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ORIGINAL ARTICLE

Effects of erosion and abrasion on resin-matrix ceramic CAD/CAM materials: An in vitro investigation

Cosima Reidelbach[1] | **Michael Swoboda**[1] | **Mathias Spraul**[1] | **Kirstin Vach**[2] | **Sebastian B. M. Patzelt**[3,4] | **Elmar Hellwig**[1] | **Olga Polydorou**[1]

[1]Department of Operative Dentistry and Periodontology, Faculty of Medicine, Medical Center – University of Freiburg, Freiburg, Germany

[2]Institute for Medical Biometry and Statistics, Faculty of Medicine, Medical Center – University of Freiburg, Freiburg, Germany

[3]Praxis für Zahnmedizin, Zimmern ob Rottweil, Germany

[4]Department of Prosthetic Dentistry, Faculty of Medicine, Medical Center – University of Freiburg, Freiburg, Germany

Correspondence
Cosima Reidelbach, Faculty of Medicine, Medical Center – University of Freiburg, Center for Dental Medicine, Department of Operative Dentistry and Periodontology, Hugstetter Str. 55 79106 Freiburg im Breisgau, Germany.
Email: cosima.reidelbach@uniklinik-freiburg.de

Abstract

The aim of the study was to evaluate the effects of erosion and abrasion on resin-matrix ceramic CAD/CAM materials [CERASMART (GC); VITA ENAMIC (VITA Zahnfabrik); Lava Ultimate (3 M)] in comparison to feldspar ceramic (VITABLOCS Mark II, VITA Zahnfabrik) and resin composite materials (ceram.x universal, Dentsply Sirona). Daily brushing and acid exposure were simulated using a brushing apparatus and a solution of 0.5 vol% citric acid. Microhardness, surface roughness, and substance loss were measured at baseline and after simulation of 1 and 3 years of function. All materials showed a decrease in microhardness after 3 years and an increase in surface roughness (Ra) after 1 and 3 years. The Ra increase was statistically significantly lower for the resin-matrix ceramics than for feldspar ceramic and similar to composite material. After 3 years, only feldspar ceramic showed no significant substance loss. In conclusion, resin-matrix ceramics demonstrate reduced roughening compared to feldspar ceramics, potentially improving restoration longevity by preventing plaque buildup, but differences in abrasion resistance suggest the need for further material-specific research. Future research should aim to replicate clinical conditions closely and to transition to in vivo trials.

KEYWORDS

CAD/CAM materials, microhardness, substance loss, surface roughness, wear

INTRODUCTION

In recent years, restorative dentistry has undergone a change towards metal-free, tooth-coloured restorations, mainly due to further developments in minimally invasive therapies [1], adhesive dentistry, and the increased demands of patients for aesthetic restorations [2]. Furthermore, computerized methods are increasingly utilized to deliver faster and metal-free restorations [3–5]. Restorative dental materials have been developed specifically for chairside CAD/CAM restorations. These include so-called resin-matrix ceramics, combining properties of both resin-based composite materials and dental ceramics. Resin-matrix ceramics supposedly exhibit reduced brittleness and hardness as well as increased flexibility and fracture toughness, compared to ceramics [6–8], which also facilitates chairside fabrication. According to their microstructural composition, resin-matrix ceramics can be divided into polymer-infiltrated ceramic networks (PICNs) and resin-based ceramics [4, 9, 10]. During the manufacturing process of PICNs, first, a porous, pre-sintered feldspar ceramic network is produced in cubic form, which is then silanized and infiltrated with a resin matrix. A combination of pressure and heat treatment cures the components. Thus, the amount of ceramics can be increased up to 86% [4, 10, 11]. CAD/CAM resin-based ceramics consist of a polymer matrix with a high amount of ceramic fillers, polymerized by pressure and heat resulting in improved mechanical properties compared to resin-based composite materials for direct application [12].

Tooth wear caused by erosive and abrasive influences is a current research focus, partially due to the decline in the prevalence of caries in recent years [13, 14]. Schlueter and Luka [15] estimated a global mean prevalence of erosion ranging between 20% and 45% in permanent teeth. Especially the daily intake of fruit juices, soft drinks, or sour fruits plays a major role in the formation of erosive defects since the tooth structure is softened and can be more easily abraded by mechanical influences [15]. Several authors discussed the resistance of various CAD/CAM materials to abrasive [16–19] and erosive influences [20–23]. However, to date there is only one study available on the effects of combined erosive and abrasive stress on CAD/CAM resin-matrix ceramics [24].

Therefore, the aim of this study was to evaluate the impact of daily exogenous erosive challenges and abrasive wear by tooth brushing on three different CAD/CAM resin-matrix ceramics in comparison to a feldspar ceramic and a direct resin-based composite material. Two hypotheses were investigated. First, resin-matrix ceramics are less susceptible to abrasive and erosive influences than resin-based composites and more susceptible than feldspar ceramics. Second, within the group of resin-matrix ceramics, polymer-infiltrated ceramic-networks are more resistant to abrasive and erosive influences than CAD/CAM resin-based ceramics.

