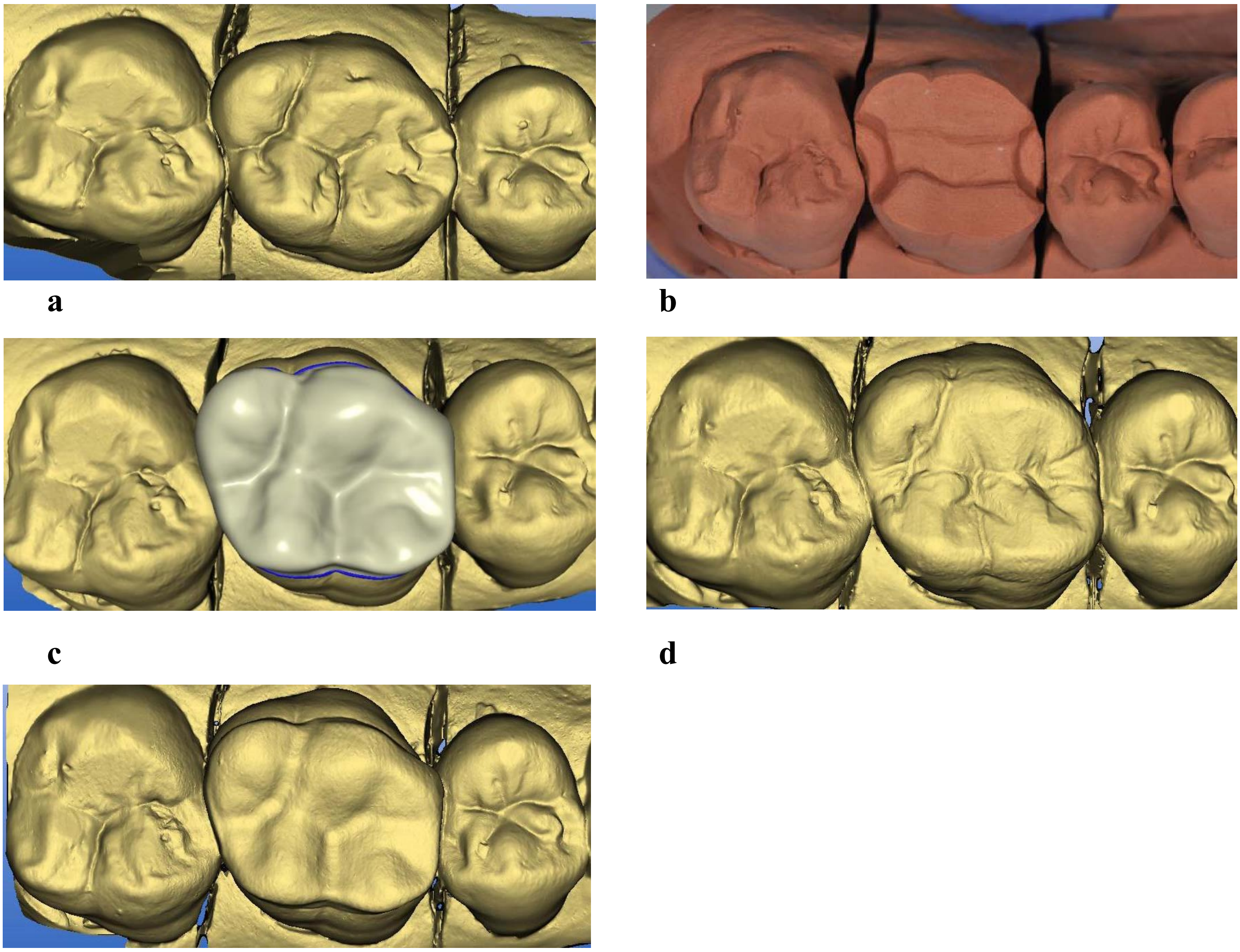
1.5 “

” software, which provides a semi-transparent view of the preselected occlusal thickness. If there was not enough tooth substance removed, the preparation was adapted and checked again. The restoration was constructed

“ ” [12]

information for biogeneric reconstruction of posterior teeth from the distal adjacent tooth. If necessary, manual adjustments of the biogeneric proposal were made on the oral/buccal and the proximal contact surfaces. Concerning the occlusal surface, adjustments were only made to achieve at least 3 occlusal contact points in the central fossa for triangular stabilisation. Afterwards, the restoration was milled with CEREC® inLab MC XL (Serial number: 106645, Step Bur 12S, cylinder pointed bur 12S) using feldspathic ceramic blanks (Mark II, VITA Zahnfabrik, Bad Säckingen, Germany). The restoration was adapted to the preparation on the saw-cut-models using diamond burs (Gebr. Brasseler, Lemgo, Germany). The approximal contacts were fitted between the adjacent teeth. The number of the occlusal contacts on the milled restorations after their adaptation to the saw-cut-models as well as the number of triangular stabilising contact situations were counted as described before.

The gypsum replicas of the ceramic partial crowns placed on the preparations were scanned using CEREC® Bluecam with the same protocol as described above. Additionally, all partial crowns were modelled in wax on the same prepared teeth, creating at least 3 occlusal contact points as it was also demanded from the computer reconstruction. The modelling was done by a senior master dental technician with more than 30 years of experience. The wax-ups were also scanned using the previously described protocol. The scanned natural tooth surface, the preparation of the partial crown, the biogeneric reconstruction and scans of the wax-up and the final milled restoration are shown in Figure 2.



a **b** **c** **d** **e**

Fig. 2: Example showing one of the 39 cases for the a) original tooth, b) the preparation of the partial crown, replacing all cusps, c) the biogeneric reconstruction, d) the professional wax-up, and e) the scanned milled restoration

Objectives

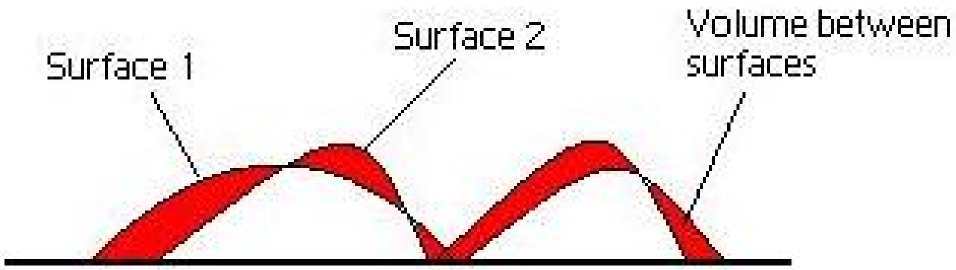
Hypothesis 1 was that the discrepancy between the natural tooth surface and the biogeneric reconstruction is less than the discrepancy between the original tooth surface and the professional wax-up.

