IN VITRO WEAR RESISTANCE OF CONVENTIONAL AND MILLED DENTURE TEETH

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ABSTRACT

Susun Theresa Kim: In vitro wear resistance of conventional and milled denture teeth
(Under the direction of Donald Ryan Cook)

The study compared the wear resistance of conventional and milled double-cross-linked (DCL) polymethyl methacrylate resin (PMMA) and nano-composite infused resin denture teeth (NC). DCL PMMA and NC conventional denture teeth, and teeth milled from a DCL PMMA resin disc (DCL-CAM) and from a nano-composite and nano-ceramic infused resin disc (NC-CAM) underwent chewing simulation. The vertical changes after each 50,000 cycles up to 250,000 cycles and volumetric changes after 250,000 cycles were quantified using the Geomagic software. The wear of the conventional and milled denture teeth approximated a linear progression between 50,000 to 250,000 cycles. The conventional NC teeth wore the most by 3.4 times vertically and 12.3 times volumetrically than the milled NC-CAM, which wore the least. The wear resistance between the conventional and milled DCL PMMA teeth was not statistically different. Regarding wear resistance, the milled denture teeth (DCL-CAM and NC-CAM) are acceptable alternatives to the conventional denture teeth.

To my uncle, you have always been my role model.

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LIST OF ABBREVIATIONS AND SYMBOLS

Ø	Diameter of circle
>	Greater than
<	Less than
≤	Less than or equal to
±	Plus or minus
A2	Common neutral tooth shade from Vita shade guide
Al_2O_3	Aluminum oxide
ANOVA	Analysis of variance
°C	Celsius
CAD	Computer aided design
CAM	Computer aided manufacturing
CS	Chewing simulation
DCL	Double-cross-linked
DCL-CAM	Double-cross-linked, computer aided manufacturing
GPa	Giga Pascal
Hz	Hertz
ISFD	Implant supported fixed denture
kg	kilogram
LAS	Laser abrasion measurement system
LL6	lower lingual, size 6
MgO	Magnesium oxide
mm	millimeter

mm/s	millimeter per second
mm^3	cubic millimeter
MPa	Mega Pascal
n	Number of samples
N	Newton
NC	Nano-composite
NC-CAM	Nano-composite/nano-ceramic, computer aided manufacturing
NFC	Nano-filled composite
p	P-value
pH	Power of hydrogen
PMMA	Polymethyl methacrylate
PVS	Polyvinyl siloxane
RPM	Revolutions per minute
SiO2	Silicone dioxide
SR	System Removable
STL	Stereolithography, Standard triangle language, Standard tessellation language
UDMA	Urethane dimethacrylate
x	times
XZ	x- and z-axes

INTRODUCTION

1. Tooth wear

Tooth wear is a ubiquitous and complex multifactorial process. Global prevalence of tooth wear is estimated to be around 30% to 50%, and the prevalence has been increasing over time (Schleuter and Luka 2018). Men seem to have slightly higher prevalence than women, and tooth wear appears to become more prevalent with older age (Schleuter and Luka 2018). A positive correlation has been found with older age and prevalence; 37% of 15 to 18 years old, 42% of 25 to 28 years old, 56% of 35 to 38 years old, 53% of 45 to 48 years old, and 62% of 55 to 60 years old people had tooth wear in Israel (Vered et al. 2014). In high risk individuals with frequent acidic episodes, the prevalence and severity of tooth wear were higher (Schleuter and Luka 2018).

1.1. Physiologic and pathologic tooth wear

Tooth wear can progress physiologically or pathologically (Alqahtani 2013). In normal physiologic wear that occurs with aging, the average occlusal wear in molars and premolars is 29 microns and 15 microns per year, respectively (Lambrechts et al. 1989). Excessive pathologic wear could lead to temporomandibular disorder, esthetic and occlusal concerns, and pathology in the tooth (Turner and Missirlian 1984; Mjör 2001). Chronic and traumatic wear can lead to changes as seen by pulp calcification, pulp necrosis, and tertiary dentin formation (Mjör 2001). Ideal restorations and enamel would have comparable wear resistance to prevent accelerated occlusal wear (Lambrechts et al. 1987).

1.2 Dental anatomy and wear mechanisms

Enamel, the hardest surface in the body, is the protective outermost layer of the tooth. Various wear mechanisms include abrasion, attrition, erosion, and abfraction, which can wear away the enamel. Once the enamel layer is worn, the underlying dentin layer, which is softer, will wear relatively easily.

Abrasion is the process of wearing from abnormal mechanical process (The Glossary of Prosthodontic Terms 2017). Vigorous toothbrushing, for example, can cause abrasion and results in smooth notches typically on the buccal surfaces near the gingival line. Attrition is a mechanical wear that results from surfaces of teeth coming into contact with itself or with an object such as during teeth grinding or clenching (The Glossary of Prosthodontic Terms 2017). Attrition results in worn incisal or occlusal teeth surfaces. Erosion is the loss of tooth structure from chemical exposure, and are on the occlusal, facial, and cervical areas depending on the acidic source (The Glossary of Prosthodontic Terms 2017). With extrinsic etiology such as lemon sucking, the buccal surfaces of the teeth are affected, and with intrinsic etiology such as regurgitation, the lingual and palatal surfaces of the teeth are affected. The translucent enamel layer is worn away and results in an appearance of teeth discoloration with the more yellow dentin layer visible. Abfraction is the loss of hard tooth substance from biomechanical loading forces, and it is believed to result from degradation of enamel or dentin (The Glossary of Prosthodontic Terms 2017). Abfraction appears as sharper notches near the gingival line. Occlusal wear is multifactorial in nature and can involve one or more of these mechanisms in a patient.

1.3. Extrinsic, intrinsic, and idiopathic etiologic factors

Etiologic factors that cause tooth wear can be extrinsic, intrinsic, or idiopathic, depending on whether the source is exogenous, endogenous, or unknown (Imfeld 1996). Extrinsic etiologic factors include masticatory function, tooth morphology and position, diet, and tooth eruption pattern (Carlsson et al. 1985). Exogenous acidic sources include chlorinated swimming pool water, fresh fruits, fruit juices, and soft drinks (Geurten 2000; Miller 1950; Imfeld 1996). Intrinsic etiologic factors include enamel hardness, enamel thickness, parafunctional habits, gastroesophageal reflux disease, and bulimia (Basha et al. 2020; Guo et al. 2011; Lavelle 1970; Murphy 1959; Turner and Missirlian 1984). Etiologic factor of erosion is considered idiopathic when the acidic origin is unknown, and the medical history and tests exclude clear etiology (Imfeld 1996). Significant tooth wear alters the morphology of the occlusal tooth surface, occlusal support, vertical dimension of occlusion, and can lead to parafunction (Ramfjord and Ash 1983).

2. Full mouth rehabilitation

For edentulous patients or patients with terminal dentition including advanced non-restorable generalized wear requiring full arch rehabilitation treatment, there are various prosthetic options. Ideal treatment plan depends on numerous factors including the amount of lip mobility, restorative space, degree of bone resorption, anatomic limitations, sufficient oral hygiene access, and facial and dental esthetics (Taylor 1991; Pollini et al 2017). Full arch treatment options include conventional complete denture, implant assisted overdenture, and implant supported fixed denture (ISFD) (Taylor 1991). For an appropriate patient, a popular and relatively cost-effective treatment option is a fixed full arch restoration on multiple implants also known as All-on-4® prosthesis (Nobel Biocare, Kloten, Switzerland) and ISFD.

2.1. Implant supported fixed denture

With an implant survival rate of nearly 99% in 5 years, Eliasson et al. concluded that 4 implants of at least 10mm length can sufficiently retain a full arch fixed mandibular prosthesis (2000). In a 10-year clinical study, a predictable success rate of mandibular ISFD that is supported by 4 implants has also been documented with nearly 95% implant related success rate and 99% prosthetic survival rate (Malo et al. 2011).

In edentulous patients or patients with terminal dentition, implant assisted overdentures and ISFDs improve the masticatory efficiency and patient satisfaction over removable prostheses (Carlsson et al. 1994; Johar 2018). While patients with complete dentures were able to generate about 80N of maximal occlusal force, adding implants for an ISFD increased the maximal occlusal force to about 250N (Carlsson et al. 1994). While none of the subjects treated with conventional complete dentures were satisfied with the masticatory function provided by the removable prosthesis, adding two or more implants for an overdenture or an ISFD resulted in all the subjects satisfied (Johar 2018). Implant assisted and implant supported prostheses are well tolerated by patients (Johar 2018).

ISFDs can be fabricated with different restorative materials. In porcelain fused to metal prosthesis, a metal framework is layered with porcelain or cemented with porcelain crowns. In zirconia prosthesis, there is no metal framework and either zirconia is veneered with porcelain or the prosthesis is a digitally milled from a solid block of material and is called monolithic zirconia. With the metal acrylic prosthesis, the metal framework gives the prosthesis strength. The teeth can be set with individual denture teeth as it is done for conventional removable prostheses such as complete denture and removable partial denture, or they can be fabricated digitally as a full arch with the subtractive or additive computer aided design and computer aided manufacturing (CAD/CAM) processes.

2.2. Complications with implant supported fixed denture

Implant supported fixed denture, however, is not without complications. The posterior denture teeth wear over time in the patient's mouth. This leads to decrease and collapse in the vertical dimension of occlusion, and the anterior teeth can fracture and debond in excursive movements. Mandibular metal acrylic resin ISFDs that are opposing maxillary conventional complete dentures were found to have complications when they were followed for 15 to 20 years (McGlumphy et al. 2017). The average time the prostheses was in service was 18.5 years. Prosthetic complications include fractured teeth, need for tooth replacement, abutment screw fracture and loosening, retaining screw fracture and loosening, stripped screw, and framework fracture (McGlumphy et al. 2017). Nearly 46% of the patients had the acrylic resin tooth fracture, and 75% of the patients experienced wear in the prostheses (McGlumphy et al. 2017).