MATERIAL AND METHODS

Five dental restorative materials were investigated: a nanohybrid resin-based composite (ceram.x universal, Dentsply Sirona), a feldspar ceramic (VITABLOCS Mark II, VITA Zahnfabrik), a PICN (VITA ENAMIC, VITA Zahnfabrik), and two resin-based ceramics (CERASMART, GC Corporation, and Lava Ultimate, 3 M). Table 1 shows the composition of these materials.

For each of the five restorative materials, 12 specimens (shade A2 or a corresponding colour) were prepared. Ceram.x universal was placed in one solid increment in a cylindrical mould, 4.5 mm in diameter and 2 mm thickness. Before polymerization, the sample was covered with a clear plastic strip to flatten the surface and to avoid the formation of an oxygen layer. Polymerization was carried out using a light curing unit (Bluephase LED, Ivoclar Vivadent) with an intensity of 830 mW/cm^2 for 20 s. Light intensity was verified using a Bluephase Meter (Ivoclar Vivadent). All other tested materials were purchased in prefabricated CAD/CAM blocks [VITABLOCS Mark II 2M2C I12 (10 × 12 × 15 mm); VITA ENAMIC 2M2-HT EM-14 (14 × 12 × 18 mm); CERASMART A2-HT 12 (10 × 12 × 15 mm), Lava Ultimate As-HT 14L (14 × 14 × 17 mm)]. The specimens were produced by cutting the blocks into slices of 2 mm thickness, using a water-cooled band saw (Mikro-Schleifsystem, EXAKT Advanced Technologies). Subsequently, the specimens were embedded in cylindrical moulds of 2.5 cm diameter using a cold mounting resin (Technovit 4071, Heraeus Kulzer). Afterwards, top and bottom surfaces were parallelized using the Mikro-Schleifsystem and polished under water cooling (Knuth-Rotor-3, Struers). For polishing, a standardized protocol was applied using silicon carbide paper in the sequence P500, P1000, P2400, P4000 grit size. The specimens were not subjected to any kind of glazing or firing. In order to obtain a reference area, one half of the specimen surface was covered with a clear adhesive strip (TESA). The uncovered half of the surface served as the simulation area.

To simulate the abrasion of the specimens caused by brushing, an automated tooth brushing simulator (ZM-3.4, supporting software V2.10A/V06.00D, SD Mechatronik) was applied. The specimens were aligned horizontally using inserts made of putty silicone, which also prevented them from slipping within the cylindrical receiving device. The heads of medium-bristled toothbrushes (Fuchs, Interbros) were cut from the handle, aligned parallel to the specimens and attached to square aluminium tubes using a two-component glue (Turbomix, Boldt & Co). Behind the brush head, a holder was fitted to hold an additional weight of 200 g. The construction was then attached to the machine's associated holding mechanism. Brushing teeth twice a day for two min each over a period of up to 3 years was simulated, as this corresponds to the consensus of recommended brushing duration [25]. The attached weight of 200 g ensured an even downforce of 2 N. Based on the assumption that the average toothbrushing involves 22 brushing cycles per min, twice daily toothbrushing for 2 min would involve 31,680 cycles per year. This corresponds to a simulated brushing duration of approximately 5 h when using a speed of 100 cycles per min. One cycle consisted of two brush strokes of 13 mm each. As an abrasive medium, natural human saliva was mixed with a toothpaste of low abrasiveness (RDA 30; elmex sensitive, GABA) in a ratio of 3:1. One healthy volunteer provided stimulated saliva, which was centrifuged three times at 10,000 rpm. For each specimen, 10 mL of the abrasive medium were added to the brushing simulation. After each simulated year, the toothbrush heads as well as the abrasive medium were renewed. After the brushing simulation, the specimens were stored in airtight boxes (Lock&Lock) containing a damp paper towel, without previously removing the abrasive medium. The containers were kept at 37°C for 24 h, which corresponded to a simulated contact time of the

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TABLE 1 Overview of the investigated dental restorative materials including information about components as provided by the manufacturers.

Material	Type	Manufacturer	LOT	Components
ceram.x universal	Light-cured nanoceramic composite	Dentsply	0886	Methacrylate-modified polysiloxane, dimethacrylates, spherical glass filler prepolymerisates (3.50–15 μm)
VITABLOCS Mark II	CAD/CAM feldspar ceramic	VITA Zahnfabrik	20,902	feldspar ceramic mean grit size 4 μm
Lava Ultimate	CAD/CAM resin-based ceramic	3 M	N736566	silica-fillers (20 nm), zirconia-fillers (4–11 nm), zirconia–silica-clusters (0.6–10 μm) BisGMA, UDMA, BisEMA, TEGDMA
CERASMART	CAD/CAM resin-based ceramic	GC	1,604,261	BIS-MEPP, UDMA, DMA silica-fillers (20 nm), barium-borosilicate glass (300 nm)
VITA ENAMIC	CAD/CAM polymer-infiltrated ceramic network	VITA Zahnfabrik	35,100	feldspar network UDMA, TEGDMA

Abbreviations: BisEMA, bisphenol A diglycidyl methacrylate ethoxylated; BisGMA, bisphenol A-glycidyl methacrylate; BIS-MEPP, bisphenol-A ethoxylate dimethacrylate; DMA, dimethylacetamide; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate.

abrasive medium with the materials for 1 year [14]. To simulate the daily influences of acidic foods and beverages, the specimens were stored in an erosive medium (pH 2.5, 0.5 vol% citric acid, Merck) for 24 h per simulated year. The pH was continuously monitored using a pH meter (PH526, WTW).

