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Solubility of Dental Ceramics in Electric Fields

Stephan John [1], Svenja Rink [1,*], Leandra Weidemann [1], Katrin Huesker [2], Wilhelm Niedermeier [1]

1. Department of Prosthetic Dentistry, School of Dental and Oral Medicine, University of Cologne, Cologne, Germany; E-Mails: stephan.john@uk-koeln.de; svenja.rink@uk-koeln.de; leandra.weidemann@uk-koeln.de; wilh.niedermeier@uni-koeln.de
2. Department of Immuno-Toxicology, Institute for Medical Diagnostics (IMD) Berlin, Nicolaistr. 22, D-12247 Berlin, Germany; E-Mail: K.Huesker@imd-berlin.de

* **Correspondence:** Svenja Rink; E-Mail: svenja.rink@uk-koeln.de

Academic Editors: Mirva Eriksson and Wei Xia

Special Issue: Advanced Ceramics and Metals in Dental Medicine

Recent Progress in Materials
2022, volume 4, issue 2
doi:10.21926/rpm.2202012

Received: April 21, 2022
Accepted: June 08, 2022
Published: June 15, 2022

Abstract

Combining dental ceramics with other prosthetic metallic restorations might release metal ions, thus affecting the oral tissues of the patients. In this study, we evaluated the electrochemical solubility of various dental ceramics in a galvanic experimental setup in vitro. Smooth and rough feldspathic and zirconium dioxide ceramics (at pH 5.5 and pH 3.0) were exposed to an electric field. Calcium, barium, and zirconium were selected as parameters to determine the solubility of both types of ceramic materials. Among all test groups, feldspathic ceramics were more soluble than zirconium dioxide ceramics at low pH. The results indicated that the solubility of zirconium dioxide was not significantly affected by the presence of an electric field, although the solubility was higher when the pH was relatively lower. The feldspathic material had a higher sensitivity to acids and electrogalvanic processes. We found that the galvanic process increases the solubility of feldspathic ceramics. The surface quality is important in an acidic medium, especially for feldspathic ceramics. Zirconium dioxide ceramics are more resistant to an acidic medium and exposure to a clinically relevant electric field.

Keywords

Dental materials; feldspathic ceramics; zirconium dioxide; ceramic solubility; corrosion; oral galvanism

1. Introduction

Dental ceramics is the preferred material for dentistry. They are highly durable, biocompatible, and naturally aesthetic, which makes them the preferred dental materials. They can be used to manufacture dentures, as an additive in dental filling materials, as a component of orthodontic appliances, and as surgical implants. Ceramics has several favorable properties, such as high-temperature resistance, wear resistance, chemical stability, and aesthetics; it also has some unfavorable properties, including low fracture toughness or brittleness. The advantageous physical properties of metals include high fracture toughness, and the disadvantages include corrosion and fatigue. Corrosive electrochemical processes that affect different alloys in the presence of saliva lead to the dissociation of metal ions resulting in various biological effects [1]. Metallic materials in the oral cavity might lead to oral galvanism and cause mucosal sensitivities [2, 3], battery taste, xerostomia [4], leukoplakia, and apoptosis in oral precancer cells [5-7]. Non-metallic materials seem to be a better alternative. However, no dental material can be recommended without any hesitation [8]. All dental cast alloys release metal ions in the oral environment that can interact with the oral tissues of the patient. In this study, we investigated whether an electric field generated by different dental alloys can influence the solubility of dental ceramics. We used two different materials, including the feldspathic ceramic material Omega 900® and the zirconium dioxide ceramic material Cercon® ht. We tested materials with smooth and rough surfaces. Rough surfaces are often caused by the dentist. When the tooth crown is adjusted, and the static and dynamic occlusion is ground in with grinding tools, rough surfaces are formed on the dental ceramic. Besides iatrogenic causes, teeth grinding and bruxism also produce rough surfaces on the dental ceramic.