The wear of the prosthesis is the most common minor complication seen in ISFDs (Papaspyridakos et al. 2019). The wear of prosthetic teeth results from abrasion, adhesion, surface fatigue, and chemical disintegration, and is affected by numerous factors including neuromuscular forces, salivary flow, abrasive environmental exposure, diet, and the restorative material (Lindquist et al. 1995). Minor complications can be repaired chair side and these complications include wear or chipping of prosthesis, loss of the screw access sealing material, screw loosening, and loss of cement retention in a cement retained prosthesis (Papaspyridakos et al. 2019). Major complications required lab repair and these complications include fracture of the prosthesis, framework fracture, abutment fracture, screw fracture, and implant fracture (Papaspyridakos et al. 2019). Only 8.9% of the prostheses did not have any minor complication after 10 years (Papaspyridakos et al. 2019). Porcelain ISFDs had 7.3% of annual wear, and metal acrylic resin ISFDs had 19.4% of annual wear, which was significantly higher (Papaspyridakos et al. 2019).

2.3. Retreading implant supported fixed denture

The wear of the denture teeth can alter the occlusal scheme, lead to interferences during excursive movements, change the vertical dimension of occlusion, and cause temporomandibular disease symptoms (Balshi et al. 2016). Retread is the clinical and lab procedure to replace the worn teeth on the prosthesis (Balshi et al. 2016). After 7.8 years on average, metal acrylic ISFDs require replacement of the denture teeth (Balshi et al. 2016). The wear of the acrylic resin teeth was affected by the restorative material, the opposing dentition, and the patient's parafunctional habits.

Retreating process is recommended when there is a loss of one third of the coronal height of the incisors or significant occlusal changes in the remaining prosthetic teeth (Balshi et al. 2016). In the retread process, the worn veneering materials on the framework are removed and are replaced with new materials at the correct vertical dimension of occlusion. The prosthesis can be processed using the traditional denture processing technique. In one prosthodontics office between 1986 to 2010, 205 arches of ISFDs were retreaded in 194 patients (Balshi et al. 2016). Retreading process was required in the shortest span of time at 6 years when the opposing dentition was ceramic metal ISFD and in the longest span of time at 12 years when the opposing dentition was a transitional prosthesis (Balshi et al. 2016).

3. Denture teeth

Several generations of denture teeth have been introduced. Porcelain teeth were the first type of denture teeth used in modern dentistry (Munshi et al. 2017). While porcelain teeth had excellent wear resistance, they had critical issues including brittleness, poor bonding to denture base, and high abrasion to the opposing dentition (Munshi et al. 2017). Acrylic teeth were then introduced in 1930s with polymethyl methacrylate (PMMA) resin (Munshi et al. 2017). The PMMA resin teeth were not brittle like the porcelain teeth, was easy to contour, and had chemical bond to the denture base, but had poor wear resistance (Munshi et al. 2017).

The double-cross-linking (DCL) agents were then added to PMMA resin teeth to create more linkages in the polymer chains and to make the structure denser and more wear resistant (Munshi et al. 2017). The urethane dimethacrylate (UDMA) based denture teeth that are reinforced with inorganic fillers then became available (Munshi et al. 2017). The fillers were designed to increase hardness, material rigidity, and wear resistance, but these teeth had poor bonding to denture base and were more brittle and porous (Munshi et al. 2017).

3.1. Ivoclar teeth

In the conventional fabrication of ISFDs, prefabricated denture teeth are used. Ivoclar denture teeth include acrylic resin teeth made from filled and unfilled PMMA resin and nano-composite (NC) resin teeth (Ivoclar Vivadent Inc, Amherst, NY). The unfilled PMMA resin teeth are the classic denture teeth where non-cross-linked polymer is polymerized with monomer and cross-linking agent. The monomer and cross-linking agent are a composite resin of methyl methacrylate, dimethacrylate, and ethylene glycol dimethacrylate.

SR Phonares II is composed of four separate layers including the composite resin facial incisal layer, the composite resin dentin core layer, the PMMA resin cervical layer, and the PMMA resin back incisal layer (Ivoclar Vivadent Inc, Amherst, NY). The company reports the composite resin in the dentin core and the facial incisal layers provide high wear resistance and esthetics. The PMMA resin in the back incisal and cervical layers facilitates bonding with the conventional denture base material. SR Phonares II facial and incisal dentin layers are composed of nano-composite resin material with UDMA matrix that is filled with high density silanized SiO_2, inorganically filled UDMA polymer, silanized SiO_2 particles, and PMMA clusters. The UDMA and other methacrylate matrix allow for high degree cross-linking that is stable and resistant to chemical wear. The silanized SiO_2 is an inorganic filler that strengthens the matrix and increases the hardness and wear resistance. Inorganically filled UDMA polymer particles reduce the polymerization shrinkage stress.

3.2. Milled teeth

Ivoclar SR Vivadent CAD (DCL-CAM) is fabricated from a high wear resistant double cross-linked PMMA resin material (Ivoclar Vivadent Inc, Amherst, NY). It is designed to fabricate definitive denture teeth. It is introduced by Ivoclar as a comparable material to the Ivoclar Vivadent SR DCL conventional denture teeth.

Crystal Ultra Hybrid (NC-CAM) is the nano-composite and nano-ceramic infused resin disc that is gaining traction among dental labs fabricating implant supported full arch prostheses (Digital Dental, Scottsdale, AZ). The company reports Crystal Ultra Hybrid combines strong and esthetic nano-ceramic with Trilor, a strong resin. While there is no peer reviewed study available on Digital Dental's Crystal Ultra Hybrid, the company website and informational flyer suggest properties including modulus of elasticity of 0.7 Giga Pascal that is gentle as natural dentin. The shock absorption is said to be similar to that of natural enamel. At 490 MPa, compressive strength is said to be greater than other nano-ceramic commercially available. At 10 GPa, Crystal Ultra Hybrid is also said to be the most flexible ceramic that flexes in the mouth and does not chip, crack, or fracture under stress. These company reported data, however, are not yet published in peer reviewed papers.

Using milled acrylic resin is estimated to have fewer prosthetic complications, but it is unknown how it will affect the retreading period (Balshi et al. 2015). In conventional fabrication of ISFD, individual denture teeth are set on a framework as they would be for overdenture or complete denture, and are processed into a definitive prosthesis with acrylic resin. With subtractive CAD/CAM process, the entire arch of teeth in milled in one piece and is attached to the framework. With a full arch of monolithic teeth, there may be fewer prosthetic complications such as tooth debonding.

3.3. Related studies

There have been numerous papers published that studied the wear of various denture teeth in vitro. Due to the different denture teeth selected, preparation of the samples, testing conditions, and antagonists selected, the results are conflicting. Some papers conclude that the composite infused resin teeth wear more, and some conclude that the DCL PMMA resin teeth wear more.

1. Stober et al. (2006)
    a. Denture teeth: SR Postaris DCL (DCL PMMA), NC Veracia (NC)
    b. Antagonist: Ø4.8mm Al_2O_3 ball (Degussit, Friatec, Mannheim, Germany)
    c. Sample size: 7
    d. Test conditions: 40N axial load in a two-axis chewing simulator, chewing speed of 8mm/s to 30 mm/s, 25°C demineralized water rinses
    e. Total cycles: 100,000 cycles
    f. Wear measurement: mean volume loss
    g. Wear results: DCL: 55 mm^3 x 10^{-3}; NC: 87 mm^3x 10^{-3}
    h. Wear conclusion: DCL PMMA < NC

2. Ghazal et al. (2008)
    a. Denture teeth: SR Orthotyp DCL (DCL PMMA), Condyloform II NFC (micro-, nano-composite)
    b. Antagonist: Steatite ceramic ball
    c. Sample size: 8
    d. Test conditions: 49N load in two-axis chewing simulator, chewing speed 30 mm/s to 55 mm/s, 5°C/55° thermocycling
    e. Total cycles: 1,200,000 cycles
    f. Wear measurements: vertical and volume
    g. Wear results:
        a. Vertical: DCL: 164 µm; NC: 117 µm
        b. Volumetric: DCL: 0.249 mm^3; NC: 0.144 mm^3
    h. Wear conclusion: DCL PMMA > NC
3. Hahnel et al. (2009)
    a. Denture teeth: SR Postaris DCL (DCL PMMA), Condyloform II NFC (NC)
    b. Antagonist: Steatite ceramic ball, resin denture teeth, steel ball
    c. Sample size: 8
    d. Test conditions: buccal and facial tooth sample of Ø5mm and 2mm thickness, 50N axially by 2mm and 50N laterally by 1 mm, frequency of 1.2Hz, 5°/55°C thermocycling
    e. Total cycles: 120,000 cycles
    f. Wear measurement: vertical and volume
    g. Wear results (against steatite):

        a. Vertical: DCL: 523µm; NC: 95µm
        b. Volumetric: DCL: 138 μm^3; NC: $8 \mu m^3$
    h. Wear conclusion: DCL PMMA > NC

4. Heintze et al. (2012)
    a. Denture teeth: Ivoclar Vivadent DCL (DCL PMMA), Candulor NFC (EDMA, silanized silica fillers, PMMA)
    b. Antagonist: molar denture tooth, Ø2.3mm conical ceramic stylus, Ø6mm ball shaped ceramic stylus, Ø2.3mm conical denture tooth stylus
    c. Sample size: 10
    d. Test conditions: 3kg load over 3mm distance, 5°C/55°C thermocycling
    e. Total cycles: 100,000 cycles
    f. Wear measurement: vertical
    g. Wear results:
        a. Ceramic stylus: DCL: 79µm; NC: 220µm
        b. Denture tooth stylus: DCL: 422µm; NC: 156 µm
    h. Wear conclusion:
        a. Ceramic stylus: DCL PMMA < NC
        b. Denture tooth stylus: DCL PMMA > NC

5. Munshi et al. (2017)
    a. Denture teeth: Blueline DCL (DCL PMMA), SR Phonares (NC)
    b. Antagonist: Ø2mm stylus from the cusp of a maxillary molar denture tooth
    c. Sample size: 6

    d. Test conditions: disc specimen from the facial denture teeth surface, 5kg vertical load, 0.7kg/mm^2 pressure, 60 RPM, 37°C distilled water
    e. Total cycles: 50,000 cycles
    f. Wear measurement: vertical
    g. Wear results: DCL: 0.31mm; NC: 1.16mm
    h. Wear conclusion: DCL PMMA < NC

6. Esquivel et al. (2020)
    a. Denture teeth: Blueline DCL (DCL PMMA), SR Phonares II (NC), Telio CAD (CAD/CAM fabricated cross-linked PMMA)
    b. Antagonist: cone shaped milled zirconia
    c. Sample size: 8
    d. Test conditions: flat surface specimens, 20N vertical load, 2mm horizontal slide, 1Hz frequency, 33% glycerin solution
    e. Total cycles: 200,000 cycles
    f. Wear measurement: volume
    g. Wear results: DCL: 17.3mm^3; CAD/CAM PMMA: 11.9 mm^3; NC: 4.3 mm^3
    h. Wear conclusion: DCL PMMA > CAD/CAM PMMA > NC

4. Statement of purpose

While clinical trials would be most relevant to study the wear of denture teeth in patients, intraoral variables such as patient's salivary pH, diet, hygiene, neuromuscular force, and parafunctional habits can affect the wear results (Munshi et al. 2017). Studying prosthetic teeth wear with an in vitro study allows us to closely control the variables. The aims of the study were to compare the wear between the conventional and milled teeth, to compare the wear between

DCL PMMA resin and nanocomposite infused resin denture teeth, and to evaluate the relative wear of denture teeth over time.

