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Wear Characteristics of Current Aesthetic Dental Restorative CAD/CAM Materials: Two-Body Wear, Gloss Retention, Roughness and Martens' Hardness

Werner H Mörmann^a, Bogna Stawarczyk^b, Andreas Ender^a, Beatrice Sener^c, Thomas Attin^c, Albert Mehf^a

^a*Department of Computer-Assisted Restorative Dentistry, Center of Dental Medicine, University of Zurich, Plattenstrasse 11, 8032 Zurich, Switzerland*

^b*Department of Prosthodontics, Dental School, Ludwig-Maximilians-University Munich, Goethestrasse 70, 80336 Munich, Germany*

^c*Clinic of Preventive Dentistry, Periodontology and Cariology, Center of Dental Medicine, University of Zurich, Plattenstrasse 11, 8032 Zurich, Switzerland*

Correspondence to: Department of Computer-Assisted Restorative Dentistry, Center of Dental Medicine, University of Zurich, Plattenstrasse 11, 8032 Zurich, Switzerland
Plattenstrasse 11, 8032 Zurich, Switzerland.

Tel.: +41 44 634 33 60; Fax +41 44 634 43 08.

Email address: werner.moermann@zzm.uzh.ch

ABSTRACT

Objectives: This study determined the two-body wear and toothbrushing wear parameters, including gloss and roughness measurements and additionally Martens' hardness, of nine aesthetic CAD/CAM materials, one direct resin-based nanocomposite plus that of human enamel as a control group.

Materials and methods: Two-body wear was investigated in a computer-controlled chewing simulator (1.2 million loadings, 49 N at 1.7 Hz; 3000 thermocycles 5°/50°/5°C). Each of the 11 groups consisted of 12 specimens and 12 enamel antagonists. Quantitative analysis of wear was carried out with a 3D-surface analyser. Gloss and roughness measurements were evaluated using a glossmeter and an inductive surface profilometer before and after abrasive toothbrushing of machine-polished specimens. Additionally Martens' hardness was measured. Statistically significant differences were calculated with one-way ANOVA (analysis of variance).

Results: Statistically significant differences were found for two-body wear, gloss, surface roughness and hardness. Zirconium dioxide ceramics showed no material wear and low wear of the enamel antagonist. Two-body wear of CAD/CAM-silicate and -lithium disilicate ceramics, -hybrid ceramics and -nanocomposite as well as direct nanocomposite did not differ significantly from that of human enamel. Temporary polymers showed significantly higher material wear than permanent materials. Abrasive toothbrushing significantly reduced gloss and increased roughness of all materials except zirconium dioxide ceramics. Gloss retention was highest with zirconium dioxide ceramics, silicate ceramics, hybrid ceramics and nanocomposites. Temporary polymers showed least gloss retention. Martens'

hardness differed significantly among ceramics, between ceramics and composites, and between resin composites and acrylic block materials as well.

Conclusions: All permanent aesthetic CAD/CAM block materials tested behave similarly or better with respect to two-body wear and toothbrushing wear than human enamel, which is not true for temporary polymer CAD/CAM block materials. Ceramics show the best gloss retention compared to hybrid ceramics, composites and acrylic polymers.

Key words:

CAD/CAM, translucent zirconium dioxide ceramics, lithium disilicate ceramic, silicate ceramics, hybrid ceramic, nanocomposite, temporary polymers, two-body wear, toothbrushing wear, gloss, gloss retention, roughness, Martens' hardness.

1. Introduction

Currently available is a range of ceramic- and polymer-based aesthetic block materials with flexural strengths below 200 MPa, which can be one-step-CAD/CAM processed in minutes by the dentist, even for large preparations, including the replacement of cusps to a fitting permanent restoration, while the patient is seated in the chair (Datzmann, 1996; Kunzelmann et al., 2007; Magne and Knezevic 2009; Mörmann, 2004). In contrast, the high-strength lithium disilicate and translucent zirconium dioxide ceramics, aesthetic CAD/CAM block ceramics, need a two-step work process in the dental laboratory consisting of computer aided design and machining as a first step and an additional heat treatment as the second step to

reach their final high strength (Bindl et al., 2003; Fischer et al., 2011; Sirona, 2011). Anyway, industrially pre-fabricated block ceramics appear to be more structurally reliable for dental applications than ceramic materials which are manually processed under dental laboratory conditions, although CAD/CAM procedures may induce surface and subsurface flaws that may adversely affect this property (Tinschert et al., 2000).

The reason for polishing temporary as well as permanent CAD/CAM restorations is to eliminate surface defects caused by machining and to establish high gloss and low roughness on the external surfaces. The critical roughness threshold for plaque formation has been reported to be 0.2 μm (Teughels et al., 2006). A smooth surface adds to the patient's comfort, as already a surface roughness in the order of 0.3 mm can be detected by the tip of the patient's tongue (Jones et al., 2004). Additionally, polishing generates the aesthetically pleasing glossy appearance like natural enamel. Gloss retention, that is, wear resistance, of dental materials towards abrasive action, such as toothbrushing, depends on their structure and is considered an attribute of longevity and quality of the material, particularly of direct resin composites (Da Costa et al., 2010; Ferracane, 2011; Heintze et al., 2006; Lee et al., 2010). Little is known of whether and how the structural reliability offered by block pre-fabrication manifests itself by the wear performance of the established, newly developed and experimental ceramic- as well as polymer-based aesthetic CAD/CAM block materials.