2. Materials and Methods

2.1 Specimens

The feldspathic ceramic material Omega 900®, tooth color A2 (VITA Zahnfabrik Rauter GmbH, Bad Säckingen, Germany), and the zirconium dioxide ceramic material Cercon® ht (Dentsply Sirona GmbH, Bensheim, Germany) with glaze-fired and roughened surfaces were examined. The composition and ingredients of the materials are shown in Table 1, Table 2, Table 3, and Table 4.

Table 1 The information on the ingredients of feldspathic ceramic Omega 900® [9].

Ingredient	**% by mass**
Silicon dioxide SiO_2	57–61
Magnesium oxide MgO	0,3–0,8
Sodium oxide Na_2O	5–6
Iron oxide Fe_2O_3	<0,3

Titanium dioxide TiO_2	<0,3
Calcium oxide CaO	1–1,5
Potassium oxide K_2O	9–10
Aluminum oxide Al_2O_3	15–16,5
Barium oxide BaO	3–4
Zirconium dioxide ZrO_2	1–1,5
Tin oxide SnO_2	1–1,5
Boron trioxide B_2O_3	0,3–0,8
Lithium oxide Li_2O	<0,3

Table 2 The information on the ingredients of zirconium dioxide ceramic Cercon® ht [10].

Ingredient	**% by mass**
Zirconium dioxide ZrO_2	>91
Yttrium oxide Y2O3	5
Hafnium oxide HfO2	<3
Aluminum oxide, Silicon oxide	<1

Table 3 The information on the ingredients of Akzent® Glaze [9].

Ingredient	**% by mass**
Silicon dioxide SiO_2	56–58
Sodium oxide Na_2O	4,5–6
Potassium oxide K_2O	3–4
Magnesium oxide MgO	<1
Calcium oxide CaO	4–5
Barium oxide BaO	1,5–2
Boron trioxide B_2O_3	9–10
Aluminum oxide Al_2O_3	6–7
Iron oxide Fe_2O_3	<1
Titanium dioxide TiO_2	0,5–1
Phosphorus pentoxide P_2O_5	<0,5
Zirconium dioxide ZrO_2	0,5–1
Tin oxide SnO_2	4–5

Table 4 The information on the ingredients of Cercon® Glaze [10].

Ingredient	**% by mass**
Silicon dioxide SiO_2	50–60
Aluminum oxide Al_2O_3	11–13
Potassium oxide K_2O	1–2
Sodium oxide Na_2O	6–8
Lithium oxide Li_2O	2–3
Barium oxide BaO	11–13
Boron trioxide B_2O_3	7–9

Calcium oxide CaO	0,5–1
Titanium dioxide TiO_2	1–2
Cerium oxide CeO_2	contain
Antimony trioxide Sb_2O_3	contain
Fluorine F	contain

All 40 feldspathic ceramic test specimens were processed as specified by the manufacturer and molded using a silicone template (1 mm thick), with an outer diameter of 11 mm and an inner diameter of 4 mm. To produce the feldspathic ceramic test specimens, the metallic washer was molded using the Provil Novo "Putty soft regular set" silicone molding compound, and a mold was obtained with which the ceramic compound was mixed, following the manufacturer's instructions. The raw mass formed was then placed on firing cotton and fired in a kiln (Vita Vacumat 300) following the manufacturer's instructions. Also, the 40 zirconium dioxide ceramic test specimens of the same size were scanned, milled, and sintered by the CAD/CAM process. Subsequently, half of the zirconium dioxide ceramic test specimens were glaze-fired using Cercon® Glaze (Dentsply Sirona GmbH, Bensheim, Germany), and half of the feldspathic ceramic specimens were glaze-fired using Vita Akzent® Glaze, to create a smooth surface. To produce a uniformly rough surface, the other twenty specimens of the two different types of ceramics were blasted with aluminum oxide (with a grain size of 110 µm). The total surface of the zirconium dioxide ceramic specimens and the feldspathic ceramic specimens were 1.85 cm² and 1.4 cm², respectively (Figure 1 and Figure 2). To dissolve free ions on the surface, all specimens were placed in ortho-phosphoric acid (45–64%) for one hour and rinsed with aqua bidest. The specimens were kept in aqua bidest for 24 h and then stored in a dry environment.