MATERIALS AND METHODS

1. Study design

The in vitro study was designed to measure the occlusal wear of denture teeth material after a predetermined number of chewing cycles. The independent variables are the type of denture teeth and the number of chewing cycles, and the dependent variables are the occlusal wear depth and volume. The project has a mixed design with the sample group being a between-subjects factor and the chewing cycles being a within-subjects factor. The group of samples were followed through the experiment and they underwent the same testing conditions.

2. Denture teeth samples

Eight Ivoclar Vivadent SR ortholingual DCL teeth commonly called the Blueline teeth (DCL) and eight Ivoclar Vivadent SR Phonares II Lingual teeth commonly called the Phonares teeth (NC) were acquired (Ivoclar Vivadent Inc, Amherst, NY). To standardize the tooth morphology across the groups, the company brand (Ivoclar Vivadent), the tooth number (mandibular right second premolar), the degree of the cusps (15 degrees), the size of the mold (LL6 mold), and the tooth shade (A2) were kept consistent in the two conventional denture teeth groups.

Each conventional denture tooth of DCL and NC groups was randomly labeled number 1 to 8. Each DCL denture tooth surface was scanned using the 3Shape E2 desktop scanner (3Shape, Copenhagen, Denmark), and the stereolithography (STL) file was exported from the stereolithography CAD software. Each of the STL file of the DCL denture tooth was used to mill a tooth of the same morphology in the Ivoclar SR Vivadent CAD disc (DCL-CAM) (REF

686173 Lot #y14881) using the Ivoclar PrograMill PM7 milling machine (Ivoclar Vivadent, Inc, Amherst, NY) and in the Digital Dental Crystal Ultra Hybrid disc (NC-CAM) (Lot #160818) using the Digital Dental Wet Mill machine (Digital Dental, Scottsdale, AZ). Therefore, each STL of a DCL tooth created one DCL- CAM tooth and one NC-CAM tooth, while maintaining the numeric labelling of the DCL samples.

Table 1. Prosthetic teeth materials

Group Name	Brand	Product	Material	Manufacturing process	Cusp Angulation	Shape	Shade	N
DCL	Ivoclar Vivadent	Vivadent SR ortholingual DCL	Filled (organic filler) polymethyl methacylate resin	Conventional	15°	Lower right second premolar (Ivoclar mold LL6)	A2	8
NC	Ivoclar Vivadent	Vivadent SR Phonares II Lingual	Second generation nanocomposite resin	Conventional	15°	Lower right second premolar (Ivoclar mold LL6)	A2	8
DCL-CAM	Ivoclar Vivadent	SR Vivadent CAD	Filled (organic filler) polymethyl methacylate resin	Subtractive CAD/CAM	15°	Lower right second premolar (Ivoclar mold LL6)	A2	8
NC-CAM	Digital Dental	Crystal Ultra Hybrid	Nanocomposite resin with nanoceramic particles	Subtractive CAD/CAM	15°	Lower right second premolar (Ivoclar mold LL6)	A2	8

2.1. Recording the baseline sample morphology for vertical wear calculations

Light body regular set Aquasil Ultra polyvinyl siloxane (PVS) (Dentsply Sirona, Charlotte, NC) was used to obtain the impression of the occlusal surface for each sample prior to the start of the experiment. This initial impression for each sample was used as the baseline prior to the start of the chewing simulation. The PVS materials were allowed to fully set according to the manufacturer’s guideline prior to separation from the samples. Each sample was appropriately labelled by the group and the sample number from 1 to 8.

2.2. Recording the baseline sample morphology for volumetric wear calculations

STL scans of DCL denture teeth that were previously acquired with the 3Shape E2 desktop scanner were used as the baseline 3-dimensional surface scans of DCL, DCL-CAM, and NC-CAM groups. NC denture tooth was scanned using the same desktop scanner.

3. Loading the samples in the chewing simulator jigs

The samples were mounted in the VariDur 200 acrylic resin (Buehler, Illinois Tool Works, Lake Bluff, Illinois) within the chewing simulator jigs. The orientation of each sample was standardized using a dental surveyor. After the acrylic resin fully set according to the manufacturer’s recommended guideline, each of the eight samples per group was placed in the corresponding chamber for testing. A Ø6mm steatite antagonist (SD Mechatronik GmbH, Feldkirchen-Westerham, Germany), which is composed of 64% SiO_2, 31% MgO, and 4% Al_2O_3, was positioned on the functional buccal cusp of each sample to stimulate clinical setting. After the total chewing simulation was completed for a group, the process was repeated for each of the remaining groups.

4. Programming the chewing simulator

The CS-4 biaxial fatigue testing machine (SD Mechatronik GmbH, Feldkirchen-Westerham, Germany) was programmed with the following settings based on a published protocol by Roulet et al. (2007): each chewing run was programmed to 50,000 cycles with simulation frequency of 1.53 Hz, cold cycles at 5°C, hot cycles at 55°C, and thermocycling number to 711. In the vertical axis, the stroke up was 2mm and the stroke down was 2mm. The speed up was set to 60.0 mm/s and the speed down was set to 60mm/s. In the horizontal direction, the stroke horizontal was 0.7mm and the speed horizontal was 40.0mm/s. The samples underwent 49N of force.

5. Chewing simulation

The chewing simulator has 8 chambers. For each group, 8 samples were loaded to the chewing simulator at a time. After each 50,000 cycles, the chewing simulator was paused to collect a PVS impression of the occlusal surface without changing the loading orientation of the samples. Each sample group underwent a total of 250,000 cycles in the chewing simulator. The 250,000 chewing cycles are equivalent to slightly over one clinical year, and, therefore, 50,000 chewing cycles are roughly 2.5 clinical months (Heintze et al. 2011).

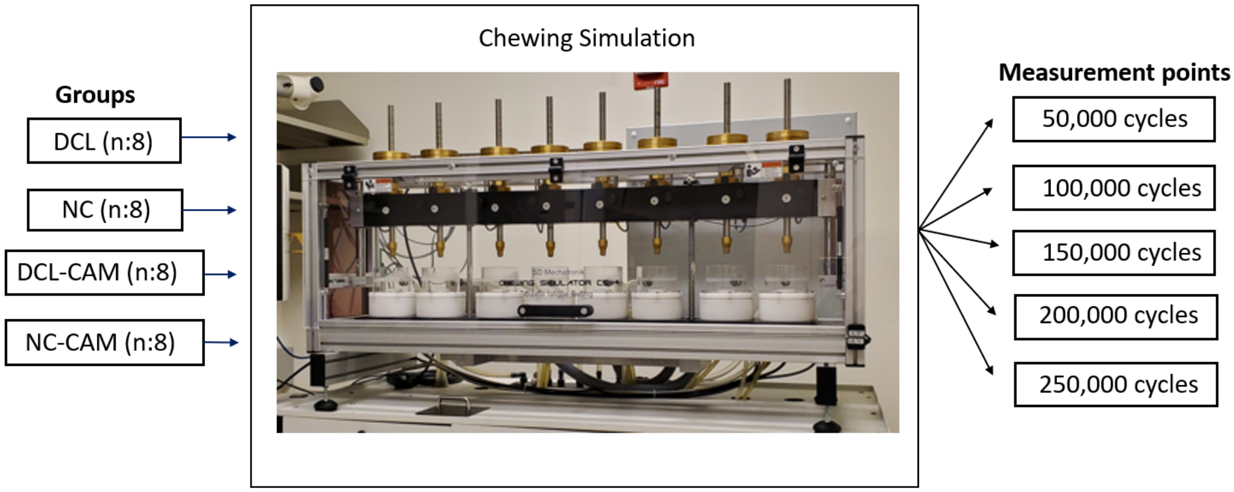


Figure 1. Flow chart of the samples undergoing chewing simulation

6. Calculating maximum vertical depth of wear

After each 50,000 cycles of chewing simulation, the machine was paused. The samples were dried with a paper towel, and the impression of the occlusal surface of the sample was made with the light body PVS. The process was repeated and the final impression was made when the chewing simulation reached 250,000 cycles for each group. The chewing simulation process was repeated for the remaining groups.

6.1. Scanning the samples

The PVS impression of a sample was placed on the Laser Scanner Laser Abrasion Measurement System-20 (LAS) desktop scanner (SD Mechatronik GmbH, Feldkirchen-Westerham, Germany). The resolution was set to 0.03mm. Each of the 192 impressions (4 groups with 8 replicates and 5 time points plus the baseline) was scanned.

6.2. Vertical data acquisition using the Geomagic software

The scanned image from the Laser Scanner was uploaded to the Geomagic software (3D Systems, Rock Hill, South Carolina). The borders of the images were trimmed to allow the baseline image of each sample and the experimental image to merge. The baseline image of a sample was used to merge with the images that were obtained after each 50,000 chewing cycles.