The group of one-step CAD-CAM materials for permanent restorations comprises feldspathic silicate ceramics (Datzmann, 1996), feldspar-based leucite reinforced glass ceramics (Chen et al., 1999; Tinschert et al., 2000), a newly developed resin-based block nanocomposite (3M Espe, 2011), an experimental isofiller resin-based composite with 'nano additives' (Lendenmann and Wanner,

2011) as well as a novel interpenetrating network ceramic (Bojemüller and Coldea, 2012; He and Swain, 2011). For temporary restorations, microfilled acrylate polymer blocks (Baltzer and Kaufmann-Jinoian, 2007) and unfilled polymethyl methacrylate blocks (Wanner, 2010) are used. The one-step CAD/CAM restorations are mostly manually polished while the two-step CAD/CAM restorations generated from lithium disilicate glass ceramics (Bindl et al., 2003; Kurbad and Reichel, 2005; Wiedhahn, 2007) or from translucent zirconium dioxide ceramics (Sirona, 2011; Vollbrecht, 2007) are normally glazed or veneered but can also be polished with standard procedures (Kurbad and Reichel, 2005; Sirona, 2011; Preis et al., 2012; Wiedhahn, 2007).

Tooth wear is a complex cumulative and irreversible process with a multifactorial aetiology (Mehta et al., 2012). Information on tooth wear in occlusal contact areas is critical, since loss of occlusal support changes the vertical dimension and the anatomy of the occlusal surface, which can induce parafunction (Ramfjord and Ash, 1979). In a three-year clinical study, CAD/CAM generated composite crowns showed preservation of occlusal anatomic form of 26.5% only versus 96% for ceramic crowns (Vanoorbeek et al., 2010). A recent analysis mentions excess wear and loosening as the major clinical weaknesses of composite crowns (Kelly, 2011). Notwithstanding recent structural improvements, wear of resin-based materials may also be an issue if used for large restorations comprising cusp replacement and multiple restorations in a quadrant (Ferracane, 2011; Kramer et al., 2009). Ideally, a restoration should have wear resistance similar to that of enamel (Lambrechts et al., 1989). The normal vertical loss of enamel from physiological wear was estimated to be approximately 20–38 μm per annum (Lambrechts et al., 1989). Vertical loss of the enamel of opposing teeth caused by ceramic crowns is not statistically different from the vertical loss of enamel at contralateral control teeth in one- and three-year clinical

studies (Esquivel-Upshaw et al., 2012; Supputamongkol et al., 2008). In vitro simulation of the wear performance of emerging new materials, especially in the form of CAD/CAM block materials, still appears to be practical for ranking different types of materials, despite the limitations of laboratory methods, notably the Zurich masticator used in this study, to mimic live conditions (Heintze et al., 2012; Lambrechts et al., 2006).

As the objective of the present investigation, two-body wear is evaluated in the contact area on discs of established and novel aesthetic CAD/CAM materials, as well as on enamel, using excised palatal cusps of the upper first molars as the antagonist stylus in a computer-controlled masticator (Göhring et al., 2002, 2003; Krejci et al., 1990a, b, c; Krejci et al., 1992; Krejci et al., 1999; Krejci and Lutz, 1990; Lutz et al., 1992; Lutz and Krejci, 2000). Based on the above-mentioned information from the literature, the tested null-hypothesis was that the established and the new aesthetic CAD/CAM materials, whether ceramic- or polymer-based, show two-body wear similar to that of enamel and that the loss of vertical dimension is similar.

Toothbrushing is a common cause of abrasion leading to physical wear of the tooth surface through a mechanical process independent of occlusion (Mehta et al., 2012). Toothbrushing influences the wear of enamel and of restorations, mainly by the abrasivity of the toothpaste slurry and by the structure of the restorative materials (Da Costa et al., 2010; Lee et al., 2010; Wiegand et al., 2008). Toothbrushing wear effects are assessed by gloss and roughness measurements (Da Costa et al., 2010; Lee et al., 2010). In the present investigation, the null-hypothesis was that gloss retention and roughness after abrasive toothbrushing show the same results for enamel and all investigated CAD/CAM materials.

Martens' hardness (Fischer et al., 2010; Shahad et al., 2007; Stawarczyk et al., 2011) is investigated to relate hardness to contact wear as well as to the effects

of toothbrushing wear. The null-hypothesis was to test whether all of the aesthetic CAD/CAM materials and enamel show the same hardness and whether there exists a correlation to two-body wear.

2. Material and methods

Human enamel (EN) as the control, aesthetic CAD/CAM block materials, viz. two high-strength ceramics, translucent zirconium dioxide ceramics (IN; inCoris TZI) and lithium disilicate (EX; IPS e.max CAD), two silicate ceramics (EC (aesthetic ceramics); IPS Empress CAD and VM; Vita Mark II), an interpenetrating network ceramic (VE; VITA ENAMIC), two resin-based block composites (LU; Lava Ultimate and EP; experimental composite) as well as one direct nanocomposite (FI; Filtek XTE) and two acrylic polymer-based temporary block materials (TC; Telio CAD and CA; CAD-Temp) were tested in this study (**Table 1**).

