WEAR OF CERAMICS AND ENAMEL IN A CHEWING SIMULATOR

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ABSTRACT

Dental ceramics are known for their excellent chemical and optical properties. The wear of human enamel and of the restorative material is often a vital and esthetical concern when selecting a restorative material for any given clinical restorative treatment.

Objective: The purpose of the study was to evaluate effect of zirconia (polished, glazed, polished then glazed, adjusted, glazed and adjusted, adjusted and polished and aged zirconia) against human enamel antagonist. A comparison was made between different zirconia, veneering porcelain (Ceramco 3) and natural enamel. Additionally, the surface roughness (Ra) of the ceramic surface was measured before and after wear testing to evaluate effect of cyclic loading on the t-m phase transformation.

Materials and methods: The study included zirconia specimens (n=8), (divided into polished, glazed, polished and then glazed, adjusted, glazed and adjusted, polished and adjusted and aged zirconia, a veneering ceramic (Ceramco 3) and an enamel (control) group. Freshly extracted and caries free mandibular 1st molars were selected to serve as antagonists. Their mesio-buccal cusps were standardized, mounted onto steel styli, stabilized with self-cure acrylic and finally cleaned with pumice. Before testing, the surface roughness of all ceramic specimens was measured using a non-contact 3D surface profilometer (Proscan 2000, UK). All specimens were mounted into brass holders and subjected to cyclic loading in newly developed UAB-chewing simulator for 400,000
cycles. The antagonist applied a vertical load of 10N onto ceramic specimens stabilized on a 2mm horizontal sliding platform at a frequency of 20cycles/min. A solution of 33% glycerin + 66% water was continuously cycled through specimens for lubrication. PVS impressions of the enamel antagonist will be taken at the baseline, 200,000 and 400,000 cycles and poured with die stone. To measure enamel and ceramic wear, 3D scans of the stone model, ceramic block, and incisor surfaces were obtained after 200,000 and 400,000 cycles with a non-contact surface profilometer (Proscan 2000, UK). To determine the volume and the depth loss, the 3D scans were superimposed with PROFORM software.

Results: Data was analyzed by ANOVA and Tukey post-hoc tests (p=0.05).
DEDICATION

I dedicate my thesis to my mom, Mrs. Dhanalakshmi.

Thank you for your unconditional love and devotion with which you have raised me into this world and a chance to prove and improve myself through all walks of life.

I dedicate my thesis to my sweet heart and fiancée, Himaja,

Thank you for all your friendship, motivation and never ending love.

I dedicate my thesis to my mentor Dr. John O. Burgess.

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INTRODUCTION

Increased patient demand for esthetic dentistry has generated interest in all-ceramic dental restorations. Better materials and innovative techniques have led many dentists to use all-ceramic crowns and inlays for the restoration of posterior occlusal surfaces. However, there has been considerable concern as to how these materials, formulated for improved strength, as compared with respect to their tendency to abrade human enamel. Ideally, any restoration should not harm (wear) of the opposing tooth surface. Owing to their strength, Ceramics in general, are considered to be more abrasive to enamel than common restorative materials, such as gold or amalgam.

There were many researchers who demonstrated the deleterious effects of ceramics on the opposing tooth. In 1986 a survey by Christensen at American academy of esthetic dentistry found "less wear on opposing teeth" to be the single most desirable need for change in posterior tooth-colored crowns. In 1971 Mahalick et al. reported enamel-porcelain wear, in vitro, to be 2.4 times greater than wear of enamel-acrylic resin and 17 times that of enamel-gold. Monasky and Taylor (1971) tested a variety of surface finishes of porcelain against tooth substance and concluded that the rate of tooth substance wear was a function of porcelain roughness. Ekfeldt and 0ilo (1988), using a bruxing subject, studied occlusal wear of porcelain, gold, and resin in vivo. They too found that enamel surfaces exhibited the greatest substance loss when opposed by feldspathic porcelain. These and other studies have led some clinicians (Rosenstiel et al., 1988; Wiley, 1989) to caution against the use of porcelain occlusal surfaces where rapid enamel attrition might be predicted, such as for a bruxer or complete-denture wearer having the porcelain opposed by natural teeth.
Dental Ceramics

Ceramics are not considered new materials as they were in use more than 10,000 years ago during the Stone Age.\textsuperscript{1} In 1723, Pierre Fauchard described the enameling of metal denture bases.\textsuperscript{2} Earliest documented use of porcelain dental reconstruction materials goes back to the late 1700s in France by de Chemant.\textsuperscript{3} The first porcelain tooth in United States was fabricated only in 1817. These porcelain teeth were embedded in vulcanized rubber bases. It was only at the beginning of the 1900s, the basic principles of individual ceramic crowns came into existence. However, it took until early 1960 before any more significant technology developments were made, when vacuum firing technology and technique to burn porcelain on metal were introduced. Alumina Reinforced introduced in the 1970s as a result of McLean and Hughes, research, glass ceramics in 1968, and Leucite-reinforced glass ceramics with pressure casting technology at the beginning of 1990. After the acid-etch technique followed the introduction in 1973 as the bonded ceramics. Today, there are developments made on the technical side, nanotechnology, and designs. In the last few decades there have been tremendous advances in the mechanical properties and methods of fabrication of these materials. Porcelain fused to metal, cast metal crowns and gold restorations were used in the past with considerable success.\textsuperscript{13} In the recent years, there is an increased concern for metal free and tooth colored restorations across the globe.\textsuperscript{14} Though porcelain based materials are still a major component of the market there have been moves to replace metal cored systems with all ceramic systems. Additionally, the increasing costs of base metal alloys and gold emphasized the need for affordable ceramics. Since then, unprecedented efforts were made for metal free, high strength ceramics with improved marginal quality.
esthetics and wear properties that can be pressed and machined.\textsuperscript{15-17} Thanks to the extensive research in the past 3 decades that helped in developing a number of all ceramic systems accounting for this increased demands of patients and dentists.\textsuperscript{18} Today, ceramic materials are a staple in dentistry, available in both naturally based and partially synthetic formulas.

Dental ceramics in restorations are essentially oxide based glass-ceramic systems. They have four fundamental features:

1. Ease of fabrication of complex shapes
2. Sufficient mechanical and corrosion resistance
3. Appropriate aesthetic appeal.

As the world is advancing in to all ceramic restorations, Lucite reinforced glass ceramics were introduced for veneers, onlay’s and single crowns.\textsuperscript{19} This was followed by the introduction of the lithium di-silicate, that lead to a remarkable increase of mechanical properties, expanding the all ceramics application to the 3-4 unit fixed partial dentures extending through the 2\textsuperscript{nd} premolars.\textsuperscript{20} In Ceram alumina and zirconia were introduced as high strength cores and indicated for single crowns and 3 unit anterior bridges.\textsuperscript{21} This glass ceramic core was prepared by a slip casting technique, and over which a porcelain veneer was layered.\textsuperscript{22} Recently, high strength ceramics were developed with metal oxides of alumina and Zirconia for use as the core material in the high load
bearing areas. It was first introduced in the biomedical sciences in early 1960s. It’s application further extended to orthopedics in 1980s, \(^{23, 24}\) and then to dentistry in 1990.\(^ {25}\)

It is ironic that there has been an emphasis and extensive research on zirconia in the recent years.\(^ {26}\)

Zirconia, specifically yttrium-stabilized Zirconia (Y-TZP), an exceptionally strong ceramic, is used as a core in an attempt to eliminate the bulk fracture of all ceramic restorations.\(^ {27}\) It has unsurpassed mechanical properties and exhibits a unique phenomenon of transformation toughening which is an ability to seal the crack propagation. Dental ceramics are known for their natural appearance and their durable chemical and optical properties. It has a flexural strength of 900-1200 MPa\(^ {28, 29}\) and fracture toughness of 9–10 MPa. m\(^ {0.5}\) As a result, all ceramics application extended to multi-unit to full arch zirconia frameworks, implant abutments and complex implant superstructures to support fixed and removable prostheses.\(^ {9-10}\) The inherent properties of the material like low thermal conductivity, low corrosion and good radio opacity are noteworthy. In addition to the above, high biocompatibility and low bacterial surface adhesion makes it the material of choice.\(^ {30}\) However, the clinical success of the zirconia based implant and other restorations has been questioned with the reports of the veneering porcelain chipping.\(^ {32}\) These failures can be attributed mainly in the veneer layer resulting from the mismatch of CTE between the zirconia and veneered porcelain, thickness and cooling rates.\(^ {33}\) In an effort to reduce these failures, highly sintered monolithic or full anatomic zirconia crowns were developed. This helps in elimination of veneering porcelain layer, improving their clinical success and reliability.\(^ {34}\)
Currently, these restorations are glazed and stained superficially for esthetics and indicated for the high load bearing areas. However, dentists have remained suspicious of the structural longevity, potential abrasivity, and fit of ceramic restorations. It was important that dental research in ceramics addresses issues of clinical survival, response during wear, and fit. These concerns have directly influenced the development of recently introduced ceramic materials and laboratory processing systems. Studies of clinical failure and damage mechanisms are crucial, because they provide data for substantial engineering improvements.