Any artifacts on the scans such as spikes and voids were removed and filled in with the Geomagic software. The baseline and the experimental files were initially merged with the tolerance setting on the “Best Fit Alignment” set to 0.08mm. Once initially merged, the samples were trimmed at the borders where they were no longer merged, which allowed the samples to be merged at a lower tolerance setting of 0.01mm.

Once the files were merged the second time, the fit was visually confirmed on the color map with green areas depicting well merged surfaces. The wear was visible as a negative change in the heat map color scale (from green to light blue to blue) as shown in Figure 3. Each heat map was confirmed that the maximum negative difference in the merged images was in the wear facet and not on an artifact or on the edges of the scan. The maximum negative distance, which quantitates the deepest point of wear, between the baseline and the experimental images was recorded. The heat maps show the relative depth, shape, and size of the wear in the groups from every 50,000 cycles up to 250,000 cycles.

7. Calculating volumetric wear

The experimental teeth after 250,000 cycles were recovered from the resin chewing simulator jigs by carefully sectioning and drilling the acrylic resin holding the tooth. The 32 teeth (4 groups with 8 replicates each) were scanned using the 3Shape E2 desktop scanner (3Shape, Copenhagen, Denmark).

7.1. Volumetric loss data acquisition using the Geomagic software

The 3-dimensional scans of the baseline teeth and the teeth after completing the 250,000 chewing cycles were uploaded to the Geomagic software (Figure 2A). Initial "Best Fit Alignment" was completed at 0.1mm tolerance which merged the two scans (Figure 2B). A "Trim with Plane" was selected in the XZ Plane (Figure 2C) to remove the excess sample surface below the occlusal surface (Figure 2D). The intaglio (Figure 2E) and cameo surface (Figure 2F) of the merged images were checked to confirm close merging. The "Best Fit Alignment" was repeated at a 0.01mm tolerance to result in a more accurate merging.

"Compute Volume to Plane" was selected in the XZ plane and the plane was adjusted to be below the wear facet in the intaglio view (Figure 2G) and in the cameo surface view (Figure 2H). The position of the align plane, the rotation of x degree, and the rotation in z degree were recorded, and the same values were used to set the plane for calculating the volume of the corresponding baseline scan to allow the equivalent portion of the sample to be used to calculate the volume (Figure 2I, 2J). The volume in mm^3 "above" the XZ plane was recorded as the volume of interest for the baseline and the experimental scans. The volume after 250,000 chewing cycles was subtracted from the baseline volume to obtain the wear facet volume. The process was repeated for the remaining samples.

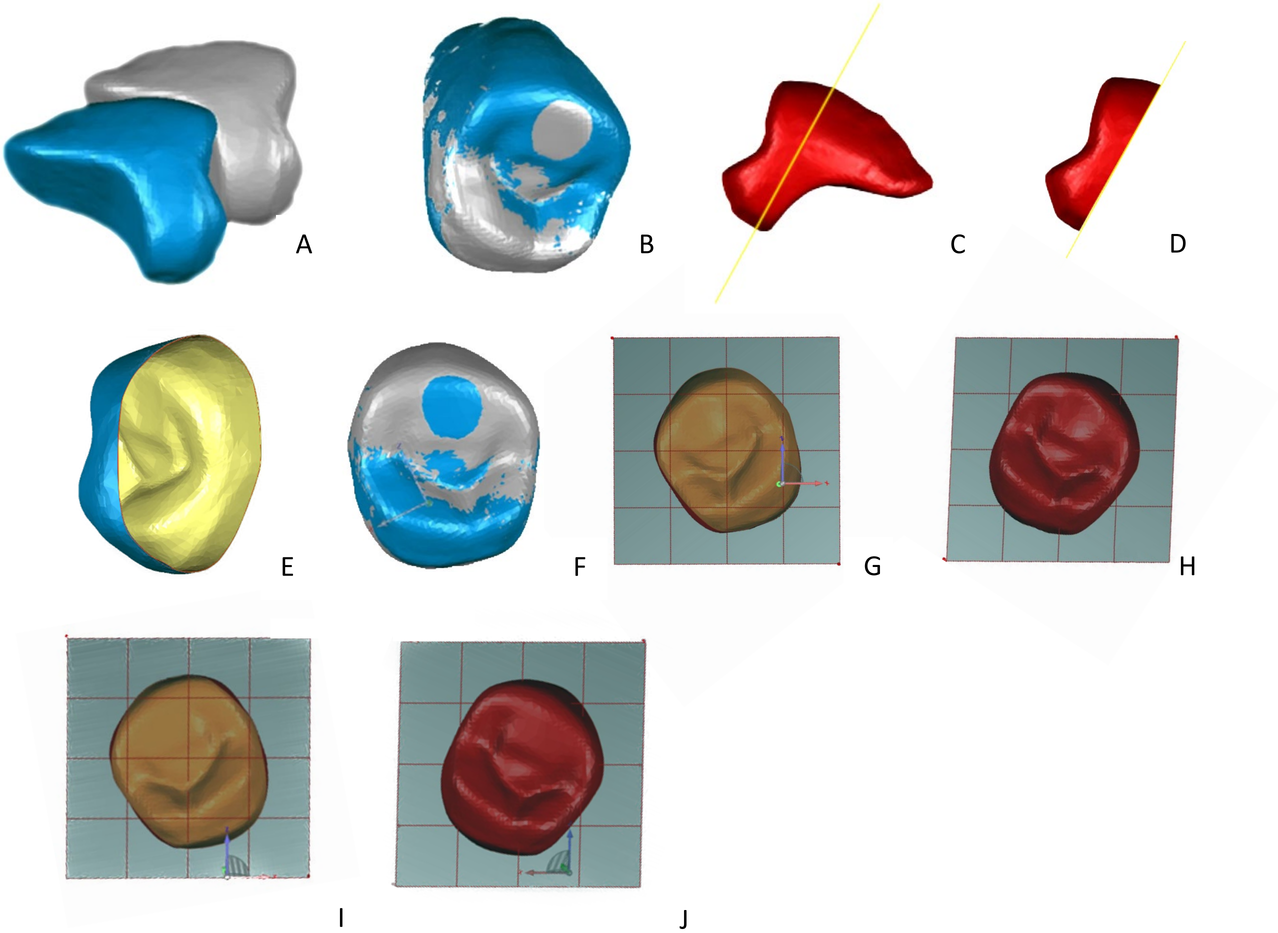


Figure 2. Preparation of the surface scans for volumetric wear calculations after 250,000 chewing cycles. A) The baseline 3-dimensional scan of a sample and the scan after 250,000 chewing cycles. B) Two scans are initially merged C) XZ plane is placed below the wear facet to section the sample below the plane D) The sample was sectioned below the specified XZ plane E) Close merging of the two images is confirmed on the intaglio of the merged images F) Close merging is confirmed on the cameo surface of the merged images G) XZ plane (in blue with red lines) is placed below the wear facet in the intaglio view and H) in the cameo surface view to calculate the volume above the XY plane. I and J) The XZ plane is placed in the same position as it was done for steps G and H for the baseline sectioned scan to calculate the baseline volume above the plane. The wear facet volume was calculated by subtracting the final volume obtained in steps G and H from the baseline volume obtained in steps I and J.

8. Statistical analyses and graphs

The GraphPad Prism software was used for the statistical analysis and to create the graphs (GraphPad Software, San Diego, CA).

8.1. Maximum vertical wear

For every 50,000 cycles up to 250,000 cycles, each group had a maximum depth measurement from each of the 8 replicates. The 8 replicates of values in mm were entered into the software in a grouped data table format. Two-way analysis of variance (ANOVA) with matched values, where each row represents a different time point, was selected. Bonferroni post-hoc test was selected to compare two groups of interest at a time. The four denture teeth groups were considered independent from one another. The level of significance was set to $p < 0.05$.

The vertical interleaved group bars were selected to plot the mean with standard deviation as shown in Figures 4 to 8. In Figures 5 to 8, the asterisk signifies a statistical significance of at least $p < 0.05$. In Figures 4 to 8, the maximum vertical loss in mm is graphed on the y-axis and the number of chewing cycles is graphed on the x-axis by a multiple of a hundred.

8.2. Volumetric wear

For each of the 8 replicates in a group, the volume of the wear facet was quantified. The 8 replicates of values in mm^3 were entered into the software in the column table format. One-way ANOVA was selected. Tukey post-hoc test was selected to compare all pairs of columns. The four denture teeth groups were considered independent from one another. The level of significance was set to $p < 0.05$.

A vertical column bar graph was selected to plot the mean with standard deviation as shown in Figure 10. The asterisk in Figure 10 signifies statistical significance of $p < 0.05$. The volumetric loss in mm^3 is graphed on the y-axis and the group is graphed on the x-axis.

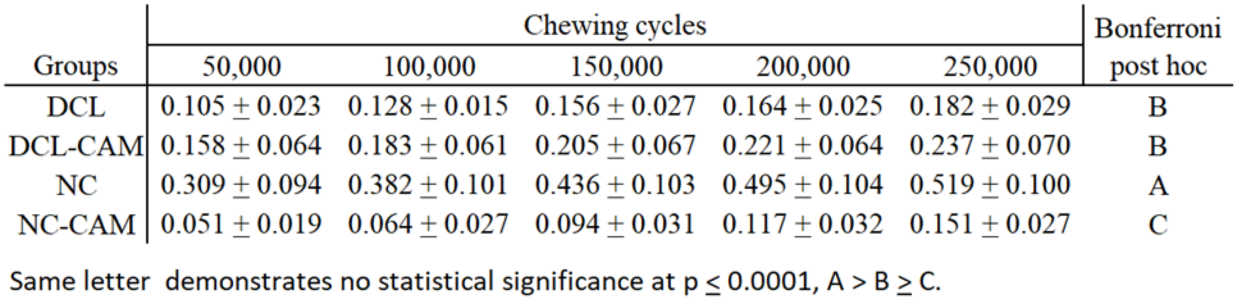
RESULTS

1. Maximum vertical wear

1.1. Heat map

The baseline sample scans merged successfully with the subsequent scans from 50,000 to 250,000 cycles. The merged area on the occlusal surface is showed as green up to ± 0.05mm of deviation as seen on the heat map scale (Figure 3). The wear on the samples after chewing simulation is shown as a negative change from the baseline scan, and is shown as light to dark blue (Figure 3). The chroma of blue shows the amount of vertical change, where darker saturation represents deeper wear in the samples. The wear facets are typically round and centered around the functional cusp where the tooth was set to occlude the steatite. As wear progresses from 50,000 to 250,000 cycles, the color of the wear area deepens from light blue to darker blue, with quantitative measurements that matches the visual trend (Table 2). The diameter and the circumference of the wear facets appear to gradually increase over time.