At three time points (t0 = baseline, t1 = 1 year and t2 = 3 years) the Knoop microhardness (KHN), surface roughness (Ra, Rt, Rz), and substance loss were recorded. For the determination of the Knoop microhardness, each material was loaded with individual weights or force, respectively [Lava Ultimate, VITA ENAMIC, and CERASMART: 200 g (1.961 N); VITABLOCS Mark II: 300 g (2.942 N); ceram.x universal: 50 g (0.4903 N)]. The measurement was performed using the Leitz Miniload 2 microhardness tester and its associated evaluation unit RZD-DO (both Ernst Leitz Wetzlar). During the measurement, a diamond indenter with the shape of a base rhombic pyramid having apex angles of 172.5° on the long side and 130° on the short side was pressed into the sample for 30 s (15s for indentation and 15s for dwell time). The long diagonal of the impression was measured for calculation. At each time point (t0, t1, and t2), five measurements of microhardness per specimen were carried out and the mean value of these five measurements was calculated. Three dimensional profilometric measurements were performed (FRT MicroProf 100, Fries Research & Technology) to determine substance loss and alterations in roughness, using the corresponding software FRT Mark III. An H0 sensor (300 μm) was used and the parameters were set at 2000 hertz measuring rate, 400 data points, 200 lines, 2506 μm/s speed. To assess the substance loss, three level measurements were carried out across the covered reference area and the simulation area of each specimen at a distance of 0.25 mm at each time point. The mean value of the three measurements was taken to represent the loss of substance. When examining the surface roughness, only the simulation area was considered. Three parameters concerning the roughness were determined. First, the arithmetic mean roughness value, Ra, represents the mean deviation of the roughness profile from the centreline. Second, the mean roughness depth, Rz, represents the sum of the highest profile peak and the lowest profile peak within a measurement section after averaging the results of five individual measurement sections. And third, the maximum height of the roughness profile, Rt, represents the distance between the highest and lowest measuring points within a measurement section.

Statistical analysis

QQ-plots were used to check the distribution of the data. For descriptive analysis, mean values and standard deviations were computed. For graphical illustration, box plots were used. In order to be able to evaluate the occurring differences and their statistical significance in the behaviour of the tested materials, the measurement results were subjected to a single-factor (one-way) analysis of variance. For comparisons of different time points within groups where homogenous variances were found, a linear mixed model was applied. For all subsequent pairwise comparisons, the method of Scheffé was used to correct for multiple testing. The significance level was

TABLE 2 Mean values and standard deviations of Knoop microhardness (KHN), surface roughness parameters (Ra, Rt, Rz), and substance loss d at baseline, at 12 months, and at 36 months.

Parameter	Material	Baseline mean ± SD	12 months mean ± SD	36 months mean ± SD
KHN (kgf/mm^2)	ceram.x universal	86.91 ± 6.55	84.15 ± 3.22	82.10 ± 1.98
	VITABLOCS Mark II	551.79 ± 18.23	367.04 ± 25.97	336.60 ± 21.33
	CERASMART	64.81 ± 1.55	64.28 ± 1.69	61.86 ± 0.80
	VITA ENAMIC	231.24 ± 13.31	233.98 ± 10.73	216.70 ± 19.92
	Lava Ultimate	90.43 ± 1.41	90.41 ± 1.21	85.83 ± 1.05
Ra (μm)	ceram.x universal	0.07 ± 0.01	0.19 ± 0.04	0.35 ± 0.09
	VITABLOCS Mark II	0.03 ± 0.01	0.17 ± 0.01	0.48 ± 0.03
	CERASMART	0.03 ± 0.01	0.09 ± 0.03	0.21 ± 0.08
	VITA ENAMIC	0.03 ± 0.00	0.11 ± 0.02	0.19 ± 0.03
	Lava Ultimate	0.03 ± 0.00	0.12 ± 0.02	0.14 ± 0.02
Rt (μm)	ceram.x universal	6.06 ± 5.34	6.29 ± 3.65	3.95 ± 0.91
	VITABLOCS Mark II	12.34 ± 6.13	20.69 ± 5.53	11.00 ± 1.65
	CERASMART	2.95 ± 3.92	1.87 ± 0.92	1.98 ± 0.68
	VITA ENAMIC	2. 23 ± 1.24	3.37 ± 1.16	3.06 ± 0.63
	Lava Ultimate	1.59 ± 2.81	4.10 ± 6.70	1.86 ± 0.57
Rz (μm)	ceram.x universal	1.82 ± 1.52	2.96 ± 1.27	6.66 ± 2.63
	VITABLOCS Mark II	4.81 ± 3.35	13.45 ± 2.69	14.74 ± 2.72
	CERASMART	0.99 ± 0.83	1.31 ± 0.43	2.55 ± 0.99
	VITA ENAMIC	1.13 ± 0.31	2.13 ± 0.39	4.71 ± 1.13
	Lava Ultimate	0.62 ± 0.54	1.87 ± 1.33	3.28 ± 2.60
d (μm)	ceram.x universal	0.15 ± 0.15	−0.68 ± 0.28	−1.84 ± 0.42
	VITABLOCS Mark II	−0.26 ± 0.19	−0.31 ± 0.27	−0.35 ± 0.33
	CERASMART	−0.11 ± 0.21	−0.81 ± 0.41	−1.77 ± 0.69
	VITA ENAMIC	−0.18 ± 0.15	−0.17 ± 0.14	−0.27 ± 0.15
	Lava Ultimate	−0.10 ± 0.18	−0.49 ± 0.23	−1.56 ± 0.59