2.1. Specimen preparation

Enamel (EN) specimens (n = 12; control) were prepared from the mesio-buccal cusp slope of caries-free, extracted mandibular first molars, which had been stored in a 0.1% thymol solution for up to one year. The buccal slope of the mesial cusp was excised from the crowns with manual cuts, using a handpiece and diamond-coated burs, trimmed, placed in the centre of the cavity of custom-made stainless steel specimen carriers (Ø 14 mm, depth 4 mm; custom-made device at the University of Zurich, Switzerland) and secured with amalgam (Dispersalloy, LOT 010425, Caulk Dentsply, Milford, DE). The enamel surface was positioned parallel to the top edge of the specimen carrier to provide a horizontal enamel surface for the antagonist to make contact.

Twelve test specimens each were prepared from size '14' blocks (14x12x18 mm) of materials EX, EC, VM, VE, LU, EP as well as from size '40' blocks (40x19x15) of IN, TC and CA. Slices (12x14 mm respectively 19x15 mm) of 4 mm thickness were cut from the blocks with a saw microtome (SP1600, Leica Microsystems, Basel Switzerland). The circumference of the cut slices was manually adjusted to fit the specimen carrier cavity and slices were embedded into the specimen carrier using self-cure acrylic resin (ScandiQuick, SCAN DIA, Hagen, Germany). The direct nanocomposite (FI) was filled into the cavity of the specimen carrier in two layers of 2 mm thickness each and five overlapping areas of each layer were light cured 40 s each with a standard LED lamp (Bluephase Ivoclar Vivadent) equipped with an 8 mm diameter light tip and an actual irradiation output of 700 MW/cm² followed by 2 min irradiation in a light oven (Spectramat, Ivoclar Vivadent). The surfaces of all specimens were flattened and polished under water-cooling in a polishing machine with P180, P500, P1200, P2400 and P4000 SiC paper at 150 rpm (Struers Waterproof Silicon Carbide Paper FEPA P#180 – 4000; Pedemax Planopol 2, Struers-Metalog, Copenhagen, Denmark).

As antagonists for each group, 12 mesio-buccal cusps of caries-free extracted upper first molars, which had been stored in 0.1% thymol aqueous solution up to one year, were excised and embedded into stainless steel carriers (cavity: Ø 8 mm, depth 2 mm; custom-made device at the University of Zurich, Switzerland) with amalgam (Dispersalloy, LOT 010425). Each of the 11 groups consisted of 12 specimens and 12 antagonists.

2.2. Quantitative and qualitative analysis of two-body wear

Thermo-mechanical loading in a computer-controlled masticator (CoCoM 2, custom-made device at the University of Zurich, Switzerland) comprised occlusal loading of

49 N at 1.67 Hz and simultaneous thermal stress with temperature changes between 5 °C and 50 °C every 120 seconds (Krejci et al., 1990a, b, c). After the loading phase, the specimens showing the least and the highest wear of every group, including their antagonists, were selected and then dried and sputtered with gold (Sputter SCD 030, Balzers Union, Balzers, FL). For the qualitative characterisation of wear patterns, the selected specimens were visually examined under a scanning electron microscope (SEM) (Carl Zeiss Supra 50 VP FESEM, Carl Zeiss, Oberkochen, Germany) and typical examples are presented (**Figs. 3, 4 and 5**).

Quantitative analysis of two-body wear on specimens and their antagonists was carried out before and after loading in a 3D-surface analyser (3DS, PPK, Zurich, Switzerland). The custom-made surface analyser consisted of a calliper needle (mechanical probe) and a measuring table scanning surface, positioned in the contact area every 100 microns in x and y totalling 100 measuring points per mm², with a resolution of 1 micron in x, y and z. Before starting the loading test, the coordinates of reference points of the surveyor's table, of the specimen and of the antagonist carriers, as well as of the occlusal contact points, were saved and exact repositioning of specimens as well as of antagonists in the 3D surface analyser after loading was allowed. The size of the measuring field was set to 9 mm² for specimens and 2.25 mm² for antagonists respectively. To prevent antagonists from drying, tape (Tesa, Beiersdorf, Hamburg, Germany) was luted circularly to the carriers and filled with tap water. Substance loss was calculated, overlaying the scanning data with congruent points and subtracting initial measurements from the final measurements. Wear in a test object was defined as the largest vertical loss of substance found to have occurred in the contact area (Göhring et al., 2002, 2003). Data was transferred to a statistical program (IBM SPSS Version 20, IBM Germany).

2.3. Toothbrushing wear effects: gloss and roughness

To evaluate the effects of toothbrushing wear, three extra specimens were fabricated with highly polished surfaces as described above out of human enamel (EN) and each of the ten test materials, IN, EX, EC, VM, VE, LU, FI, EP, TC, CA (**Table 1**). Surface quality was assessed with gloss and roughness measurements.