Table 2. Maximum vertical loss



Groups	Chewing cycles					Bonferroni post hoc
	50,000	100,000	150,000	200,000	250,000	
DCL	0.105 ± 0.023	0.128 ± 0.015	0.156 ± 0.027	0.164 ± 0.025	0.182 ± 0.029	B
DCL-CAM	0.158 ± 0.064	0.183 ± 0.061	0.205 ± 0.067	0.221 ± 0.064	0.237 ± 0.070	B
NC	0.309 ± 0.094	0.382 ± 0.101	0.436 ± 0.103	0.495 ± 0.104	0.519 ± 0.100	A
NC-CAM	0.051 ± 0.019	0.064 ± 0.027	0.094 ± 0.031	0.117 ± 0.032	0.151 ± 0.027	C

Same letter demonstrates no statistical significance at $p \leq 0.0001$, A > B ≥ C.

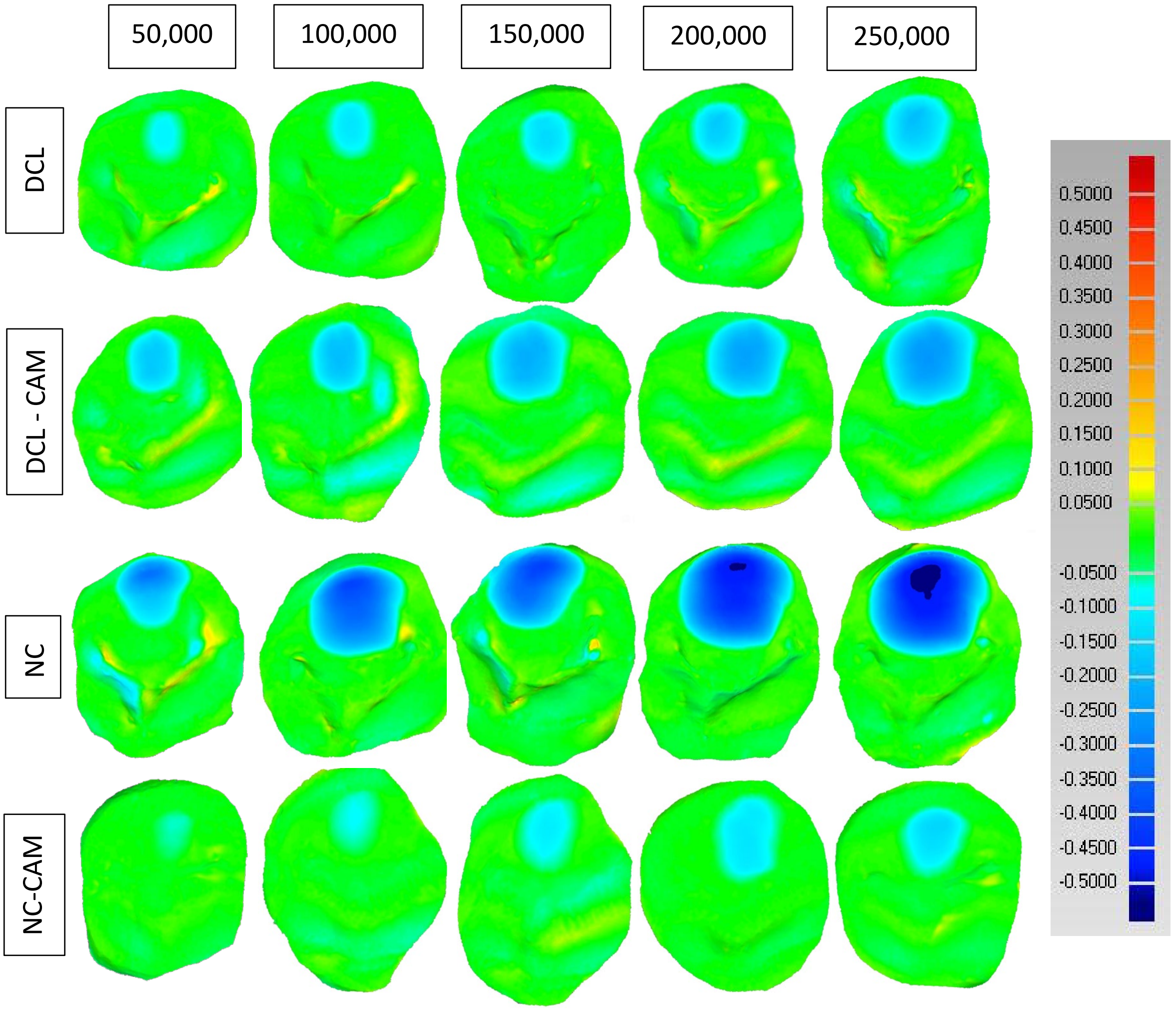


Figure 3. Heat map of the vertical changes after 50,000 to 250,000 chewing cycles.

1.2. Linear progression of wear

Over the experimental period up to 250,000 chewing cycles, the maximum vertical wear gradually increased for each group. A linear trend was observed from 50,000 to 250,000 cycles for each denture tooth group. This suggests that wear after a longer time point may possibly be extrapolated and predicted. Figure 4 shows the gradual increasing trend of the vertical wear in each group.

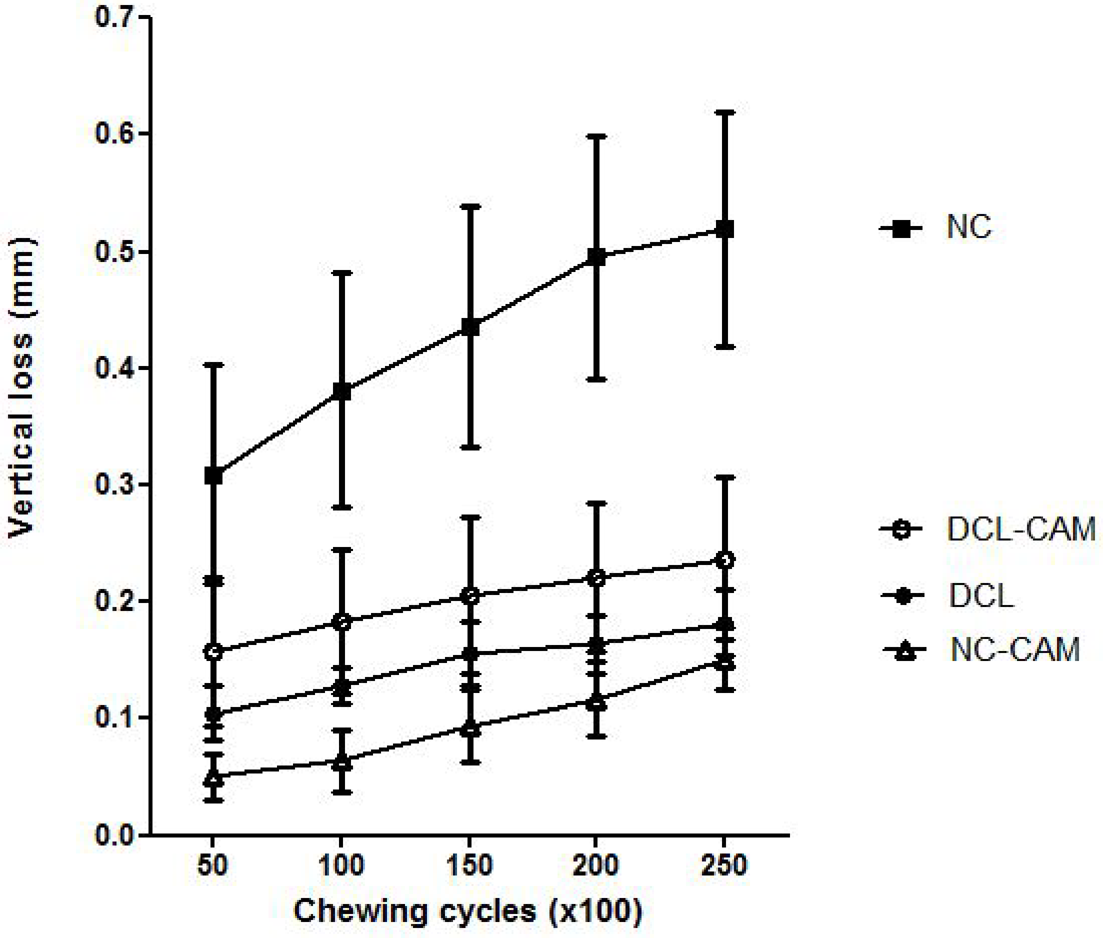


Figure 4. Vertical wear of the groups over 250,000 chewing cycles in mm. Mean and standard deviation are shown.

1.3. Wear in conventional denture teeth

Between the DCL and NC denture teeth, the NC denture teeth had a significantly greater maximum vertical wear at each of the measured chewing cycles including in the final 250,000 cycles (p<0.0001) (Figure 5). The NC's maximum wear depth was 2.8 to 3.0 times greater than that of DCL between 50,000 to 250,000 chewing cycles (Table 2).