**Wear**

Tooth wear is a complex physiological process that occurs as a result of tribiological interactions in oral cavity. Wear of materials is a complex and an unpredictable phenomenon. In historical perspective, teeth that were heavily worn were found in human skulls dated as early as 160,000 years ago. Tooth wear can be attrition, abrasion, adhesive, fatigue and corrosive wear. Attition or two body wear and abrasion or three body wear are the common variants experienced by tooth in life time. It is influenced by a variety of factors like the thickness of enamel, abrasiveness of food, patient’s oral habits, musculo-skeletal and neuromuscular control. The tooth loss is generally compensated with a mesial and occlusal tooth movement resulting from deposition of the cementum at the apex. The physiological occlusal contacts are point-point, edge-edge, Point- Area, and Edge-area. This character of occlusal contacts makes chewing easier forming abundant spill ways on the occlusal table. But, due to their very high strength, ceramic restorations are more prone to wear adjacent and antagonist tooth.
leading to non-physiologic area to area contacts. Similar to the tooth, restorations are also subjected to wear, and the material loss can be in the form of microploughing, microcracking, microcutting and microfatigue. The systemic complications of ingestion of worn particles are yet to be determined. The major biological effects caused by the loss of vertical dimension and tissue alteration affecting the somatognathic system cannot be ruled out.

Experiences from the past decade prove that tooth wear occurs in an increasing number of cases in dental practice. Tooth surface losses or ‘tooth wear’ refers to the pathological loss of tooth tissue by a disease process other than dental caries. The different wear mechanisms are involved with the biomechanical factors of mastication. An ideal wear simulation would incorporate both abrasion and attrition. Mastication involves two processes that affect wear, abrasion and attrition. Abrasion occurs in the presence of food as the jaw closes. It begins when both mandibular and maxillary teeth contact the food bolus and ends when the two teeth contact each other. Because the teeth do not come in direct contact during abrasion, this stage is termed the contact free area (CFA) region of wear. This stage of wear involves abrasive, adhesive and corrosive wear. Attrition begins when the mandibular and maxillary teeth directly contact and ends when they separate. This is termed the occlusal contact area (OCA) region of wear. This stage of mastication involves abrasive; adhesive and fatigue wear. The primary variables affecting the mechanism of wear include the properties of the two contacting materials and the surrounding and interfacial media. The rehabilitation of the lost tooth material is often very difficult, irrespectively of whether it is needed because of functional or esthetic causes.
Clinical Significance of wear

A major concern in clinical practice is the wear resistance of resin materials used in restorations especially involving posterior occlusion.\textsuperscript{1, 2} Two distinct kinds of wear have been described by Kawai & Leinfelder.\textsuperscript{3} One of these is wear initiated by generalized conditions (the type of wear generated by a food bolus during mastication) and the other is wear generated under localized conditions (represented by direct tooth to materials contact). Some authors \textsuperscript{4, 5} have suggested that localized wear may be a more important contributor to the breakdown of a material and contact wear may be more than two times as great as that in non-contact areas. While clinical studies offer the most meaningful data on the performance of a given material. Clinical wear bears a multifactorial etiology, understanding the mechanism of action is an important step in an appropriate restoration material selection. Each material selected should meet the individual wear behavior and needs. Individual factors may enhance the wear rates: aggressive tooth brushing, parafunctions, diet, acidic/aqueous environment, surface geometry, and diminished tooth support. Failure of ceramic restoration due to creation of micro cracks/flaws, poor masticatory function, impaired aesthetic appearance, Sensitivity, Secondary caries and Systemic effects through ingested wear products. Biological consequences are related to pain of the temporo-mandibular joint (TMJ), the elongation of antagonists, loss of periodontal ligament and tilting and movement of adjacent teeth. In spite of it being frequently mentioned as possible consequences, there is little evidence that occlusal wear as such leads to the dysfunction of the TMJ, to muscle pain or periodontal disease.
Supportive treatment following restoration is important to monitor wear rates. However, the time involvement and costs associated with clinical studies have driven dental manufacturers to have a strong interest in the use of wear simulation of prototype materials as a screening tool and predictor of clinical performance. Leinfelder et al.\textsuperscript{6,7} developed a laboratory simulator capable of evaluating both generalized and localized wear. This system transfers masticatory stresses to a composite specimen by means of a flattened polyacetal stylus (generalized wear) or a stainless steel conical stylus (localized wear) in the presence of slurry of polymethylmethacrylate beads (PMMA). This device has facilitated the development of \textit{in vitro} studies capable of helping predict \textit{in vivo} performance. Previous work\textsuperscript{6} showed a correlation between \textit{in vitro} wear and \textit{in vivo} generalized wear of dental restorative materials.

**Mechanisms of Wear**

Wear takes place at two surfaces: occlusal surface and proximal surface

Wear at contact-free occlusal area- CFOA

Wear at the occlusal contact area- OCA

While chewing, opposing dentition traps a layer of food and grinds it as the teeth move past one another. The chewing forces produced during this phase are modeled ranges between 10-20 N. At the end of chewing cycle, sliding motion stops as the teeth reach centric occlusion. The chewing force is heightened between a range of 50-150N. Wear tribology and bio-tribocorrosion defines wear as a complex phenomenon and an ‘overall effect’ of a number of inter-related processes.
Two-body Wear:

In two-body abrasion, surfaces are rubbed away by direct contact. During this movement, the asperities must either fracture or deform. At a microscopic level, no surfaces are smooth and hence they contact by the reunion of their asperities. If both surfaces are ‘brittle’, there is fracture of the asperities. If one surface is ‘soft’, then the harder surface will plough into it, rising up ‘chips’, which eventually fracture away. Gradually, all the asperities fracture and the cumulative effect of loss manifests as wear.

In the oral cavity, these conditions predominantly occur during ‘non-masticatory tooth movement’. ‘Attrition’ is a form of two-body abrasion tooth wear that can be considered ‘physiological’ as it has been described as a prerequisite for ‘balanced occlusion’. It is the physiological wearing away of dental hard tissues as a result of tooth-to-tooth contact without the intervention of foreign substances that causes localized wear at occlusal
contacts. The wear rate of enamel at occlusal contact areas in molars is about 41 m per year.

Three body Wear:

Surfaces are rubbed away by ‘intervening slurry of abrasive particles’. The pressure between the surfaces is transferred to the particles, which then cut away the asperities. In the mouth, this type of wear occurs during ‘mastication’ and is common in patients who eat an abrasive diet. During the early stage, when the occlusal surfaces are separated by the food bolus, the abrasive particles act as slurry and abrade the whole surface. They abrade the surface in the ‘food shedding pathways’ because of the shearing action of food on contact stress. This process is very common in restorations with ‘buccal or palatal extensions’, as these take the main force of the masticatory slurry in the escape root of the groove. The process tends to hollow out the softer regions on a surface. As the teeth begin to approximate during the ‘later stages’ of mastication, the remaining slurry particles get trapped between the asperities, in pits and in surface grooves. If both
surfaces are of similar morphology then the abrasive particles may transfer between scratches and cause more or less equal loss of both surfaces.

![Figure 3: Three body wear](image)

**Fatigue wear**

Some of the movement of the surface molecules is transferred to the subsurface causing rupture of intermolecular bonds and a zone of ‘subsurface damage’. Micro cracks form within the subsurface and coalesce to the surface, therefore causing loss of a fragment of material inducing fatigue wear.
Adhesive wear

This occurs when there is a high attraction between surfaces such that ‘cold welds’ between the asperities. As the movement continues these micro-welds fracture, but not along their original line of fusion. This type of wear is normally seen in metals.
Tribo-chemical wear (dental erosion)

It is caused when chemicals weaken the inter-molecular bonds of the surface and potentiate the wear processes. There is interplay of erosion, attrition and three-body abrasion. In the oral cavity, acids normally cause ‘extrinsic effects’ such as dietary acids or ‘intrinsic effects’ resulting from gastric reflux. These acids weaken only the surface molecules. These are then rubbed away by the movement of the surfaces and immediately the underlying surface is attacked by the acid.

Biomechanics of Mastication

Mastication, or the chewing cycle, can be divided into three steps: 1) the preparatory phase begins as the teeth start to separate from the previous chewing cycle and ends as the jaw closes immediately prior to the teeth contacting a food bolus, 2) the crushing phase starts as the food bolus is crushed by the teeth and ends when the teeth first contact, 3) the gliding phase starts with tooth-tooth contact and finishes as teeth begin to separate. Of the three phases, only the second two phases place force on the teeth and contribute to wear. During the crushing phase, food particles are interposed between

Figure 5: Adhesive wear
the two teeth and contribute to the wear process. The mode of wear occurring during this chewing phase has been termed abrasion. During the gliding phase, wear occurs by the contact of the opposing teeth. This mode of wear is termed attrition.\textsuperscript{40} These two wear modes will be discussed.

**Other Types of Wear**

Mechanical wear of dental restorations occurs during other physiologic events such as interproximal (between two neighboring teeth) wear, toothbrush abrasion, deglutition and parafunctional tooth movements (such as bruxing).\textsuperscript{41} The mechanics of interproximal wear and toothbrush abrasion requires a different modeling system than masticatory wear and therefore will not be discussed in this thesis.\textsuperscript{42-44} Parafunctional movements, particularly nocturnal bruxing, involves grinding of teeth without interposing food particles and often at greater loads than masticatory forces.\textsuperscript{45} This type of wear follows similar mechanics to masticatory wear, however, with different testing parameters (ie without abrasive medium, at increased loads, and with bidirectional sliding)

**Wear of Ceramic Restorative Materials**

The wear rate of an ideal restorative material should approximate that of enamel.\textsuperscript{1} Lambrechts et al.\textsuperscript{2} reported vertical wear of enamel to be between 20 µm to 40 µm per year when opposing enamel in the premolar and molar regions, respectively. Surface texture and surface hardness have each been investigated as possible determinants of wear rate.\textsuperscript{3} However, surface hardness has been shown to be a poor indicator of wear.
Ceramic wear testing remains difficult to assess in both in vitro and in vivo controlled evaluations. In vitro ceramic investigations are most often studied by the use of flat ceramic specimens opposing either human cusps in their natural anatomic state or flattened (ground) enamel. Jacobi et al., used human canines opposing flat specimens of ceramics and of gold and found type III dental gold to be less abrasive than any of the six ceramic surfaces tested. Wear of the enamel was measured as weight loss of the enamel samples, with their design Jacobi et al. 6 also showed the outer cerammed layer of cast Dicor (Dentsply Intl. Inc., York, Pa.) specimens to have abrasiveness similar to that of conventional porcelain. Various methods have been used to evaluate wear. It has been noted that the sum of the vertical loss of enamel and of the restorative material can be a key to evaluating wear characteristics relative to clinical performance.