Hypothesis 2 was that the difference between the natural tooth surface and the biogeneric restoration is less than the difference between the original tooth surface and the milled ceramic restoration due to the milling process.

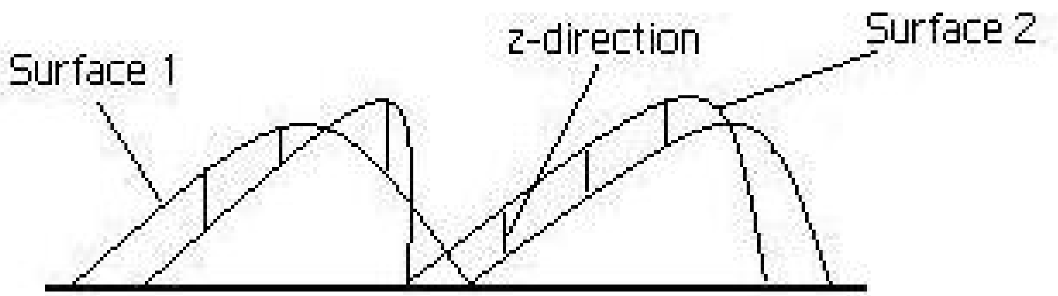
Data processing

All data sets were decrypted into the stl-format and transformed to a high-field data format (.xv) for matching purposes (Dent Visual v3.00) [10]. Three data sets were generated. First, we assessed the difference between the original tooth surface and the biogeneric reconstruction. Second, the difference between the original tooth and the wax-up was evaluated. Third, the difference between the natural tooth and the milled restoration was determined. All of the respective pairs were matched.

As field of interest the occlusal surface of the first molar maximum 1.0 mm outboard the connection line of the cusps was selected. This selection was done to avoid any influence of possible oral/buccal adjustments. Next, an image was generated to show differences between the two matched surfaces, along with descriptive data (Match3D, v2.50) [15]. The discrepancy between the two surfaces was evaluated in two ways. A graphical view of the principles behind these two methods is shown in Figure 3.



a



b

Fig. 3: Methods for determining the discrepancies between the two matched surfaces by a) volume differences and b) differences in z-direction

First, we determined the complete volume between the two surfaces divided by the flat area of the selected field of view. Second, the difference between the two surfaces in the z-direction was calculated by the span between the 20% and 80% quantiles according to the following formula [10]:

$$\Delta z = \frac{Q_{80\%} - Q_{20\%}}{2}$$

Statistical analysis

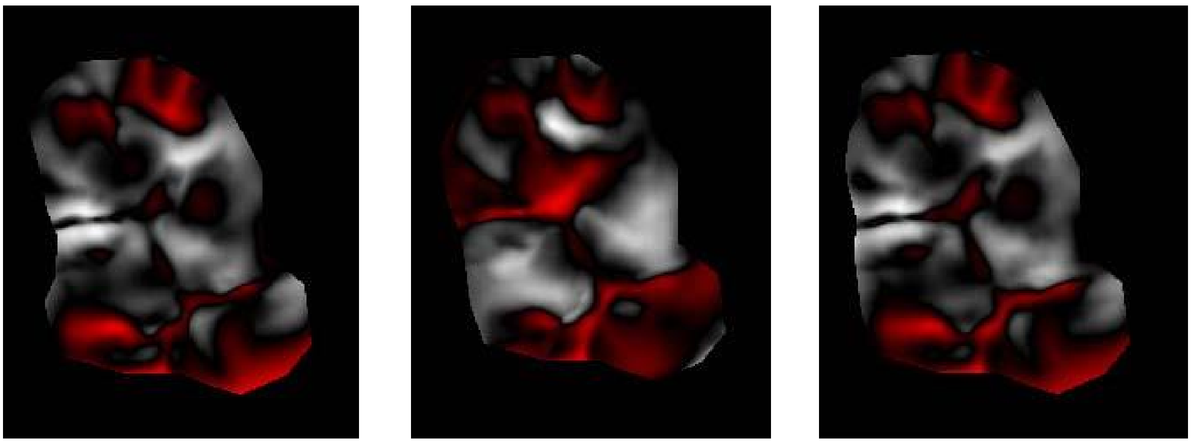
The statistical analysis of the data was performed using SPSS software (version 19). The mean and standard deviation (SD) of the described value differences were calculated across all cases. This was completed for both methods (volume/area, z-difference). To confirm the normal distribution of the data, a Kolmogorov-Smirnov analysis was performed [16].

F yp p p ’ -test (p 0.99 α-level 0.05, and corrected according to Bonferroni adjustment to 0.025 for 2 multiple tests). Correlations between the two methods used to describe the differences between the surfaces were later assessed using the Pearson product-moment correlation coefficient ($p \leq 0.01$).

The number of contact points (mean ± SD) and the percentage of triangular stabilised cases were given for the original teeth as well as the milled restorations.

RESULTS

Thirty-nine participants (mean age 23.0 ± 2.4 years) with 39 first molars (upper jaw n = 19, lower jaw n = 20; 1 tooth per person) were included in the study. The mean difference between the natural tooth surface and the biogeneric reconstruction was 184 ± 36 µm (volume/area) and 187 ± 41 µm (z-difference). The mean difference between the natural tooth surface and the wax-up was 263 ± 40µm (volume/area) and 269 ± 45 µm (z-difference). Finally, the mean difference between the natural surface and the milled restoration was 182 ± 40 µm (volume/area) and 184 ± 41 µm (z-difference). Images indicating the differences between these three pairs are shown in Figure 4.



a **b** **c**

Fig. 4: Images showing differences between a) natural surface and biogeneric reconstruction, b) natural surface and professional wax-up, and c) natural surface and scanned milled restoration

All different data sets showed normal distribution (Kolmogorov-Smirnov test, $p = 0.432$, $p = 0.950$, $p = 0.162$, $p = 0.745$, $p = 0.522$, $p = 0.599$).

