Quality Assessment of Five Randomly Chosen Ceramic Oral Implant Systems: Cleanliness, Surface Topography, and Clinical Documentation

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Purpose: After some initial setbacks in the 1970s, ceramic implants seem to be a promising alternative to titanium implants. Since the surface of an implant system represents the interface to surrounding biologic structures, the study focuses on cleanliness and surface topography. Clinical documentation of the corresponding systems completes the picture and allows a better evaluation of zirconia implant systems. ***Materials and Methods:*** Five different ceramic implant systems were selected randomly and purchased via blind-shopping: Z5s (Z-Systems), ZiBone (COHO), W implant (TAVDental), ceramic. implant (vitaclinical), and BioWin!/Standard Zirkon Implantat (Champions-Implants/ZV3 system). Three samples of each implant system underwent scanning electron microscopy (SEM) imaging and elemental analysis (EDS). Where appropriate, subsequent Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS) was performed to identify the chemical nature of impurities. Surface topography was evaluated, and a search for clinical trials in the PubMed database, on the websites and by written request to each dental implant manufacturer, was performed. ***Results:*** Surfaces of Champions implants (ZV3) and Z-Systems implants were relatively clean, whereas the other investigated surfaces of vitaclinical, TAV Dental, and ZiBone implants all displayed organic contaminations on their surfaces. Four of the investigated ceramic implants showed a moderately rough implant surface. Only the vitaclinical ceramic.implant had minimal surface roughness. Three ceramic designs—vitaclinical, ZV3, and Z-Systems—had clinical trials documented with up to 3 years of follow-up and results varying between 82.5% and 100% survival. TAV Dental W and ZiBone implant systems lacked properly conducted clinical recording of results. ***Conclusion:*** The results of this study showed that it is technically possible to produce zirconia implants that are largely residue-free. On the other hand, the variety of significant residues found in this analysis raises concerns, as contamination may lead to undesirable biologic effects. The lack of clinical studies in peer-reviewed journals does not seem to be relevant for the approval of marketing, nor does the lack of surface cleanliness. In the authors' opinion, a critical analysis of these aspects should be included in a more stringent future analysis prior to the marketing of oral implant systems. *Int J Oral Maxillofac Implants 2021;36:863–874. doi: 10.11607/jomi.8837*

Keywords: ceramic implants, dental implants, implant contamination, implant surface, scanning electron microscopy, surface, surface properties, zirconia

Ceramic implants were among the first ones used in the osseointegration era. Schulte and Heimke[1] (1976) used aluminum oxide implants, so-called Tübingen implants, to replace single teeth. Schulte's clinical work was of high quality for its time. The Tübingen implants demonstrated direct bone contact,[2] but they suffered from increasing brittleness, leading to an increasing number of fractures, the longer the time in situ. Kyocera single crystal aluminum oxide implants had similar problems with decreasing implant stability. These unforeseen events led to a bad reputation for ceramic implants, and for a time, ceramic oral implants disappeared from the market.

However, in the last 20 years, a return of ceramic implants has been seen, this time manufactured from zirconia. Zirconia is frequently used in orthopedic surgery, eg, as cup arthroplasties, but it must be noted that such zirconia cups have a considerable thickness compared with an oral implant. Indeed, the first generation of zirconia oral implants showed increasing fracture rates over time,[3] a problem that, however, seems to have been solved with the advent of newer, stronger forms

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of zirconia. Nevertheless, fatigue may still occur in situ over a longer period of time, possibly resulting in mechanical problems.[4] In addition, there is a theoretical risk that the precise mode of enlarging the surface of zirconia may cause increasing problems with the mechanical strength of the material. Zirconia has some esthetic benefits compared with titanium, particularly in cases of bone resorption, as the white color might be less disturbing if the implant surface is exposed. Another assumed preference concerns patients with a titanium allergy, which is, however, difficult to ascertain since there are no generally accepted patch tests to detect possible titanium allergy.[5] This means that observed allergy to titanium may just as well represent an allergy to one of many other metals totaling approximately 0.3% of commercially pure (c.p.) titanium. There is also a psychologic component in that some patients may prefer ceramic material to metal for whatever reason. Therefore, zirconia implants have increased in popularity even if they are used in numbers far below c.p. titanium at present.

