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LITERATURE REVIEW
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Wear of dental ceramics

Desgaste das cerâmicas odontológicas

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ABSTRACT

Based on the development of adhesive dentistry, minimally invasive restorations in ceramics are used as alternatives to restore a tooth. Dental ceramics are largely applied in the dentistry field mainly due to their esthetic and mechanical strength. One of the ceramic properties to be well known before its use is the wear resistance that should be compatible with the antagonist wear behavior to avoid unwanted performance. Therefore, several methods have been performed to assess the ceramic materials wear behavior considering different conditions present in the complex oral medium. This study aimed to compile the methods used to investigate dental ceramics wear and to describe the wear mechanisms involved on them. Obtaining and analyzing data is also addressed to discuss the results obtained from different methods, as well as the clinical analysis of wear and future perspectives on this topic. In conclusion, many methodologies are available to measure the ceramic wear. Therefore, the methods must be selected based on the clinical significance of each study and should follow previously reported parameters for standardization, allowing literature comparison.

KEYWORDS

Dental Materials; Ceramics; Dental wear; Dental restoration wear; Methods.

RESUMO

Com base no desenvolvimento da odontologia adesiva, restaurações minimamente invasivas em cerâmica são utilizadas como alternativas para restaurar um dente. As cerâmicas odontológicas são amplamente aplicadas na área odontológica principalmente devido à sua estética e resistência mecânica. Uma das propriedades da cerâmica a ser bem conhecida antes de seu uso, é a resistência ao desgaste que deve ser compatível com o comportamento de desgaste do antagonista para evitar desempenhos indesejados. Portanto, vários métodos têm sido realizados para avaliar o comportamento do desgaste dos materiais cerâmicos considerando diferentes condições presentes no complexo meio oral. Este estudo teve como objetivo compilar os métodos utilizados para investigar o desgaste das cerâmicas odontológicas e descrever os mecanismos de desgaste envolvidos nos mesmos. A obtenção e análise de dados também é abordada para discutir os resultados obtidos a partir de diferentes métodos, bem como a análise clínica do desgaste e perspectivas futuras sobre esse tema. Em conclusão, muitas metodologias estão disponíveis para medir o desgaste cerâmico. Portanto, os métodos devem ser selecionados com base na relevência clínica de cada estudo e devem seguir parâmetros previamente relatados para padronização, permitindo a comparação da literatura.

PALAVRAS-CHAVE

Materiais dentários; Cerâmicas; Desgaste dentário; Desgaste de restauração dentária; Métodos.

CRITICAL REVIEW

Introduction

Wear is the damage characterized by surface morphology changes and volume loss during use, as a consequence of different mechanisms. To understand each of the wear mechanisms, it is worth mentioning that the oral medium is complex; therefore, not only chewing is directly acting on restorative materials surfaces, but also food, temperature and pH variation, frequency and force of chewing, as well as the antagonist. Some degree of physiological tooth wear is expected over a lifetime. The rate of progression varies between individuals and not all tooth wear needs treatment. Tooth wear can be defined as pathological if it is beyond the physiological level relative to the individual's age and if it interferes with the self-perception of well-being [1].

Differences in nomenclatures were previously raised in relation to the terms linked to the wear process in Engineering and in Dentistry also related to the wear process of the dental structure as well as for restorative materials evaluation. Mair (1992) [2] presented that in engineering, fundamental wear mechanisms are Abrasion, Adhesive wear, Fatigue wear, Erosive wear, Corrosive wear and Fretting wear. The authors deeply described each mechanism and summarized that in Dentistry, the terminology to describe wear were Attrition, Abrasion and Erosion. Later, four wear mechanisms have been presented as related to dental wear processes depending on the mechanism of action: Adhesive wear, Abrasive wear, Fatigue wear and Corrosive wear [3,4].

Adhesive wear results from the contact between two surfaces and transfer from one material surface to the other. This occurs due to a cold welding between the material and the antagonist, which after a certain amount of movements will result in material loss from one surface to another [2-4]. In addition, these transfers can also result in particles liberation in the medium acting now as a third-body that will promote abrasion between the surfaces.

Abrasive wear occurs when a hard antagonist or particles damages the material surface. It is divided in two- or three-body wear, according to the presence of contact between the surfaces (two-body) or the absence of contact but with the presence of a third-body that will promote abrasion [2-4]. Toothbrushing is an example of abrasion wear in which the toothpaste acts as the third body. Finally, attrition is the advocated term for physical loss of mineralized tooth substance caused by tooth to-tooth contact.

Fatigue wear is a consequence of repeated contact on the material that leads to crack propagation from surface and subsurface damage. Fatigue will occur with a defect initiation followed by mechanical degradation until the critical load is reached under dynamic load [2-4]. Abfraction has been presented as an example of fatigue wear in teeth [3].

The term erosion is largely applied in the dental field for the effect of a chemical agent on a surface. However, *Corrosive wear* is the most appropriate term to refer to the wear of a surface that has suffered a chemical reaction that degraded itself. In the last decades, an increase of erosive tooth wear risk has been observed, especially in adolescents [5,6]. The etiology of this condition is related to extrinsic factors such as the frequent consumption of acidic beverages, and to intrinsic factors such as gastroesophageal reflux and eating disorders [7]. Thus, the erosion simulation has been largely applied to investigate the influence of acid agents on dental substrates [8-13] and on the longevity of restorative materials [2-4,14-17].

Regardless of the mechanism definition, it is very difficult to simulate the wear present in the oral environment. In addition, the association of two or more mechanisms is very common to occur, which can even difficult the definition of the wear process origin [2-4] since attrition and abrasion can be a consequence from all four wear mechanisms [3]. In the end, wear is dependent on the evaluated materials/adjacent structures and morphology, their interaction and the medium.

Dental ceramics are widespread materials for oral rehabilitation, with their well-defined mechanical and wear resistance. Lambrechts et al. [18] estimated that the annual enamel wear rate of a molar is 38 μm, while the average wear of a glass-ceramic is around 0.34 mm^3 per year [19]. However, it is important to assess the wear of the material that could lead to a long-term failure, and to assess the wear caused on the antagonist. Sripetchdanond et al. [20] showed that enamel wear is 4 times greater when the antagonist is lithium disilicate than zirconia. Tougher ceramics as zirconia promote lower enamel wear than glass-ceramics as lithia-based or leucite ceramics, because ceramics with higher hardness reduce the formation of hard three-body particles [19].

It is worth mentioning that the wear can compromise the restorative material and the antagonist's morphology and also the vertical dimension of occlusion [21]. Therefore, to preserve mainly the natural enamel, the restorative material is commonly selected not only due to its properties, but also due to the promotion of less antagonist wear. Several factors affect enamel and restorative materials' wear, such as hardness, surface conditions, coefficient of friction, as well as, microstructure factors, as presence of porosities, voids and crystal characteristics [22].