set at $p < 0.05$. The statistical analysis was performed using STATA 14.2 software (StataCorp).

RESULTS

At baseline, the values for microhardness, substance loss, and surface loss differed between the evaluated materials. Therefore, the differences to the baseline values were computed for each material, each tested parameter, and each time period, in order to examine changes over time.

Knoop microhardness

Mean values and standard deviations of the Knoop microhardness are given in Table 2. The differences from baseline values for each material and tested time period are presented as box plots in Figure 1.

At the baseline measurement t0, the VITABLOCS Mark II ceramic was the hardest material with a mean KHN of 551.79 ± 18.23, followed by VITA ENAMIC, Lava Ultimate, and ceram.x universal (Table 2). However, the difference between ceram.x universal and Lava Ultimate was not statistically significant ($p = 0.417$). CERASMART showed the lowest baseline hardness of the tested materials at a mean KHN of 64.81 ± 1.55. Over the course of the investigation, all materials showed a loss of microhardness. VITABLOCS Mark II showed a substantial and statistically significant decrease in microhardness after simulation of 1 ($p < 0.001$) and 3 years ($p < 0.001$) compared to baseline (Figure 1), with a loss of microhardness of up to 39%. Ceram.x universal, CERASMART, VITA ENAMIC, and Lava Ultimate each exhibited a small, yet statistically significant change in microhardness only after 3 years ($p < 0.05$). Microhardness differed statistically significantly between 1 year and 3 years for all materials except ceram.x universal. After 1 year, the decrease in microhardness was statistically significantly

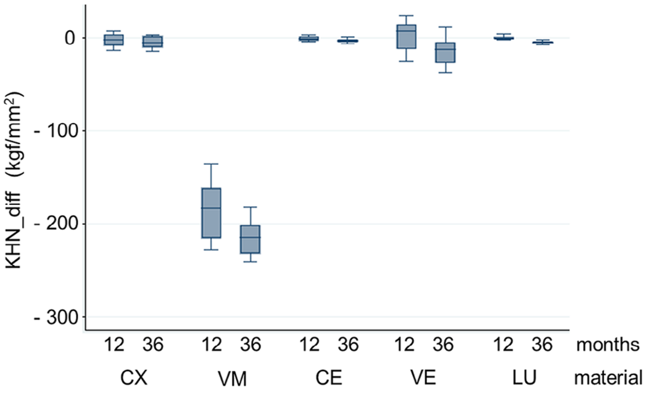

FIGURE 1 Box plots showing the differences from baseline values of the microhardness (KHN) for all tested materials at 12 months and at 36 months.CE, ceram.x universal; CERASMART; CX, Lava Ultimate LU, VE, VITA ENAMIC; VITABLOCS Mark II; VM.

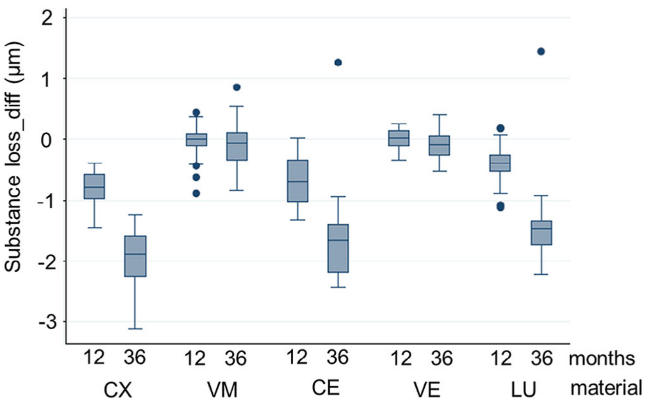

FIGURE 2 Box plots showing the differences from baseline in the substance loss for all tested materials at 12 months and at 36 months (dots denote outliers).CE, ceram.x universal; CERASMART; CX, Lava Ultimate LU, VE, VITA ENAMIC; VITABLOCS Mark II; VM.

different between all materials except between ceram.x universal and Lava Ultimate ($p = 0.267$), as well as between VITABLOCS Mark II and VITA ENAMIC ($p = 0.066$). After 3 years, there was a statistically significant difference in the decrease in microhardness between the tested materials ($p < 0.001$); however, this was no longer visible after correcting for multiple testing.

Substance loss

Mean values and standard deviations of substance loss are given in Table 2. The differences from baseline values for each material and tested time period are presented as box plots in Figure 2.