Although there are some differences between ceramic and metallic implants, similarities exist, such as the fact that both groups of materials represent foreign bodies[6] and that both types of implant surfaces can have surface impurities.[7] Another difference is the fact that titanium implants displayed a temperature gradient that was three times lower than zirconia implants in an experimental test of implant placement in ribs.[7] The reason for this noticeable rise in temperature during the placement of a zirconia implant was regarded as a result of its poor thermal conductivity. Therefore, the authors recommended a very slow insertion torque when placing zirconia implants.[8]

Ion release from titanium dental implants and titanium particles surrounding the peri-implant tissue are common findings.[9,10] In a comparative study, it was observed that zirconium elements were also found in mucosal tissues adjacent to ceramic implants.[11] Peri-implantitis around zirconia implants has either not been observed at all[12] or diagnosed as a relatively common problem by others.[13] Whether these different observations depend on the precise type of zirconia implant used or on the multitude of definitions available for what is to be regarded as peri-implantitis is unknown.[14] From a clinical point of view, varying figures have been reported in the literature but with an average 92% survival rate at 1 year of follow-up in one study.[15] In an analogy with titanium implants, it is possible that the precise survival rates of zirconia may be related to the precise type of implant design tested, which is why the present study aimed for individual clinical records for each one of the implant systems analyzed in this article.

The main aim of this study was to analyze the level of cleanliness and to conduct a quality assessment of the surfaces of five randomly selected ceramic implant types. The surface cleanliness of some metallic implants was analyzed in a previously published pilot study.[7] The main methodologic difference between the present study and the previously published pilot analysis is that three randomly selected specimens of each implant type were evaluated, whereas only one implant of each design was researched in the pilot study. In contrast to the previous study, subsequent chemical analyses were performed in the case of conspicuous impurities in order to obtain information on the exact nature of contaminants. It would seem reasonable to demand that clinically used implant surfaces show the highest possible level of cleanliness prior to implantation.

Other aims of the present study included the analysis of surface topography and the clinical outcome of the included ceramic implants. When manufacturing zirconia, a surface structure of a relatively smooth nature commonly results. In most cases, the surface is then roughened up to higher levels of S_a, where S_a describes the average height distribution. Some studies are claiming that microrough zirconia with a S_a of approximately 0.6 µm will display a similar bone response to that of titanium implants with a doubled S_a.[3,16,17] This statement, which—if correct—would presumably only apply to the very type of zirconia investigated in these studies, will be critically analyzed in the present investigation.

MATERIALS AND METHODS

Inclusion of Zirconia Implant Designs

Previous studies have described many types of zirconia implants that have not yet been put on the market,[18] and it has been seen that such designs are of less value than clinically marketed specimens. The present study identified 18 zirconia implant types that have been on the market for 1 year or more and gave each system a number on a ticket that was placed in a container. After careful shaking of the container, an assistant picked five numbers from the container that then represented five different oral implant systems. The selected systems were the Z-Systems from Switzerland with the Z5s implant, the COHO system from Taiwan with the ZiBone implant, the TAV Dental system from Israel with the W implant, the vitaclinical system from Germany with the ceramic.implant, and the Champions-Implants/ZV3 system from Germany with the BioWin! and Standard Zirkon Implantat (the implant has two brand/type names on the packaging). All implants were bought from the respective companies by dental colleagues, to ensure that implants were received from the standard production lines.

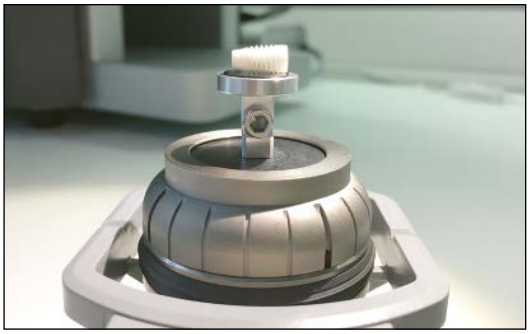


Fig 1 Implant sample mounted on SEM sample holder in cleanroom environment.

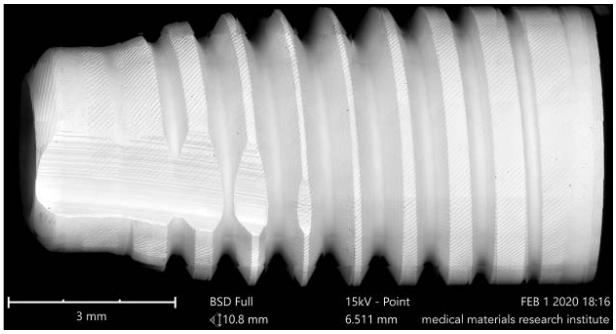


Fig 2 Digitally composed SEM mapping image, Z5s implant (Z-Systems). Backscattered electrons (BSE) illustrate possible differences in the chemical composition of the sample.

Methods for the Study of Surface Cleanliness

Three samples of each implant type were carefully unpacked, mounted on the sample holder of a scanning electron microscope (SEM) without touching the implant surface, and subsequently analyzed in the SEM. In order to avoid any artifacts from the ambient air, the sample preparation and the scanning process were carried out in a particle-free cleanroom environment (according to Class 100 US Federal Standard 209E, Class 5 DIN EN ISO 14644-1; Fig 1).