Figure 1 A zirconium dioxide ceramic test specimen with a rough surface.

Figure 2 A feldspathic ceramic test specimen with a rough surface.

2.2 Preliminary Tests

In preliminary tests, the materials were stored for 72 h in sodium chloride (NaCl, 0.9%) solution. Subsequently, 20 mL of the sample solutions were taken to conduct a multi-element analysis (MEA). For the analysis, calcium and barium acted as the ingredients and relevant parameters to determine the solubility of feldspathic ceramic (Figure 3). For zirconium dioxide ceramic, zirconium was used as the parameter for the solubility test. The analysis was performed by inductively coupled plasma mass spectroscopy (ICP-MS).

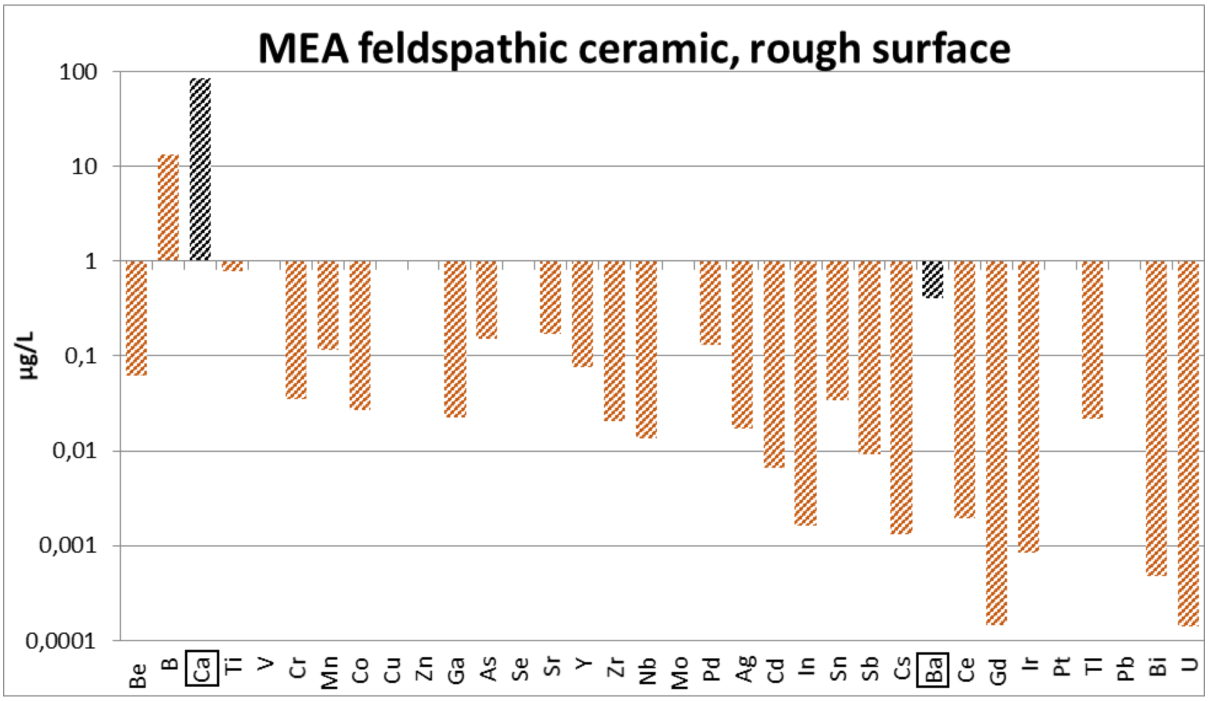

Figure 3 Logarithmic representation of the results of the multi-element analysis (ICP-MS) to determine the solubility of the components of a feldspathic ceramic material (Vita Omega 900®); only elements with measurable concentrations are shown. The original ingredients, i.e., calcium and barium, showed very high solubility and are presented as gray bars. Other elements might also be produced by the manufacturing tools and processes.