Regarding the natural tooth surface, the biogeneric reconstruction was significantly more precise than the professional wax-up (t-test, $p < 0.0001$ by volume/area, $p < 0.0001$ by z-difference). Thus, hypothesis 1 was accepted. Also regarding the natural tooth surface, there was no significant difference between the milled restoration and the biogeneric reconstruction (t-test, $p = 0.423$ by volume, $p = 0.110$ by z-difference). Thus, hypothesis 2 was rejected. No loss of accuracy was noted during the milling process as values both before and after milling were nearly identical.

Based on the final data set, power calculation was performed (power = 1 at the set significance level of 0.0025) [17].

The two different methods of determining differences between the surfaces showed correlation with statistical significance ($p \leq 0.01$ $r = 0.965$ for the biogeneric reconstructions, $r = 0.914$ for the wax-ups, and $r = 0.952$ for the milled restorations).

On the original gypsum casts a mean of 2.8 (± 0.7) occlusal contacts were found guaranteeing a triangular stabilisation of the respective tooth in 28 out of the 39 cases (71.8%). Following the same protocol, a mean of 3.0 (± 0.5) occlusal contacts were found on the milled restorations with a triangular stabilisation in 34 out of the 39 examined partial crowns (87.2%).

DISCUSSION

We evaluated discrepancies ranging from 182 µm to 187 µm between the natural tooth surfaces and the biogeneric reconstructions or milled restorations, respectively, with no significant differences. The discrepancies between the natural tooth surfaces and the wax-ups were significantly greater, at approximately 265 µm. To the best of our knowledge, there is no other study comparing complete occlusal reconstructions to their original morphologies. A deviation of 150 µm from the original morphology has been reported for inlay reconstructions with an earlier software version [10]. This is in the same range as our findings, considering that complete occlusal surfaces were reconstructed in our study. The significantly higher discrepancies of the wax-ups found in our study were also reported by a previous study [18]. We found no significant differences regarding CAD reconstruction and milled restorations, which is consistent with an earlier study that compared contact point patterns between virtual reconstruction (CEREC® 3D) and milled CAM restorations and showed high levels of agreement [7]. This suggests that there is only a minimal loss of information from the CAD reconstruction during the milling process. We did not make major adjustments to the occlusal design because we wanted to evaluate the agreement between the uninfluenced biogeneric software function and natural morphology.

When reporting the above mentioned discrepancies, one must take into account the critical steps involved in the manufacturing process, especially scanning and milling, which can cause a certain degree of imprecision. The used scanning device (CEREC® Bluecam) has been associated with an accuracy of 19-35 µm, depending on the size of the scanned region [19]. This is negligible compared to the presented discrepancies of 182–269 µm. The software acquires the data for the biogeneric reconstruction not only from the distal adjacent tooth, but it also takes the antagonist situation into account. The bite registrate, however, may be a possible factor of imprecision as the antagonist could show signs of erosion, abrasion or an insufficient restoration. In this study, we looked after intact original tooth morphology of the distal adjacent tooth as the main information for the biogeneric reconstruction is gathered from this tooth. Regarding the milling process, a milling device accuracy of 53–140 µm has been reported, but for an older milling unit type [20]. Although we measured the difference between CAM restorations and natural tooth morphologies, we obtained discrepancies ranging from 182 µm to 184 µm. While milling imprecision seems to be a considerable part of such discrepancies, they may be irrelevant because no significant differences were observed with the CAD reconstructions with respect to the original morphology.

When looking at the number of occlusal contacts, it can be stated that there is no loss of stabilisation of the restored teeth. We showed that it is possible to reconstruct a full triangular stabilisation with the biogeneric tooth model with minimal adjustments during the reconstruction, even when there was no such stabilisation in the original situation.

To date, many different methods have been described to assess the discrepancy between original tooth morphology and CAD reconstructions, wax-ups or final CAM all-ceramic restorations. Subjective questionnaires have been used to evaluate the naturalness of the biogeneric reconstructions versus conventional CAD reconstructions, favouring biogeneric function [12]. Many authors have also evaluated vertical increases in the incisal plate of the articulator as an indicator of the quality of the occlusal surface. This method has been used for the evaluation of conventional CAD reconstructions, with values between 480 µm and 999 µm and 460 ± 190 µm for biogeneric reconstruction [12, 22, 23].

Another way to evaluate the quality of an occlusal surface reconstruction was reported recently. A dental technician rated the morphology of CAD crowns (CEREC® v2.80) regarding anatomical structure parameters, such as the location of the main fissure line, in comparison to conventional pressed all-ceramic crowns. The authors found no significant difference [21]. To describe the precision of CAD reconstructed occlusal surfaces, the same group compared the original contact point patterns to either the CAD reconstruction or conventionally manufactured IPS Empress crowns after occlusal adjustment. They found that the CAD reconstructed crowns showed 87% agreement in contact patterns while the conventional pressed ceramic crowns showed a 95% agreement, which was not statistically significant in difference [21]. Using a similar method, another study compared the contact point patterns and found a high level of agreement between milled crowns and CAD reconstructions. That study found a 78% agreement regarding number, 76% agreement regarding localisation and 65% agreement regarding the size and shape of the contact points [7].