SEM imaging and qualitative/quantitative elemental analysis (EDS) was performed by a Phenom proX Scanning Electron Microscope, equipped with a high-sensitivity backscattered electron (BSE) detector; EDS Analysis detector type: Silicon Drift Detector (SDD) Thermoelectrically cooled (LN2 free), detector active area: 25 mm^2. The data were evaluated using Phenom Elemental Identification (Vers. 3.8.4) and Automated Image Mapping (Vers. 2.0.2) software.

Prior to the detailed analysis of potential impurities, up to 600 single high-resolution SEM images of each implant in 500× magnification were digitally composed in the "Image-Mapping" mode into one large SEM image, showing the full size of the implant from shoulder to apex at a viewing angle of approximately 120 degrees (Fig 2).

Material-contrast imaging (images performed from 500× to a magnification of 10,000× in BSE mode) gave additional information about the chemical nature and allocation of different remnants or contaminations on the sample material. The mapping image of a sample made it possible to identify areas of interest for a subsequent EDS spot analysis. The elemental composition of particles was determined, and where possible, the differential spectra of particles were achieved to subtract signals from the core material and thus focus on signals from the superficial contamination.

Implant types that showed considerable impurities in the SEM imaging were subsequently examined by Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS), a method that determines the elemental, isotopic, or molecular composition of a surface or particulate impurities.[19,20]

ToF-SIMS data of sterile packaged implant samples were acquired at Tascon, a commercial provider of analytical service. For ToF-SIMS analysis, an IONTOF TOF. SIMS5-300 instrument (IONTOF) was used, equipped with a 30-keV bismuth liquid metal ion gun, a 20-keV Ar gas cluster sputter source, a 2-keV Cs/O_2 sputter source, and a low-energy electron flood gun. Data analysis was performed using SurfaceLab7.1 software (IONTOF).

Evaluation of Surface Topography of Included Ceramic Implants

The surface topography was evaluated with a 3D optical Profilometer using white light laser, gbs, smart WLI extended (Gesellschaft für Bild und Signalverarbeitung). A 50× objective was used for all measurements. The data were evaluated using MountainsMap Imaging Topography 7.4 (Digital Surf) software. Surface roughness parameters were calculated after removing errors of form and waviness. A Gaussian filter with a size of 50 × 50 µm was used. The measuring area was 350 × 220 µm for all measurements. Each implant was measured on nine areas, three flanks, three tops, and three valleys randomly distributed over the entire implant, as Wennerberg and Albrektsson described in 2000.[21]

The surface variation was described in height-, spatial-, and surface enlargement aspects. Four parameters were selected: S_a measured in µm; S_{ds}, which is a measure of the density of summits over the measured area, measured in $1/µm^2$; S_{sk} (skewness), a parameter that describes the asymmetry of the surface deviation from the mean plane; and S_{dr}, which describes the surface enlargement compared with a totally flat reference area, measured in percent.

Clinical Documentation of Included Ceramic Implants

A search for available clinical trials regarding the dental implant systems was done. Initially, the websites of

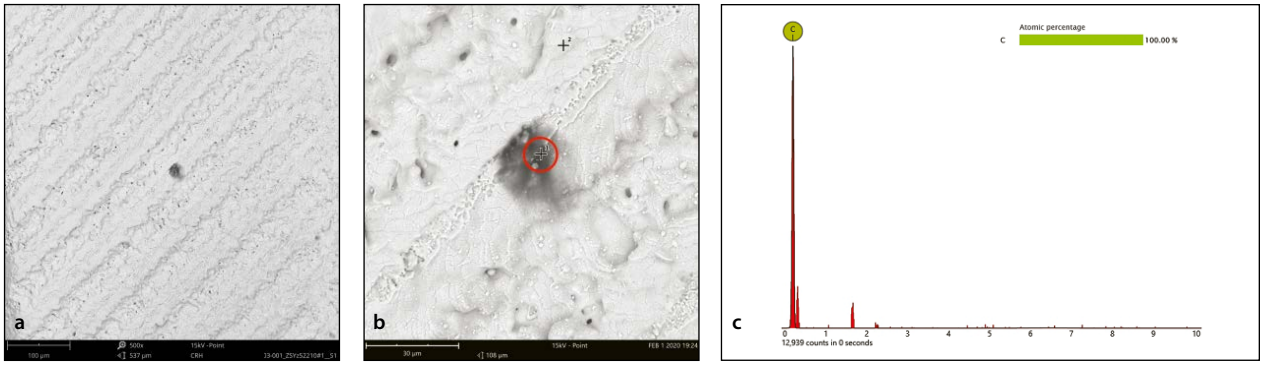


Fig 3 SEM/EDS analysis of the Z5s Implant (Z-Systems). *(a)* SEM 500×, *(b)* SEM 2,500× with marked spots for EDS analysis, *(c)* differential EDS spot measurement (#1 minus #2); quantitative and qualitative elemental analysis of an organic particle (20 to 30 µm).

each dental implant manufacturer were searched on October 15, 2019: https://zsystems.com, www.zibone.com, www.tavdental.com, www.vitaclinical.com, and www.zv-3.com. In addition, the manufacturers were contacted via their respective contact emails on their websites, requesting any scientific documentation regarding clinical performance such as published papers or summaries of ongoing projects. If no response was received within 1 week, a reminder was sent.