In dental ceramics, toughness and roughness [19] plays a role in the wear process, since in brittle materials wear occurs by fracture. The ceramic surface condition and ability to resist the crack propagation predicts both its longevity and wear potential. In a very simplified way, the ceramic fracture involves a critical defect, which propagates through a crack in the material until it reaches the critical load leading to a catastrophic fracture. These microdefects can be inherent to the material, such as a pore or void generated in the processing, it can be caused by an adjustment with burs or during polishing procedures, or even it can be caused by repeated contact on the ceramic surface (wear facets) during chewing.

Several studies corroborated this information, including clinical reports [23-27]. The repeated sliding contact on the ceramic surface will lead to compressive stresses before movement, shear stresses at the contact interfaces, and tensile stresses at the trailing edge of the antagonist [28]: the fatigue wear. The fracture toughness of a ceramic determines how much it will resist until the crack propagates, that is, it is determined by the size of the microstructural unit of a ceramic that will determine the SCG (subcritical crack growth) resistance. The crack propagation will be favored by humidity (stress corrosion mechanism) and affected by the material's microstructure [29] since the grain structure will determine the crack growth profile [30,31].

In vitro studies regarding the wear behavior of dental materials are influenced by the applied load, length of the sliding movement, number of cycles or time, the surface finishing of the antagonist, testing environment, etc. There is no consensus in literature about the testing parameters, but commonly the "physiological loads" are in the range of 0.4 to 75 N. However, it's common to find studies that used around 100-200 N load, trying to simulate the worst case scenario, such as that observed in non-physiological conditions, e. g. bruxism. Regarding the horizontal sliding, this movement is around 0.5-1 mm [28,32-34] based on the occlusal guidance amplitude.

Studies use steatite, brittle ceramics, zirconia, stainless steel or even dental enamel as antagonists during the tests. Steatite is a magnesium silicate–based ceramic [34] has a similar property to porcelain, glass-ceramics, and dental enamel, its use has been extensively proven in the literature and is considered the standard for fatigue wear tests [31,32,35]. Spherical shapes with a radius of 3 mm are generally used to approximate the midrange of the molar cusps radii (2-4 mm) and thus increase the clinical relevance of the studies. Zirconia balls can also be used in order to limit the antagonist wear, as mentioned by Wendler et al. [28]. The contact of the antagonist with the ceramic surface causes an initial wear phase in which the wear scar is properly formed (run-in stage). As these scars increase, the steady-state wear stage is observed, generally after 10^3 cycles. Thereafter, the increase in width and depth of the wear facets is followed by the material volume loss.

The restorative material wear is multifactorial and changes for each oral cavity [36,37]. Therefore, wear tests aim to predict the typical clinical wear resistance of a material. Different wear simulation methodologies were developed to investigate the wear behavior of different dental materials in the long term, since wear measurements *in vivo* are complicated and time-consuming [8,37]. To simulate the processes that occur in the oral medium, the wear simulation methods cover different loads, movements, contact type and duration, medium, presence of food bolus simulator, toothpaste, saliva or water [19]. Besides that, different outcomes are used with limitations to characterize and predict the behavior of different materials under standardized conditions [38].

In summary, the *in vitro* tests reported in the literature to investigate dental ceramics wear are: Two-body-wear, three-body wear, toothbrushing and corrosive wear. Therefore, this overview aimed to present the wear tests methodology, how data is obtained and how *in vivo* ceramic wear is being investigated.

WEAR SIMULATION METHODS FOR CERAMICS INVESTIGATION

Three-body wear test

Advocated as a sensitive way to measure differences in the structural integrity, this method simulates the occlusal wear mimicking clinical conditions [39]. The main difference in this method is the third body. Thus, the abrasive activity of the food bolus is considered using solid particles that are pressed against the ceramic surface and the antagonist during chewing [39-43]. This method has been reported to evaluate the wear resistance of a ceramic material or the durability of an extrinsically characterization [39,43].

According to Lambrechts et al. [44], there are several equipment to perform the three-body wear, such as Oregon Health Sciences University Oral Wear Simulator (OHSU) and University of Alabama Wear Simulator. This review focused on the description of the Academic Center for Dentistry Amsterdam (ACTA) wear machine as presented in the ISO/TS 14569 [45]. This device consists of two motor-driven cylindrical wheels rolling over each other (Figure 1) with 15% difference in the circumferential speed. To standardize the method, some parameters are predefined and must be pre-checked during a pilot study. The force between the wheels is kept at 15 N, the rotational speed of the antagonist wheel is 129 rpm while the speed of the specimen wheel is 60 rpm, and both wheels rotate in opposite directions with resulting slip rate of 15%. All this happens inside a bowl containing the third body.

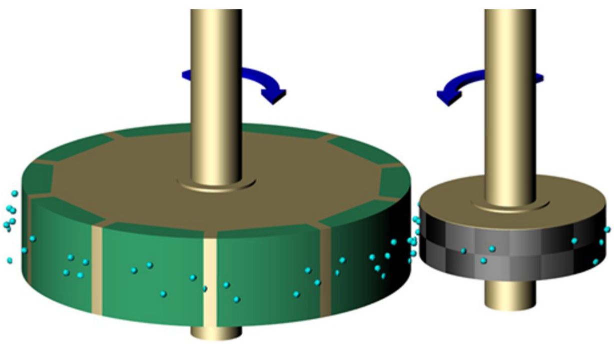

Figure 1 - Schematic illustration of specimen wheel, antagonist wheel and third body movements in a three-body wear test.

The freshly made abrasive medium (the slurry that simulates food bolus) is used until 200,000 cycles which is around 55 h 30 min testing [46]. After this period, the water evaporates and the slurry is no longer properly abrasive; therefore, it must be replaced by a new one. The receipt (Figure 2) to standardize the third body abrasiveness consists of: 120 g of pandan rice (low fat white rice) grains crushed in an electric coffee processor for 1 minute; 25 g of millet seed shells mixed with the rice during 1 min using a blender; 1 g of a water-soluble bacteriostatic preservative and 270 ml of buffer solution (pH = 7) of 41.1g KH_2PO_4 and 9.3g NaOH in 1L water with 1g NaN_3 stabilizer. It is important to mention that there are several types of reported third body, limiting the comparison of data between studies.