Surface gloss measurements were carried out three times on each of the three specimens using a glossmeter (ZGM 1020 Gloss 60° Mini-measuring head; Zehntner, Hoelstein, Switzerland). After this, one half of the high gloss surface was covered by adhesive tape (Scotch Magic, 3M France, Cergy Pontoise) and the unprotected side was mechanically brushed (toothbrush: PARO M39, Esro, Thalwil, Switzerland; load: 250 g; cycle frequency: 60/min; time: 25 min) using 96 g of toothpaste slurry (Depurdent toothpaste, Dr. Wild, Basel, Switzerland, 38.4 g; artificial mouthfluid (Klimek et al., 1982) 61.5 g; 0.1 g antifoaming agent, Fluka, Buchs, Switzerland) per brushing sample. After brushing, the protecting tape was removed, and surface gloss measurements were repeated on both brushed and unbrushed areas. Additionally, surface roughness measurements were performed in the centre of both areas using an inductive surface profilometer (Form Talysurf S2, Taylor Hobson, England).

2.4. Martens' hardness measurements

To evaluate the Martens' hardness (ZHU 2.5; Zwick; Ulm, Germany), the specimens of gloss measurements were used. The diamond indenter of the hardness tester was used on the polished surface of the specimens with a load of 10 N for 20 seconds. The Martens' hardness was tested three times on each specimen.

2.5. Statistical methods

The data sets were analysed with statistical software (IBM SPSS Version 20, IBM Germany). Descriptive statistics with mean, standard deviation and 95 % confidence intervals for all tests and groups were computed. The Kolmogorov-Smirnov test for normal distribution and the Levene test for homogeneity of variances were applied. For the two-body wear results, statistical differences between the tested materials as well as the corresponding antagonists were assessed with one-way ANOVA (analysis of variance) and the post hoc test Tamhane. For gloss, roughness and hardness results, to detect differences between the tested materials, one-way ANOVA, together with the post hoc Scheffé test, was applied. The influence of mechanical brushing within the material groups was compared with a paired two sample Student's t-test.

3. Results

3.1 Two-body wear quantitative analysis

The bar diagram (**Fig. 1**) shows the results of two-body wear measurements of the control group EN (enamel against enamel) and the wear in the contact area of all test materials acted upon by the enamel antagonist. Three types of colour-coded bars present the wear data of the materials (m-wear) in blue, wear of the antagonist (a-wear) in green and the total vertical loss as the sum of the material and the corresponding antagonist (t-wear) in yellow. **Table 2** presents the results of the statistical analysis indicating the statistical differences ($p < 0.05$) between materials (m), antagonists (a) and total (t) vertical loss.

Aesthetic ceramics EX, EC, VM, hybrid ceramic VE, the block- (LU) and direct (FI) composites as well as the experimental composite (EP) do not show any significant differences of m-, a- and t-wear compared to the control, thus not rejecting

the hypothesis. In contrast, zirconium dioxide ceramic (IN) exhibits zero m-wear characterising its wear behaviour as being totally different from that of the enamel (EN) and that of all other restorative materials. Moreover, the a-wear ($25.5 \pm 13 \mu\text{m}$) and t-wear ($25.5 \pm 13\mu\text{m}$) were both significantly less than the EN a-wear ($54.5 \pm 32 \mu\text{m}$) and the EN t-wear of the control group ($91.2 \pm 38 \mu\text{m}$), thus rejecting the hypothesis. Likewise, the hypothesis was rejected by the very low t-wear ($40.5 \pm 16 \mu\text{m}$) of the experimental block composite EP on the one hand, as well as by the extreme m-wear of the polymer block materials (TC $107.3 \pm 36 \mu\text{m}$; CA $98.8 \pm 33 \mu\text{m}$) and their extremely low a-wear (TC $12.1 \pm 6 \mu\text{m}$; CA $12.8 \pm 9 \mu\text{m}$) on the other.

The disilicate EX and silicate ceramic EC showed the highest a-wear. However, no significant differences existed in m-, a- and t-wear between EX, EC, VM and the hybrid ceramic VE (**Fig.1, Table 2**). The nanocomposite block material LU, the direct composite FI as well as experimental block composite EP caused significantly less a-wear than the lithium disilicate ceramic EX, without exhibiting significantly different m-wear. Block nanocomposite LU and direct nanocomposite FI showed no significant differences in any category of two-body wear between each other (**Table 2**). However, FI additionally exhibited significantly lower a-wear compared to both silicate ceramics EC and VM without showing significantly different m-wear (**Fig.1, Table 2**). The wear characteristics of hybrid ceramic VE and nanocomposite LU as well as FI appear similar with respect to the m-, a- and t-wear data (**Fig.1**).

The experimental block composite EP showed significantly less a-wear than the ceramics EX, EC and VM as well as less m-wear than EC and LU. The temporary acrylic polymers TC and CA form a group with significantly higher m-wear than enamel and all ceramic and composite permanent materials as well.

3.2 Two-body wear qualitative analysis

The results of the qualitative SEM analysis are presented in **Figures 2, 3 and 4**, showing image pairs of contact areas on specimens and corresponding antagonists after 1.2 million chewing actions.