Furthermore, a search for clinical trials in the PubMed database (PubMed.gov, US National Library of Medicine, National Institutes of Health) was performed on October 27, 2019. The search terms "dental implants" [MeSH] and "dental implants"[free text] were used in combination with the product or the manufacturers' names. No limits were set. A further search was conducted on April 1, 2020, to find out whether any additional papers had been added since October 2019: ((„dental implants"[MeSH Terms] OR („dental"[All Fields] AND „implants"[All Fields]) OR „dental implants"[All Fields]) AND Z-Systems[All Fields]), („dental implants"[MeSH Terms] OR („dental"[All Fields] AND „implants"[All Fields]) OR „dental implants"[All Fields]) AND Z5[All Fields]), („dental implants"[MeSH Terms] OR („dental"[All Fields] AND „implants"[All Fields]) OR „dental implants"[All Fields]) AND coho[All Fields]), („dental implants"[MeSH Terms] OR („dental"[All Fields] AND „implants"[All Fields]) OR „dental implants"[All Fields]) AND Zibone[All Fields]), („dental implants"[MeSH Terms] OR („dental"[All Fields] AND „implants"[All Fields]) OR „dental implants"[All Fields]) AND TAVDental[All Fields]), („dental implants"[MeSH Terms] OR („dental"[All Fields] AND „implants"[All Fields]) OR „dental implants"[All Fields]) AND W[All Fields]), („dental implants"[MeSH Terms] OR („dental"[All Fields] AND „implants"[All Fields]) OR „dental implants"[All Fields]) AND vitaclinical[All Fields]), („dental implants"[MeSH Terms] OR („dental"[All Fields] AND „implants"[All Fields]) OR „dental implants"[All Fields]) AND ceramic.implant[All Fields]), („dental implants"[MeSH Terms] OR („dental"[All Fields] AND „implants"[All Fields]) OR „dental implants"[All Fields]) AND ZV3[All Fields]), („dental implants"[MeSH Terms] OR („dental"[All Fields] AND „implants"[All Fields]) OR „dental implants"[All Fields]) AND Standard Zirkon Implant[All Fields])).

Finally, a search of the reference lists of systematic reviews identified throughout the search process was performed.

RESULTS

Surface Cleanliness

Z-Systems, Z5s Implant. The analyzed implant samples (expiration dates: October 2022 and December 2022) showed less than 10 organic particles (10 to 30 µm; Figs 2 and 3a to 3c). The implant surface displayed aluminum oxide particles, probably as part of the production process. None of the three analyzed implant samples showed systematic contamination. No pattern for the distribution of particles was found.

COHO Biomedical Technology, ZiBone. The three samples of ZiBone's ceramic implant showed a mixed picture (all samples' expiration date: May 2022). While one sample showed less than 10 organic particles with a diameter of 10 to 20 µm, another sample from the same batch showed approximately 50 organic particles (5 to 40 µm), especially on the outer thread flanks near the apex of the implant (Figs 4a to 4c).

The third sample presented the same number of organic particles with no pattern of distribution. In addition to this, one sample showed particle conglomerates (20 to 30 µm) with significant amounts of silicon, magnesium, calcium, and aluminum (Figs 5a to 5c). Subsequent ToF-SIMS analysis of a sterile packaged sample detected talc, DBSA, and fatty acid ester (results not shown).