Clinical studies have attempted to measure wear of ceramics in vivo. 36 High budgetary cost and extensive involvement, however, limits the occurrence of in vivo experiments.37

Additionally, the subjective nature of qualitative wear assessment and the technical difficulty of quantitative wear measurement reduce the reliability of in vivo wear analysis. In response, both industry and academia have developed in vitro wear testing methods. Several analyses have been performed to correlate the results of in vitro wear testing methods with in vivo results. Despite these attempts, the in vivo to in vitro correlations are often dependent on the testing systems used to produce in vitro wear and the materials examined. 38
Mechanical Properties Related to Wear

In vitro wear testing of dental composites is less costly and time consuming than in vivo wear testing, however, the complexity and involvement of laboratory wear testing are not trivial. For this reason, researchers have explored physical and mechanical properties of dental composites that could be used to predict their wear. Several studies have proposed equations to calculate wear based on a composite’s hardness, flexural strength, fracture toughness, and modulus of elasticity. A brief discussion of several of these properties will be given.

Strength

Strength is the resistance to plastic deformation. In crystalline materials, such as metals and ceramics, plastic deformation occurs by slip, kinking, twinning or phase transformation.

Elastic Modulus

Elastic modulus is a measure of the flexibility of a material and it is measured from the slope of a stress-strain curve. As noted earlier, the elastic modulus of a material will affect its tendency to wear by fatigue or abrasion. Under the same stress, a material with a low modulus will be more likely to undergo elastic deformation leading to fatigue than a high modulus material which may experience abrasion.
Toughness

Toughness is the amount of energy a material can absorb before fracture. It is measured as the area under a stress strain curve. Therefore, it is a function of the both the strength of a material and its deformation before failure. A special kind of toughness measurement, called fracture toughness measures the amount of stress required to propagate an existing crack.

Hardness

Hardness is the ability of a material to resist indentation forces. Despite an assumed positive correlation between hardness and wear, the wear nature of the materials is still a concern.

Wear simulation devices

Many research centers have developed a wide variety of wear testing devices, each with a different degree of complexity. The International Standards Organization (ISO) published a 2001 technical specification for wear titled “Dental Material, Guidance on testing of wear. Part2. Wear by two-and/or three-body contact”. This specification describes eight wear testing methods including: DIN, Acta, Zurich, Alabama, Freiburg, Minnesota, OHSU, and Newcastle. Two studies by Heintze compared the wear ranking of nine restorative materials in five of these systems (Acta, Zurich, Alabama, Freiburg, and OHSU) and found that wear ranking was dependent on the testing system.
Tooth brushing machines:

In common, a toothbrush/dentifrice abrasion concept is used consisting of programmable brushing techniques and paths, dentifrice abrasive slurry, no. of cycles, time & load.

![Tooth brushing simulator](image)

Figure 6: Tooth brushing simulator

Two-body wear machines

A variety of two-body wear simulators have been designed and used with varying degree of success to imitate clinical wear. Some of the two body systems are Two-body abrasion single-pass sliding, Two-body wear rotating counter sample, Taber Abraser, Pin-on-disk Tribometer, Oscillatory wear test, Modified polisher and Fretting test.
Three-body wear machines

Many three-body wear simulator research centers are trying to mimic the oral environment and biological variables intending to rank restorative material according to their wear resistance in comparison to reference materials.

(a) ACTA wear machine:

The ACTA device has two metal wheels rotate in different directions with a difference of about 15% in the circumferential speed while being in close contact with each other. The test specimens are placed on the circumference of one wheel whereas the other wheel serves as antagonist. The force with which the two wheels are put together is adjusted with weights or springs. The stylus is made of a textured and hardened steel counter-wheel. Medium used rice/millet seed shells suspension. A sliding movement with 15–20 N of modifiable force (ranging between 0–50 N), 1.0Hz frequency and 100,000-200,000 cycles is used. Set-up: sample chamber with multi-chambered sample wheel, holding up to 12 sample materials. The rotational speed of both motors ranges between
0–170 rpm and is independently adjustable. Variables playing roles are contact stress, moving speed, mutual slip (15%). This machine is disapproved because it does not closely simulate the biomechanical processes of dental wear.

![ACTA wear machine](image)

Figure 8: ACTA wear machine

(b) OHSU: Oregon Health Sciences University Oral Wear Simulator:

The OHSU device does not have an integrated force sensor and the forces for abrasion testing (20 N) varies between 17 and 19N from one device to another. The sliding distance varies from 5.36 to 6.24mm, causing variation in the contact time. There is no systematic force/time measurements carried out with the OHSU device. The forces are measured on a regular basis with a force sensor of a 10Hz measuring frequency. This system is a multi-mode simulator. Stylus is enamel and conical, Medium used is poppy seeds and PMMA beads. Movement is impact + sliding, and loading is electro-magnetic. Frequency is 1.2 Hz with 50,000–100,000 no. of cycles.
(c) University of Alabama Dental Wear Simulator

The Alabama wear simulator uses springs to generate an appropriate force. The stylus is made of polyacetal and flat in shape. Conical styli of a variety of materials were used for localized occlusal contact wear simulation. Medium used is PMMA beads. Movement: impact and rotation of 30°. Force exerted is 75.6 N, vertical with a frequency of 1.2 Hz. It is a four-station device with number of cycles ranging from 100,000–200,000–400,000. In this wear set-up, multiple wear patterns can be seen. Generalized wear as simulation of the wear during mastication. Localized wear as simulation of attrition by occlusal contact. Antagonistic enamel wear is simulated by wear of enamel created by direct contact with the restorative materials. Vertical wear is measured as enamel height loss, material stylus height loss, and total vertical height loss (the sum of the enamel height loss and the restorative material height loss).
(d) Zurich computer-controlled masticator

The stylus in this simulator is enamel. Medium is water (+alcohol + tooth brushing). Movement: impact (+sliding) with a lateral movement of 0.2 mm, Force: 49 N with a frequency of 1.7 Hz. Loading is electro-magnetic. Number of cycles range from 120,000, 240,000, 640,000 and 1,200,000 load cycles. Set-up: masticator. Variable: toothbrush/toothpaste abrasion and chemical degradation. CoCoM wear simulator has a rubber socket that simulates the periodontal ligament and produces a sliding movement of the sample, thus leading to a softening effect during wear simulation. The elastic modulus of the rubber dam changes over time and these changes are accelerated by thermocycling.
(e) BIOMAT wear simulator

The stylus is SS304 counter-body. Medium is water and has an impact (+sliding) movement. Force is 20 MPa. Loading is by weights. Set-up: reciprocal compression-sliding wear instrumentation. Variable: shock absorbing layer, Oral temperature is 37 °C.
(f) Minnesota: MTS wear simulator

The MTS chewing simulator is the only device with an incorporated force sensor. The hydraulic actuator produces a force, which is controlled within narrow limits in the descent/lifting and lateral movements; in addition, the force profile (“haversine waveform”) is highly reproducible. Simulator controllers regulating the force (load cell), force profile (dual trace oscilloscope) and vertical and lateral movements are incorporated into the testing device. The MTS chewing simulator is an adapted version of the MTS device, which is widely used by medical companies for the biomechanical testing of artificial hip and knee joints and implants. Stylus used is a tooth, Medium: water giving a Movement: sliding. Force is 13.35 N and loading is hydraulic. Number of cycles vary from 120,000, 240,000, 640,000 and 1,200,000 load cycles.

Set-up: masticator. Variables are contact stress, moving speed, mutual slip, and third-body composition.

Figure 13: MTS wear simulator
(g) Willytec Wear simulator

The Willytec chewing simulator has been commercially available since 1997. This simulator is utilized to load crowns and bridges for fracture tests and to evaluate the deterioration of the marginal integrity of restorations placed in extracted teeth. Stylus used is enamel, empress (diameter 2.36 mm). Medium is water. Movement: gnashing, slippage, striking with lateral movement of 0.7 mm. Force: 50 N with Loading by weights. Number of cycles is 120,000 cycles.


Simulators have been developed to measure the in vitro wear of dental materials; each of these machines has their advantages and limitations.

In 2006, Heintz conducted a study correlating the results of the different wear simulating devices with ACTA, OHSU, Willytec and Zurich wear devices on eight different composites. Specimens were prepared at the Ivoclar Vivadent laboratories, specimens were sent to different testing sites and collected and data was analyzed. Heinz concluded that the relative ranks of the materials differed significantly between the wear devices. This is the only published paper to date in relation to validation of all systems. The major limitation of the study was that the testing protocol and the method for measuring wear at the individual test sites were not standardized. This study design did not allow featuring difference in wear data to the wear simulator alone. Variation would also arise from the differences in antagonist material, number of cycles, temperature, pH, slurry medium, and wear measurement technique. Each of these variables has been proven to affect wear rates of composite materials. An accurate comparison is done
between wear rankings for the testing devices based on the load profiles and wear patterns, which differentiate the wear devices. The Minnesota wear device is more expensive and complex than the other devices and is located in only one test site. The BIOMAT wear device simulates only two body wear. The Alabama wear simulating device has been used prolifically in the United States. Existing oral wear devices have varying methods of simulating the abrasion and attrition phases of wear.