In contrast to most other studies in the literature, the current paper utilised a mathematical approach to assess discrepancies between the different occlusal surfaces. We used a matching software with an automatic matching routine, which superimposed the two data sets and guaranteed the same orientation of the compared surfaces via a least square fitting routine [15]. On the one hand, output was measured using volume differences between two matched occlusal surfaces, which was divided by the flat area of the selected field of interest (first molar). On the other hand, differences in z-direction were calculated for several ten thousand surface points dependent on the specific surface [15]. Information related to the z-differences was shown as span between the 20% and 80% quantiles [10, 18]. In comparison to giving only the mean and standard deviation, quantiles were used to avoid any overestimation of the z-differences of steep peripheral surface areas. Both methods to describe the different images led to the same results and consequently showed a high level of correlation (> 90%) in our study. This mathematical approach was also used very recently in a clinical study [18], in which biogeneric reconstructions were compared with wax-ups in vivo, though without information regarding the intact, original tooth morphologies. However, the aim of our study was to assess the potential of biogeneric tooth models to create occlusal surfaces as close as possible to the original morphologies. This goal was achieved by first taking impressions of natural, unrestored, and caries free teeth, followed by preparations performed on gypsum replicas.

During the study, we missed a virtual articulator that was included into the software for the purpose of accounting for dynamic occlusal contacts during crown design. This may have been one potential source of compromised precision regarding the clinical use of the software. In particular, older individuals may have had teeth that were already restored or abraded, with little morphological details remaining. Consequently, the biogenerically-reconstructed surfaces would have shown fewer relevant details.

CONCLUSION

Within the limits of the study, there was a high level of agreement between biogenerically reconstructed occlusal surfaces and the original tooth morphologies, even when all tooth cusps were replaced. Moreover, information regarding the surface pattern was not lost during the milling process. This enables a more natural morphology of the CAD/CAM restorations for state of the art clinical indications. Examples include biogeneric reconstructions of full crowns or fixed partial dentures using innovative materials such as lithium silicate ceramics [24], as well as fabrications of long-term provisional crowns made of new polymer materials, such as VITA CAD-Temp® for CEREC® [25].

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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8 Veröffentlichung II

Comparison of chairside and laboratory CAD/CAM to conventional produced all-ceramic crowns regarding morphology, occlusion, and aesthetics

2015

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ABSTRACT

Objectives: There are many ways to produce all-ceramic crowns. CAD/CAM procedures compete against conventional fabricated restorations. As different methods of production may produce variable results, this study aims to compare chairside and laboratory-based CAD/CAM-systems to conventional crowns regarding their similarity to original tooth morphology, number of occlusal contacts, occlusal adjustment time, and subjective aesthetic perception.

Material and Methods: Impressions of caries-free jaws were taken, and the resulting gypsum casts were scanned with a laboratory scanner. Preparations for all-ceramic full crowns were performed on first molars, and three different restorations were made: CEREC-restorations (CER), laboratory-produced CAD/CAM crowns (LABCAD), and conventional waxed-up/pressed ceramic crowns (CONV). Time for occlusal adaptation and the number of occlusal contacts were noted. Two dentists performed aesthetic gradings of restorations. Statistical analysis included one-way-ANOVA with LSD-Post-Hoc-Test, t-test, and Kruskal-Wallis Test.

Results: Metrical deviations of the re-scanned crowns to the original, unprepared tooth surface were 220.55 ± 54.31µm for CER, 265.94 ± 61.39 for LABCAD and 252.44 ± 68.77µm for CONV group. One-way-ANOVA showed significant lower deviations for the CER group. LABCAD crowns showed significantly more occlusal contacts, whereas CONV crowns required least time for occlusal adaptation and excellent aesthetic gradings.

Conclusion: All three methods had pros and cons regarding different parameters. Further improvements of CAD/CAM software shall lead to restorations comparable to conventional restorations in all aspects, especially in aesthetics.

Clinical relevance: All tested methods of production for all-ceramic crowns produced clinically acceptable results. Thus, in an individual case, the method

y ’ p .

INTRODUCTION

In the field of CAD/CAM technology in dentistry, different philosophies exist regarding the manufacturing process of dental restorations. Systems with intraoral scanning devices and in-practice milling-devices allow for a quick p . T p “ ” crowns. Other manufacturers provide only intraoral scanners with the possibility to transfer the scanned data sets to a commercial dental laboratory for CAD/CA . T “ ” of CAD/CAM dentistry is the digital acquisition of gypsum casts made from conventional impressions, which is followed by the CAD/CAM process in the dental laboratory [1-5]. All of these methods are currently used, but few studies have directly compared objective parameters between these methods. A very important issue in evaluating dental restorations is the reconstruction of harmonic occlusal surfaces regarding the original anatomy, aesthetic and functional parameters. A recent study showed that the CEREC system (Sirona, Bensheim, Germany) could reconstruct partial defects of the original occlusal surface with an accuracy of 222.0 ± 47.7 µ y accurate than a control group with waxed-up restorations by a dental technician with values of 310.2 ± 78.8 µ [6]. A other study showed the same effect even for complete occlusal surfaces [7]. Additionally, the biogeneric tooth model, first introduced in 2005 [8], seems to be superior to conventional CAD systems [9]. As most of the laboratory CAD software is based on standard morphology databases with individual adaptation to the concrete situation, targeting results similar to that obtained by biogeneric systems is still of great interest. To our current knowledge, there is no study investigating the precision of restorations fabricated with laboratory CAD systems in comparison to a CAD/CAM concept based on an intraoral scanner.

Another important factor to investigate is the time needed for adjustment of the occlusal surface for each manufacturing method. In a recent study, this time

“ ” “ y”

[10].

As there have been many improvements to software and milling parameters in the last five years [11], this study aims to investigate the performance of different CAD/CAM strategies on preparations for all-ceramic full crowns. Therefore, three restorations for each preparation were made: one using the CEREC system (Omnicam and MC XL milling device), one restoration with the help of a laboratory scanner/milling-unit combination (scanner: Tizian Smart Scan, Schütz Dental, Rosbach, Germany; milling system: CoriTEC 550i, imes-icore, Eiterfeld, Germany), and one restoration conventionally waxed-up and pressed from ceramic blanks by a dental technician. These finished restorations were evaluated regarding the number of occlusal contacts achieved, the time needed for occlusal adjustment, and the accordance of the restoration surface to the original morphology. Additionally, a subjective aesthetic grading of the restorations was conducted.

MATERIALS AND METHODS

Participants

The study was granted ethics approval by the local ethics committee at the University of Munich (No. 022-10).