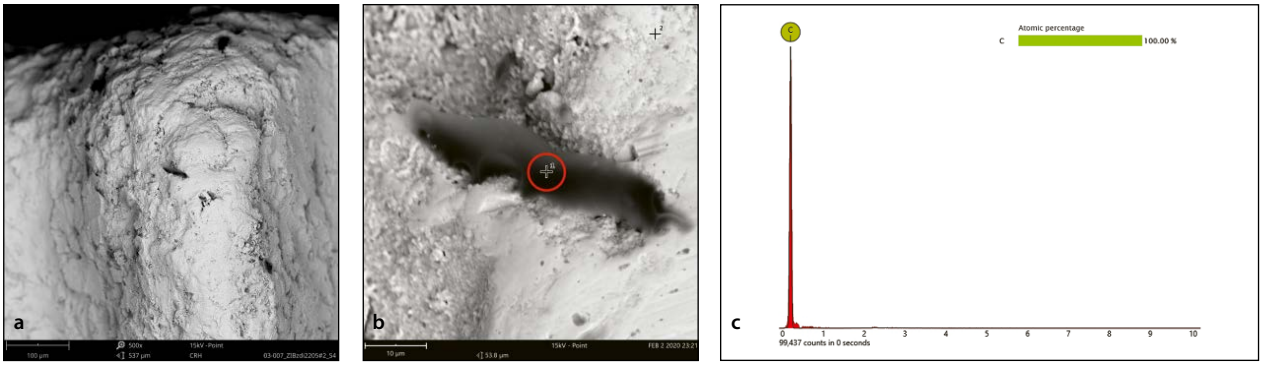


Fig 4 SEM/EDS analysis of the Zibone Implant (COHO Biomedical Technology). *(a)* SEM 500×, *(b)* SEM 5,000× with marked spots for EDS analysis, *(c)* differential EDS spot measurement (#1 minus #2); quantitative and qualitative elemental analysis revealed organic nature of the particle.

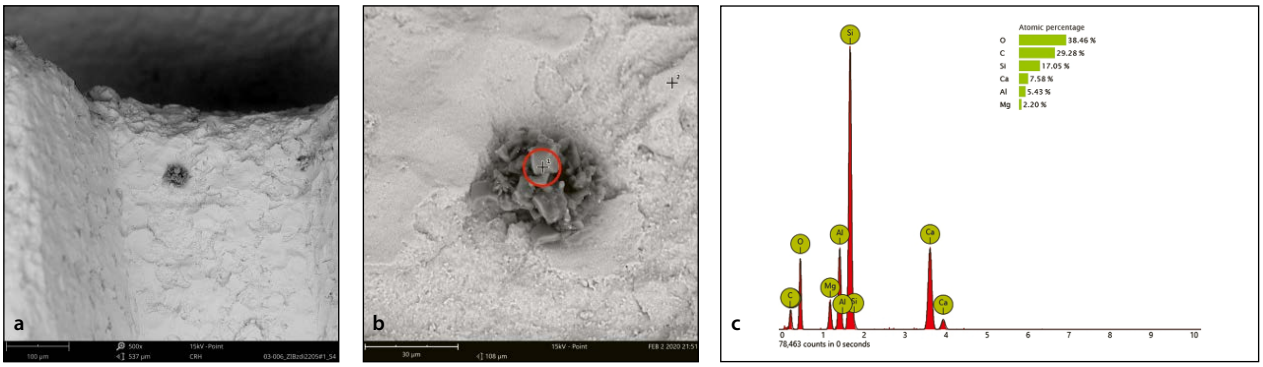


Fig 5 SEM/EDS analysis of the Zibone Implant (COHO Biomedical Technology). *(a)* SEM 500×, *(b)* SEM 2,500× with marked spots for EDS analysis, *(c)* differential EDS spot measurement (#1 minus #2); quantitative and qualitative elemental analysis showed different elements of the compound.

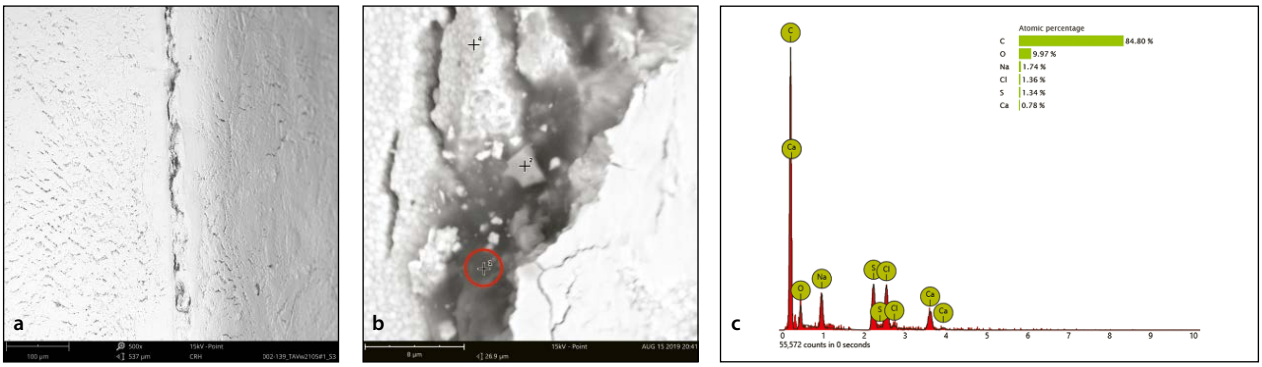


Fig 6 SEM/EDS analysis of the W Implant (TAV Dental). *(a)* SEM 500×, *(b)* SEM 10,000× with systematic organic contamination in a long material crack (> 500 µm) on the implant shoulder, *(c)* differential EDS spot measurement (#1 minus #4). This organic impurity revealed mainly carbon and small amounts of oxygen, sodium, chlorine, sulfur, and calcium in the elemental analysis. (The embedded grey particle #2 showed signals of aluminum oxide.)