The BIOMAT, OHSU, Minnesota and Willytec devices have a stylus that impacts the composite specimen and slides a certain distance (Yap et al., 1999; Condon & Ferracane, 1996; DeLong & Douglas, 1983; Kunzelmann et al., 2001). The Leinfelder wear testing device stylus impacts the composite specimen and rotates 30 degrees (Leinfelder & Suzuki, 1999). These devices all incorporate both the abrasion and attrition phases of mastication. The ACTA device has two wheels, a wheel containing composite specimens and one steel counter surface wheel, that rotate next to each other at slightly different speeds (de Gee & Pallav, 1994). This device measures only the abrasion phase of mastication. A round-robin test with the ACTA, OHSU, and Willytec revealed that these devices measure different wear mechanisms. Despite prolific wear testing by industry and academia with these devices, the International Standards Organization (ISO) has not specified a standard wear testing system (Heintz et al., 2005).

Broadly, oral wear simulating devices incorporate three methods of producing wear: sliding, sliding with impact, and rotation with impact. The effects of sliding wear (abrasive and adhesive mechanisms) were compared with impact wear (abrasive, adhesive and fatigue mechanisms) using a BIOMAT simulator. The comparative rankings of seven restorative materials (including two composites) differed significantly
between the two methods, and the study concluded that “there is no correlation between impact-cum-sliding wear and non-impact sliding wear” (Yap et al., 1999). There has not been a study that has analyzed the effect of wear produced with impact and rotation to wear produced with impact and sliding.

Comparison of Devices

The major difference between the individual devices is the method of force delivery. Several methods of load delivery exist in wear simulating devices, including springs, weights, and electric or hydraulic actuators.

The current Alabama wear testing device applies a load by a spring-calibrated stylus. The stylus has a helical compression spring that when depressed a recorded distance will respond with the intended force. This system applies Hooke’s Law, which states that the load applied by a spring is proportional to its displacement. The limitation of a spring-based system, however, is that the relationship between load and displacement only applies within the elastic limit of the spring. This limits the range of forces that can be reliably produced with a spring-based system. Additionally, the elastic properties of the spring are liable to deteriorate over the lifetime of the spring, particularly with a dynamically loaded spring. Therefore, a spring-calibrated system will require frequent calibration and maintenance of the styli and could lead to inter-specimen variability if springs in different stations deteriorate preferentially. The Acta device also applies a normal force by spring-loading, and may be susceptible to spring degradation.
Other testing devices apply vertical force by means of a weight-calibrated stylus, such as the Willytec and Biomat devices. The advantages of weight-controlled loading include the ability to reliably apply an indefinite range of forces and the lack of a source of deterioration or alteration of the load with time. The disadvantage of weight loading, however, is that it creates force impulses from the impact force.  

An impulse force is a force in excess of the static load dependent on the descending velocity of the stylus. Heintze measured forces impulses in the Willytec device and determined that they range from 3-4 times the static force. The development of an impact force is also dependent on the resilience of the specimen and specimen holder.

Another mode of applying force is by electric or hydraulic actuators, as used by the OHSU and Minnesota devices respectively. A disadvantage of the use of actuators for wear testing it that a force sensor is required to verify that the intended load is being applied. The Minnesota device incorporates load sensors and the OHSU device does not.

**Contributing factors for in-vitro wear simulation**

1. **Standardization of the antagonist: Counter sample materials**

The choice of the counter sample is a critical factor in establishing the pattern of wear and in achieving an efficient in vitro wear testing system. A variety of factors including hardness, wear surface evolution and frictional coefficients have to be considered, relative to the tribology of the in vivo situation. Assessment of potential counter sample materials should be based on the essential tribological simulation supported by
investigations of mechanical, chemical and structural properties. Antagonists standardized for shape and size and according to materials should show mean values similar to those found in natural, non-standardized cusps. Krejci et al. measured the shapes and sizes of palatal cusps of non-erupted human upper third molars. Natural enamel antagonists are preferable for the simulation of wear in the occlusal contact area.

2. Composition of the antagonist

A variety of antagonist has been used which include enamel, gold, ceramics, stainless-steel, Annealed chromium-steel counter bodies, Alumina ball: diameter 10 mm and Dental porcelain. A study by Heintz concluded that enamel provided similar wear results as two different ceramic antagonists and produced no more variation in the wear data\textsuperscript{16}.

3. Shape of the antagonist

A variety of antagonist such as flat, ball or rounded, flattened enamel surfaces, enamel harvested from extracted human third molars and machined into cusps with a 5 mm spherical radius or hemi-spherically and Standardized human enamel cusps with a uniform contact area have been used.

4. Load/force

In the load/force diagram several variations are possible. Static and/or sinusoidal cyclic and dynamic, Contact loads ranging from 1, 10, 20, 25, 50, 75, 100 N, Contact loads ranging from 1.7, 3.2, 4, 6.7, 9.95, 16.2 kgf/cm\textsuperscript{2}. Chewing force of 53 or 75.6 N
maximum force, Abrasion load: 20 N and attrition load: 90 N and Resiliency of the periodontal ligament.

5. Contact area size: force per unit surface area. Facet area

The importance of the effect of contact area dimensions on the wear of composite specimens and their opposing enamel cusps was evaluated in vitro by Krejci et al.

Table 1: PHYSIOLOGIC FORCES OF MASTICATION

<table>
<thead>
<tr>
<th>Test Method</th>
<th>Measured Forces</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber sheet sensors with varying hardness (molar area)</td>
<td>100N (hard), 126N (harder), 140N (hardest) [max]</td>
<td>(178)</td>
</tr>
<tr>
<td>Encapsulated load cell placed between teeth (molar area)</td>
<td>50-100N (elastic), 20-150N (plastic) and 30-60N (brittle) [mean]</td>
<td>(179)</td>
</tr>
<tr>
<td>Strain gauge in denture tooth</td>
<td>3-17.5N [mean] 49-78N [max]</td>
<td>(182)</td>
</tr>
<tr>
<td>Strain gauge in bridge pontic area</td>
<td>20N (potatoes) and 60N (carrots) [mean]</td>
<td>(183)</td>
</tr>
<tr>
<td>Strain gauge in single prosthetic molar</td>
<td>92N (meat), 126N (carrots), 129N (biscuit) [max]</td>
<td>(184)</td>
</tr>
<tr>
<td>Strain gauge in frame around natural molars</td>
<td>21.7N (cookies) and 59.5N (carrots) [mean]</td>
<td>(186)</td>
</tr>
</tbody>
</table>

6. Number of cycles

In order to compare results different studies, number of cycles should be taken into consideration. Ranging from 5000, 10,000, 25,000, 50,000, 100,000 to 120,000.

7. Chewing frequency: frequency of load cycles

The chewing frequency used in vitro studies varies from 1.2 to 1.7 Hz.

8. Duration of tooth contact
The duration of tooth contact during the in vitro loading should mimic the in vivo situation. Load and time significantly influence wear.

9. **Sliding speed: relative speed of opposing surfaces**

The sliding speed (2.5 mm/s) during the in vitro simulation should be comparable with the in vivo situation.

10. **Temperature**

Temperature plays a plasticizing effect. Constant temperature (20, 37 °C) or thermocycling (5–55 °C) should be maintained.

11. **Food bolus during mastication**

Variety of food bolus or slurry can be used during mastication movement simulating such as Slurry of water and unplasticized PMMA beads, PMMA powder, Hydroxyapatite slurry and Millet-seed/PMMA-beads mixture.

12. **Lubricant and friction**

Oral lubricants consist of saliva, plaque and pellicle. Together they form a boundary lubrication system, because the thickness of the lubricant layer is insufficient to prevent asperity contact through the film. Effectiveness of boundary lubricants is influenced by their chemical properties than their viscosity. The buffering capacity of saliva and plaque is important in minimizing the corrosive effects of acids (thickness of 100–500 nm) may act as a protective layer. Several liquids are incorporated in the three-
body wear machines, like: Water, alcohol, acids, olive oil, olive oil/CaF slurry, artificial saliva, yes or no inclusion of bacteria.

13. pH

pH conditions seem to influence dramatically the wear conditions and therefore they should be controlled carefully during in vitro wear testing. Following pH levels (1.2, 3.3, and 7.0) are frequently used during wear simulation. They should mimic plaque acids, gastric acids and dietary acids. If human enamel is used as counter body, acidity of the medium has an impact on the wear behavior. Interplay of abrasion, attrition and erosion of human enamel under several different pH conditions has been tested. Combination of erosion and abrasion resulted in significantly greater wear than erosion alone. Simultaneous erosion and abrasion resulted in about 50% more wear than alternating erosion and abrasion. Chewing of acidic foods with some abrasive properties might cause enhanced tooth wear. Dentin is more susceptible than enamel to erosion and abrasion alone or combined. Load and time significantly influence enamel wear both in acid and neutral conditions. Depth of dentine erosion significantly increases non-linearly with time and significantly decreases with increasing pH. Dentin is susceptible to erosion even at relatively high pH, the tubule system is readily exposed and dentine, unlike enamel, shows little propensity to remineralize.

14. Enzymes

Enzymes seem to have the potential to degrade the samples during in vitro testing. de Gee et al. used esterase solution in the ACTA wear machine. Chemical cycling can
induced a generalized swelling of the composite samples and a modified wear curve. These enzymes can be generated in saliva and by bacterial metabolism.

15. Enamel structure and physiology related to microwear

Enamel structure has an effect on microwear. The micro structural element is important in direction of shearing force relative to enamel prisms and crystallite orientation. The different responses of prismatic and nonprismatic enamels to abrasion reflect the influence of structure at the level of organization of crystallites rather than prisms per se. Variation in crystallite orientation in prismatic enamels may contribute to optimal dental function through the property of differential wear in functionally distinct regions of teeth.