During the observation period of 3 years, ceram.x universal showed the highest substance loss ($-1.84\ \mu m \pm 0.42$), followed by CERASMART ($-1.77\ \mu m \pm 0.69$) and Lava Ultimate ($-1.56\ \mu m \pm 0.59$). For these three materials, substance loss was detected after both 1 and 3 years. Between ceram.x universal and CERASMART, the difference was not statistically significant after 1 ($p = 0.917$) and 3 years ($p = 0.892$). However, a statistically significant substance loss could be detected between ceram.x universal and Lava Ultimate after 1 year ($p = 0.043$) but not after 3 years ($p = 0.214$). For VITA ENAMIC, a small yet statistically significant substance loss ($-0.27\ \mu m \pm 0.15$) was observed only after the 3-year period ($p = 0.007$). VITABLOCS Mark II showed no statistically significant substance loss over the whole observation period of 3 years ($p = 0.320$).

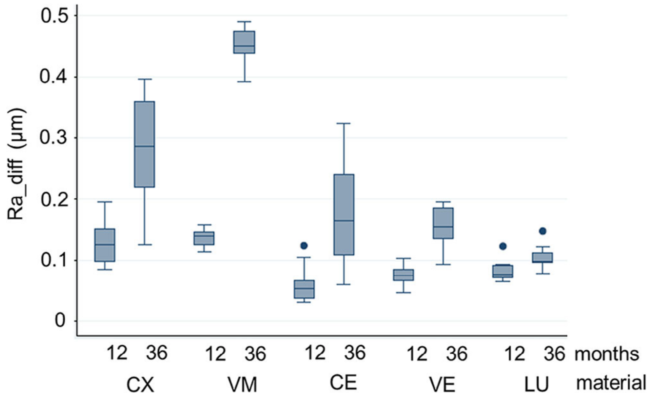

FIGURE 3 Box plots showing the differences from baseline in the average roughness (Ra) values for all tested materials at 12 months and at 36 months (dots denote outliers).CE, ceram.x universal; CERASMART; CX, Lava Ultimate LU, VE, VITA ENAMIC; VITABLOCS Mark II; VM.

Surface roughness

Mean values and standard deviations of surface roughness parameters Ra, Rt, and Rz are given in Table 2. The differences to baseline for each material and tested time period are presented as box plots in Figure 3 for Ra, Figure 4 for Rt, and Figure 5 for Rz.

Ceram.x universal was determined as the material with the highest mean roughness (Ra) at baseline ($0.07\ \mu m \pm 0.01$), which differed statistically significantly from all other tested materials ($p < 0.001$, Table 2). Between the other materials, no statistically significant difference in mean roughness could be observed ($p > 0.05$) at baseline. All materials exhibited an increase in the arithmetic values r Ra both after 1 and 3 years (Figure 3). This increase was highest for the VITABLOCS Mark II ceramic ($0.48\ \mu m \pm 0.03$) and lowest for Lava Ultimate ($0.14\ \mu m \pm 0.02$). VITABLOCS Mark II showed the highest value of the maximum roughness depth (Rt) at baseline (Table 2), and this differed statistically significantly from all other tested materials ($p < 0.001$). Between

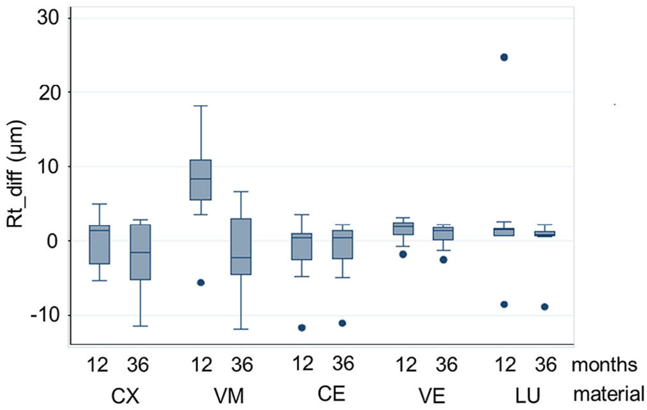

FIGURE 4 Box plots showing the differences from baseline in the maximum roughness depth (Rt) for all tested materials at 12 months and at 36 months (dots represent outliers). CX, ceram.x universal; VM, VITABLOCS Mark II; CE, CERASMART; VE, VITA ENAMIC; LU, Lava Ultimate.