2.3 Test Procedure

To simulate physiologic conditions, 160 mL of 0.9% saline (Braun Co., Melsungen, Germany) was used as the electrolyte solution (pH 5.5). In the other series, 160 mL of a 0.9% saline solution was acidified to pH 3.0 using orthophosphoric acid. The electric field was generated by a microprocessor-controlled self-adjusting DC power supply that could be regulated in 0.1 V steps within a range of 0–30 volts. Two fine gold plates (30 × 50 × 1 mm) (Fine Gold 999; Degudent Dentsply, Hanau, Germany) were used as electrodes. Each test specimen was positioned using a nylon thread between the electrode plates. They were in contact with the electrodes on both sides and placed in the electrolyte solution (Figure 4). Another test specimen of the same material with identical surface properties was placed in the same electrolyte solution in another jar without an electric field. The test was conducted for 72 h at a voltage of 0.3 V (field strength 27 V/m). To minimize polarization of the experimental setup and based on previous studies, the switching frequency used was 1 Hz [11]. The complete experimental setup was done on a sterile bench (Figure 5). For all experiments, the test conditions (temperature, humidity, air pressure, etc.) were identical. Plastic tweezers were used to precisely position the test specimens between the electrode plates (double-sided contact). After 72 h, the electrolyte solution was stirred, and 2 mL of the sample was pipetted. To obtain data on solubility (dependent on the surface), the measured ion concentrations were converted using the surface area of the samples. Simultaneously, each series of measurements was completed by taking positive and negative controls. Each sample was measured, and the concentration was calculated by the Qtegra software (Thermo Fisher) using a five-point standard curve (multi-element standard by ESI Elemental Service & Instruments GmbH, Mainz, Germany). To validate the results statistically, each test procedure was repeated three times under the same conditions. At the beginning and the end of each test, the pH of the electrolyte solution was determined using pH indicator strips (non-bleeding Neutralit pH 0.0–14.0, Merck, Darmstadt, Germany), and the temperature of the electrolyte was measured using a glass bulb temperature sensor.

Figure 4 A zirconium dioxide ceramic test specimen with double-sided contact with the gold sheet electrodes in the electrolyte.

Figure 5 The complete experimental setup on a sterile bench.

2.4 Statistical analysis

Each experiment was repeated three times under identical conditions, and each sample was measured three times. All data were checked for plausibility and presented as the mean value (MV) ±standard deviation (SD). The data were evaluated statistically by performing ANOVA for multiple comparisons with a significance threshold at $\alpha = 0.05$ and corrected by the post-hoc method, according to Tukey.

3. Results

3.1 Feldspathic Ceramics

The solubility values of calcium and barium for the glaze firing feldspathic dental ceramic in (two-sided) contact with the electrodes vs. the controls, i.e., without an electric field, were not significantly different (Table 5). However, the solubility of barium ions was significantly higher at pH 3.0 than at pH 5.5 in an electric field ($p < 0.05$).

Table 5 The measurements of the calcium and barium-concentration for feldspathic ceramics, glaze-fired, with or without an electric field. The mean values and standard deviations are shown. Statistically significant differences between pH 3.0 and pH 5.5 (two-sample t-test) are denoted by '*': noticeable increase ($p < 0.05$), '**': significant increase ($p < 0.01$), and '***': highly significant increase ($p < 0.001$).

pH value	Calcium-concentration				Barium-concentration			
	pH 3.0		pH 5.5		pH 3.0		pH 5.5	
Field strength	MV µg/cm²	SD	MV µg/cm²	SD	MV µg/cm²	SD	MV µg/cm²	SD
0 V/m	10,42	9,43	8,60	4,36	0,07	0,06	0,00	0,00
27 V/m	14,29*	5,44	11,82	1,63	0,11***	0,02	0,01	0,007

The release of calcium and barium for feldspathic dental ceramic with roughened surfaces in an electric field vs. the control is shown in Table 6. The solubility of calcium and barium of all test samples (pH 3.0 and 5.5) in an electric field was significantly higher than the solubility in the controls (without an electric field).