TAV Dental, W implant. The analyzed implant samples (expiration dates: May 2021 and June 2024) presented a very mixed picture. The first sample showed remarkable organic impurities (5 to 80 µm), especially at the implant shoulder and distributed over the entire implant (Figs 6a to 6c). One particle (10 to 15 µm) showed additional traces of magnesium, sulfur, sodium, and chlorine, while another particle (3 to 5 µm) contained traces of titanium and aluminum; one particle contamination (4 to 6 µm) indicated significant traces of iron in the elemental analysis (Figs 7a to 7c). While the first sample presented significant organic contamination, the second implant showed less particulate contamination of organic nature. Instead, several apparently melted impurities (20 to 60 µm) were found with clear traces of silicon, oxygen, sodium, and aluminum (possibly aluminum sodium silicates; Figs 8a to 8c). The same components were detected in an impurity of

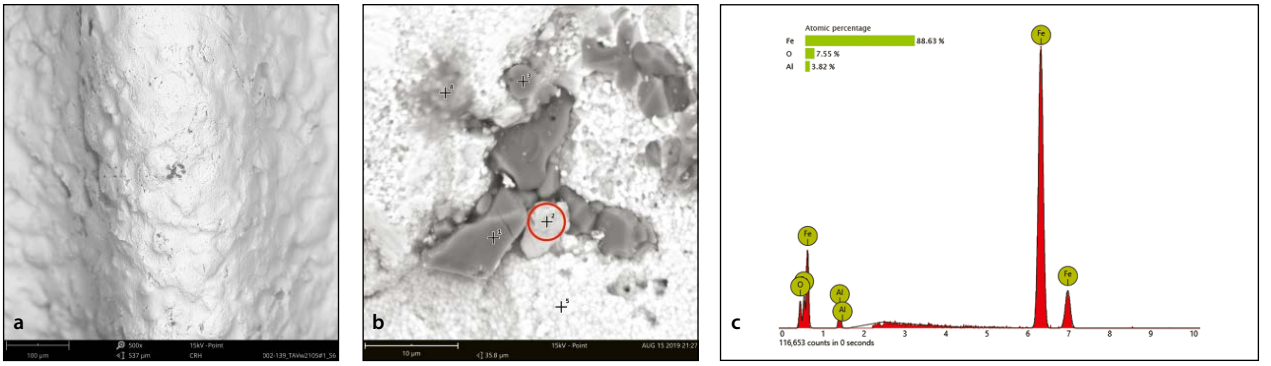


Fig 7 SEM/EDS analysis of the W Implant (TAV Dental). *(a)* SEM 500×, *(b)* SEM 7,500× with marked spots for EDS analysis, *(c)* differential EDS spot measurement (#2 minus #5). Quantitative and qualitative elemental analysis of the particle (3 to 5 µm) showed iron, aluminum, and oxygen. (# 1 and #3 are most likely remnants of aluminum oxide particles; #4 is of organic nature.)