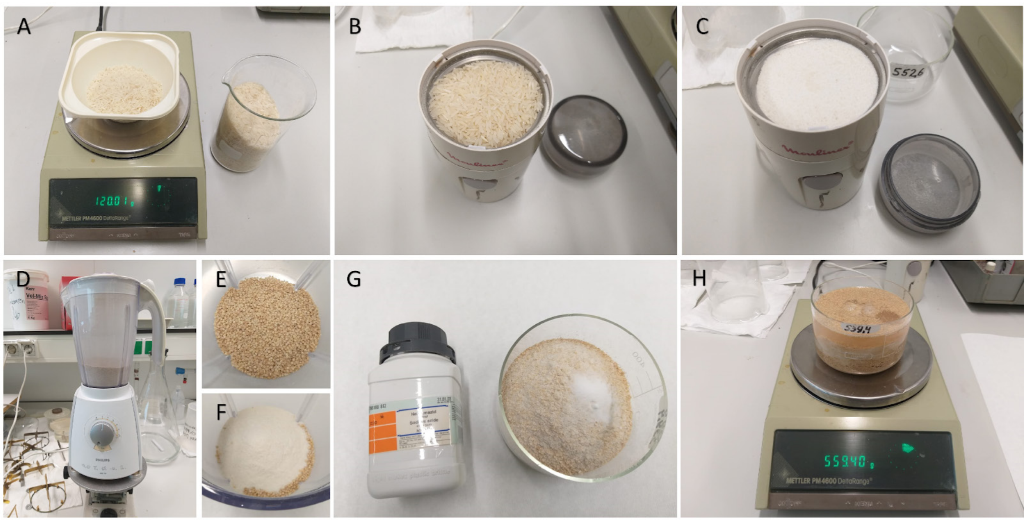

Figure 2 - (A-H) Three body slurry manufacturing recipe: 120 g of pandan rice grains (A) crushed in a food processor (B and C) for 1 minute; 25 g of millet seed shells mixed with the rice during 1 min using a blender (D-F); 1 g of a water-soluble bacteriostatic preservative (G) and 270 ml of buffer solution (pH = 7) (H).

To prepare the specimens, a wheel is used to accommodate 10 specimens in rectangular chambers. Prior to aligning and fixing the specimens in each chamber with cyanoacrylate based adhesive, the specimens must be cleaned in an ultrasonic bath with distilled water for 5 min [47,48]. Next, to standardize all specimens dimensions before the wear test, the specimens need to be ground to ensure a wheel standardized in 48 mm diameter (Figure 3). The grinding process is performed in two steps using the ACTA wear machine. Diamond antagonist wheels in different grits (D 126 and D15) rotate against the specimen wheel during 200,000 cycles.

After 24 h stored in distilled water, the specimens are ready to be tested. The number of cycles depends on the purpose of the study. Usually for different restorative materials, a test run consisted of 200,000 cycles [41,42,45]. It is estimated that 200,000 cycles of three-body wear cycles corresponds to 6 months of physiological wear [45]. This number of cycles have also been reported when investigating ceramics wear resistance [39,43,49]. However, depending on the evaluated material and behavior, it can vary between 140,000 [34] and 1×10^6 cycles [39].

Before the wear test and using a profilometer (PRK profilometer No. 720702, Perthen GmbH, Hannover, Germany), the surface profile is analyzed through 10 tracings in 10 fixed positions. Each reading/tracing considers 1000 measuring points and a step distance of 100 μm between them. After the wear run, to measure the amount of worn ceramic surface, unworn reference planes on both sides of the specimens should be recorded (Figure 4). Those references are used to calculate wear depth from the difference to the worn surfaces [39,47]. Therefore, after each wear run, 10 tracings are performed again in the same predefined points to determine the average vertical loss and the standard deviations in μm of each group by calculating the arithmetical mean of 40 tracings [41].

Depending on the evaluated purpose, the wear rate can also be obtained and informed in percentage (%) based on the average thickness for a known layer (100%) that has been removed during the test, e. g., an external characterization layer [39] (Figure 5).

Two-body wear tests

The two-body simulates the non-masticatory tooth movement and through it is possible to predict the wear behavior of dental materials [44]. The main differences between three- and two-body wear tests is that the two-body wear test has contact between specimen and antagonist [48,49]. In the literature, it is possible to observe different methods for two body wear, traditionally using a sliding methodology, where the materials are tested in pairs under nominally non-abrasive conditions [44]. For example, to evaluate the ceramic finishing protocol (glaze or polishing) on the antagonist wear [50,51].

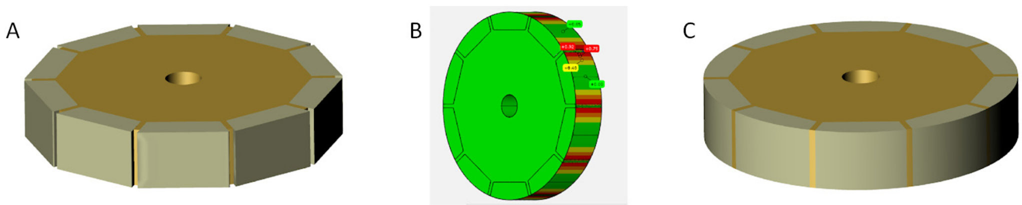

Figure 3 - (A-C) Specimen wheel preparation. Schematic illustration of (A) specimens glued in the specimen wheel, (B) grounded specimens during preparation to obtain a (C) perfect circular wheel sample.

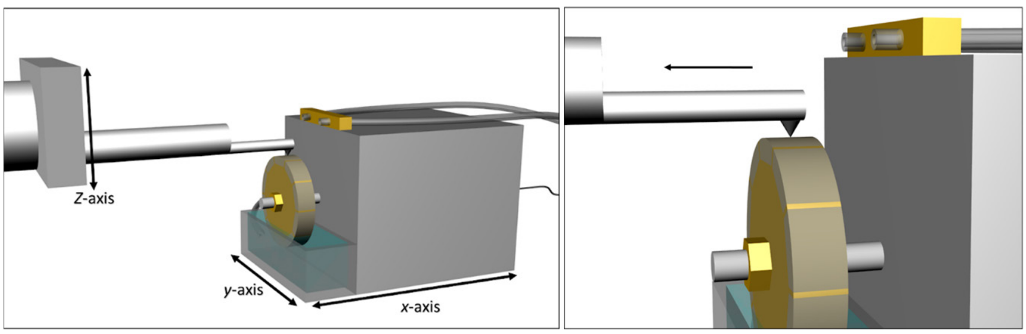

Figure 4 - Schematic illustration of wear analysis showing the different coordinate axes and the wheel position during the measurement.