16. Wear debris

Impact of wear debris at the zone of impact and friction should be examined more carefully.

Three-body Wear

Three-body wear occurs in the presence of food in vivo. The properties of food particles that will determine their abrasiveness include hardness, size and shape. In vitro studies have reported both increased and decreased wear in the presence of third-body particles and it may be these differences in food properties that determine whether food acts as abrasive particles or lubricant bodies in vivo.

Anthropological studies have shown that dietary hardness is closely linked with human enamel wear. Types of food particles have been categorized as those that: 1) do
not crumble and remain homogeneous during chewing (ie gum), 2) are soft and break down quickly during chewing (ie bread) are hard and crunchy and break down slowly (ie peanuts). Most likely, the hard and crunchy food will be the most abrasive. A study by Lucas et al measured the hardness of “fallback” foods, the hard and raw foods available in nature. Vicker’s hardness values of seeds shells ranged from 126.3-271.5MPa, seed kernels ranged from 2.5-7.2MPa and vegetables ranged from 0.2-1.3. Other studies have shown that moisture content of seeds significantly reduces their hardness.

A study by Peyron et al. measured the sizes of food particles expectorated from a human subject following mastication with sieves and LASER diffraction analysis. The study demonstrated that about 80% of the particles obtained from vegetables were larger than 2mm and 60% of the particles obtained from nuts were smaller than 400μm. Of the nut particles that were smaller than 400μm only about 30% were smaller than 100μm, however this size distribution may be skewed due to the swallowing of smaller particles. Pallav et al. showed that decreasing the size of abrasive particles from 3μm to 1μm allowed direct contact between enamel and a composite specimen.

Both natural and synthetic substances have been used in food-simulating slurries in vitro. Early in vitro wear testing studies determined that using a slurry of millet seeds and polymethyl methacrylate (PMMA) beads produced wear patterns similar to in vivo wear data. PMMA beads were later used alone because this material does not degrade through the wear testing cycle. Other natural and synthetic materials have been used in third-body slurries including: poppy seeds, calcium di-phosphate and glass micro beads.
Two-body Wear

Two-body wear occurs in the mouth during parafunctional habits such as bruxism or phases of chewing without intervening food particles. This tooth contact is lubricated by saliva except in cases of severe xerostomia and hyposalivation. Salivary proteins, such as proline-rich glycoproteins and mucins, give saliva its lubricating properties. The efficacy of lubrication is dependent on the viscosity and dynamic viscosity of saliva. Viscosity has been reported as 3cP for stimulated saliva and 6cP for unstimulated saliva and the dynamic viscosity on the order of 10\(^{-4}\) Pa\(\cdot\)s. The viscosity of saliva will in part determine the method of lubrication of saliva.

A lubricant can be classified as hydrodynamic or boundary depending on its Sommerfield number, a function of the viscosity of the lubricant and the applied load and sliding speed of contacting surfaces. Hydrodynamic lubricants are viscous and physically separate two contacting surfaces. Boundary lubricants act by separating surfaces by a thin molecular film. The lubricant’s Sommerfield number is plotted against its coefficient of friction on a McKee-Petroff curve to determine its mode of lubrication. Experiments with human saliva have demonstrated that saliva behaves in the region of boundary lubrication.

![McKee-Petroff curve](image)

Figure 14: McKee-Petroff curve
Different saliva-simulating lubricants have been evaluated in *in vitro* wear testing devices. Natural saliva was compared to mucin-based artificial saliva (MC), carboxymethylcellulose-containing saliva (CM), and water. The MC provided similar lubrication as saliva through the first 100,000 cycles of testing.\textsuperscript{78} At that point; the saliva began to show decreased lubricating ability, presumably due to break down of constituent proteins.\textsuperscript{78, 79}.

**Antagonist Material**

Many surfaces may act as a counter surface during in vivo wear, including metal and ceramic crowns and enamel tooth structure. A recent clinical study compared wear of tooth structure opposing metal and ceramic. Less wear was measured on enamel opposing a lithium disilicate and gold-alloyed crown than a crown veneered with feldspathic porcelain. Additionally, the authors noted that less wear was observed on natural enamel-enamel contacts than any of the enamel opposing restored surfaces.\textsuperscript{80} Their study demonstrates that enamel, ceramic, and metal all behave differently as a counter surface antagonist. In vitro wear simulating devices have incorporated metal, ceramic and enamel antagonists; however, enamel is considered the gold standard. Disadvantages of natural enamel as an antagonist do exist, including: inhomogeneity in enamel, differences in morphology and size of teeth, and potential bio-contamination issues.

Variable crystal structure orientation in enamel causes regions of natural teeth to experience preferential wear.\textsuperscript{81} Wear studies have addressed the inhomogeneity of enamel by using ceramic or metal as a replacement antagonist material. Shortall et al. measured mechanical properties and wear of steatite (ceramic), feldspathic porcelain, and
stainless steel and compared them to natural enamel. Feldspathic porcelain had the most similar properties to enamel and therefore the best simulating ability of the materials tested. Studies have compared composite wear with steatite and feldspathic porcelain to enamel.

 Composite wear against enamel and steatite did not correlate with each other because steatite acted through a more aggressive adhesive wear mechanism than enamel antagonists. Feldspathic porcelain produced similar composite wear as natural enamel, however, using porcelain antagonists did not reduce variability in wear testing. In conclusion, there is no perfect substitute for enamel in wear testing.

 Differences in morphology and size of teeth have been addressed by attempting to standardize enamel cusps used for wear testing. Measurements of palatal cusp sizes of human upper third molars determined that a ball of 0.6mm radius best represents the shape of a tooth. Studies which have standardized enamel antagonists in composite and ceramic wear testing have shown that standardizing enamel does not reduce variability in wear testing. Additionally, wear results produced from standardized enamel cusps did not correlate with wear from natural enamel cusps. A criticism of most methods of standardizing enamel cusps is that the enamel at the surface of the cusp tip is ground to achieve a desired shape. Studies have shown that enamel hardness decreases moving closer to the dentin-enamel junction, and it is hardest at the enamel surface. Therefore, removing the hard enamel surface during standardization will affect the wear properties of the enamel antagonist.
Newly modified UAB- Chewing simulator

The original Alabama wear device operates by a motor-driven upper member driving a row of styluses into a lower well of lubricated specimens. Each stylus contains a spring to apply a known force on the specimen and an internal mechanism to cause 30 degree rotation upon contacting the specimen. The end of the stylus houses a stainless steel ball that acts as an antagonist. The major modifications to the Alabama wear testing device include: substitution of spring-control for weight-control of load application, replacement of stylus rotation with horizontal sliding, and the addition of lubricant pumps. Each addition will be described.

Figure 15: Modified Alabama wear testing device.

(A) Weight-calibrated antagonist stylus, (B) Cam to drive the horizontal movement of the specimen platform, (C) Specimen base, (D) Specimen well and (E) Lubricant storage.
Design of Load Application

Load application is supplied by the weight of the antagonist styluses. The load is calibrated by addition of lead shot into the hollow bodies of the styluses or calibrated plates on top of the styluses. The load can be varied between 10-70N. The stylus is raised from and lowered to the specimen by lifting and releasing collars on the motor-driven upper member. The impact speed is therefore controlled by the rate of the motor, which also controls the testing frequency. The impact of the stylus force is dampened by the specimen holders and the acrylic used to embed specimens in the holders.

Figure 16: Modified Alabama wear testing device – one cycle is divided into quarters in the diagram as the main shaft turns counter-clockwise.

(A) Base, (B) Cam follower, (C) Main shaft, (D) Cam, (E) Upper member, (F) Collar, (G) Antagonist styli, (H) Specimen well, (I) Specimen
Design of Sliding Mechanism

The sliding motion was accomplished by placing the specimen well on a base above a gliding track (A and B). Horizontal translation of the base is driven by a cam on the shaft that controls vertical movement of the styluses and a cam follower attached to the base (C, D, and E). As a result, vertical and horizontal interactions of the styluses and specimens are synchronized. The stylus is lowered onto the specimen such that they contact as the specimen begins to slide forward 2mm, and after the stylus is lifted off, the specimen slides backward to its original position. The sliding speed of the specimens is also dependent on the speed of the motor.

Figure 17: Sliding mechanism of modified wear device.

(A) Gliding track (B) Base (C) Cam follower (D) Cam and (E) Shaft to control styluses
Design of Lubricating System

Lubricant pumps were added to cycle lubricant from a storage beaker to the surfaces of the specimens. The lubricant is electromagnetically stirred in a 100mL beaker. Lubricant is pumped into channels in the plexiglass lids of the specimen wells to deposit a vortex of liquid over individual specimens. The runoff is collected in the bottom of the wells and drained back to the storage beaker. Flowing solution on the specimens serves the dual purpose of providing lubrication and removing wear debris.

Figure 18: Specimen well.

(A)Lubricant inlet tube, (B) Lubricant channels in plexiglass lid, (C) Lubricant outlet.

Figure 19: Individual specimen with lubricant vortex applied to the surface.
Measurement of Force Impulses

A force impulse is a force in excess of the static load dependent on the descending velocity of the stylus.\textsuperscript{56} Impulse forces were measured at varying testing frequencies (cycles/sec) and loads. A testing cycle was defined as the descent from the uppermost vertical position of a stylus and its complete ascending return to that same position. The descent speed of the stylus was determined by dividing the descending distance of the upper member of the device (26mm) by half the cycle time. A 200lb capacity 100Hz load cell (360-122-1BS; Toroid Co, Huntsville, AL) was attached to a data acquisition system (Model 5100 Scanner; Vishay, Raleigh, NC). A 6mm block of acrylic was fitted on the load cell to simulate the dampening effects of the embedding acrylic. The load cell was positioned directly below the stylus. Static loads were calibrated by the addition of lead shot and weighted plates. Data were examined to determine the peak impulse force and duration for every cycle.