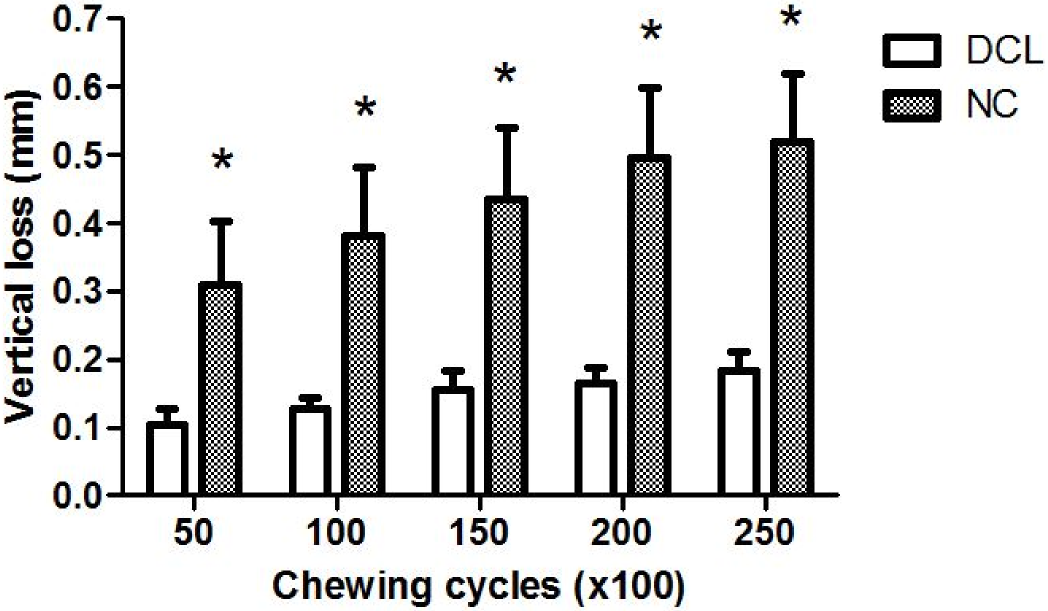


Figure 5. Vertical wear of the conventional denture teeth over 250,000 chewing cycles in mm. Mean and standard deviation shown. *Group NC is significantly different from Group DCL ($p < 0.0001$).

1.4. Wear in milled teeth

Between the two milled teeth, DCL-CAM and NC-CAM, the difference was statistically significant at all time points from 50,000 to 250,000 cycles ($p < 0.01$) (Figure 6). DCL-CAM's maximum wear depth was 1.6 to 3.1 times greater than that of NC-CAM between 50,000 to 250,000 chewing cycles (Table 2). After 250,000 chewing cycles, NC-CAM wore 0.151 ± 0.027mm, and DCL-CAM wore 0.237 ± 0.070mm ($p < 0.01$). The numerical difference in the value of the vertical wear between the two groups is less than 0.1mm after 250,000 cycles. The vertical wear in NC-CAM is 65% of the amount of vertical wear in DCL-CAM after 250,000 chewing cycles.

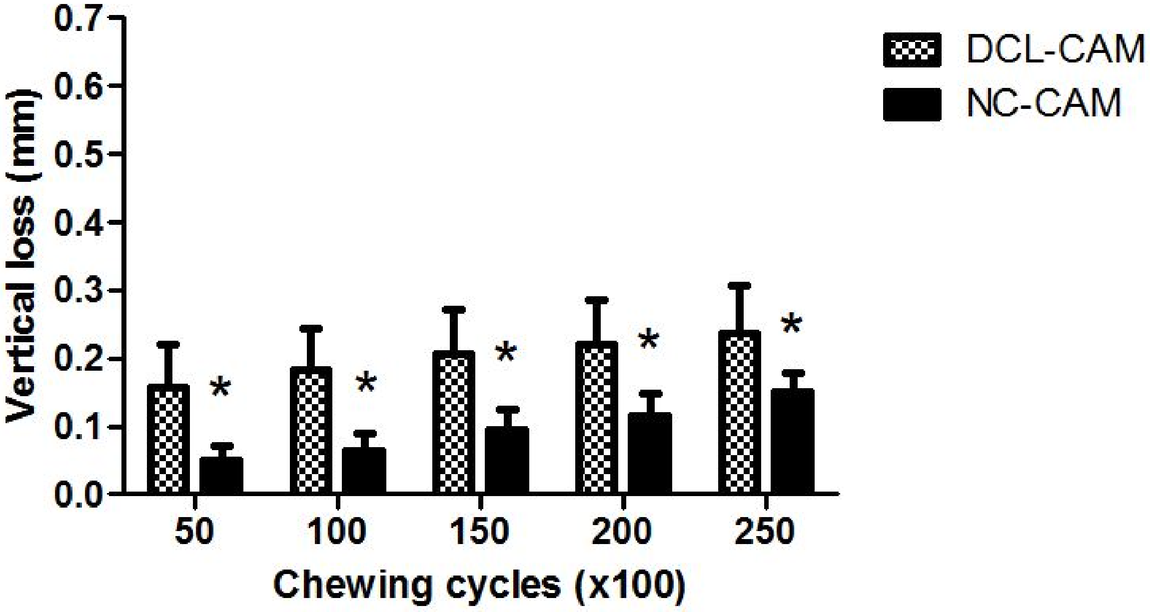
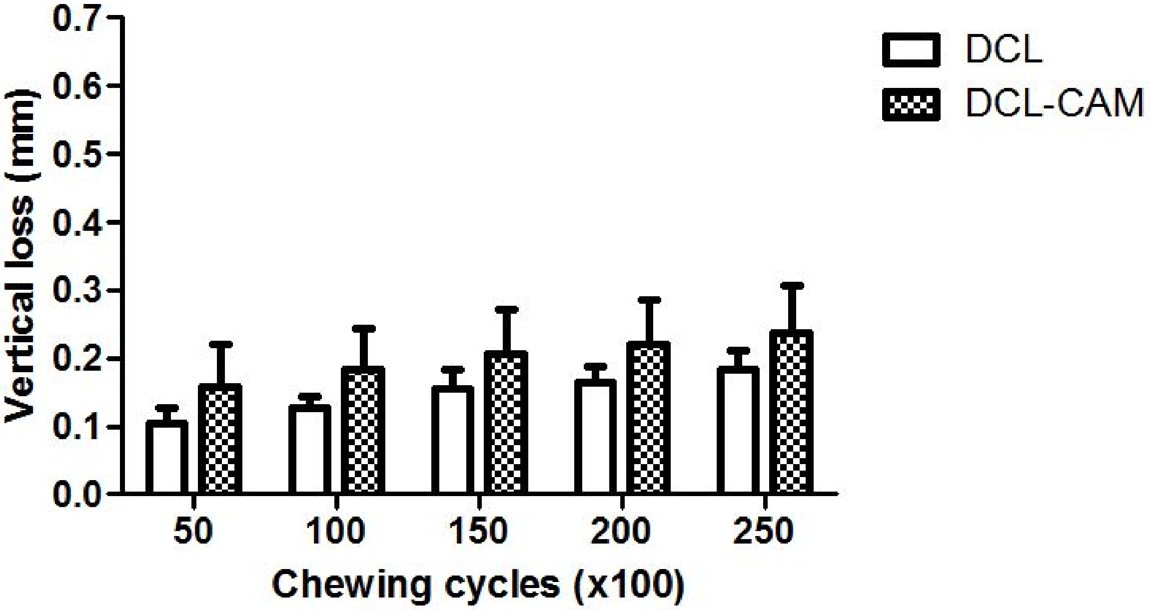


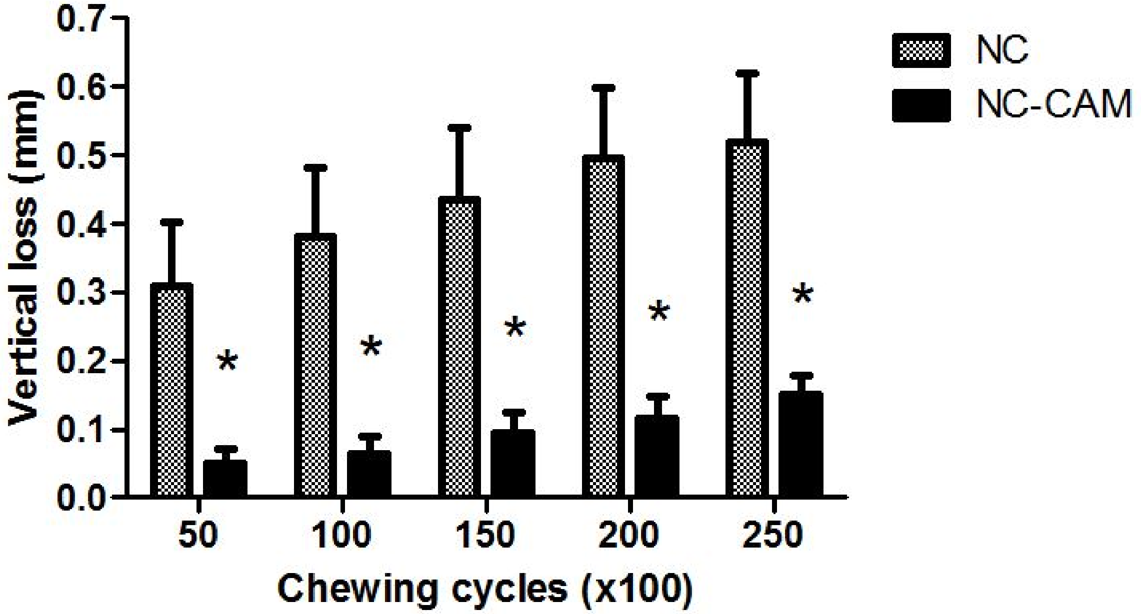
Figure 6. Vertical wear of the milled denture teeth over 250,000 chewing cycles in mm. Mean and standard deviation shown. *Group NC-CAM is significantly different from Group DCL-CAM ($p < 0.05$).

1.5. Milled versus conventional teeth

Between the conventional and milled DCL PMMA resin denture teeth (DCL and DCL-CAM), the wear was not statistically significant at $p \leq 0.05$ (Table 2, Figure 7A). The vertical wear values of the conventional and milled DCL PMMA resin denture teeth were 0.182 ± 0.029 mm and 0.237 ± 0.070 mm, respectively, at 250,000 cycles. These wear measurement values were between those of NC and NC-CAM.



A)



B)

Figure 7. Vertical wear of the conventional versus milled teeth over 250,000 cycles in mm. Mean and standard deviation are shown. A) Conventional and milled double-cross-linked polymethyl methacrylate denture teeth. B) Conventional nano-composite and milled nano-composite and nano-ceramic infused resin denture teeth. * Group NC-CAM is significantly different from Group NC ($p < 0.05$).