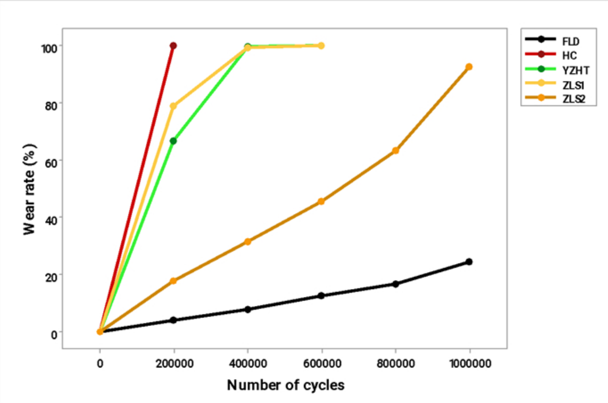

Figure 5 - Curve fit for the wear rate vs. time according to the three-body wear test and different ceramic materials (YZHT = high translucent yttrium-stabilized tetragonal zirconia polycrystal, FDL = Feldspar ceramic, ZLS1 = reinforced glass ceramic stained in 1 step, ZLS2 = reinforced glass ceramic stained in 2 steps and HC = Hybrid ceramic).

To evaluate the two-body wear behavior of dental ceramics, previous studies used a pin-on-disk apparatus [52,53]. For that, polished discs samples (2 mm thickness) are scanned individually before the wear test by a scanner (e.g. CEREC AC Omnicam, Sirona, Brazil) or a profilometer (e.g. CyberSCAN CT 100; CyberTECHNOLOGIES GmbH, Eching-Dietersheim, Germany). Then, the samples must be embedded in acrylic resin, with the finished surface up, using a plastic mold. The pin-on-disk is a method widely applied, for that a pin with a radiused tip as antagonist is positioned perpendicular to the sample, usually a flat disc (Figure 6). The test machines apply a movement, either the pin or the disc can slide, reproducing the wear path [51]. The movement also can be revolving. The pin is pressed against the sample at a specified load (the literature reported a range from 5 N to 30 N) [54,55] by hydraulic or pneumatic systems and also by weights [56].

The antagonists can vary in composition. Natural enamel is required to achieve clinical conditions, however, different morphologies lead to variations on the results [35]. As an alternative, steatite is used for *in vitro* wear studies to allow test standardization and a feasible results analysis [33,57]. Stainless steel, dental porcelain and alumina are also materials applied to assess materials wear resistance [35,44].

The lubrication is necessary in order to remove residues and also to mimic the oral environment. For that, the tests can be performed in distilled water at room temperature [50], in 33% glycerin lubricant [58] or in those two combined [59]. The literature also reports the use of normal saline emulsion [60] or artificial saliva [61,62].

In addition to the load and the lubrication mentioned above, the two-body wear methodology involves other parameters such as frequency, sliding distance and number of cycles. Chewing activity mainly occurs in the range of 0.94 Hz and 2.17 Hz [63]. However, in order to reduce time-consuming, studies use a higher cyclic frequency, being possible to find in the literature a range from 1,7 to 30 Hz [55,64]. Regarding the number of cycles, 1250,000 correspond to one year of clinical masticatory effort [65] and, as well as the previous parameters, it is possible to find a range in the literature, e.g. 120,000 cycles [66] and also ten times greater than that [33]. Considering mandibular movements, closing during chewing promotes occlusal contact between teeth or restorative material and teeth [67-69]; in addition, the sliding movement is also an essential component to wear tests since it promotes material micro fatigue [70]. Therefore, sliding movement is applied from 0,3 mm to 15 mm [50,60,71].

The wear is measured by volume loss (mm^3) and wear depth (mm). Although the greater accuracy, volume loss is less reported than wear depth once clinically a tooth height loss is easier to visualize than volumetric tooth loss [33]. Linear measures are obtained as the length of the pin changes; and, to assess the disc wear, profilometers or scanners [53,64] can be used [55]. Besides that, wear can be quantified by weighing both specimens before and after the test [50,51,72].

Another methodology to study wear-resistant materials is the ball-on-flat. This method applies the same parameters as described above for the pin-on-disk method, however, in this case, a spherically specimen slides against the flat disc, resulting in hertzian contact pressure [73] (Figure 7). The antagonist can be of different materials, such as zirconia (r = 6,35 mm), steatite (r = 3mm) and alumina (r = 3,17 mm) [33,74,75]. The sphere slides or rotates against the polished flat surface at a fixed frequency (~ 0,4 – 2 Hz) delivering a specific load (10N - 200N) [33,75]. The same parameters mentioned before are followed for lubricant medium and number of cycles.

For the ball-on-flat specimens the wear can be assessed by topographical reconstruction.

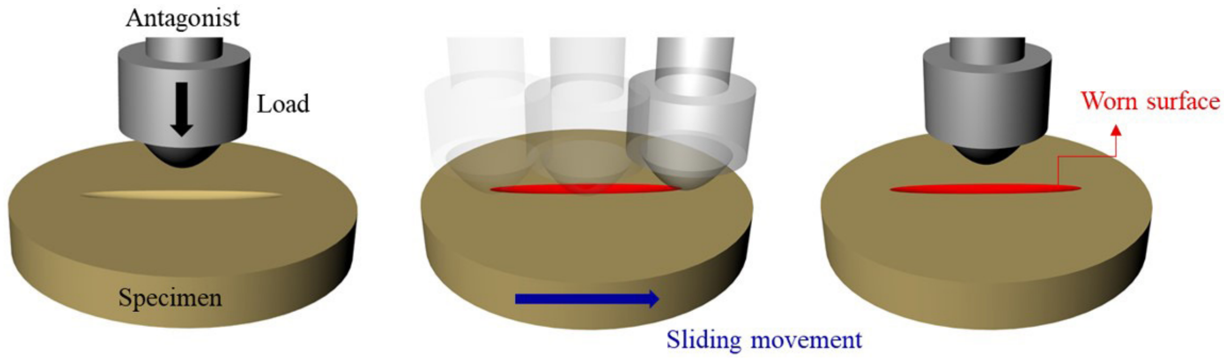

Figure 6 - Operating diagram of the two-body wear machine testing a pin against a disc specimen.

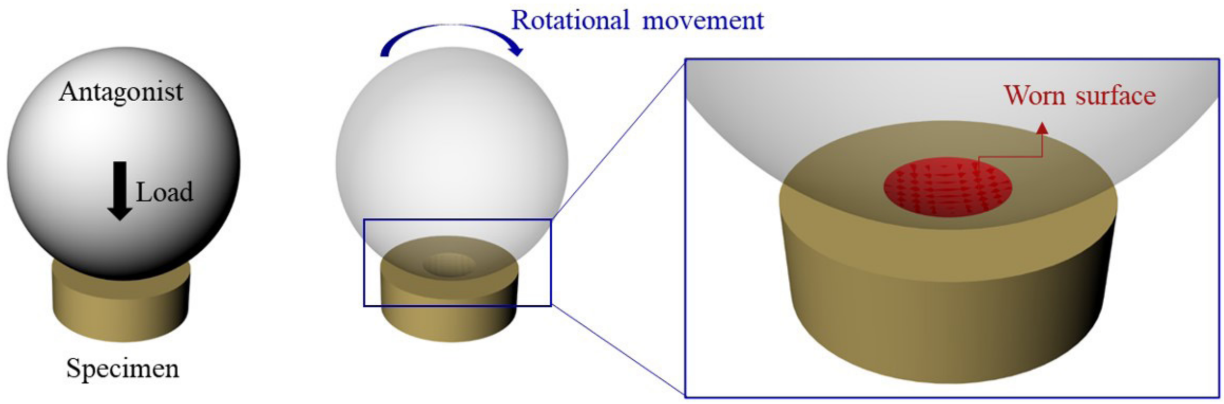

Figure 7 - Schematic illustration of the two-body wear machine testing a ball against a specimen.