Table 6 The measurements of the calcium and barium-concentration for feldspathic ceramics, roughened, with or without an electric field. The mean values and standard deviations are shown. Statistically significant differences between pH 3.0 and pH 5.5 (two-sample t-test) are denoted by '*': noticeable increase ($p < 0.05$), '**': significant increase ($p < 0.01$), and '***': highly significant increase ($p < 0.001$).

pH value	Calcium-concentration				Barium-concentration			
	pH 3.0		pH 5.5		pH 3.0		pH 5.5	
Field strength	MV µg/cm^2	SD	MV µg/cm^2	SD	MV µg/cm^2	SD	MV µg/cm^2	SD
0 V/m	69,67**	7,1	9,56	2,36	3,30***	0,25	0,05	0,02
27 V/m	299,45**	36,28	114,08	14,54	21,48*	5,77	10,76	0,96

3.2 Zirconium Dioxide Ceramic

At pH 5.5, glaze-fired zirconium dioxide ceramic material showed no significant differences in the solubility of zirconium ions in an electric field compared to the controls. At pH 3.0, zirconium dioxide ceramics showed a significant increase in the solubility of zirconium ions compared to the controls (without an electric field). For glaze-fired and roughened zirconium dioxide ceramics, the solubility of zirconium at pH 3.0 was significantly higher than that at pH 5.5, irrespective of the presence of an electric field (Table 7).

Table 7 The measurements of the zirconium ion-concentration for zirconium dioxide, glaze-fired and roughened, with and without an electric field. The mean values and standard deviations are shown. Statistically significant differences between pH 3.0 and pH 5.5 (two-sample t-test) are denoted by '***': highly significant increase ($p < 0.001$).

pH value	glaze fired				roughened			
	pH 3.0		pH 5.5		pH 3.0		pH 5.5	
Field strength	MV µg/cm^2	SD	MV µg/cm^2	SD	MV µg/cm^2	SD	MV µg/cm^2	SD
0 V/m	0,26***	0,01	0,003	0,0001	0,25***	0,02	0,001	0,0003
27 V/m	0,31***	0,009	0,002	0,001	0,29***	0,05	0,001	0,0003

3.3 Comparison of All Materials

For all test groups, feldspathic dental ceramics was more soluble than the zirconium dioxide material at lower pH. The results showed that the chemical solubility of the zirconium dioxide dental ceramics was not significantly affected by the presence of an electric field. The solubility was higher at lower pH. The values of the tested feldspathic ceramic material indicated a higher sensitivity to electrogalvanic processes.

4. Discussion

In this study, we investigated the influence of an electric field and different pH values on the solubility of dental ceramics. The electric field had a strength of 27 V/m. This was the maximum field strength that could be achieved in vitro, which also corresponded to the intraorally occurring values measured previously in vivo [12-15]. This field strength can be easily achieved in vivo when a potential of 270 mV arising from gold and non-noble metallic restoration exists at a distance of 10 mm, which is easily possible in the mouth in between two crowns. Considerably greater electric field values were measured in oral environments in several in vivo studies [12-18]. Using this field strength, Novakovic, Kunze, and Katehsari determined the highest solubility values when the material to be examined was in contact with the electrode plates on both sides and obtained good results. This also corresponds to the conditions in the oral cavity since metallic restorations are usually in direct contact with the materials being examined, such as teeth, cement, or ceramic restorations. The double-sided contact between the test specimens and the gold electrode plates simulated the in vivo contact conditions of a ceramic restoration. Moreover, galvanic field strengths generated by different metals can alter other accompanying materials like corrosion [19] or biological structures such as oral tissue [1, 6, 7]. We considered these findings in this study and selected the maximum field strength of 27 V/m with electrode plate contact on both sides [11, 20, 21].