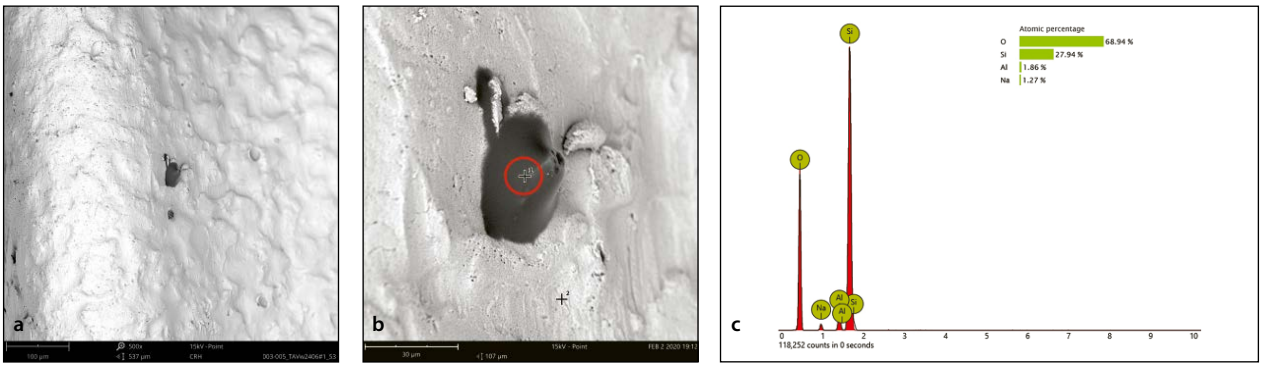


Fig 8 SEM/EDS analysis of the W Implant (TAV Dental). *(a)* SEM 500×, *(b)* SEM 2,500× with marked spots for EDS analysis, *(c)* differential EDS spot measurement (#1 minus #2); quantitative and qualitative elemental analysis of the particle (30 to 60 µm) showed signals of silicon, oxygen, aluminum, and sodium.

the third sample (10 to 50 µm). In addition, this sample showed a solid metal particle of 20 to 40 µm with iron, silicon, aluminum, magnesium, and potassium in the elemental analysis. External implant threads showed small aluminum oxide particles (2 to 5 µm) as an accumulation in an area of 20 to 30 µm in diameter. In the ToF-SIMS analysis of a sterile packaged implant sample from the same type, point-accumulations of aliphatic hydrocarbon compounds were noticeable (results not shown here).

vitaclinical, ceramic.implant. All three samples (expiration dates: July 2020, October 2020, and October 2023) showed a pattern of organic contamination, where major areas with a length of up to 1.0 mm at the implant shoulder and the first implant thread were covered with numerous organic particles (Figs 9a to 9c). In addition, more than 50 organic particles with a variation of 10 µm to 1 mm in diameter were found on the implant surface of all samples in random distribution. The elemental analysis of one mainly organic particle (10 to 15 µm) on sample #1 revealed significant signals of iron and minor traces of chromium, potassium, chlorine, and sulfur (Figs 10a to 10c).

As photographic images of the implant packaging indicate, one reason for the massive organic contamination at the implant shoulder and the first thread of all samples of this implant type can be the packaging itself (Figs 11 and 12).

Two sterile packaged samples of the same implant type were examined (expiration dates: October 2020 and October 2023) by ToF-SIMS. As in the correspondent SEM imaging, one sample showed significant contamination in the area of the first implant thread. The plastic packaging material in contact with the implant surface was subjected to the same analysis. The matching of data with reference-spectra showed that both packaging and contamination consist of polyacetal, also known as polyoxymethylene (POM), which is an engineering thermoplastic (Fig 13). From this result and the position of the contamination on the threads, it can be concluded that a mechanical transfer of packaging material to the implant surface occurred.

Another organic residue on the implant surface of the second sample turned out to be polysiloxane. The analysis indicated additional residues of dodecylbenzene sulfonic acid (DBSA) and erucamide ($C_{22}H_{43}NO$). DBSA is a surfactant and is used, interalia, as a component in detergents,[22] while erucamide is used, interalia, as an anti-adhesive agent for plastics.[23]

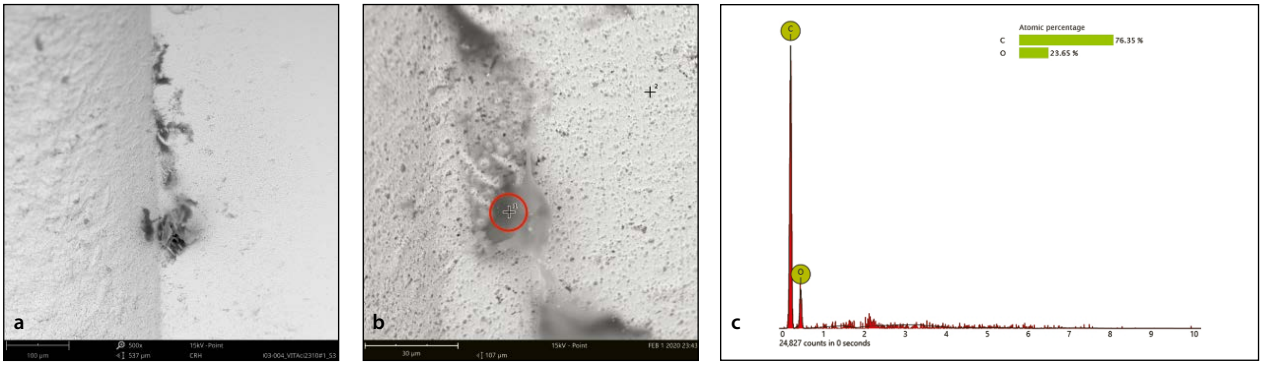


Fig 9 SEM/EDS analysis of the ceramic.implant (vitaclinical). *(a)* SEM 500×, *(b)* SEM 2,500× with marked spots for EDS analysis, *(c)* differential EDS spot measurement (#1 minus #2); quantitative and qualitative elemental analysis of a real contamination (particle sizes 10 to 100 µm) on the first implant thread showed signals of carbon and oxygen.