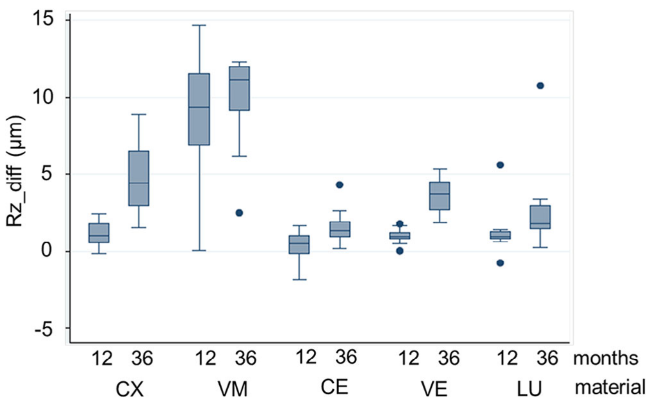

FIGURE 5 Box plots showing the differences from baseline values of the mean roughness depth (Rz) for all tested materials at 12 months and at 36 months (dots represent outliers). CX, ceram.x universal; VM, VITABLOCS Mark II; CE, CERASMART; VE, VITA ENAMIC; LU, Lava Ultimate.

the other materials, no statistically significant baseline differences were observed for Rt ($p > 0.05$). After 1 year, only VITABLOCS Mark II ($p < 0.001$) and VITA ENAMIC ($p < 0.001$) showed a statistically significant increase of their maximum roughness depth (Figure 4) with a mean increase in Rt of 20.69 μm ± 5.53 for VITABLOCS Mark II and 4.10 μm ± 6.70 for VITA ENAMIC. A statistically significant difference in Rt between 1 year and 3 years could only be observed for VITABLOCS Mark II.

For the mean roughness depth (Rz), VITABLOCS Mark II showed the highest value at baseline (4.81 μm ± 3.35, Table 2), which differed statistically significantly from all other tested materials ($p < 0.001$). Between the other materials, no statistically significant differences could be observed for Rz ($p > 0.05$). Lava Ultimate showed the lowest mean roughness depth at baseline (0.62 μm ± 0.54). Only VITABLOCS Mark II and VITA ENAMIC showed a statistically significant change in Rz after 1 year (both $p < 0.001$), with a mean increase of Rz of 13.45 μm ± 2.69 for VITABLOCS Mark II and 1.87 μm ± 1.33 for VITA ENAMIC. Between 1 and 3 years of observation, the increase in Rz was statistically significant for ceram.x universal, CERASMART, and VITA ENAMIC ($p < 0.001$). Over the entire observation period of 3 years, all tested materials showed a statistically significant increase in Rz ($p < 0.001$), the highest being 14.75 μm ± 2.72 for VITABLOCS Mark II and the lowest being 2.55 μm ± 0.99 for CERASMART.

DISCUSSION

In the present study, three CAD/CAM resin-matrix ceramics were evaluated and compared to a feldspar ceramic and a resin-based composite regarding surface alterations after simulated erosive and abrasive influences. Considering the results presented above, the first hypothesis set at the beginning of this study can be rejected, as the resin-matrix ceramics outperformed the feldspar ceramic in terms of microhardness and surface roughness. However, the second hypothesis can be partially confirmed, as the PICN evaluated in this study showed significantly smaller substance loss compared to the resin-based ceramics.

Although there are several studies concerning the resistance of CAD/CAM materials to abrasive [16–19] or erosive [20–23] challenges, there is, to the best of our knowledge, only one other study evaluating the effects of both abrasive and erosive influences on these materials [24]. Picolo et al. [24] simulated 3 years of aggressive erosive challenges caused by gastroesophageal reflux events, in combination with abrasion by tooth brushing. They reported a decrease in microhardness and an increase in surface roughness and biofilm adhesion after the simulated wear. The revealed effects were more severe for glass ceramics and PICNs than for resin-based ceramics. However, the study design included a highly erosive medium of 0.7% hydrochloric acid (pH = 1.2 ± 0.2) with an exposure time of 91 h per simulated year. As frequent exposure to gastric acid presents a strong erosive challenge, the results of Picolo et al. [24]—while important for a specific group of patients—are thus not comparable to those of the present study, since the daily erosive influences on the average patient are likely to be far lower. To our knowledge, no other study exists to date investigating daily erosive and abrasive challenges by foods, beverages, and tooth brushing.

A wide variety of study protocols for the simulation of daily erosion or abrasion events are described in the literature, varying greatly in the number of brush strokes per cycle, number of cycles, or duration of exposure [14]. The chosen brushing time representing twice daily brushing for 2 min and the use of

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a 200 g weight corresponds to the average daily brushing time and physiological force used and is recommended for studies observing abrasion of tooth substances [14]. Regarding the abrasive medium used, the mixing ratio of 3:1 (saliva and toothpaste) is often used in other in vitro studies [26, 27]. In the present study, human saliva was used, as saliva substitutes cannot mimic all properties of natural saliva; for example, they miss typical proteins and ions which can influence the abrasiveness [28, 29]. However, it must be considered that human saliva is subject to individual variations (e.g., in pH, viscosity, and enzyme activity), which can either act protectively by promoting pellicle formation and lubrication against abrasion or increase erosive effects through proteolytic activity [30]. As an erosive medium for simulation purposes, many authors have described the use of citric acid [27, 31, 32]. A concentration of 0.5% citric acid corresponds to common soft drinks and acidic drinks with a pH of approximately 2.5 [31, 33]. Various authors assume a daily contact time of the teeth with erosive media between 5 and 12 min [27, 31, 34]. However, there are major differences depending on the individual lifestyle and behaviour. Moreover, the lack of regulating biological factors such as salivary flow, tooth structure, anatomy, and occlusion as well as the effect of soft tissue represent a disadvantage compared to in vivo studies. For this reason, the review of Wiegand and Attin [14] recommended a study design in which an erosive cycle does not exceed a period of 2 min. In this study, a brushing time of 2×2 min per day was considered adequate.