The test specimens had a surface area of 1.4 cm² (approx.) for feldspathic ceramic and 1.85 cm² (approx.) for zirconium dioxide. From a clinical perspective, the dimensions of the specimens corresponded approximately to the size of a single-tooth restoration. To produce the test specimens, the ceramic powder was mixed with the modeling liquid (butanediol) according to the manufacturer's instructions. The liquid evaporated without leaving any residue during the preheating phase of the firing program [22]. Therefore, this liquid probably did not affect the solubility of the ceramic.

Surprisingly, ceramics could be dissolved by electrolytic processes, as well as by changes in the pH. Feldspars are chemically aluminosilicates. These are tectosilicates with SiO_4 tetrahedra in which the silicate is partially substituted by aluminum. Replacing tetravalent silicate with trivalent aluminum creates a negative charge per exchanged tetrahedron that can be compensated by monovalent or bivalent cations. These cations are weakly embedded in the framework of the tetrahedral structure. Such a structure has high chemical strength, shows unstable bindings, and can exchange cations easily. The chemical bonds between silicate and oxygen or aluminum and oxygen are mostly covalent. Thus, the framework cannot be attacked chemically very effectively. However, this is different for the embedded cations, as they are generally weakly bound. A commercial mixture generally comprises Na_2O, K_2O, Al_2O_3, and SiO_2. When a feldspathic ceramic is dissolved, cations are released as ionic bonds break. The presence of Na^+ ions in the electrolyte solution helps to exchange the ions and gets embedded into the aluminosilicate framework, while cations, such as Ca^{2+} and Ba^{2+}, get dissolved [23].

The feldspathic ceramic gets dissolved by surface-controlled mechanisms, dominated by hydrolysis reactions [24]. Under acidic conditions, feldspathic ceramics generally get dissolved by a combination of ion-exchange reactions between charge-balancing cations (Na^+, K^+, and Ca^{2+}) and protons (H^+ and H_3O^+) and the hydrolysis of Al-O and Si-O framework bonds [24, 25]. The pH of saliva is 6.5–7.2 at rest but can drop below 5.5 during ingestion and have even lower values in plaque [26].

Acid-producing bacteria in the dental biofilm produce such an acidic environment. Furthermore, disorders, such as Bulimia or gastrointestinal reflux, can briefly make the saliva highly acidic. The composition of the electrolyte is very important as the substances dissolved in it largely determine its solubility, and a concentration gradient builds up between the ions dissolved in the electrolyte and the ions still bound to the test specimen. The effort required to enter the solution increases as the difference in concentration between the previously dissolved ions and the bound ions becomes greater [27]. As the environment becomes more acidic, the solubility increases, which is further intensified by an electric field. The dissolution of feldspathic ceramics is strongly dependent on the pH and is dominated by the effects promoted by protons or hydroxyl groups [28]. When the pH is close to 7, low levels of H^+ are available to compete with other cations on the surface of the minerals [25, 28].

We used fine gold electrodes (99.9% fine gold). Any other sensor is either not applicable (e.g., hydrogen standard electrode) or might contaminate the electrolyte (e.g., calomel electrode). Thus, some studies used “pseudo-reference electrodes” (including 999 fine gold), which can be calibrated with the hydrogen standard electrode against the electrolyte used. Fine gold electrodes are chemically and mechanically very stable and have a known potential against the electrolyte, which are favorable properties for corrosion tests [11, 20, 21, 29]. Regarding this, a question arises whether these electrode plates can generate an electric field alone, without the application of an external voltage. The plates generate a low voltage when they are dipped in an electrolyte, although the potential of this effect is lower than –30 mV and produces a field strength lower than 3 V/m [29]. Therefore, this intrinsic potential between the electrodes and the electrolyte has to be considered whenever exact correlations between the power of an electric field and its effect are calculated, and the possibility that the solubility of the controls is slightly influenced by the activity of this small field cannot be excluded.