Figure 2 presents as follows. In a) pitted wear patterns are shown both on the specimen enamel on the left as well as on the antagonist's enamel contact area on the right. In b) the specimen image shows the IN zero wear contact area appearing slightly polished with diffuse boundary. The antagonist's contact area appears with a smooth flat, well-delineated surface. In c) the EX-specimen image left shows the margin zone of the contact area exhibiting circular fracturing of the material. The corresponding margin zone of the enamel antagonist shows a pitted surface as well as slight cracking. In d) the EC-specimen image left shows the margin zone of the contact area exhibiting circular cracking. The wear contact surface of the antagonist appears essentially flat with distinct sliding grooves.

Figure 3 presents as follows. In e) on the VM silicate ceramic surface a very clearly delineated contact area is shown with an exposed internal structure consisting of a partially broken-off matrix and flattened filler particles. The enamel surface of the antagonist shows a clearly delineated flattened and smooth contact area interrupted by larger and smaller spots with pitted bare enamel structure. In f) the VE hybrid ceramic specimen image shows the contact area delineated by a sharp line from the polished specimen surface. The contact surface resembles the non-contact polished surface with only slight pitting at the internal side of the boundary line and in the central contact area. The contact surface of the enamel antagonist looks smooth with only minor pitting. In g) the contact area of the LU CAD/CAM nanocomposite specimen shows slight pitting inside the demarcation line and fine microcracks running across the contact area. The corresponding contact surface on the enamel

antagonist appears essentially smooth. In h) the contact area of the FI direct nanocomposite specimen shows the margin zone of the contact area exhibiting circular cracking as well as some microporosity and pitting. The wear contact surface of the antagonist appears essentially flat with distinct sliding grooves.

Figure 4 presents in i) the EP experimental CAD/CAM composite contact area with blurred boundaries. Within the contact area the structure of the material shows filler particles of different sizes, only slight pitting, as well as scarce micropores and a single lost filler particle cavity. The surface of the enamel antagonist appears smooth. In k) the contact area of the TC CAD/CAM unfilled polymer material shows a circular crater-like formation accompanied by circular parallel-running crack lines. On the antagonist, practically no evident wear effect can be seen. In l) the contact area of the CA CAD/CAM microfilled polymer material shows circular step-like fracturing material. On the antagonist the contact area is slightly visible on the cusp tip at low magnification.

3.3 Gloss

The results of the gloss measurements are presented in **Table 3** as gloss units (GU). Machine polishing created a high gloss value of 53 GU on enamel (EN) and similar high gloss values between 57 GU on lithium disilicate (EX) and 50 GU on unfilled polymer (TC). The gloss value of zirconium dioxide ceramic (IN) of 128 GU was completely out of the range of that of the enamel control (EN) and of all other permanent as well as provisional restorative materials.

Abrasive toothbrushing reduced the gloss value of enamel (EN) significantly by 53%, and brushing caused significant gloss reductions on the materials (EX 5%; EC 2%; VM 2%; VE 27%; LU 21%; FI 29%; EP 40%; TC 78% and CA 71%). After brushing, the gloss values (GU) of the permanent restorative materials, whether

ceramics, (EX (54), EC (51), VM (51)), hybrid ceramic (VE (41)), CAD/CAM nanocomposite (LU (44)), direct nanocomposite (FI (39)) or experimental CAD/CAM composite (EP (32)) were all significantly higher than the gloss value of the brushed enamel control surfaces (EN (25)). Among the permanent restorative CAD/CAM materials, gloss retention in the group of lithium disilicate EX (54) and silicate ceramics EC (51) and VM (51) was significantly the highest, followed by the group formed by hybrid ceramics VE (41), CAD/CAM nanocomposite LU (44) as well as the direct nanocomposite FI (39). After brushing, the gloss value of experimental CAD/CAM composite EP (32) was significantly lower than those of the aforementioned groups but was still significantly higher than the gloss value of the brushed enamel control EN (25). The different gloss retention of permanent CAD/CAM materials clearly rejects our hypothesis. However, only the provisional CAD/CAM polymer materials TC (GU 11) and CA (GU 15) showed significantly lower gloss retention than brushed enamel EN (GU 25).

3.4 *Roughness*

The results of the roughness (R_a) measurements are presented in **Table 4**. The R_a -value of **the** polished enamel control surface EN was not significantly different from that of zirconium dioxide ceramic IN. Also, the enamel R_a (EN) was similar to the polished surfaces of lithium disilicate (EX) and silicate ceramics (EC, VM) and was also similar to the R_a of polished hybrid ceramic (VE) and CAD/CAM nanocomposite (LU), direct nanocomposite (FI) as well as experimental CAD/CAM composite (EP) and even similar to the R_a of the temporary CAD/CAM polymer TC. The R_a of the polished temporary CAD/CAM polymer CA was not significantly different from the permanent experimental CAD/CAM composite EP.

After brushing the enamel control surfaces, EN as well as all permanent and provisional CAD/CAM materials show higher R_a -values except zirconium dioxide ceramic IN, which exhibits an insignificant lower R_a after brushing. The differences of R_a between polished and brushed surfaces were significant for all tested materials except for zirconium dioxide ceramic (IN) and silicate ceramic EC. After brushing, the R_a -values of ceramics (IN, EX, EC, VM), hybrid ceramic (VE) and CAD/CAM nanocomposite (LU), direct nanocomposite (FI) and experimental CAD/CAM composite (EP) were all not significantly lower than the enamel (EN) surfaces while the R_a -values of the temporary CAD/CAM polymers TC and CA showed higher R_a -values than enamel, the differences however, were not significant. But the significant differences between the polished surface R_a -group ^(a) EN, EX, EC, VM, TC on one side and group ^(b) IN, VE, LU, FI, EP on the other plus R_a -group ^(c) EP and CA reject our hypothesis for equal roughness of machine-polished surfaces. The same applies for the significant differences between brushed groups ^(a) and ^(b) (**Table 4**).