Between the conventional nano-composite and milled nano-composite and nano-ceramic infused resin denture teeth (NC and NC-CAM), the difference was statistically significant at all time points from 50,000 to 250,000 ($p < 0.0001$) (Figure 7B). NC's maximum wear depth was 3.4 to 6.1 times greater than that of NC-CAM (Table 2). After 250,000 cycles, NC wore 0.519 ± 0.100mm and NC-CAM wore 0.151mm ± 0.027 mm ($p < 0.0001$). The numerical difference in the vertical wear values between the two group is 0.368mm after 250,000 cycles. The vertical wear in NC-CAM is 29% of the amount of vertical wear in NC after 250,000 cycles.

1.6. Compiled data

The complied grouped graph shows the maximum vertical wear of all the denture teeth groups (Figure 8). In general, after each 50,000 chewing cycles, NC had the highest vertical wear, and NC-CAM had the lowest vertical wear (Table 2). The vertical wear values of NC-CAM were significantly lower than NC and DCL-CAM, the values of DCL and DCL-CAM were not statistically significant, and the values of NC was significantly higher than DCL and NC-CAM ($p < 0.05$).

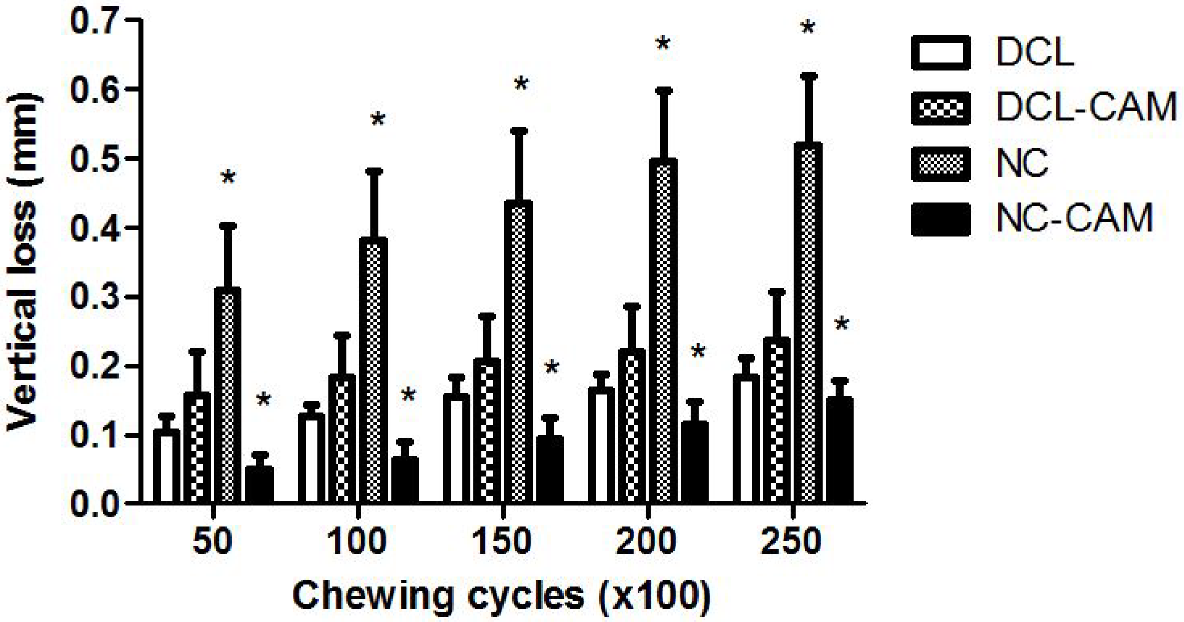


Figure 8. Vertical wear of the groups over 250,000 chewing cycles in mm. Mean and standard deviation shown. * Group NC-CAM is significantly different from Groups NC and DCL-CAM, and Group NC is significantly different from Groups DCL and NC ($p < 0.05$).

2. Volumetric wear

2.1. 3-dimensional images of the volumetric wear

Figure 9 shows the 3-dimensional baseline scan of the DCL sample (Figure 9A), which was used to fabricate DCL-CAM sample (Figure 9B) and NC-CAM sample (Figure 9D), and the baseline scan of the NC sample (Figure 9B). The baseline scans were acquired prior to the start of the chewing simulation. The different sizes of the wear facets are seen on the scans of the samples after 250,000 cycles (Figure 9E, 9F, 9G, 9H). The wear facet of the NC tooth (Figure 9G) appears larger, and the wear facet of the NC-CAM tooth (Figure 9H) appears smaller than those of DCL (Figure 9E) and DCL-CAM (Figure 9F) teeth. The baseline and final sample scans were merged to calculate the wear facet volumes of the four groups (Figure 9I, 9J, 9K, 9L).

2.2. Volumetric loss calculation after 250,000 cycles

After 250,000 cycles were completed, the volumes lost in each group were quantified using the Geomagic software (Figure 10). Of the conventional denture teeth, NC's wear facet volume (0.348 $\pm$ 0.209 mm^3) was 6.0 times greater than that of DCL (4.288 $\pm$ 0.936 mm^3) after 250,000 cycles ($p < 0.001$) (Table 3). Of the two milled denture teeth, DCL-CAM's wear facet volume (1.219 $\pm$ 0.609 mm^3) was 3.5 times that of NC-CAM (0.348 $\pm$ 0.209mm^3) after 250,000 cycles ($p < 0.05$). The difference between the wear facets volume of the conventional (DCL) and milled (DCL-CAM) PMMA teeth was statistically not significant. Of the nano-composite infused denture teeth, the conventional NC's wear facet volume (4.288 + 0.936mm^3) was 12.3 times larger than that of milled NC-CAM (0.348 $\pm$ 0.209mm^3) after 250,000 cycles ($p < 0.001$). The general trend and the significance that were observed with the volumetric measurements were comparable to the results obtained from the maximum vertical changes.

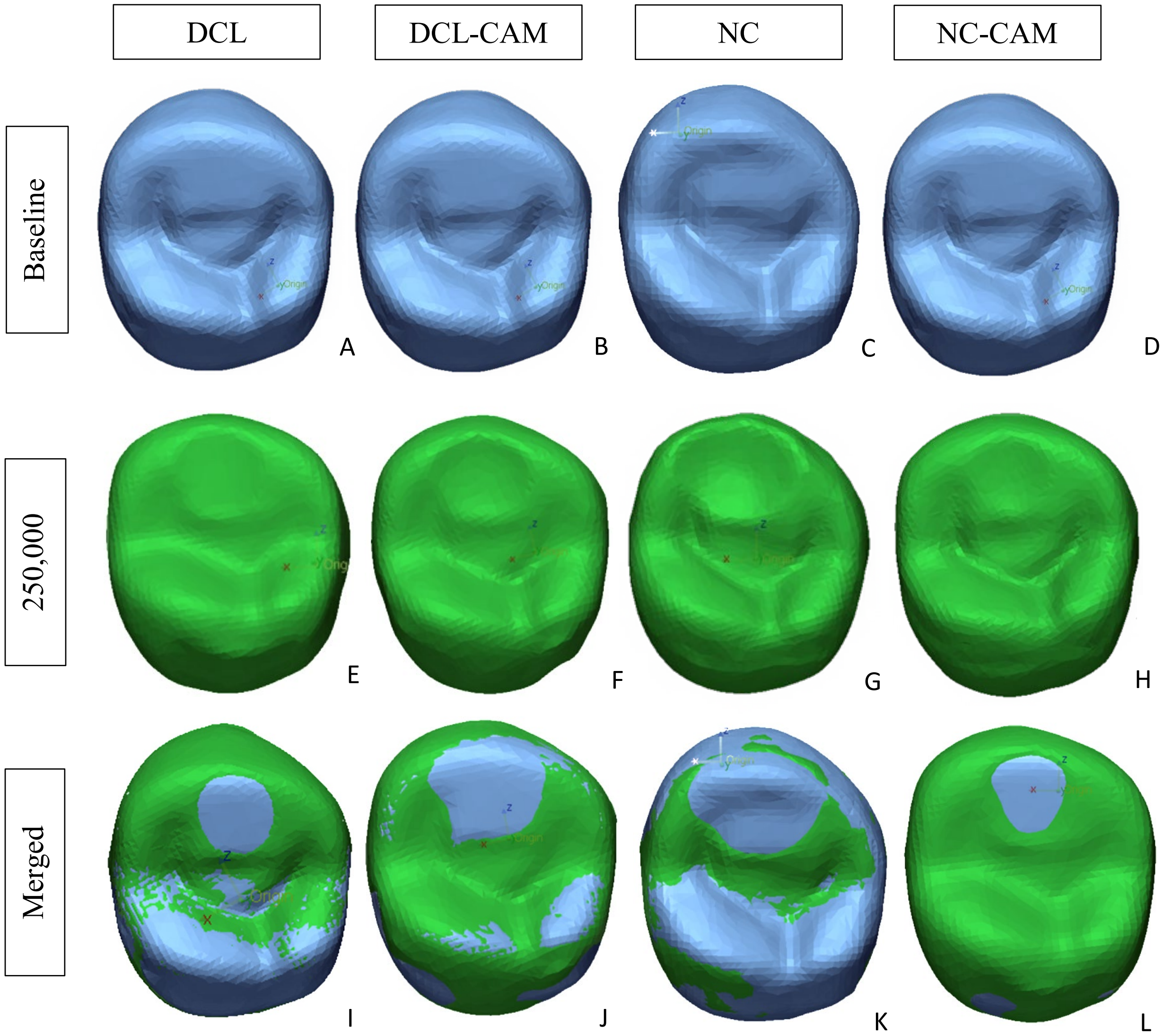


Figure 9. 3-dimensional scanned images. A) Baseline occlusal scan of the Group DCL, which was used to fabricate B) Group DCL-CAM and D) Group NC-CAM. C) Baseline occlusal scan of the Group NC. E) Occlusal scan of DCL after 250,000 cycles. F) Occlusal scan of DCL-CAM after 250,000 cycles. G) Occlusal scan of NC after 250,000 cycles H) Occlusal scan of NC-CAM after 250,000 cycles. I) Baseline and final DCL scans merged. J) Baseline and final DCL-CAM scans merged. K) Baseline and final NC scans merged L) Baseline and final NC-CAM scans merged.