In terms of microhardness, the PICN ranked between conventional ceramic and resin-based composite materials. These findings are in accordance with previous studies [16, 17, 35]. The microhardness correlates with the content of filler particles of the materials [36]. Only VITABLOCS Mark II revealed a substantial and statistically significant decrease in microhardness after both 1 and 3 years, whereas the other materials only exhibited a statistically significant decrease after 3 years. It has previously been discussed that the glass phase of feldspar ceramics is more susceptible to erosive attacks than the polymer matrix in composites and resin-matrix ceramics [20, 24]. In glass ceramic materials, the acidic solution is suspected to weaken the silicate framework allowing the erosive medium to penetrate deeper into the vitreous matrix and to disturb its integrity in a larger area [20, 24]. In contrast, ceramics without a glass phase, like zirconia, do not exhibit the same susceptibility [37]. In the case of resin-based composites, the decrease in microhardness is presumably caused by the hydrolysis of the ester compounds of the polymer chains, combined with increased water absorption [20, 32]. It has also been described by others [20, 32] that the loss of microhardness is dependent on the exposure time. Backer et al. [20] identified no changes in microhardness of Lava Ultimate after exposure with artificial gastric acid (pH = 1.2) after 24 h; however, Yu et al. [32] showed a decrease in microhardness after 4 weeks in citric acid (pH = 2.29).

Despite an identical polishing protocol, ceram.x universal had the highest roughness at baseline among all materials concerning the arithmetic mean roughness (Ra). This might be due to the integration of prepolymers and the larger filler size compared to the resin-based ceramics Lava Ultimate and CERASMART, as well as a lower degree of conversion [38], which might result in a weaker incorporation of the fillers in the matrix overall. All tested materials showed a statistically significant increase in Ra after both 1 and 3 years compared to baseline. Lava Ultimate revealed the lowest roughening, as expressed in the Ra value, among all tested materials, which might be attributed to the high filler content in combination with the small filler size. However, the resin-matrix ceramics CERASMART, VITA ENAMIC, and Lava Ultimate did not exert a statistically significant difference in Ra compared to ceram.x universal after both 1 and 3 years.

Looking at the maximum roughness depth (Rt), VITABLOCS Mark II had the greatest Rt value at baseline. The reason for this could be deep persistent scratches on the surface caused by the sawing process that could not be completely removed by polishing due to the hardness of the material (Figure 6). Several authors have described how resin-based composites, ceramics, and resin-matrix ceramics experience roughening by acid attack alone [20, 31, 37, 39]. One explanation for the better performance of the resin-matrix ceramics compared to the feldspar ceramic in terms of surface Ra and Rz could be the combination of simulated erosion and abrasion. This could be due to the above-mentioned lower susceptibility of the polymer matrix to acids. In addition, inorganic fillers are observed to dissolve out of the polymer matrix due to erosive influences [20]. On the other hand, abrasion-induced polishing phenomena, as described for CERASMART and Lava Ultimate [19], could reduce the resulting surface roughness in the softer resin-matrix ceramics. Furthermore, in the specific case of VITA ENAMIC as a polymer-infiltrated ceramic network, Yu et al. [32] assumed that the polymer matrix protects the glass phase of the feldspar ceramic from erosive attack and thus from further roughening.

Looking at the results of this study with regard to substance loss, it is noticeable that the resin-based ceramics (CERASMART, Lava Ultimate) behave more like resin-based composites with regard to their abrasion resistance. In contrast, the PICN VITA ENAMIC behaves more like a feldspar ceramic. Although some studies on the abrasion behaviour of resin-matrix ceramics are already available, their results are difficult to compare due to the difference in study designs [17, 18]. Lawson et al. [17] showed that the loss of substance within the resin-matrix ceramics was not significantly different from each other and comparable to human enamel. Another study observed higher substance loss for Lava