Figure 20: Force impulse measurement. (A) Stylus, (B) Load Cell
Figure 21: Representative graph of impulse force measurement. The graph represents a static load of 20N tested at 1 Hz.

Types of Antagonists

Enamel

Enamel is the gold standard for intraoral wear simulation as it is the natural material in the mouth. It is composed of hydroxyapatite (HA) crystals embedded into an organic matrix. The HA crystals compose 95% of enamel and wear by brittle fracture, similar to ceramics. The orientation of HA crystals divide enamel into 5µm rods separated by inter-rod enamel. Analysis of enamel subjected to sliding wear reveals that it fails by microcracking. The arrangement of HA into rod structure in enamel can hinder the propagation of cracks by redirecting them. Additionally, the inter-rod enamel is less
wear resistant than the enamel rods. Therefore, enamel is an anisotropic material as its mechanical properties are dependent on the orientation of its rods.

Based on this information, several theories can be made about the behavior of enamel as a counter surface. Since enamel and its major constituent HA both fail by forms of brittle fracture, the worn surface of enamel will probably roughen to produce sharp edges. These sharp edges of enamel would be capable of abrading an opposing material. The orientation of enamel into 5µm rods may also cause preferential wear around the rods, leading to 5µm projections on the worn enamel surface.

*Ceramic*

The types of ceramics used as antagonists in in vitro wear testing can generally be divided into two categories, those which contain a glassy phase and those which do not. Feldspathic porcelain and glass-ceramics both contain a glassy amorphous matrix which is reinforced with a crystalline phase, typically leucite. Alumina and zirconia, on the other hand, are polycrystalline ceramics without a glass phase. The materials behave slightly differently in wear testing. Feldspathic porcelain and glass-ceramics are susceptible to fracture through their glassy phase. Crystals within the glass matrix strengthen the material through dispersion strengthening and help prevent fracture. Glass-ceramics have demonstrated failure at the interface of their crystals and glass matrix. These crystals are more abrasive than the surrounding glass and can more easily damage opposing enamel. In summary, glass containing ceramics can cause abrasive wear of opposing materials by fracturing through their glassy phase and exposing hard abrasive crystals on their surface.
Zirconia and alumina are polycrystalline ceramics with no glass content. The high crystal content of these materials increases their fracture resistance. A study by Liu and Xue found that zirconia maintained a smooth surface during sliding wear at relatively low normal loads. Increasing the normal load above 20N altered the mechanism of wear from plastic deformation to microcracking. Therefore, the behavior of polycrystalline ceramics as antagonists may be load dependent.

**Metal**

Unlike ceramics which fail by brittle fracture, metals undergo plastic deformation during wear. Therefore, the hardness of a metal will affect its ability to cause wear. Aside from hardness, the surface roughness of an antagonist is also important in determining its wear producing ability. The surface of a metal has a micrographic topography of between 0.1-100 microns (average about 3 microns) resembling hills that is determined by manufacturing. The common manufacturing method of the stainless steel balls used in the Alabama wear testing device is to trim wrought wire into short cylinders which are then die-punched into spheres. The edges of the balls are then refined, polished to a mirror finish and hardened by heat treatment. On the surface of the metal is typically a 1-10nm oxide layer and a contaminant layer of a few nm.
Statement of the problem

Monolithic zirconia crowns have excellent mechanical properties; however, antagonist enamel wear produced by zirconia requires further investigation. Additionally as zirconia transforms from the partially stabilized tetragonal phase to the monoclinic phase surface roughening may occur further increasing wear of the opposing enamel.
HYPOTHESIS AND AIMS

Null Hypothesis:

No significant enamel wear difference will be produced by glazed, polished, adjusted or aged zirconia compared to feldspathic porcelain and enamel-enamel wear.

Specific Aims:

1. To measure the wear of human enamel against polished and glazed zirconia and compare it with commercially used veneering porcelains.
2. To measure enamel wear on adjusted zirconia specimens.
3. To measure enamel wear opposing artificially aged zirconia.
4. To correlate zirconia surface roughness and opposing enamel wear.
MATERIALS AND METHODS

Study groups

<table>
<thead>
<tr>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polished Zirconia</td>
</tr>
<tr>
<td>Glazed Zirconia</td>
</tr>
<tr>
<td>Polished and Glazed Zirconia</td>
</tr>
<tr>
<td>Glazed and adjusted Zirconia</td>
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<tr>
<td>Aged Zirconia</td>
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<tr>
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</tr>
<tr>
<td>Adjusted Zirconia</td>
</tr>
<tr>
<td>Enamel (control)</td>
</tr>
<tr>
<td>Ceramco 3 (negative control)</td>
</tr>
</tbody>
</table>

Table 2- The study included zirconia, enamel and feldspathic porcelain.

Materials used:

1) 50 micron aluminum oxide
2) NTI® CeraGlaze Polisher (Green: Coarse) from Axis Dental
3) NTI® CeraGlaze Polisher (Blue: Fine) from Axis Dental
4) NTI® CeraGlaze Polisher (Yellow: Superfine) from Axis Dental
5) Intra-oral DiaShine FINE polish from VH Technologies used with soft bristle polishing brush
6) FCZ Glaze
7) Zir-Cut™ Diamonds from Axis Dental
STUDY DESIGN

Figure 22: The study was conducted in 3 phases.

1. Preparation of ceramic and enamel specimens.
2. Cyclic loading of specimens.
3. Wear determination.
SPECIMEN PREPARATION

Ceramic blocks were cut in the dimensions of 7x11x6mm±0.3 mm. Each group had 8 specimens.

Zirconia polished

• Specimens were sandblasted with alumina at 50psi and steam cleaned.

• The specimens were pre-polishing using light pressure and no water with the NTI® green polisher.

• NTI® blue polisher is used to create the initial high shine. Light to medium pressure is applied enough water to create slurry, you will see the glossy look reappear on the specimen.

• NTI® yellow polisher at medium to light pressure to achieve a "wet" shine.

• DiaShine with a soft bristle polishing brush to achieve high gloss.

• Once high gloss was achieved, the specimens are steam cleaned.

Zirconia with no polish but glazed

• The specimens were sandblasted with alumina at 50psi and steam cleaned.

• FCZ Glaze was mixed to a creamy consistency and painted onto specimen and baked according to parameters below.
Table 3: Firing parameters for glazed zirconia

### Zirconia polished then glazed

Specimens were sandblasted with alumina at 50psi and steam cleaned.

- The specimens were pre-polishing using light pressure and no water with the NTI® green polisher.

- NTI® blue polisher was used to create the initial high shine. Light to medium pressure is applied enough water to create slurry, you will see the glossy look reappear on the specimen.

- NTI® yellow polisher at medium to light pressure to achieve a "wet" shine.

- DiaShine with a soft bristle polishing brush to achieve high gloss.

- Once high gloss was achieved, the specimens are steam cleaned.

- FCZ Glaze was mixed to a creamy consistency and painted onto specimen and baked according to parameters below:
Table 4: Firing parameters for polished and glazed

Zirconia glazed then “adjusted”

Specimens were sandblasted with alumina at 50psi and steam cleaned.

- FCZ Glaze was mixed to a creamy consistency and painted onto specimen and baked according to parameters below:

Table 5: Firing parameters for glazed and adjusted zirconia

- The glazed surface is than adjusted using a fine grit (30µm) diamond bur
- This adjustment is done using a high speed hand piece (friction grip) with water cooling and light pressure to avoid heat buildup and micro fractures
• The above fine diamond (red stripe) was used for 5 seconds at 40,000 rpm.

**Zirconia polished then thermocycled**

Specimens were sandblasted with alumina at 50psi and steam cleaned.

• The specimens were pre-polishing using light pressure and no water with the NTI® green polisher.

• NTI® blue polisher was used to create the initial high shine. Light to medium pressure is applied enough water to create slurry, you will see the glossy look reappear on the specimen.

• NTI® yellow polisher at medium to light pressure to achieve a "wet" shine.

• DiaShine with a soft bristle polishing brush to achieve high gloss.

• Once high gloss was achieved, the specimens were steam cleaned.

• The specimens were than aged in an autoclave for 10 hrs at 2lb pressure @ 275°F.

• Than the specimens were subjected to thermo cycling for 10,000 cycles at 5-55°C with a dwell time of 30 sec.

**Zirconia adjusted and polished**

• The red stripe diamond is used for 5 sec.

• This adjustment was done using a high speed hand piece (friction grip) with water cooling and light pressure to avoid heat buildup and micro fractures.
• The above fine diamond (red stripe) was used for 5 seconds at 40,000 rpm.

The specimens were pre-polished using light pressure and no water with the NTI® green polisher.

• NTI® blue polisher was used to create the initial high shine. Light to medium pressure was applied enough water to create slurry; you will see the glossy look reappear on the specimen.

• NTI® yellow polisher at medium to light pressure to achieve a "wet" shine.

• DiaShine with a soft bristle polishing brush to achieve high gloss.

• Once high gloss was achieved, the specimens were than steam cleaned.

Zirconia adjusted

The ceramic surface was adjusted using a fine grit (30µm) diamond bur.

• This adjustment was done using a high speed hand piece (friction grip) with water cooling and light pressure to avoid heat buildup and micro fractures.

• The above fine diamond (red stripe) was used for 5 seconds at 40,000 rpm.

Enamel

• The enamel specimens were produced from flat labial enamel surface of maxillary central incisors.
• The Freshly extracted central incisors were collected and their roots were sectioned with a tooth grinding wheel.

• Then the flatted labial crowns surface were placed in brass cylinders and stabilized with self-cure acrylic resin.