3.5. *Martens' Hardness*

Zirconium dioxide ceramic (IN) was the ceramic with the out of scale highest hardness of all tested materials. The results of the Martens' hardness measurements are presented in **Table 5**. The IN-values-excluded statistical analysis shows that the hardnesses of leucite reinforced silicate ceramic EC, of lithium disilicate (EX) ceramic and of silicate ceramics VM were similar to the hardness of enamel (EN). Hybrid ceramic (VE) showed the lowest hardness of all ceramic materials (IN, EX, EC, VM) tested and exhibited a similar hardness to resin-based composite materials (LU, FI, EP). Hardness of temporary CAD/CAM polymers TC and CA showed the lowest values. The significant differences reject our hypothesis that all CAD/CAM materials offer the same hardness.

4. Discussion

4.1 Aspects of wear testing

This study investigated frictional wear, that is, masticatory attrition, as well as abrasion by toothbrushing. Methodically, attrition is defined as the physiological wearing away of the tooth structure as a result of tooth-to-tooth contact, as in mastication, without (two-body wear) or with abrasive substance (three-body wear) intervention (Eccles, 1982; Mehta et al., 2012). The clinical manifestation of attrition shows the appearance of a flat circumscribed facet on enamel and/or on restorative material. As the lesion progresses, there is a tendency towards the reduction of the cusp height and flattening of the occlusal inclined planes (Mehta et al., 2012) leading to a loss of vertical dimension as also shown in the present two-body wear experiment in **Figures 2 to 4**. Wear assessments from a group of patients suggest that wear is normally a slow process (Bartlett, 2003). How well this phenomenon can be imitated experimentally, with the help of artificial masticators to assess the adequacy of restorative materials, still remains a matter of discussion (Heintze 2012; Lambrechts et al., 2006).

Lambrechts et al. (2006) characterised the Zurich computer-controlled masticator as a three-body artificial wear machine. However, in the present study, the Zurich wear system did not include toothbrushing with abrasive slurry in addition to mastication but the effects of toothbrushing were assessed separately on additional specimens. Consequently, masticatory action implied two bodies only, the polished material specimen and the non-standardised natural enamel as the antagonistic stylus (Krejci et al., 1999). Wear measurements and SEM evaluation were restricted to the occlusal contact area (Krejci et al., 1999). This experimental arrangement is in accordance with two-body wear as defined by the ISO/TS wear norm 14569-2

(2001). As control for the material specimens, again human enamel served as the reference for permanent and for temporary restorative materials. If we accept the estimate of normal vertical loss of enamel from physiological wear to be approximately 20–38 μm per annum (Lambrechts et al., 1989), the mean total wear of 96.8 μm found for enamel in the present study after 1.2 million chewing impacts, would meet the lower end of the estimate of Lambrechts et al., (1989) with 19.4 μm total enamel wear per annum, given that the equivalence of our laboratory test to a 5-year clinical service period is valid (Krejci and Lutz, 1990) or at least weakly related (Heintze, 2012). Anyway, it establishes the reference for the wear rates of the restorative materials and should allow comparative evaluation and ranking, particularly of the new and experimental CAD/CAM materials such as IN, VE, LU and EP, under the conditions of the present study.

4.2. Two-body wear of zirconium dioxide ceramics

The zero m-wear for monolithic zirconium dioxide ceramics (IN) and minimal a-wear (25.5 μm) of its enamel antagonists both impressed (**Fig.1; Table 2**), even though these properties have already been reported for zirconium dioxide ceramics by recent laboratory studies (Jung et al., 2010; Preis et al., 2012; Rosentritt et al., 2012; Stawarczyk et al., 2012). The contact area of IN looked slightly polished at the end of the test, while, other than the rougher contact areas of the control facets of a-enamel against m-enamel (**Fig. 2a**), its enamel antagonist showed a still denser, very smooth and flat surface on the wear facet (**Fig. 2b**). If monolithic translucent zirconium dioxide ceramic is considered to be used for CAD/CAM generated non-veneered crowns in patients with natural teeth as antagonists, it should be kept in mind that our in vitro mastication test started with a highly machine-polished specimen of IN with very low roughness ($R_a = 0.026 \mu\text{m}$; **Table 4**), exhibiting a regular dense fine particle

structure and the highest hardness of all materials tested in the present study (**Table 5**); whereas the enamel controls started the test with natural unpolished m-enamel surfaces. Machine polishing results in a significantly higher surface gloss than manual polishing with tools for intraoral polishing (Heintze et al., 2006). Abrasive treatment of zirconium dioxide ceramics raises structural aspects but polishing may enhance the strength of zirconium dioxide ceramics (Vagkopoulou et al., 2009). Air abraded zirconium dioxide ceramic specimens polished extraorally by a dental technician with a goat hairbrush and diamond paste yielded similar low two-body wear of enamel antagonists as in the present study (Stawarczyk et al., 2012).