The electrical potential applied in this study was generated by a special microprocessor-controlled voltage generator that had an average auto-regulating mechanism with an accuracy of ±0.05 V. Cyclic voltammetry was performed by the set.

The temperature of the electrolyte was measured at the beginning, in the middle, and at the end of the experiment using a glass bulb temperature sensor. The results showed that the temperature remained relatively constant and differed only slightly (maximum of ±0.5 °C) from the ambient room temperature.

To prevent the glass containers used in this study from releasing ions, “Schott Glass” containers (Schott & Gen., Mainz, Germany) were used, which are very stable chemically and physically, as shown in several studies [11, 20, 21, 29]. The negative and positive controls taken for all measurements confirmed that the data on the solubility of the tested elements were not influenced by the components of glass containers. Moreover, the experimental setup excluded electrochemical dissolution of the glass containers as far as possible, and glass was not used between the electrodes where the electric field was the most powerful. Beyond this area, the efficacy of the electrostatic field dropped rapidly.

Besides describing the medical consequences for the patient, material-related consequences were also described, according to which the dental materials were dissociated. This is because of the dissolution of heteropolar and metallic bonds by external electrical energy, which in the case of oral galvanism, can lead to electrical field strengths of up to 100 V/m [30].

The feldspathic ceramics with a roughened surface had the highest measured solubility. Even in the absence of an electric field, calcium ions were soluble in the ceramic material; in the presence of an electric field, the solubility increased by 92%.

Barium ions from roughened feldspathic ceramics at pH 5.5 had very low solubility. In an electric field, the concentration increased to 99.6%.

Barium is an alkaline earth metal and does not occur in elemental form due to its high reactivity. Barium and its water-soluble compounds are toxic. They easily dissolve in almost all acids (except in concentrated sulfuric acid). Barium oxide is used as an additive in dental veneering ceramics to control the adaptation of the thermal expansion coefficient (CTE) to form a network [31]. Barium is also found in the human body. The average level of barium in tissues is 100 parts per billion (ppb) and is slightly lower in blood and bone (up to 70 ppb). About 1 mg of barium is ingested daily with food [32]. Due to the low values, their effects can be neglected.

The zirconium dioxide ceramic samples showed similar results for smooth and roughened surfaces in an electric field at pH 5.5. Roughened zirconium dioxide, which occurs in clinical cases due to grinding or bruxism, was insoluble at pH 5.5, not even in the presence of an electric field. Therefore, zirconium dioxide ceramics might be less sensitive to the effects of an electric field than to the effects of acids. We found a significant increase in the solubility of zirconium ions in an electric field compared to their solubility in the controls (without an electric field) at pH 3.0. During treatment in the acidic solution (pH 3.0), the atomic structure on the surface might have changed, or small microcracks in the zirconium dioxide ceramic might have expanded. Due to the molecular structure of water, water molecules have a dipole character and the ability to dissolve ions, especially cations in solids, such as dental ceramics. Kvam et al. showed that the breakage of bonds in zirconium dioxide ceramics by water dipoles strongly depends on the pH of the surrounding solution [33].

The human body contains about 300 mg of zirconium, whose physiological function is undetermined [34]. According to Schroeder and Balassa, the daily oral intake of zirconium is about 3.5 mg [35]. About 0.15 mg of zirconium is excreted daily in urine and 4 mg in feces [36]. Schroeder et al. (1968) showed the influence of zirconium intake through an animal experiment. Mice were given 5 mg of zirconium sulfate in their drinking water for the rest of their lives. The lifespan of the treated mice was lower than that of untreated mice, which was inferred to be caused by the slight toxicity of zirconium [37]. In that experiment, the survival rate of Long-Evans-rats was not affected, but there was a significant increase in glucosuria [38]. Since the measured values of the zirconium ions in this study were very low, the adverse effects of zirconium can be neglected.