• Then the surface is steam cleaned and polished with flour of pumice.

Porcelain (Ceramco 3)

• The specimens were built and fired according to manufacturer’s instruction accounting for shrinkage

• The testing surface is ground to a flat surface using 400 grit on polishing wheel

• The surfaces were than finish with a fine diamond bur (Brasseler fine diamond - 30 micron - red stripe).

• The specimens were than sandblasted using 50 micron alumina at 30 psi

• Ultrasonically cleaned.

• Ceramco 3 Overglaze was mixed to a creamy consistency and painted onto the specimens and baked according to parameters below:

<table>
<thead>
<tr>
<th>Firing Parameters</th>
<th>Pre-Dry</th>
<th>Low Temp</th>
<th>Heat Rate</th>
<th>Vac</th>
<th>Vac Start</th>
<th>Vac Stop</th>
<th>Hi Temp</th>
<th>Hold</th>
<th>Cool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramco Overglaze</td>
<td>3 min</td>
<td>650°C</td>
<td>70°C/min</td>
<td>No</td>
<td>x</td>
<td>x</td>
<td>935°C</td>
<td>30 s</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3 min</td>
<td>1202°F</td>
<td>126°F/min</td>
<td>No</td>
<td>x</td>
<td>x</td>
<td>1715°F</td>
<td>30 s</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 6: Firing parameters for ceramco 3 specimens.
Enamel Styli preparation:

• Freshly extracted mandibular molars were taken and their cusps were standardized by cone shaped diamond bur (Brasseler, USA) in a straight hand piece (NSK, Japan).

• The sides of the cusp were trimmed to the smallest possible dimensions.

• The standardized cusp was mounted on to an metal styli and stabilized with self-cure acrylic.

• The antagonist surface is than cleaned and polished with flour of pumice.

• Initial Impressions of the enamel cusps were obtained with a PVS light body.

Figure 23: Extracted Mandibular Molar (Above)

Figure 24: Standardization of the enamel cusp (Below)
Cyclic Loading in the newly modified UAB-Chewing Simulator

The invitro study was carried out on a newly modified UAB chewing simulator. The Alabama wear method has proved its reliability from the past two decades. Its earliest publication was in 1989 by Drs. Leinfelder and Suzuki and hence it is also known as Leinfelder-Suzuki wear method. This was modified from the basic Roulet method. The Alabama wear method later included modifications such as integration of a 30º clockwise rotations as the stylus hits the surface, and replacing the metal stylus with a fiber glass stylus. According to a recent review, it has the highest citation frequency, followed by ACTA, OHSU, Zurich and MTS wear simulators. The Alabama wear method is also included in the ISO Technical Specification on the wear by two/three body contact.
Traditionally many wear testing devices used two body wear, three body wear, pin on a block or disk, tooth brush simulators for determining the wear. Their results varied and the correlation to clinical wear was not established. This can be attributed to the variations in the force, motion and the testing conditions. Due to the considerable attention given to the validation of existing wear methods, a more clinically relevant wear device, a chewing axis simulator was redesigned to improve the reliability. The eight station machine is a highly precise instrument applying designed load along the longitudinal axis. It is designed to allow lateral movement up to 8mm. A variable amount of load from 5N-400N can be applied during the wear testing. A custom made thermocycler runs in conjugation with the wear testing machine. It maintains the constant flow of hot/cold fluids on the specimens.

A timer automatically alters the hot and cold cycles in specified time. The fluid circulated, is a mixture of glycerol and water in the ratio of 1:3. The medium has produced a reproducible wear in controlled conditions when compared to others. (Lawson N, IADR-2010) The formulation of solution is maintained by an electo-magnetic stirrer (Corning, USA). In the study longitudinal force of 10 N was applied by enamel styli on the flat ceramic/enamel (Control) specimens, which were positioned on a 2mm horizontal sliding platform. These enamel styli contacted the lower flat specimens with a frequency of 20cycles/min and continued for 400,000 cycles.

Impression protocol

Imprint (3M ESPE) a light body Impression material (Type 3: Light-bodied consistency, Classification ISO 4823) cartridge was inserted in a hand-powered
dispensing gun (3M ESPE, St. Paul, MN, USA). A mixing tip was installed on the cartridge and the dispenser and a small amount of base and catalyst were dispensed to ensure even flow of both the catalyst and the base (mixing ratio 1:1). The trigger was squeezed to dispense the impression material evenly on the specimen surface. A single operator was involved in the impression making procedure to reduce the number of variables. Vinyl gloves were worn during manipulation of the material because latex gloves inhibit the polymerization of polyvinyl siloxane (PVS) materials. The impression was allowed to polymerize for 5 minutes after seating at an ambient temperature of 21 ± 2° C and humidity of 33%. At this temperature the setting time of the impression material would be in-creased. According to the manufacturer at 72° F (22° C) Imprint light body Impression Materials have a minimum work time of 2 minutes 15 seconds and a minimum removal time of 5 minutes from start of mix. In this study the impression was seated on the enamel styli for 6 minutes and 10 seconds.

![Figure 27: Impressions of cusps](image)

**Casts**

All the impressions were poured to scan in the order they were tested. The impressions were washed thoroughly with tap water, to remove any remaining slurry and
dried with air water syringe to ensure no excess liquid remained. 32 ml distilled water, accurately measured in a measuring cylinder at 23 ± 2°C was placed in a wet vacuum bowl (Whip Mix Corporation, Model #6500, Louisville, US). 140 grams of Silky-Rock was then vacuum mixed for another 30 seconds under 27 psi/Hg in a Whip Mix Combination unit (Whip Mix Corporation, Louisville, US). The mix was poured at an ambient temperature of 23 ± 2°C and humidity of 34 ± 1%. Using a stone vibrator set in a slow mode the mixed stone was slowly poured in the impressions, and care taken to prevent distortion. A new enamel stylus was used for each wear simulation. The samples were retrieved after one hour (30 minutes recommended by the manufacturer). They were inspected for bubbles and other visible defects in the area of the preparation. Specimens with such defects were discarded and new impressions were made. The specimens were then carefully sectioned to obtain the desired occlusal surface, the margin of the maxillary premolar were evaluated for any defects during sectioning. The samples were sectioned to make it easier to scan the sample with the non-contact 3D profilometer. Samples were kept in a sealed plastic container at room temperature to avoid moisture contamination.

**Determination of volumetric wear & depth loss**

A highly accurate non-contact surface profilometer, the Proscan 2000 (Scantron Industrial Products Ltd., England), was used to scan the surfaces of the antagonist surfaces and enamel styli impressions made there.
The use of the (S-Type) chromatic sensor allows examination of dark and rough surfaces with the object viewed in any orientation or auto-leveled using the proprietary software Proscan and Proform. It scans any surface over an area up to 150mm x 100mm. It uses a focal multiplexing sensor with up to 0.005μm resolution. Safe white light is transmitted through a lens, which has a built in spectral aberration. Takes the white light and divides it into the full spectral field, focusing each different color frequency at a slightly different point through a defined measuring range. When an object is placed within this range, only one particular color frequency reflects back from the surface. Information passes back into processor where a spectrometer analyzes the signal and converts it to a measurement. Proscan combines these measurements with the precise location of a moving X and Y linear table, giving three co-ordinates from which a three dimensional profile is created. Results of the surface profile appear immediately on the computer monitor and an image of the graphical 3-D representation can be saved on the computer.
Casts scanning protocol

The casts that were obtained from impressions of each of the enamel styli were scanned using Proscan 2000 (Scantron, UK). These casts were placed on a metal block, affixed with wax, to the flat scanning platform of the Proscan 2000. The casts were aligned in a straight line such that each horizontal line of the cast met its corresponding horizontal line on the adjacent cast in a straight line. This would enable the Proscan software to read off designated random points on the lines. An area of 4 X 4 mm\(^2\) was scanned with a step size of 20 µm. Therefore, the total casts of the enamel styli were scanned at baseline, 200,000 cycles using the Proscan software and results. Wear volumetric loss differences between a baseline impression and 200,000 cycles were obtained using the Proform software by superimposition of the obtained 3D scans.
Results

The statistical analysis method used to compare means was repeated measures ANOVA. Separate analyses were conducted for volumetric wear and volume loss. Tukey–Kramer post hoc test was used for pair wise comparison of group means.

Wear of the ceramics:

The polished zirconia showed no signs of wear after 400,000 cycles. The glazed zirconia had the highest wear among the zirconia groups with a mean volume loss of 0.38 ± 0.1 mm$^3$ and a depth loss of 80.8 ± 25.9 µm at 200,000 and a mean volume loss of 0.62 ± 0.16 mm$^3$ and a depth loss of 106.2 ± 26.2 µm at 400,000 respectively. The polished and glazed zirconia has a significant less wear than the glazed zirconia with a mean volume loss of 0.27 ± 0.06 mm$^3$ and a depth loss of 57.3 ± 9.8 µm at 200,000 cycles and a mean volume loss of 0.49 ± 0.1 mm$^3$ and a depth loss of 89.3 ± 14.3 µm at 400,000 respectively. The mean enamel-enamel volume and depth loss was 0.24 ± 0.08 mm$^3$ and 79.6 ± 11 µm at 200,000 cycles and 0.42 ± 0.11 mm$^3$ and 108.8 ± 18.84 µm at 400,000 cycles. The porcelain (Ceramco3) reported the highest amount of volume and the depth loss of 0.87 ± 0.1 mm$^3$ and 137.1 ± 25 µm at 200,000 cycles and 1.29 ± 0.1 mm$^3$ and 194.2 ± 27.3 µm at 400,000 cycles.
Table 7: Ceramic Wear with the means and Standard deviation of the groups

<table>
<thead>
<tr>
<th></th>
<th>Ceramic volume loss (mm³)</th>
<th>Original roughness (µ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200,000</td>
<td>400,000</td>
</tr>
<tr>
<td>Polished zirconia</td>
<td>0.00±0.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.00±0.0&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Glazed zirconia</td>
<td>0.381±0.1&lt;sup&gt;c,d&lt;/sup&gt;</td>
<td>0.62±0.16&lt;sup&gt;c,d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Polished then re-glazed zirconia</td>
<td>0.27±0.06&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.49±0.10&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Glazed and adjusted Zirconia</td>
<td>0.32±0.08&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.53±0.09&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Artificially aged zirconia</td>
<td>0.00±0.00&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>0.00±0.00&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Ceramco3</td>
<td>0.87±0.13&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.2±0.18&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Adjusted and Polished zirconia</td>
<td>0.00±0.00</td>
<td>0.00±0.00</td>
</tr>
<tr>
<td>Adjusted zirconia</td>
<td>0.00±0.00</td>
<td>0.00±0.00</td>
</tr>
<tr>
<td>Enamel</td>
<td>0.24±0.08&lt;sup&gt;d&lt;/sup&gt;</td>
<td>0.49±0.11&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
</tbody>
</table>
Fig 30: Graph representing the volumetric ceramic loss at 200,000 and 400,000 cycles.