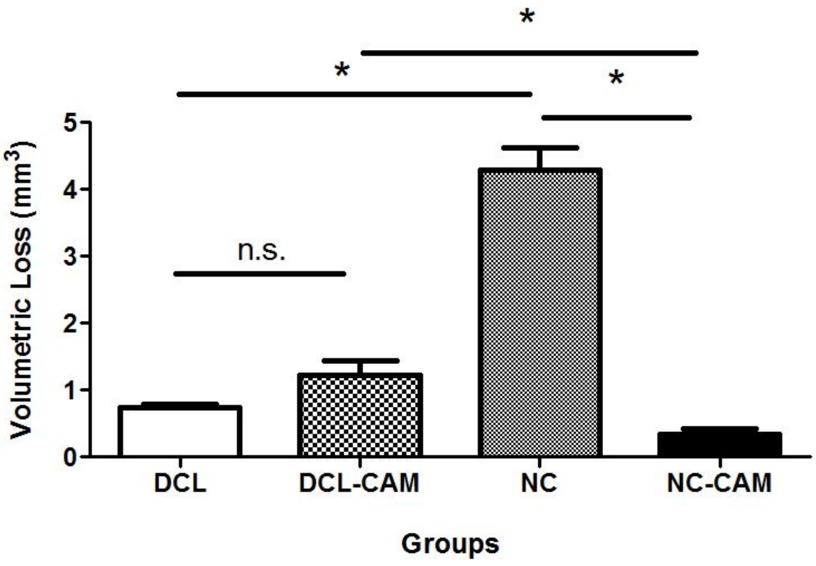


Figure 10. Volumetric wear of groups after 250,000 cycles in mm^3. Mean and standard deviation shown. * Group NC-CAM is significantly different from Group DCL-CAM and NC, and Group NC is significantly different from Groups DCL and NC-CAM ($p < 0.05$).

Table 3. Volumetric Wear

Groups	Volume	p-value	Tukey post hoc
DCL	0.741 ± 0.138	p < 0.0001	B
DCL-CAM	1.219 ± 0.609		B
NC	4.288 ± 0.936		A
NC-CAM	0.348 ± 0.209		C

Same letter demonstrates no statistical significance at $p \leq 0.0001$, $A > B \geq C$.

DISCUSSION

1. Summary of objectives

Whether the fabrication method of the prosthetic teeth (milled and conventional) and the composition of the prosthetic teeth (DCL PMMA resin and nano-composite and nano-ceramic infused resin) affect the wear resistance were evaluated. This study showed that the composition affects the wear resistance, namely that the nano-composite (NC) had a lower wear resistance than nano-composite and nano-ceramic infused resin teeth (NC-CAM). NC-CAM had a higher wear resistance, and in terms of clinical significance, appeared to be at least comparable to the wear resistance of DCL PMMA resin teeth (DCL and DCL-CAM). When the composition of the teeth was equivalent (DCL and DCL-CAM), the method of fabrication (conventional or milled) did not affect the wear resistance.

Previously, some studies found more wear with double-cross-linked PMMA resin teeth, and some studies found more wear with the nano-composite resin teeth. The variability in the results appear to be due to the difference in material composition of DCL PMMA resin and the nano-composite resin teeth selected, the antagonist used, and the testing conditions. The vertical wear values of the conventional DCL PMMA resin teeth that were seen in this study fall in the ballpark of values observed by Heintze et al. (2012), where they found 0.08mm of vertical wear after 100,000 cycles and by Munshi et al. (2017), where they found 0.3mm of vertical wear after 50,000 cycles. The vertical wear values of the conventional NC resin teeth that were seen in this study also fall in the ballpark of values observed by Heintze et al. (2012), where they found

0.2mm of vertical wear after 100,000 cycles and by Munshi et al. (2017), where they found 1.2mm of vertical wear after 50,000 cycles.

In a clinical wear study with complete denture teeth, Ivoclar Vivadent SR Orthotype PE teeth, which are unfilled PMMA resin teeth, had a mean wear of 0.103 ± 0.057 mm one year after insertion (Lindquist et al. 1995). This present study used DCL PMMA teeth, which are fabricated with the organic fillers to be more wear resistant. This present study's vertical wear of 0.182 ± 0.029 mm after 250,000 cycles, or roughly one clinical year, was within the ballpark of the wear observed in vivo with the unfilled PMMA resin teeth by Lindquist et al (1995).

The antagonist material would affect the wear of the samples, and it is, therefore, an important selection for the design of an in vitro wear study. The antagonist choice was previously found to significantly affect the wear of the denture teeth (Hahnel et al. 2009). A steatite, also known as soapstone, is spherical, has the hardness properties similar to ceramic, has a shape of a cusp, is easily available, and thus can be standardized (Roulet et al. 2017). Additionally, compared to artificial teeth or steel antagonist, a steatite was found to improve the differentiation of vertical and volume loss in resin denture teeth (Hahnel et al. 2009). Most importantly, its wear and force when functioning is similar to enamel (Ghazal et al. 2008). The 6mm diameter steatite was selected as the antagonist in this study.

2. Clinical applications

This study provides information on how milled denture teeth compare with the conventional denture teeth regarding their wear resistance. The study also presents data on the difference in wear resistance between DCL PMMA resin teeth and nano-composite and nano-ceramic infused resin teeth. There have been conflicting findings in published studies that previously compared DCL PMMA resin and nano-composite resin teeth. The results appear to be conflicting due to the different methodology including antagonist selection and sample preparation. As the occlusal surface of denture teeth is critical in the occlusal scheme and to maintain the vertical dimension of occlusion, using the unaltered denture tooth's occlusal surface as it would be used clinically appeared more relevant.

The results of this study may assist clinicians in selecting the prosthetic teeth for fabrication of various prostheses. In metal acrylic ISFD, wear of the posterior teeth tends to precipitate other complications, including chipping and debonding of the denture teeth. The experiment also studied a novel prosthetic material, milled nano-composite and nano-ceramic infused resin disc, which is gaining traction as a restorative material of choice for prosthetic teeth of full arch prostheses. Its wear resistance appears promising as it appears comparable to, if not better than, the standard DCL PMMA resin teeth. Milled DCL PMMA resin teeth and milled NC-CAM teeth can be used in place of the conventional denture teeth in various prostheses including complete denture, removable partial denture, overdenture, and ISFD. Wear resistance of restorative material is a factor that clinicians must consider, because it is important in maintaining patient's vertical dimension of occlusion and in avoiding prosthetic complications especially in patients with parafunctional habits and with more abrasive opposing dentition.

Fabrication method does not seem to be a determining factor in the wear resistance. The fabrication method itself, if the prosthetic teeth are milled, will not affect the material's wear resistance. Rather, the composition of the prosthetic teeth appears to be more critical in the material's wear resistance. As the wear of NC was 3.4 times vertically to 12.3 times volumetrically more than that of NC-CAM, a prosthesis fabricated with milled NC-CAM may possibly take 3.4 to 12.3 times longer than NC to wear an equivalent amount.

3. Limitations of the study

The chewing simulation cycles in this study was equivalent to about one clinical year (Heintze et al. 2011). The findings of the study can predict the relative wear of the tested materials. As the trend appears linear, the relative findings may also hold true for a longer period of time, but the results cannot directly predict how much wear may be observed after a longer period of time, for example, after five or ten years.

As our wear trend appear linear, if we were to extrapolate our data to ten clinical years, the vertical wear that was seen in NC may be about 5mm, about 2mm for DCL and DCL-CAM, and about 1.5mm for NC-CAM. The amount of wear that may be seen in NC after ten years would be destructive to the prosthetic teeth. Comparatively, the wear that may be seen in NC-CAM after 10 years would be relatively mild.

It is beyond the scope of the study to estimate the wear of the different groups with different antagonists as well as the wear of the groups clinically. For the purpose of studying wear of the four groups opposing a steatite, the study results show the relative wear in vitro. At an estimated one clinical year, the different denture teeth show a significant difference in the amount of wear, where NC has significantly greater wear compared to the three other groups.

4. Future studies

As NC-CAM is a new material with no peer reviewed paper, more studies would be beneficial to understand the material further. The wear on the antagonist by NC-CAM would be an important and interesting future study. While the wear resistance of NC-CAM was promising, its abrasiveness has not yet been studied in a peer reviewed paper. The wear resistance and abrasiveness properties are important factors for clinicians in selecting the denture teeth material. If NC-CAM is selected as the prosthetic teeth for its wear resistance, clinicians also need to know when it may be used based on its relative wear resistance to the various antagonist materials such as PMMA resin, enamel, zirconia, feldspathic porcelain, and gold.

It would be also interesting to study the wear resistance of printed denture teeth fabricated from the additive CAD/CAM process. Longer term in vitro study would be helpful to determine whether the findings that were seen after 250,000 cycles, or 1 clinical year, would be the same after five to ten clinical years. After five to ten years, most metal acrylic ISFD prostheses that were fabricated with conventional denture teeth require the retreading process. Finally, a clinical study to relate the findings of this in vitro study would be most relevant to guide the clinicians with the prosthetic material selection.

CONCLUSION

The wear of conventional and milled denture teeth increases in a linear progression. NC denture teeth wore the most and appeared least wear resistant. NC-CAM denture teeth wore the least and appeared most wear resistant. The conventional DCL PMMA resin teeth (DCL) that were fabricated from processing the polymer and monomer raw materials in a mold had an equivalent wear resistance to the milled DCL PMMA resin teeth (DCL-CAM).

Denture teeth selection is important to delay the retreading process and to avoid other prosthetic complications. As this study is an in vitro study with experimental conditions that were set based on other published papers, we cannot predict the exact amount of wear that may be seen clinically and after a longer period of time. The relative wear that was observed, however, is a useful information. The milled denture teeth (DCL-CAM and NC-CAM) appear to be solid alternatives to the conventional denture teeth in terms of their wear resistance.

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