Inclusion criteria for this clinical study required participants to have had at least one jaw with complete second dentition without active carious lesions, restorations or other defects of tooth hard substances such as erosion or abrasion. Patients with conservative or prosthetic restorations, extended fissure sealings, or signs of malocclusion such as Angle Class II or III or uni-/bilateral crossbite were excluded from the study. After selection of potential candidates for participation, informed written consent was obtained from all participants willing to take part in the study.

Impressions, models and preparations

Impressions of the complete jaws of patients were taken with addition-curing silicone (Aquasil Ultra, Dentsply De Trey, Konstanz, Germany). The antagonist jaw was molded with alginate (Trealgin Chromatic, Schütz Dental, Rosbach, Germany). For patients with both jaws meeting the inclusion criteria, the jaw for impression was randomly selected using a random selection program (SPSS, version 22, SPSS Inc., Chicago, IL, USA). Habitual occlusion contacts of the patients were marked with occlusion foil, and the situation was photographed for further reconstruction of the original occlusal situation.

The impressions were poured out twice with type IV gypsum (MM Dental, Gummersbach, Germany), and saw cut models were prepared. The gypsum casts of the upper and lower jaw of each patient were manually adapted in habitual occlusion and placed in a semi-adjustable articulator (Artex, AmmanGirrbach, Pforzheim, Germany). The occlusal contacts were marked with occlusion foil, and the contact pattern was confirmed to be nearly identical in number and position with the documented intraoral situation. All materials were used ’ ions.

A randomly chosen first molar was then prepared for a complete all-ceramic crown restoration. The same dentist, with experience in the preparation design of all-ceramic restorations, performed all of the preparations. Based on the recommendations for all-ceramic restorations, we verified a minimum occlusal and circular removal of tooth substance of 2 mm. This verification was performed to avoid any fractures due to an insufficient thickness of the ceramic restoration. In addition, the cervical margin was formed as accentuated chamfer preparation, and all inner edges were rounded to finish the preparation [11, 12].

Construction procedures of all-ceramic crowns

For every preparation, three ceramic crowns were made by different procedures. A “ p ” (CONV) by an experienced dental technician blinded to the original tooth morphology. After the wax restoration was embedded, the lost-wax-form was pressed out of feldspathic ceramic (PM 9, VITA Zahnfabrik, Bad Säckingen, Germany).

The CEREC system, representative of the systems used in private dental practices, was used to design the first group of crowns (CER group). For this system, the preparations on the gypsum casts were scanned with the CEREC Omnicam (software version 4.2) from all directions to gather a complete virtual image of the preparation. The minimum occlusal thickness was set at 1.5 mm ’ p . A to the same protocol, the antagonist quadrant and a buccal scan of the two gypsum casts in habitual occlusion were performed. After the virtual models were trimmed and the preparation margin was placed, the insertion axis was determined to be as best as possible parallel to the axis of the respective tooth and perpendicular to the occlusal plane. The reconstruction was performed via “ ” C R C . T gathers information from the remaining, intact tooth morphology to generate a natural occlusal surface convenient to the adjacent teeth [8, 14]. Only minimal adjustments to the restoration proposal of the software were made on the proximal and oral/buccal surfaces, to guarantee an optimal biogeneric design of the occlusal anatomy. Finally, the restorations were milled out of feldspathic ceramic blanks (Mark II, VITA Zahnfabrik) on a CEREC inLab MC XL device (serial number: 106645, Step bur 12S, cylinder pointed bur 12S).

In the final group, incorporating the laboratory CAD/CAM process (LABCAD), the gypsum casts were scanned with a stripe-lite-scanner (Tizian Smart Scan, Schütz Dental) according to the protocol of the integrated software: Separated scans of the prepared tooth stump and the adjacent teeth were performed, followed by a scan of the antagonist jaw and a scan in habitual occlusion of the upper and lower jaw. The design of the restorations was performed with the help of the CAD-software by a dental technician well versed in CAD/CAM procedures (Dental Designer 2014, v2.9.9.3, 3shape). This software selects fitting tooth morphologies from a database included in the software, which was manually adapted to the individual situation and the antagonist anatomy by “ ” . ing of the restorations was performed using feldspathic ceramic blanks (VITA Mark II) with a laboratory CAM-device (CoriTEC 550i, 4 axis used during fabrication, imes-icore) and diamond burs with a minimum thickness of 0.6 mm of the final bur under constant water-cooling.

All restorations from the three groups were adjusted to the preparation with diamond burs when necessary (Gebr. Brasseler, Lemgo, Germany). Therefore, the marginal fit was checked with a dental probe and the internal fit was adjusted, so that a smoothly coat with occlusion spray was achieved. The proximal contacts were adapted to obtain an exact fit of the restoration on the gypsum, so that shimstock foil could pass through the proximal contact with slight inhibition. Afterwards, the occlusal contact situation was adapted in an articulator until no more bite rising through the restoration could be detected. This adaptation was done with the help of occlusion and shimstock foil. The time needed for adaptation of the occlusal surface was measured and noted for each restoration in all groups. When this process was finished, the numbers of occlusal contacts on the restorations were counted.

To compare the morphology of the restorations to the original tooth morphology, the gypsum casts with the respective restoration placed on the prepared teeth were scanned again with the Tizian Smart Scan system. In addition, the original tooth morphology from the second gypsum was scanned with the same protocol as described previously.

Data processing

All scan data sets for each restoration and the data sets of the original tooth morphology were saved as stl-data-sets and transformed to a high-field data format (.xv) to facilitate the matching process (Dent Visual v3.00, [15]). Figure 2 shows a representative set of restorations along with the original morphology.