**Enamel wear**

The wear of the antagonist enamel is considered to be the key with the advent of the monolithic zirconia. The enamel opposing the polished zirconia showed a very minimal wear with a mean volume and depth loss of $0.11 \pm 0.04 \text{ mm}^3$ and $106 \pm 89 \mu \text{m}$ at 200,000 cycles and $0.21 \pm 0.05 \text{ mm}^3$ and $304.39 \pm 180.6 \mu \text{m}$ after 400,000 cycles. The enamel opposing glazed zirconia showed a significantly higher wear than the polished zirconia with a mean volume and depth loss of $0.87 \pm 0.21 \text{ mm}^3$ and $464.7 \pm 95 \mu \text{m}$ at 200,000 cycles and $1.18 \pm 0.2 \text{ mm}^3$ and $659.5 \pm 65.6 \mu \text{m}$ after 400,000 cycles. The polished and glazed zirconia showed a considerable low wear than the glazed zirconia with a mean volume and depth loss of $0.59 \pm 0.1 \text{ mm}^3$ and $353.2 \pm 72.1 \mu \text{m}$ at 200,000 cycles and $0.88 \pm 0.12 \text{ mm}^3$ and $528.1 \pm 69.1 \mu \text{m}$ after 400,000 cycles. The enamel to enamel wear is
slightly higher than the polished zirconia with a mean volume and depth loss of 0.29 ± 0.21 mm³ and 255.9 ± 153.1 µm at 200,000 cycles and 0.49 ± 0.2 mm³ and 362.7 ± 136 µm after 400,000 cycles. The veneering ceramic showed the highest amount of wear then all the groups with a mean a mean volume and depth loss of 1.46 ± 0.5 mm³ and 635.6 ± 278 µm at 200,000 cycles and 2.15 ± 0.5 mm³ and 779.6 ± 213 µm after 400,000 cycles.

<table>
<thead>
<tr>
<th></th>
<th>Opposing enamel volume loss (mm³)</th>
<th>Original roughness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200,000</td>
<td>400,000</td>
</tr>
<tr>
<td>Polished zirconia</td>
<td>0.11±0.04&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.21±0.05&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Glazed zirconia</td>
<td>0.87±0.21&lt;sup&gt;cd&lt;/sup&gt;</td>
<td>1.18±0.2&lt;sup&gt;cd&lt;/sup&gt;</td>
</tr>
<tr>
<td>Polished then reglazed zirconia</td>
<td>0.59±0.1&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.88±0.12&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Glazed and adjusted Zirconia</td>
<td>0.29±0.15&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.43±0.19&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Artificially aged zirconia</td>
<td>0.16±0.04&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>0.25±0.05&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Ceramco3</td>
<td>1.46±0.5&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.15±0.5&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Adjusted and polished Zirconia</td>
<td>0.18±0.06</td>
<td>0.29±0.08</td>
</tr>
<tr>
<td>Adjusted zirconia</td>
<td>0.25±0.05</td>
<td>0.37±0.06</td>
</tr>
<tr>
<td>Enamel</td>
<td>0.29±0.21&lt;sup&gt;d&lt;/sup&gt;</td>
<td>0.49±0.2&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Table 8: Mean and SD of the volume loss of Enamel antagonist
Fig 3: Graph representing the volumetric enamel loss at 200,000 and 400,000 cycles.
Figure 32: Representative Enamel cusp at Baseline, 200,000 and 400,000 cycles respectively (left to right)
Discussion

The tested groups represent the commonly used ceramics in dentistry. The groups of zirconia that are polished, glazed and polished and glazed were included to simulate clinical needs. A group of commonly used glazed veneering ceramic (ceramico3) and flat enamel specimens served as the control. In the pre-test stage the surface roughness is obtained for all the groups by obtaining the preliminary scans with a 3D non-contact profilometer (PROSCAN, UK).

A 3 body wear testing was conducted simulating the clinical conditions in the modified Alabama wear machine. An average human masticatory force of 10N and a frequency of 0.4 Hz were used. Envelope motion provided a slide of 2mm with the opposing surfaces in contact. Enamel antagonists were shaped identically and standardized for clinical replication. These testing conditions play a key role in determining the ceramic wear. A third body medium comprising, a mixture of glycerol and water, in the ratio of 1:3 was constantly thermocycled on to the specimens. This solution produced a reproducible wear. (Lawson N, in press) The temperatures ranged between 5º -55º and cycled for every 30 sec. This helps in removing the debris and also in artificial aging of the specimens. The homogeneity of the solution is maintained by an electromagnetic stirrer (Corning, USA). The study is carried out for 400,000 cycles accounting for a clinical service of 18 months. To visualize the loss of the antagonist and the ceramics, wear was determined at 200,000 and 400,000 cycles.

The ceramic specimens of the polished zirconia showed no traces of wear. The glazed zirconia showed a considerable amount of wear with a loss of surface glaze within the first 200,000 cycles exposing substructure zirconia. There is a considerable loss
thereafter. This can be well established with some of the clinical studies that show the loss of the glaze within 6 months of clinical function. Polishing the subsurface zirconia and then glazing can decrease the wear rate of zirconia when compared with a zirconia that is unpolished and glazed. The high wear of the glazed zirconia can be due to the presence of weak glaze as top structure. This can get further exaggerated by the presence of the worn particles leading to the formation of the wear tracts as the particles plough the surface. The amount of the ceramic wear is considerably less in the polished then glazed zirconia. So it is desirable to use the polished and glazed zirconia in esthetics demanding clinical situations. In all the other instances highly polished zirconia should be preferred.

Figure 33: Antagonist Enamel loss
Human enamel is used as the antagonist in the study. The concern of inhomogeneity of the enamel for in vitro studies can be addressed by careful qualitative examination of tooth and cusp standardization. Steatite is considered as an enamel alternative, but it has high hardness, roughness and high wear potential than enamel. The degree of antagonist wear is believed to be proportional to the surface hardness. But, the findings of the study show that polished zirconia is a wear kind material. This disproved the stigma that hardness is primordially responsible for the wear of ceramics, as zirconia has a hard surface. It also emphasizes the importance of surface roughness of the specimens. This can be well substantiated by the studies of Anusavice KJ that actuated the importance of surface roughness and environmental factors. The glazed zirconia showed a considerable amount of wear of the antagonist. This can be explained from the fact that the glaze on the surface is porcelain composite with properties similar to the feldspathic porcelain. So the surface loss of glaze created rougher areas during the wear testing and causing an exposure of the harder crystalline phases aggravating the loss of the opposing enamel further. This continues and slowly decreases by the exposure of the subsurface rough zirconia. The antagonist enamel wear of the polished and glazed zirconia is slightly less in comparison with only glazed zirconia. This can be explained by the fact that there is a severe loss of enamel initially as it ploughs through the weak glaze material similar to the glazed zirconia and expose the subsurface polished zirconia. As polished zirconia is wear friendly to the antagonist, there was less wear reported thereafter. Clinically the use of the polished zirconia is highly recommended than the glazed zirconia unless a clinical situation demands high esthetics. Also polishing the surface of the crown in subsequent follow up can be more desirable.
The enamel opposing the veneering ceramic showed the highest amount of wear than all the groups. This can be interpreted as the initial loss of glaze that further continued exposing the hard subsurface porcelain crystal phases. So, though zirconia is hard, it is considerably softer than the porcelain and kind to the opposing dentition. Further, the studies involving the pH changes of the oral cavity and randomized control clinical trials are needed for effectively addressing the problems.

**Conclusion**

Within the limitations of the study, the use of monolithic zirconia as crowns can be beneficial without veneered porcelain. This helps the use of zirconia in the space compromised situations with good esthetics and function. The surface roughness of the zirconia is the key in terms of wear of the opposing dentition. Highly polished zirconia is more desirable than the glazed zirconia and if the esthetics demands a glazed restoration, polishing the surface before glazing is advised. Examining for any roughed areas and polishing the crowns in follow-up can be beneficial.

**Future research**

Each research study poses more questions than answers. The results of the study need to be analyzed with the help of the supporting tests. The area of the wear tract has to be analyzed with x-ray diffraction and the roughness after the wear testing can be calculated with atomic force microscopy. Efforts need to direct including the pH cycling and thermocycling during the wear testing. The particulate that is obtained with wear testing should be filtered and analyzed.
References

5. www.sfgate.com/cgi bin/article.cgi?f=/c/c/2003/06/12/FOSSIL.TMP&type=science.)