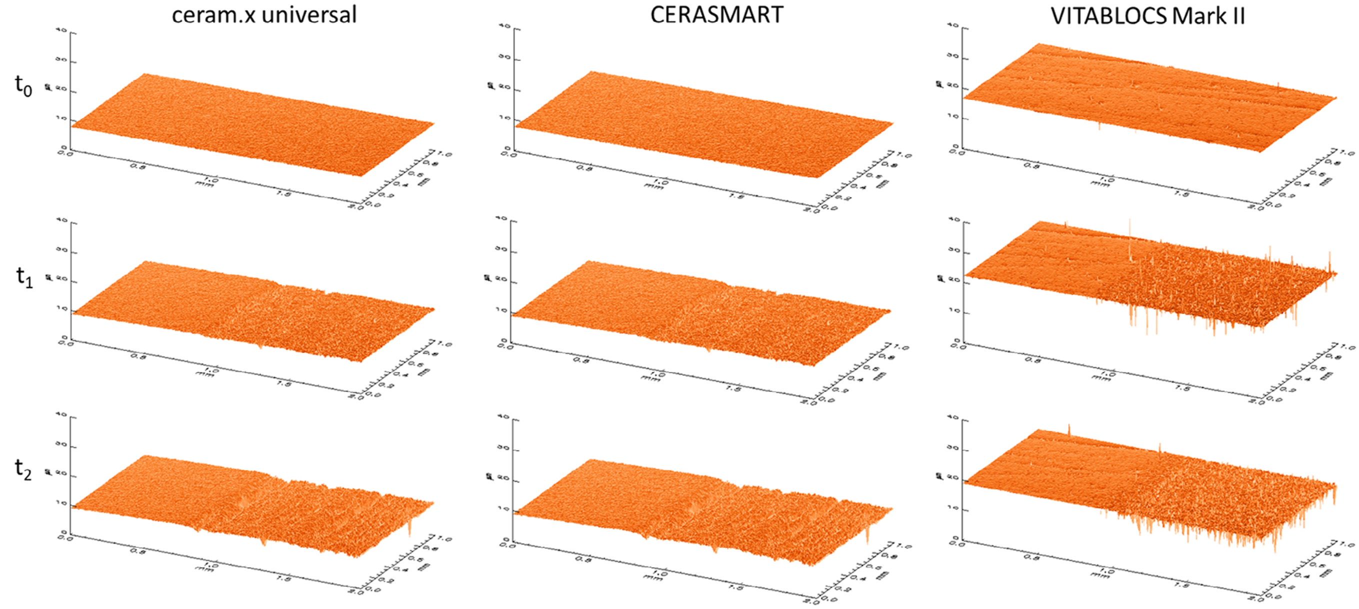

FIGURE 6 Exemplary images of 3D profilometric data of materials ceram.x universal, CERASMART and VITABLOCS Mark II at baseline (t0), at 12 months (t1), and at 36 months (t2).

Ultimate and CERASMART than for VITA ENAMIC, while VITA ENAMIC behaved similar to the ceramic materials IPS Empress CAD and IPS e.max CAD [18]. With the exception of ceram.x universal, the loss of substance is related to the hardness of the material in this study. It is possible that the soft polymer matrix is simply brushed away after the loss of the inorganic fillers. The lower surface roughness suggests that this happens very evenly. One reason for the higher abrasion resistance of the resin-based ceramics compared to ceram.x universal, despite lower hardness in the case of CERASMART and equivalent hardness in the case of Lava Ultimate, could be the standardized industrial manufacturing of CAD/CAM blocks with improved mechanical properties.

The in vitro setup of this study simplifies the complex oral environment, omitting clinically relevant factors such as salivary flow, microbial activity, and temperature variations that can influence material behaviour. The study design did not include a cyclic alternation between abrasive and erosive procedures, which is characteristic of the oral environment. Future research should aim to address these constraints to provide a more nuanced understanding of CAD/CAM resin-matrix ceramics performance in practical dental applications. Another limitation might be the non-flat specimen surfaces resulting mostly from erosion that may introduce some inconsistencies to the hardness measurements, although the determination of Knoop hardness has been commonly used for evaluation of eroded dental hard tissues or restorative materials for many years [40].

This in vitro study has provided insight into the durability and performance of CAD/CAM resin-matrix ceramics in the context of erosion and abrasion. Within the limitations of the study discussed above, it can be concluded that both erosive and abrasive influences, as they can be expected in the oral cavity, have a considerable effect on CAD/CAM resin-matrix ceramics after a simulated period of 3 years. The observation that resin-matrix ceramics exhibit less roughening than feldspar ceramics could impact the long-term success of restorations by preventing plaque accumulation. Moreover, the differences in abrasion resistance among the tested resin-matrix ceramics highlight the need for further research to identify the most suitable materials for specific clinical indications. In this study, VITA ENAMIC seems to represent a compromise between resin-based composites and glass ceramics combining the positive properties of both material groups. Future research should strive to mimic clinical conditions more closely and to further translate these in vitro findings into in vivo clinical trials, with the objective of guiding clinicians in making informed material choices.

AUTHOR CONTRIBUTIONS

Conceptualization: Olga Polydorou; **Methodology**: Olga Polydorou; **Formal analysis**: Kirstin Vach; **Investigation**: Michael Swoboda; Mathias Spraul; **Validation**: Sebastian Patzelt; Cosima Reidelbach; **Writing—original draft preparation**: Cosima Reidelbach; **Writing—review and editing**: Olga Polydorou; Sebastian Patzelt; Mathias Spraul; Kirstin Vach; Michael Swoboda; Elmar Hellwig; **Supervision**: Olga Polydorou; Elmar Hellwig; **Project administration**: Olga Polydorou.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

ORCID

Cosima Reidelbach https://orcid.org/0000-0001-9207-2674
Michael Swoboda https://orcid.org/0009-0009-5320-481X
Mathias Spraul https://orcid.org/0000-0002-9396-791X
Kirstin Vach https://orcid.org/0000-0001-9278-2203
Sebastian B. M. Patzelt https://orcid.org/0000-0002-1434-5398
Elmar Hellwig https://orcid.org/0000-0003-1880-5256
Olga Polydorou https://orcid.org/0000-0003-1428-0843

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