In the clinical situation however, after cementation, contact areas mostly need to be adjusted manually by corrective grinding with rotating diamond-coated instruments creating rough surfaces. Whether rough zirconium dioxide ceramic surfaces can be manually polished in the mouth to a degree which does not forward excessive wear of the antagonist, will have to be proved, before monolithic zirconium dioxide ceramic crowns can be considered as single tooth restorations opposing natural teeth. One case report of upper and lower full-arch fixed detachable implant-retained restorations, manufactured from monolithic zirconium dioxide ceramic, at least shows that no fractures and no wear occurred on the full zirconium dioxide ceramic teeth functioning against each other after two years of clinical service (Rojas-Vizcaya, 2011), despite concerns regarding the structural stability of zirconium dioxide ceramics when exposed to the oral environment (Koutayas et al., 2009).

4.3. Two-body wear of silicate and hybrid ceramics

In the present study, wear of material specimens (m-wear) tended to increase the lower the hardness of the material. On the other hand, antagonists showed lower

enamel wear the lower the hardness of the material specimens, except zirconium dioxide ceramic IN. After zirconium dioxide ceramic IN, lithium disilicate EX was the hardest and the acrylic polymers TC and CA were the softest materials (**Fig.1; Tables 2 and 5**). Glass ceramics EX and EC showed circular cracking patterns parallel to the inside fringe of the facet, VM exposed its filler structure whereat the fillers were flattened at the facet's surface (**Fig. 3a**). The facets of the enamel antagonists show typical sliding patterns or exposure of local enamel structures (**Fig. 2 c, d; Fig. 3a**). As opposed to findings in other laboratory studies (Jung et al., 2010; Preis et al., 2012; Rosentritt et al., 2012) the wear of enamel antagonists by feldspathic ceramic (VM) and glass ceramic (EC) was not significantly different from that of zirconium dioxide ceramics (**Tab. 2**).

The hybrid ceramic VE (Bojemüller and Coldea, 2012; Giordano, 1996, 2000, 2005; He and Swain, 2011) tends to result in lower a-wear than other ceramics except zirconium dioxide ceramic, which is still lower, and VE shows a-wear like composites and acrylic polymers in the present study. The m-wear of VE itself is similar to that of the other ceramics, except zirconium dioxide ceramic, and also similar to that of composites (**Fig. 1; Table 2**). Thus, wear performance of VE combines the characteristics of ceramic and composites and by trend appears similar to that of the CAD/CAM block nanocomposite LU, while at the same time it is not significantly different from that of enamel (**Fig. 1; Table 2**). Its hardness is positioned significantly below that of enamel and stays at the low end of the hardness of ceramics while being not significantly higher than that of composites (**Table 5**). In the SEM at 1 Kx the fringe of the contact area shows a sharp line and the contact surface exhibits only minimal pitting. This reaction of the hybrid structure to the repetitive impact of the antagonist may be influenced by its modulus of elasticity of 30 GPa (Bojemüller and Coldea, 2012), which positions VE between resin-based

composites (~ 15 GPa; 3M ESPE (2011) and feldspathic ceramic (VM: ~ 60 GPa; Bojemüller and Coldea, 2012; Datzmann, 1996) as well as between dentin (5–17 GPa) and enamel (60 GPa; Menig et al., 2000). The modulus of elasticity of 30 GPa of VE opens up a section of elastic properties for restorative materials, which has so far not been accessible. Concerning thermo-cycling in the present investigation up to 50°C, the coefficient of thermal expansion of hybrid ceramic ($11.9\text{-}12.4\cdot 10^{-6}\text{K}^{-1}$) stays on the side of ceramics ($8.8\cdot 10^{-6}\text{K}^{-1}$, Datzmann, 1996) and of the natural tooth (enamel $10\cdot 10^{-6}\text{K}^{-1}$; dentin $11.4\cdot 10^{-6}\text{K}^{-1}$; Toparli et al., 2000).

4.4. Two-body wear of resin-based and acrylic polymer materials

The CAD/CAM block nanocomposite LU (3M ESPE 2011) and the direct light curing composite FI (Ferracane, 2011; Kramer et al., 2009) do not differ significantly in any aspect from the two-body wear in the present study (**Fig. 1; Table 2**). This may confirm that the physical properties of resin-based composite as a material for the fabrication of dental restorations, particularly full posterior crowns, are not improved structurally by block-fabrication for CAD/CAM use as with ceramics (Tinschert et al., 2000) at least with respect to the degree of conversion of direct and block composite (Kelly, 2011; Vanoorbeek et al., 2010). However, close inspection of the contact surfaces at 1Kx magnification shows some micropores and flaws as well as circular microcracking in the direct composite material FI, which are not visible in the CAD/CAM block composite LU to the same extent, apart from singular very fine microcracks (**Figs 3c and 3d**). The slight difference of gloss between LU (44 GU) and FI (39 GU) may hint at a slightly less dense surface quality of the direct composite compared to the CAD/CAM block material. While the wear behaviour of both nanocomposites poses no problem, as shown in the present study (**Figs 3c and 3d**), possibly the low modulus of the elasticity of composites (10–15 GPa, 3M ESPE,

2011) under load may contribute to the loosening of composite crowns after some clinical service time, while the higher E-moduli of ceramics do not (Kelly, 2011; Vanoorbeek et al., 2010). However, for overlay restorations, the elastic properties of a CAD/CAM composite proved to be beneficial compared to the performance of ceramics (Magne and Knezevic, 2009). Resin-based composite CAD/CAM inlays performed as well as porcelain CAD/CAM inlays after three years of clinical service (Fasbinder et al., 2005).