By comparing the solubility of the two ceramics, which differed in structure and area of application, we found that the resistance to chemical influences was significantly higher in zirconium dioxide ceramics. Their resistance to clinically relevant electrical field effects was also higher than those of feldspathic ceramics. Since the solubility of bright-fired feldspathic ceramics was lower than that of the roughened ones, we inferred that the glossy layer on the surface is very important for protecting the material from external influences. This confirmed the widespread opinion that dental ceramics with a smooth surface have a denser structure and higher strength due to fewer surface defects, which was reflected in the results of our study by a lower solubility of these specimens compared to that of the roughened specimens.

The solubility of dental ceramics depends on the pH of the oral cavity**.** Even if the chemical solubility of a ceramic material in an alkaline environment is higher than that in an acidic environment [39], from a clinical perspective, more attention should be paid to the effects of acid on the ceramic since a pH of 6.5 or less prevails in the oral environment [26]. The electrolyte used was 0.9% NaCl solution (Braun, Melsungen, Germany) that has a pH of 4.5–7.0. The pH of the pure saline solution was 5.5 in test complex 1, and after acidification with ortho-phosphoric acid (Harvard Cement®), the pH was 3.0 (test complex 2). The pH of saliva is 6.5–7.2 at rest but can drop below 5.5 during food intake and is even lower in plaque. The composition of the electrolyte is very important, as the substances dissolved in it largely determine the solubility, and a concentration gradient builds up between the ions dissolved in the electrolyte and the ions still bound to the test specimen. The isotonic saline solution contains 154 mmol/L sodium and chloride ions; thus, it is a relatively homogeneous electrolyte in which the substances present have negligible interactions.

In the oral cavity, a constant flow of saliva is generated (turnover) with continuous secretion and consumption, but the tests were performed here in a closed system. The composition of saliva, with its organic and inorganic components, differs from the saline solution used in this in vitro study. These components, such as enzymes and sodium, potassium, and fluoride ions, can also influence the concentration gradient of the dissolved ions in vivo.

Acids in the oral cavity might occur not only due to the consumption of food and drinks but also due to other reasons, for example, through oral intake of medication that interfere with saliva, with strong fluctuations in the pH of the oral cavity [40]. Endogenous and/or exogenous factors influence the pH in the oral cavity, such as gastroesophageal reflux, bulimia, dietary components, drugs, and alcohol. Buffer systems and simulated saliva can neutralize the environment after about 30 min [41].

5. Conclusion

Ceramic restorations in the oral cavity are exposed to frequent fluctuations in the pH. This implies that the surface of the ceramic restorations is exposed to recurring attacks, with the alkali ions of the ceramic being exchanged for hydrogen ions from the acid. If metals are also present in the oral cavity, the resulting electric fields can further increase the solubility on the ceramic surface.

In conclusion, the results of this in vitro study showed that in the presence of a clinically relevant electric field, the solubility of calcium and barium increases in feldspathic ceramic. The results suggested that an electric field does not influence the solubility of the zirconium dioxide ceramic. We also found that the solubility of zirconium dioxide ceramic material in an acidic environment at pH 3.0 was higher than that at pH 5.5. The quality of the ceramic surface is very important, especially for feldspathic ceramics.

Acknowledgments

Prof. Dr. rer. nat. Johannes Beck from the Department of Inorganic Chemistry at the University of Bonn for giving chemical advice.

Author Contributions

All authors whose names appear on the submission made substantial contributions to the conception or design of the work. **John S:** conceptualization, planned and performed the experiments, analyzed data, writing – review & editing. **Rink S:** conceptualization, analyzed and discussed data, interpretation of data, writing – original draft, writing – review & editing.

Weidemann L: analyzed and discussed data, interpretation of data, writing – review & editing. **Huesker K:** analysis and data interpretation, writing – review & editing**. Niedermeier W**: conceptualization, interpretation of data, supervision, writing – original draft, writing – review & editing.

Competing Interests

The authors have no conflicts of interest relevant to this article.

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