The volume loss (mm^3) and wear depth (mm) can be quantified with 3-dimensional (3D) images obtained by a micro– computed tomography scanner (micro-CT 40; Scanco Medical AG) [33] or a laser scanner (SD Mechatronic Laser Scanner LAS-20) [76]. The collected data is analyzed using a 3D reconstruction software (3D-System Geomatic Wrap). By means of mesh editing and model superimposition, the maximum wear depth and volume loss can be obtained by model comparison before and after wear [76-78].

Another two-body wear method test will be described using the ACTA wear machine, as illustrated in Figure 8. For this test, the specimen wheel is prepared as described for the three-body wear test above (Figure 3). In addition, the machine works with the same parameters presented for the three-body wear test (spring force of 15 N, 200,000 cycles and rotation speed of 1 Hz). As well as, the average vertical loss can be determined according to the difference between the un-worn lateral references and the worn surface (Figure 4), where the abrasive wheel contacted [49]. In the two body wear test, the antagonist or abrasive wheel is in direct contact with the specimen wheel and can be made in different materials, such as: stainless steel [39,43,49], ceramics [48], enamel [48] and resin composite [46].

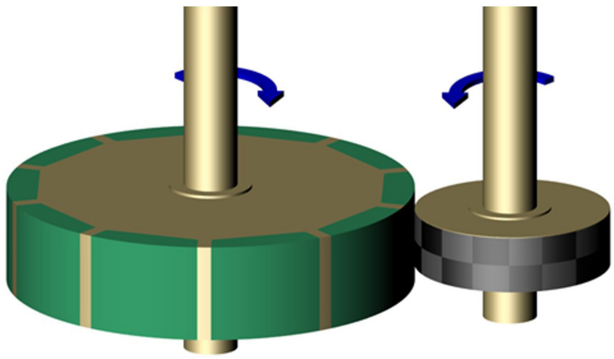

Figure 8. Schematic illustration of specimen wheel and antagonist wheel in a two-body wear test.

Toothbrushing

Toothbrushing simulation is widely used to evaluate the abrasion wear of ceramic materials, as well as, the wear of the glaze or the extrinsically stain layer [79-84]. However, depending on how and when toothbrushing is performed, as well as the type of dentifrice and toothbrush used [85], toothbrushing frequency and force of brushing, dental wear may increase [14]. Some studies reported the negative influence of toothbrush on color stability of extrinsic characterized glass ceramics [81,86] also, with the association with thermocycling [82] for lithium disilicate and zirconia.

The number of toothbrushing cycles needed to simulate the toothbrush wear varies between different studies, ranging from 7300 strokes [87,88] to 150.000 strokes [84]. In a pilot clinical study, it was found that the average person brushes between 25-30 cycles per day on a given surface [89]. This equates to 9125 to 10950 cycles per year, thus, it can be considered that 10.000 strokes simulates 1 year of toothbrushing. In addition, 50,000, 100,000, and 150,000 cycles have been advocated [82] as proportionally corresponding to approximately 5, 10, and 15 years of brushing in the oral environment.

Previous studies recommend replacing the toothbrushes every 10,000 [90] to 50,000 strokes [91]. Another parameter that can influence the toothbrush test is the load. In habitual toothbrushing, force peaks reaching 10 N can occur, however, the mean brushing force was found to be 2.3 ± 0.7 N (max. 4.1 N) [92], being recommended for in vitro studies to adopt a representative load of 2 N to 3N.

The toothbrush bristle arrangement also plays a role in the results, being the ordinary/flat-trimmed toothbrushes more abrasive than the feathered ones [93]. The ISO/TR 14569-1:2007 [94] provides guidelines for test methods for the assessment of resistance to wear by toothbrushing. This standard establishes that soft toothbrushes with nylon bristles and rounded tips should be used. Moreover, it is recommended that the toothbrush be angled at 15° in relation to the direction of brushing to minimize the formation of grooves on the specimen's surface [95] (Figure 9).

The toothpaste abrasiveness can significantly influence the loss of color and gloss of ceramic restorations [96]. The abrasiveness of the toothpastes is usually determined by the REA (relative enamel abrasiveness) or RDA (relative dentine abrasiveness). These values compare the abrasiveness of the tested toothpaste to a standard one, given a score of 10 to 100. As sound dentin is considered more susceptible to abrasion than enamel, the RDA value has become the main parameter to characterize the abrasiveness of the toothpastes. Unfortunately, most of the toothpaste manufacturers do not refer to the RDA and REA values.

For the toothbrush simulation, a slurry of the toothpaste and deionized water should be prepared in a ratio of 1:3 (w/w) [83,84,97] (Figure 10). The main purpose of the slurry is to obtain a consistency that better simulates the conditions in the oral cavity. It is possible to find studies using a 1:2 (w/w) [96,98] or 1:1 (w/w) ratio [81], however a thick slurry can influence the results, being necessary to standardize the ratio to allow comparisons among studies. When using brushing simulation machines, 1mL of the suspension should be injected onto the specimen surfaces every 30 seconds [99].

When the study includes enamel and/or dentin specimens, the toothpaste slurry should be prepared by using artificial or human saliva instead of deionized water. This substitution is recommended due to the remineralizing potential of these specimens when in contact with saliva and fluorides from the toothpaste [100].