The experimental CAD/CAM block composite EP (Lendenmann and Wanner, 2011) shows promising wear performance (**Fig. 1; Table 2**), whereas the acrylic polymer materials TC (Wanner, 2010) and CA (Baltzer and Kaufmann-Jinoian, 2007) exhibit a significantly higher m-wear than all permanent restorative materials in the present study, confirming their temporary character.

4.5 Toothbrushing wear: roughness and gloss retention

Zirconium dioxide ceramic machine-polished specimen surfaces, as prepared for toothbrushing wear testing, yielded the high gloss value of 128 GU, which we attribute to its high refractive index and high whiteness (Vagkopoulou. et al., 2009) both increasing the remission of light (**Table 3**). Abrasive toothbrushing even slightly increased the gloss of zirconium dioxide ceramics to 133 GU, its roughness staying the same, no doubt related to the very high hardness of zirconium dioxide ceramics (**Table 5**). The gloss of polished enamel (53 GU) as well as that of all other polished material specimens lay between 50 and 57 GU, significantly lower than that of zirconium dioxide ceramic (IN) while the roughness (R_a) values of polished enamel and the polished specimens of all other materials were not significantly different from that of zirconium dioxide ceramic (IN) with the exception of the acrylic temporary material CA showing significantly less roughness.

The experimental toothbrushing wear in the present study significantly reduced the gloss of enamel and of all material specimens, except zirconium dioxide ceramic, by the high abrasivity of the toothpaste slurry used and formed material groups of similar gloss retention. The ceramics EX, EC and VM formed a top group of high gloss retention between 51 and 54 GU with Martens' hardness between 2739 MH and 4156 MH including enamel with 3228 MH (Table 5). Another group of good gloss retention and lower hardness was formed by the hybrid ceramic VE (41 GU) together with block nanocomposite LU (44 GU) and direct nanocomposite FI (39 GU). The temporary acrylic polymer materials TC and CA with initial excellent polishability and high gloss of 50 to 51 GU proved to be very susceptible to abrasive toothbrushing, reducing their gloss to 11 GU and 15 GU with corresponding surface roughness of 0.32 to 0.36 microns. Roughness of this magnitude is way above the critical threshold for microbial plaque accumulation (Teughels et al., 2006) making regular hygiene controls indispensable during the clinical service time of temporary restorations.

5. Conclusions

Within the limitations of this in vitro study, it can be concluded that: all permanent aesthetic CAD/CAM block materials tested, whether ceramics, hybrid ceramics or resin-based nanocomposites and even direct nanocomposites, behave similarly or better with respect to two-body and toothbrushing wear than natural enamel, which is not true for temporary acrylic polymer CAD/CAM block materials. Ceramics show the best gloss retention compared to hybrid ceramics, composites and acrylic polymers.

Conflicts of Interest

The authors declare no conflicts of interest.

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Legends of Tables and Figures

Table 1. Type of specimens, brands, code, number (N) of specimens per group, manufacturers, and batch numbers of the materials tested for two-body wear.

Table 2. Significant differences (one-way-ANOVA and Tamhane post hoc test, $p < 0.05$) between two-body wear data (vertical loss) of all tested groups relating to the results in Figure 1: m = material, a = antagonist and t = total vertical loss.

Table 3. Gloss (relative units GU) of polished surfaces and surfaces after

toothbrushing. Homogenous subsets a, b, c and d represent significant differences according to one-way ANOVA with Scheffé post hoc test. The effect of toothbrushing was assessed with a paired two sample Student's t-test.

Table 4. Roughness Ra (μm) of polished surfaces and surfaces after toothbrushing. Homogenous subsets a, b and c, represent significant differences according to one-way ANOVA with Scheffé post hoc test. The effect of toothbrushing was assessed with a paired two sample Student's t-test.

Table 5. Martens' hardness of polished surfaces. Homogenous subsets a, b, c, d and e represent significant differences according to one-way ANOVA with Scheffé post hoc test. IN was excluded from statistical analysis because of its out of scale values.

Fig. 1. Bar diagram of contact wear (vertical loss) of all tested groups. SD: standard deviation.

Fig. 2. SEM images a, b, c, d, showing the contact areas of a) enamel (EN) and of material (IN, EX, EC) specimens on the left hand side and the contact area of the corresponding antagonist on the right hand side after 1.2 million chewing cycles. All images show 1000x magnification.

Fig. 3. SEM images e, f, g, h, showing the contact areas of material specimens (VM,

VE, LU, FI) on the left hand side and the contact area of the corresponding antagonist on the right hand side after 1.2 million chewing cycles. All images show 1000x magnification.

Fig. 4. SEM images showing the contact areas of EP/EN, TC/EN and CA/EN. All images 1000x magnification except CA-Antagonist 150x.