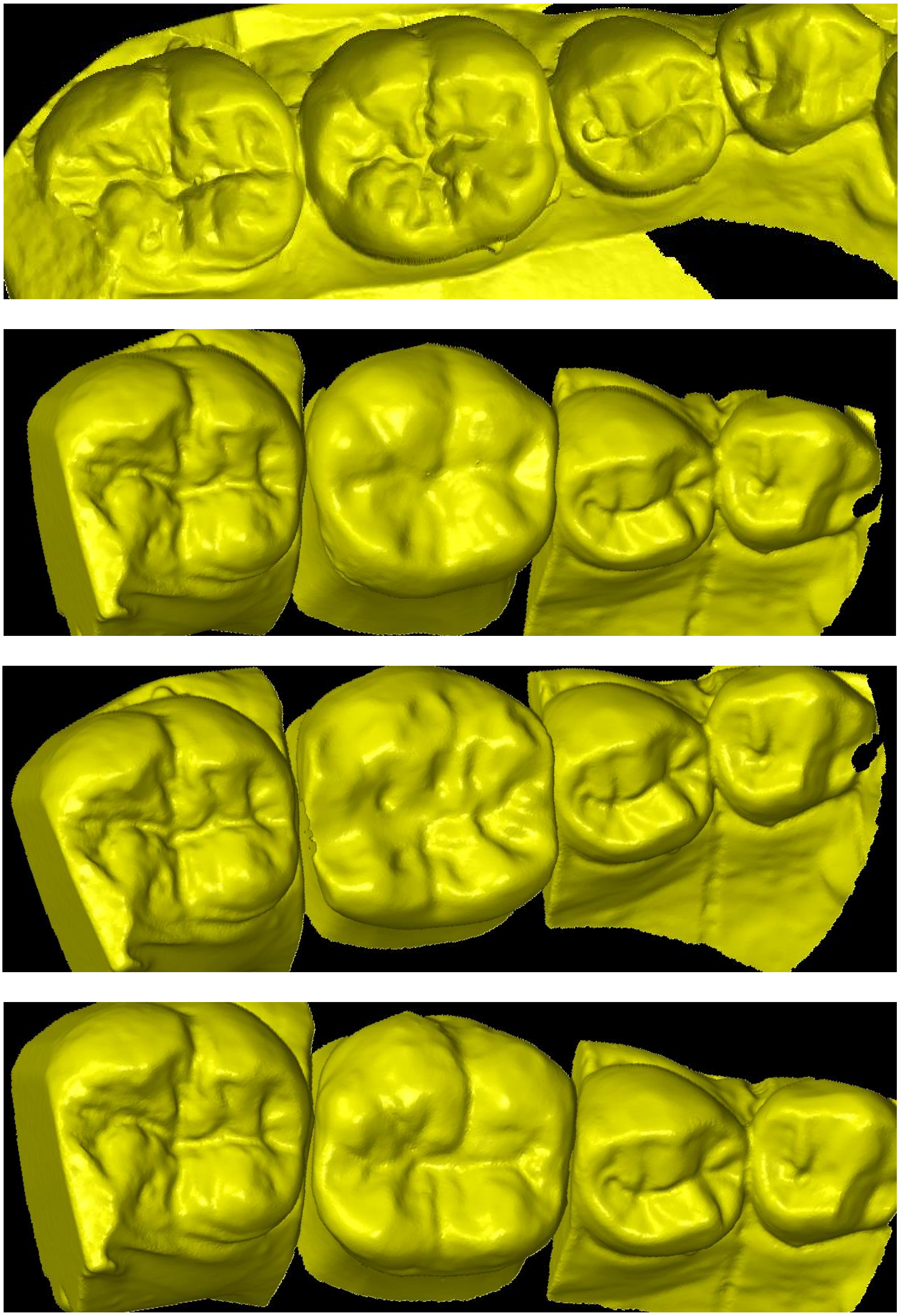

Fig. 2: Exemplary case for a) natural tooth surface, b) CER restoration, c) LABCAD restoration, d) CONV restoration

The three different restoration groups were each matched to the original morphology via a best-fit algorithm (Match3D, v2.50; [16]). The field of interest was determined as the area inside a line 1 mm outside the connection line of the cusps to avoid any influence of adjustments on the buccal/oral surface made during cutting the sprues. After this matching process, difference images between the two surfaces were generated along with descriptive statistic data. The discrepancies were determined by two different methods. One method was the determination of the volume between the two matched surfaces, which was

y (“ / ”).

Therefore, the absolute values of positive and negative deviations were added. The second method was based on the differences between the surfaces in the z-direction by a calculation of the 20 and 80% quantiles according to the

(“ q ” [15]).

$$\Delta z = \frac{Q_{80\%} - Q_{20\%}}{2}$$

This range was chosen to avoid any influence of errors on the margin of the field of interest.

To evaluate the aesthetics of the restorations, they were rated with the help of a visual analogue scale (VAS). The examiners evaluated the naturalness of the occlusal morphology in regard to a harmonic overall impression of the

. T “0” (p y)

millimeters and then noted. Two dentists performed duplicate evaluations with two weeks between the ratings. The overall workflow is illustrated in Figure 1.