After the toothbrushing simulation, it is recommended to clean the specimens by an

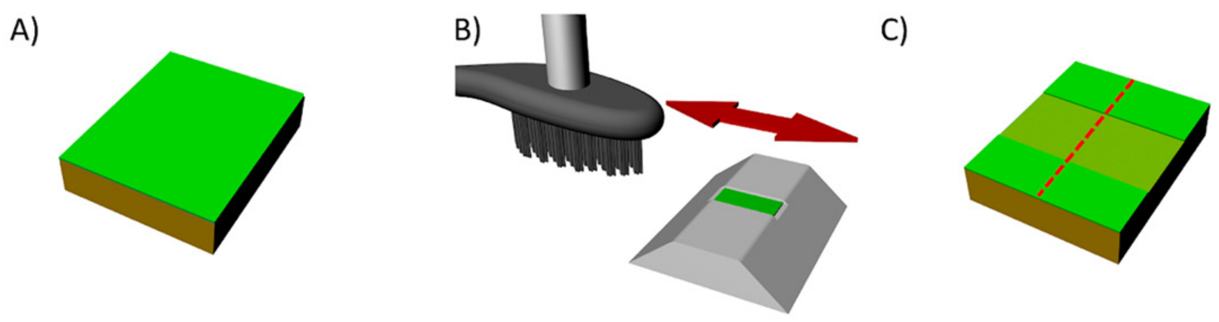

Figure 9 - (A-C) Schematic illustration of a toothbrushing simulation. (A) Intact surface, (B) Toothbrush head positioning and brush directions and the metallic device positioned over the specimen. (C) Inspection path of the wear profile after the toothbrushing simulation.

Figure 10 - Toothpaste solution being prepared for the toothbrushing simulation.

ultrasonic bath for 10 minutes [101]. This procedure will remove surface debris, allowing comparison between specimens. The amount of wear in micrometers can be obtained by contact profilometer by using the Rz parameter [83,84,99] or a dedicated software [97]. In addition, the wear values can be obtained by 3D laser-measuring microscopy [102] and vertical loss of dental cusp [103].

To standardize the method, two parallel grooves can be marked at the lateral area of the specimen's surface as reference, allowing the superimposition of the initial and final surface profiles (Figure 9C). A metal strip containing an orifice can be used to protect these grooves, so only the central area will be brushed [83,84,97] (Figure 9B). A custom-made device is used to place the specimens in the same position before and after brushing. The depth of the abraded area can be calculated based on the subtraction of the initial profile from the final profile by using a dedicated software program [97]. In addition, the specimen's surface profile can be exported in linear graphs (Figure 11) for illustration [83,84]

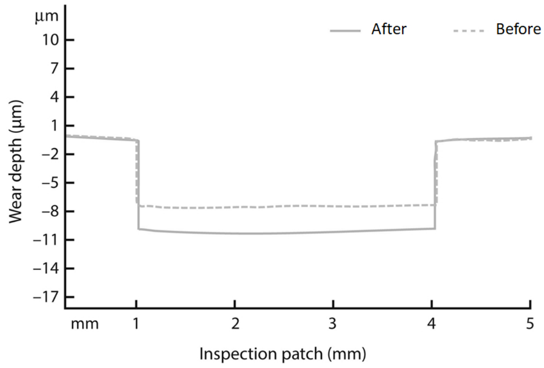

Figure 11 - Surface profiles of a hybrid ceramic before and after 15 years of toothbrushing simulation.

Corrosive wear

Considering corrosive wear on ceramics, the scientific data is scarce. It is worth mentioning that the evaluation of a ceramic wear corrosion investigates the material abrasiveness since it enhances the material roughness leading to the wear of the antagonist [75,104]. In addition, corrosion wear could compromise the material mechanical properties; since different from teeth, they do not have any self-healing mechanisms [75]. Švančárková et al. [75] evaluated the corrosive wear of lithium disilicate using the ball-on-flat two-body wear test after two different corrosion simulations (quasi-dynamic with two corrosive media or static according to the ISO 6872) [105]. According to the literature, the corrosive wear or chemical durability can be measured by weight loss as well as the concentration of leached ions into the corrosive medium [75,104,106].

Considering the erosion simulation protocols, different acidic agents have been reported to affect the ceramic surface roughness and morphology [107,108], color stability [106], hardness [105,109], flexural strength [104] fracture toughness [110] or ion leaching [75,108]. In addition, ISO 6872 [104] indicates 4% acetic acid; while different chemical agents have been used, such as: citrate buffer solution, juices [108,110]; citric acid and lactic acid [105,106,111,112]; simulated gastric HCl, white wine, soda drink [110]; or acidulated fluoride mouthwash solutions [113], during different times of exposure; which makes the results comparison difficult. Therefore, this overview strongly recommends a standardization for solutions and the use of profilometry to investigate the wear rate and material volume loss, as performed before [7].

RESULTS INTERPRETATION

During wear tests, an extended damage accumulation zone is formed on the ceramic surface, with defects that will be initiators and will lead to crack growth [23]. Therefore, fatigue degradation is closely related to wear. Repeated contact causes subsurface cone cracks, which are initiated by tensile stress, but grow chemically-assisted by water (stress corrosion) mechanism. The ceramic surface morphology, density and also crack-surface angles are closely related to the friction coefficient at the interface and the fracture toughness of the material undergoing this cyclic fatigue. Materials with higher toughness such as zirconia will exhibit enhanced resistance to crack propagation and lower wear, while glassy matrix ceramics (lithium disilicate and feldspathic, for example) will be more prone to a propagation of partial cone cracks during sliding contact fatigue and will present higher wear rate [31,114,115]. Wendler et al. [28] analyzed the sliding fatigue wear of five different CAD/CAM ceramics (IPS e.max CAD from Ivoclar Vivadent, Suprinity partially crystallized, Enamic and Vitablocs Mark II from Vita Zahnfabrik, and Lava Ultimate from 3M Espe) against zirconia indenters (antagonist). Their results showed that glass ceramics (e.max CAD, Suprinity and Vita Mark II) have a greater zone of subsurface damage regarding the fatigue wear mechanism, while composite materials as Lava Ultimate do not have this subsurface damage area, but show greater wear facets due to predominant abrasion effect. Hybrid ceramic materials such as Enamic, on the other hand, show a combination of the above, with large surface wear scars associated with greater subsurface damage.

Comparing similar material using different wear methods, it is possible to affirm that different wear methods promote different surface patterns [49,116]. Surface roughness has been reported as an important factor on the beginning of the wear process; however, the ceramic material microstructure has the most important effect in the wear rate. This is due to the fact that surface roughness is immediately changed during the wear procedure. Therefore, wear resistance is influenced by the grains arrangement and materials hardness and composition [49,117]. However, after any of the mentioned methods, the surface morphology or surface roughness must be evaluated due to its effect on the materials properties, such as flexural strength [118,119], wettability [50,120], survival rate [121], as well as, on the biofilm formation [120,122,123].

At least two wear tests are advocated to characterize the material wear resistance. However, different sets do not allow direct comparison or equivalent wear behavior [116]. Two-body wear presents higher wear depth due to the contact between specimens and antagonist, while three-body wear presents less abrasion promoted by the third-body. Normally, the third body contains soft particles and not all of them cause wear [3], being also reported as damping agents [19]. In the two-body wear, the wear is much higher then the shape of the evaluated material is modified according to the shape of the hard antagonist [2,53,74]. Even if the similarity between highest wear depth provided by different tests is reported [49], their purpose of investigation is different. Therefore, implications based on their results must be done considering the test's characteristics.

Minimal variation between the *in vitro* methods [45] are necessary to easily detect differences between materials. In addition, clinical studies are essential for the evaluation of material performance in function. However, they are complex, involving ethical issues, time consuming, dependent on patient collaboration, but crucial to validate *in vitro* methods [19].

SEM as a complementary analysis

After the wear simulations and material loss analysis, the worn surfaces are submitted to a surface analysis using a Scanning Electron Microscope at different magnifications (Figure 12, 13) [39,43,50,51,72,75,97]. This analysis is used for a qualitative measure of the caused damage or to observe the surface morphology after a wear process. For that, the specimens can be directly investigated [39,43,49,83,84,86,107,124] or indirectly through an impression procedure using polyvinyl siloxane and poured epoxy resin inside the molde [48]. Therefore, materials also can be tested in complex geometries, as tooth restorations [33,77,78]. In this case, to analyze the progressive wear, impressions can be obtained to manufacture stone cast models (Type IV gypsum). The casts should be scanned

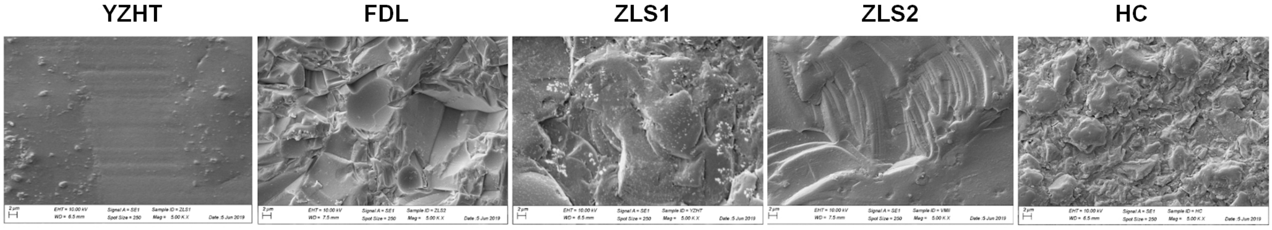

Figure 12 - Surface topography under SEM analysis with 5000×magnification of the different materials after the three-body wear test (YZHT = high translucent yttrium-stabilized tetragonal zirconia polycrystal, FDL = Feldspar ceramic, ZLS1 = reinforced glass ceramic stained in 1 step, ZLS2 = reinforced glass ceramic stained in 2 steps and HC = Hybrid ceramic).

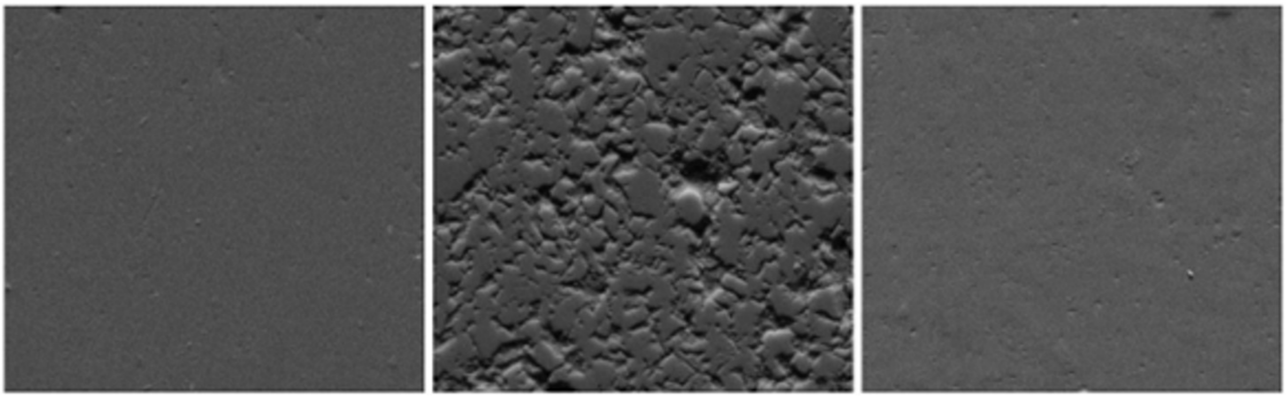

Figure 13 - Scanning electron microscopy images, ×3000, after artificial toothbrushing of (from left to right) a leucite ceramic, a hybrid ceramic and a felspathic ceramic.

as a baseline and sequentially as the wear circles intervals. After that, the 3D images are analyzed in a software program (e.g. GOM Inspect; GOM) and the volume loss can be measured by overlapping the images [77], allowing the analysis in different intervals.

With direct investigation, the specimens should be cleaned and placed on aluminum stubs, sputter coated with gold and observed in a scanning electron microscope [97]. Cross-sectioned specimens can also be used to analyze subsurface damage. Generally the specimens are included in epoxy or acrylic resin after the wear simulations, a sagittal or transverse cut can be made in the direction of the wear scar, so this cross-section is polished with diamond pastes [125]. Using this type of method, it is possible to observe the partial cone cracks for the subsurface damage evaluation [28].

Clinical assessment of ceramic wear

The fast development of different intraoral scanners has allowed clinicians to make early diagnosis of dental wear [126-128]. In addition, scanners allow the impression procedure to be more comfortable, easier and faster, making the treatments more practical, comfortable and agile [129]. The surface wear is analyzed according to the volume change, maximum and average profile losses, according to quantitative monitoring of clinical wear [126,130] (Figure 14). Epoxy resin models from conventional impressions have also been reported as an alternative for wear measurement [131].