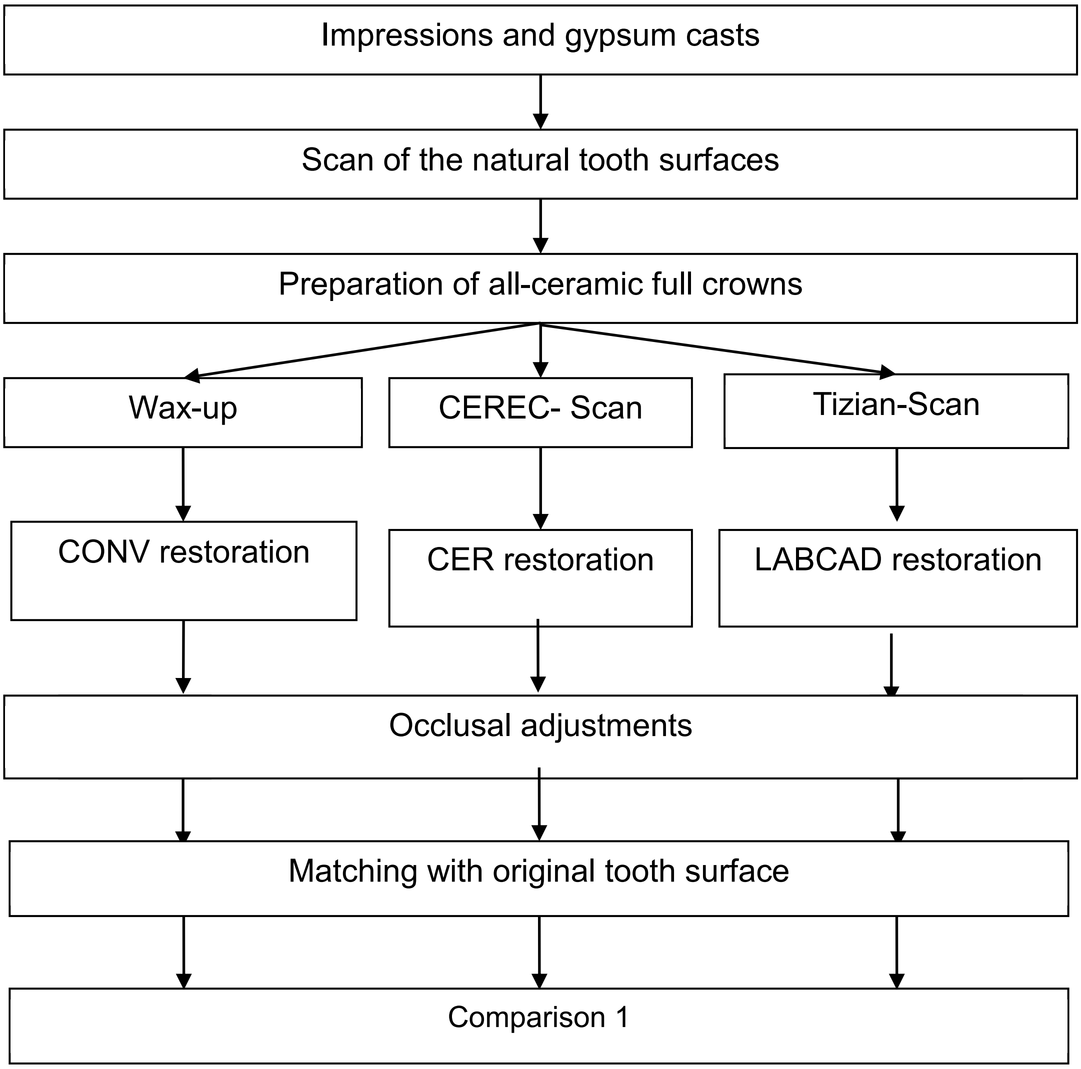

Fig. 1: Workflow from the impressions to statistical analysis

Statistical analysis

Statistical analysis of the collected data was performed using SPSS statistical software (version 22). The differences for all methods (z difference, volume/area) were analyzed by one-way ANOVA with LSD-Post-Hoc tests (α-Level for all tests 0.05). Additionally, the time needed for occlusal adaptation was also analyzed by one-way ANOVA with LSD-Post-Hoc test. The y p y ’ test ($p < 0.05$).

In addition, the number of contacts achieved for every restoration was analyzed via the nonparametric Kruskal-Wallis Test (α-Level 0.05). Further tests between the groups were conducted by Mann-Whitney-U-Tests with an adjustment of the significance level to 0.016 for three multiple tests (correction after Bonferroni).

T VA y p y ’

t-tests were performed to evaluate possible differences between the groups (α-Level 0.016 for three multiple tests). Intra- and inter-rater reliability were visually analyzed via Bland-Altman-plots [17].

RESULTS

To evaluate the discrepancies between three different fabrication methods for full-ceramic single crowns, impressions were taken from 22 patients. Based on the selected 22 sets of teeth, crowns were manufactured for each group and matched to the original tooth morphology after optical acquisition of the crown surface.

The differences between the surface of the original tooth and the adapted crown made by the CEREC system (CER) were 220.55 ± 54.31 µm by the volume/area method and 229.27 ± 64.82 µm by the quantile method. Accordingly, the deviation for the CONV and LABCAD group was 252.44 ± 68.77 µm (265.94 ± 61.39 µm) by the volume/area method and 266.43 ± 69.47 µm (274.55 ± 65.62 µ) y q . ’ y significant between the groups (*p* = 0.842). One-way ANOVA analysis showed a significant difference between the discrepancies to the original tooth morphology for each manufactory group ($p = 0.03$; $\eta^2 = 0.093$). LSD Post-hoc tests showed a significant smaller discrepancy for the CEREC crowns than for the crowns made by the laboratory CAD system ($p = 0.21$, volume/area method; $p = 0.21$, quantile method). Moreover, no differences between the groups were observed.

The descriptive results for the number of contact points, time needed for occlusal adjustment and the aesthetic grading are given in table 1.

	Number of occlusal contacts (mean ± SD)	Time needed for occlusal adaptation [s] (mean ± SD)	Aesthetic grading (examiner 1) (mean ± SD)	Aesthetic grading (examiner 2) (mean ± SD)
Original tooth		---	---	---
CER	5.7 ± 1.5	129 ± 73	65,9 ± 12,9	67,2 ± 22,1
LABCAD	7.1 ± 1.9	120 ± 51	68,0 ± 6,6	57,4 ± 18,5
CONV	5.3 ± 1.9	68 ± 43	81,5 ± 5,3	76,1 ± 12,8

Table 1: Summary of the results regarding occlusion and aesthetics

Regarding the number of contact points achieved by the restoration, it can be stated that all restorations showed the minimum number of three contacts (one “A” “B” “C” p) en shown to be necessary for a correct occlusal triangulation. Furthermore, the Kruskal-Wallis-Test showed significant differences between the three groups (p = 0.003). The following comparisons with the Mann-Whitney-U-Test between two groups each showed that the number of contact points of the LABCAD group was significantly higher than the CER and the CONV groups (p = 0.008; p = 0.002).

When determining the time needed for occlusal adaptation, one-way ANOVA (’ : p = 0.119) showed highly significant influences on the method chosen for fabrication of the crowns (p = 0.001, η^2 = 0.189). Post-hoc LSD tests showed that the time needed for adaptation was significantly lower in the CONV group than in the CER and the LABCAD groups (p = 0.001; p = 0.003), whereas the CER and the LABCAD groups showed no significant differences.