The quantitative maximum vertical substance loss is calculated as a difference between the first scanning and the second scanning during follow-up (Figure 15). Initially, the three-dimensional models are superimposed using a 3D analysis software, e.g. GOM Inspect [126,127], Geomagic, David-Laserscanner [132], or softwares used in the dental practice, such as Trios Patient Monitoring tool. After importing the baseline (initial) model and the second scanning (or model with wear), it is necessary to perform the virtual alignment of both. For that, the best-fit alignment can be used when the models are strongly compatible. Or, a three-point alignment in which geometric references are pre-determined. The software choice and the comparison mode as well as the models alignment depend on the complexity of each case. The superimposition of

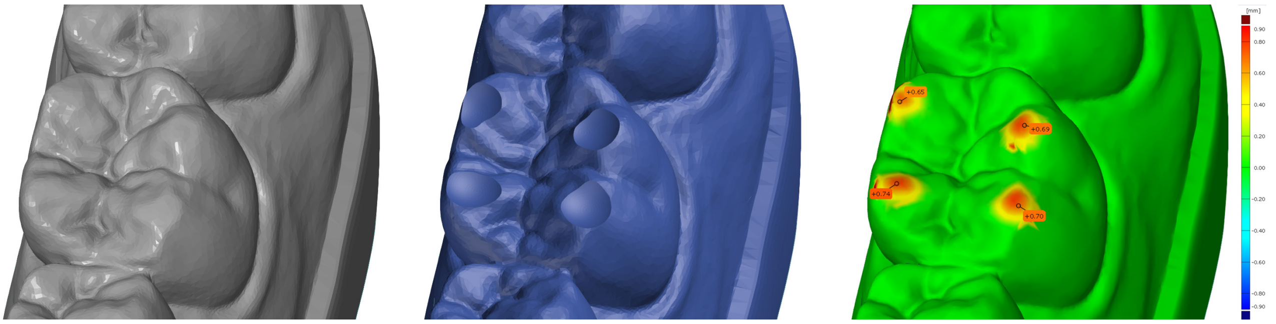

Figure 14 - Schematic illustration of tooth wear evaluation using digital impression and superimposition method. From left to right, initial scanning, scanning after a period in function and superimposition in forming wear depth in mm, according to the colorimetric scale.

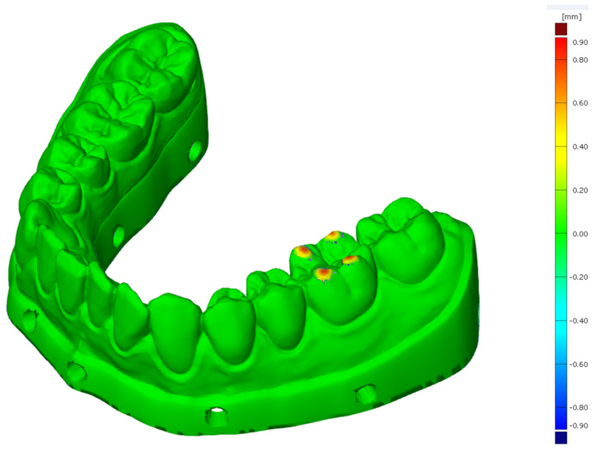

Figure 15 - Schematic illustration of a model presenting the difference between the first scanning and the second scanning for monitoring through colorimetric scale.

models is defined as Parametric Inspection and calculates wear depth values in mm. Besides the comparison of wear depth, most of the time the calculation of the material volume loss is necessary. For that, the volume difference can be quantified using other software, e.g., Materialise [133], Siemens Unigraphics NX 10 [132] or the internal monitoring program in the scanner [126,134].

Schlenz et al. [127] have investigated the wear process in natural dentition and observed, after 12 months follow-up, a mean loss at cusps ranging between 31 and 43μm in young adults (18-25 years). This reinforces the need for monitoring and allowing early diagnosis of wear. The authors reinforce that the digital impression accuracy plays an important role in the tissue loss evaluation in a micrometer scale. However, the difficulty in defining references *in vivo*, concerns regarding the surface alignment [134] and results interpretation.

Dental ceramics are not very susceptible to wear, and because of their wear rates close to the natural enamel, ceramics may be a good restorative alternative for oral rehabilitation [49]. An *in vitro* study evaluated the wear of implant-supported crowns in different materials (lithium disilicate, zirconia, hybrid ceramic and porcelain fused to metal) before and after 5-years chewing simulation. The crowns were evaluated using laboratorial and intraoral scanners [133] and there was no difference between both to detect the ceramic volume loss. Differently, Aladağ et al. [132] during an *in vivo* study have found, after 6 months, that hybrid ceramic shows higher mean wear value (0.38mm^3) compared to lithium disilicate (0.27mm^3). In addition, the authors evaluated crowns in zirconia reinforced lithium silicate (0.14mm^3) and a resin matrix ceramic material (0.45mm^3). The authors have precisely described their evaluation method, which were the following steps: Digital impression of the restorations, antagonist tooth, adjacent teeth, interocclusal registration and occlusal contact points using the scanner software (Cerec 4.2, Sirona, Bensheim, Germany), followed by the generation of .stl files; Next, the files were exported for superimposition (David-Laserscanner, V3.10.4, Berlin, Germany). Then, using the third software (Siemens Unigraphics NX 10, Siemens PLM Software, Plano, TX, USA), the images were converted into solids and a specific area was chosen for analysis (0.005 mm tolerance). Finally, the difference between them, as volume loss, was calculated.

Future perspectives

Advances in dental science enable different ceramics to be used for various indications. And, mainly due to their esthetic and strength, the use of ceramic restorations have increased. The assessment of ceramic wear using different simulations provide information regarding the restorative material behavior under different conditions. The materials assessment, especially materials in development or recently-launched is very important to understand how the material will behave during function. However, the simplification in the procedures are necessary for studies standardization and data assessment and comparison. The reproducibility between methodologies must be possible to decrease the variability in obtained data and to direct clinical studies.

In vitro investigations present limitations while they try to simulate the oral medium. It is important to mention that only one method cannot provide universal data since the method does not simulate all factors present inside the oral cavity [44,134], e.g., saliva, different loads, pH and temperature variation, different brushing devices, food textures, brushing and chewing frequencies, diets, use of mouth risings, etc. In addition, the complexity of the wear process is very difficult to simulate [4,134,135]. Therefore, the results obtained from different *in vitro* methods must be evaluated carefully. And therefore, to complement the *in vitro* studies, further clinical reports and studies are advocated with patients monitoring tools to provide data regarding ceramic materials wear resistance during function. This study has the limitation of considering the most common *in vitro* methods to investigate different ceramic wear behavior.

Considerations

With the limitation of this study, the following conclusion can be drawn:

Different methodologies are available to simulate wear in ceramic restorative materials. Most of the time to evaluate the ceramic wear resistance, but also to investigate the glaze and/or the external characterization wear rate, or even its effect on the antagonist wear rate. However, it is important to select carefully the method for each investigation, based on the main purpose of the study and focusing on the answer that the methods can provide. In addition, the appropriate data collection should be performed to provide information equivalent to the evaluated topic. Finally, the tests should follow similar parameters for standardization and to allow comparison between different studies.

Author's Contributions

NCR, MGA, LMMA: Methodology, Investigation, Writing – Original Draft Preparation, Writing – Review & Editing, Visualization. CJK: Investigation, Writing – Original Draft Preparation, Writing – Review & Editing, Visualization, AMODP: Conceptualization, Methodology, Investigation, Writing – Original Draft Preparation, Writing – Review & Editing, Visualization, Supervision, Project Administration.

Conflict of Interest

The authors have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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Regulatory Statement

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