The aesthetic grading of the achieved restorations by the three different methods showed major differences between the groups. The VAS-values of the CONV group were significantly superior to the values of the LABCAD and CER groups (both $p < 0.0001$). Between the values of the LABCAD and the CER groups, no significant differences were found. Bland-Altman-plots for intra- and inter-rater reliability showed a high accordance between the examiners and between the first and second aesthetic grading. Table 1 shows the exact numbers for the number of occlusal contacts, time needed for adjustment, and aesthetic grading for each group.

DISCUSSION

In this study, we wanted to investigate the differences of occlusal morphologies of full all-ceramic single crowns. Three different fabrication methods were chosen. The CER group showed discrepancies of approximately 225 µm representing the slightest differences to the original teeth surfaces, whereas the LABCAD group showed statistically significant greater discrepancies of approximately 270 µm. This is a surprising result, because the burs of the LABCAD systems are smaller (final bur diameter 0.6 mm) than those used in the CEREC-system, which would lead to the estimation that the LABCAD system would result in smaller discrepancies. Therefore, the reason for the higher discrepancies in the LABCAD group must be assumed in the reconstruction or scanning process. The CONV group containing waxed-up and pressed ceramic restorations showed discrepancies of approximately 260 µm, which was not statistically significantly different from the other groups. Looking on the volume/area method, it was interesting, that none of the fabrication methods showed a tendency on too high or too low restorations. The values for positive and negative deviations were nearly identical in most of the cases.

Previous studies have already shown that the implemented biogeneric system for tooth reconstruction in the CEREC software creates excellent occlusal tooth morphologies close to the original [7, 6]. In contrast to our study, Litzenburger and colleagues investigated the discrepancies of CAD-designed partial crowns to the original morphology compared to the discrepancies of waxed-up restorations by a dental technician. Those authors found differences of 310.2 ± 78.8 µm for the waxed-up restorations and 222.0 ± 47.7 µm for the biogeneric reconstruction. Another group of investigators found that the occlusal surfaces of biogeneric restorations (CEREC software v3.8beta) are close to the wax-up proposal of dental technicians [18].

Additionally, other authors have found that the computer generated surface differs from the milling result [19]. As occlusal adaptation is necessary in most cases, we decided to compare the surfaces of the restorations after an occlusal adaptation step of the fabricated ceramic restorations. Necessary changes to the occlusal surface to achieve acceptable occlusal conditions are included in the difference values measured by the following matching process. In 2009, a study reported that there was no significant difference between the contact patterns of CAD partial crowns (CEREC v3.00) and those of conventionally waxed-up restorations [20]. In contrast to those results, we found significant differences regarding the number of occlusal contacts between the groups. In our study, the LABCAD group showed the most occlusal contacts (7.1 ± 1.9), which was significantly more than those in the CER and CONV groups. Another study investigated different CEREC software types, where the CEREC connect software proved to be more effective than the inLab software in reconstructing the original contact patterns [21]. All of these results regarding the occlusal contacts, lead to the conclusion that all three manufacturing philosophies are able to reconstruct satisfactory occlusal surfaces. Especially there was no restoration with less than 3 occlusal contacts. Regarding the time expenditure needed for occlusal adjustment, the CONV group needed significantly less time for adaptation compared to the CER and LABCAD groups. This outcome may be due to the exact chance of reproduction of occlusal surfaces by the dental technician and a high precision of the pressing procedure. Other studies showed no significant differences in the adjustment time needed for different fabrication methods [10] or the time was difficult to measure in order to the different production philosophies examined in the respective study [22]. Furthermore, very few studies have investigated the differences between different laboratory CAD/CAM systems. One explanation may be the multitude of systems available. The few existing studies primarily focus on the accuracy and reliabil y y y “ ” y where systems with 5 milling axis showed the highest trueness for occlusal surfaces [23].

When examining the subjective aesthetic evaluation of the occlusal morphology, we found that the restorations waxed up by a dental technician and pressed from feldspathic ceramic showed the highest aesthetic grading significantly higher than those of the LABCAD and CER groups. Although, the restorations fabricated in the study had not been polished before aesthetic grading, this statistics should be reliable, as all restorations had the same conditions. Nevertheless, the overall VAS score would probably had been higher, if the restorations would have been polished before grading. In contrast to our results, Reich and coworkers did not find significant differences between CEREC and conventional restorations [10]. The significant differences and the superiority of the conventional restorations in regard to aesthetics found in the present study can be explained by the individual process of waxing up the restorations by an experienced dental technician, which lead to highly aesthetic occlusal morphologies. However, taking into account the morphology of the adjacent or antagonist teeth, these surfaces are not as close to the original, unprepared tooth as restorations generated with a biogeneric algorithm.

CONCLUSION

Based on this study, we can state that all tested methods for manufacturing all-ceramic full crowns produce acceptable results meeting a high technical standard, but some differences between the groups could be found. This circumstance can be explained by the different results within the parameters investigated. As expected, the biogeneric CEREC software delivers the most accurate restoration regarding the closure to the original surface, whereas the LABCAD group showed the most occlusal contact points resulting in the best occlusal triangulation. Regarding aesthetics, the conventional waxed-up restoration continues to deliver the best-rated results. Considering all of these results, it seems that there is no ideal method to fabricate all-ceramic restorations. In the future, further improvements of CAD/CAM systems can be expected, especially those focusing on the aesthetics of the restorations. This issue and the possibility of handling a large scope of dental materials will lead to an ongoing dissemination of CAD/CAM systems in dentistry.

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Conflict of interest

The author Maximilian Kollmuss declares that he has no conflicts of interests.
The author Stefan Kist declares that he has no conflicts of interests.
The author Julia Eliette Goeke declares that she has no conflicts of interests.
The author Reinhard Hickel declares that he has no conflicts of interests.
The author Karin Christine Huth declares that she has no conflicts of interests.

Ethical approval

This article does not contain any studies with animals performed by any of the authors.

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.

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Die Literaturangaben der jeweiligen Veröffentlichungen finden sich jeweils im T “R ” P !

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