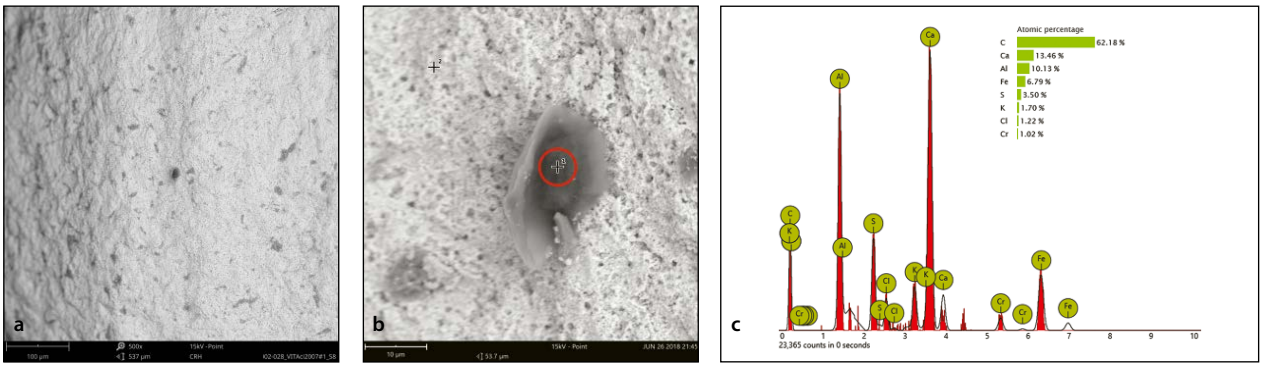
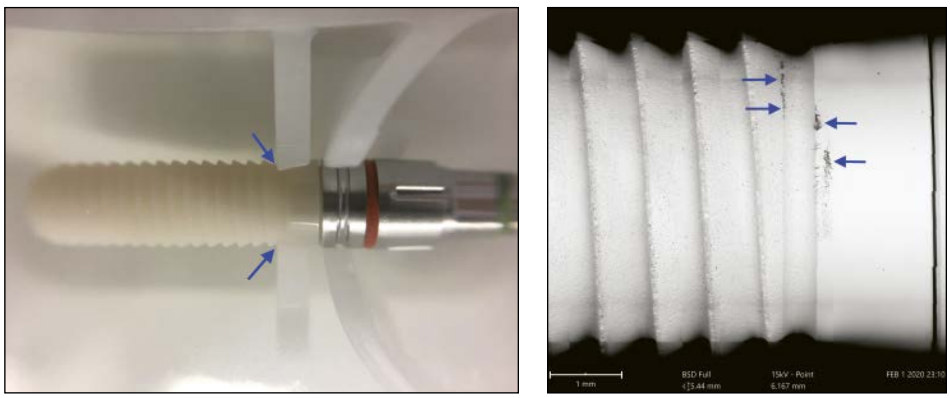


Fig 10 SEM/EDS analysis of the ceramic.implant (vitaclinical). *(a)* SEM 500×, *(b)* SEM 5,000× with marked spots for EDS analysis, *(c)* differential EDS spot measurement (#1 minus #2); quantitative and qualitative elemental analysis of single particle (10 to 20 µm) showed interalia signals of different metals.

Fig 11 *(Left)* Photographic image of the ceramic.implant fixation inside the packaging (vitaclinical).

Fig 12 *(Right)* SEM mapping image of the same implant. Material contrast shows traces of foreign material (dark particles, allocated in a range of 1 to 1.5 mm) on the implant shoulder and the first implant thread.



Champions-Implants, BioWin! (ZV3, Standard Zirkon Implantat). The analyzed samples of the BioWin! (ZV3) implant (expiration dates: July 2022, August 2022, and November 2022) showed only particles of aluminum oxide (10 to 30 µm). Within the scope of this analysis, organic impurities could not be detected (Figs 14a to 14c and 15).

Surface Topography

Four of the implants evaluated displayed a moderately rough surface with S_a levels between 1 and 2 µm. The S_{dr} percentage for these four implants varied considerably from 83 (BioWin!/ZV3) up to 261 for Z-Systems. One implant, the vitaclinical, had minimally rough surfaces[24] with a S_a of 0.7 µm. This implant had a similar S_a value to machined, metallic implants (Table 1).

Clinical Documentation

ZV3 and vitaclinical responded to emails. ZV3 provided a case report and two clinical trials, a 2-year follow-up of 52 patients with a survival rate of 95.8%,[25] and a 3-year follow-up of 74 patients with 121 implants with

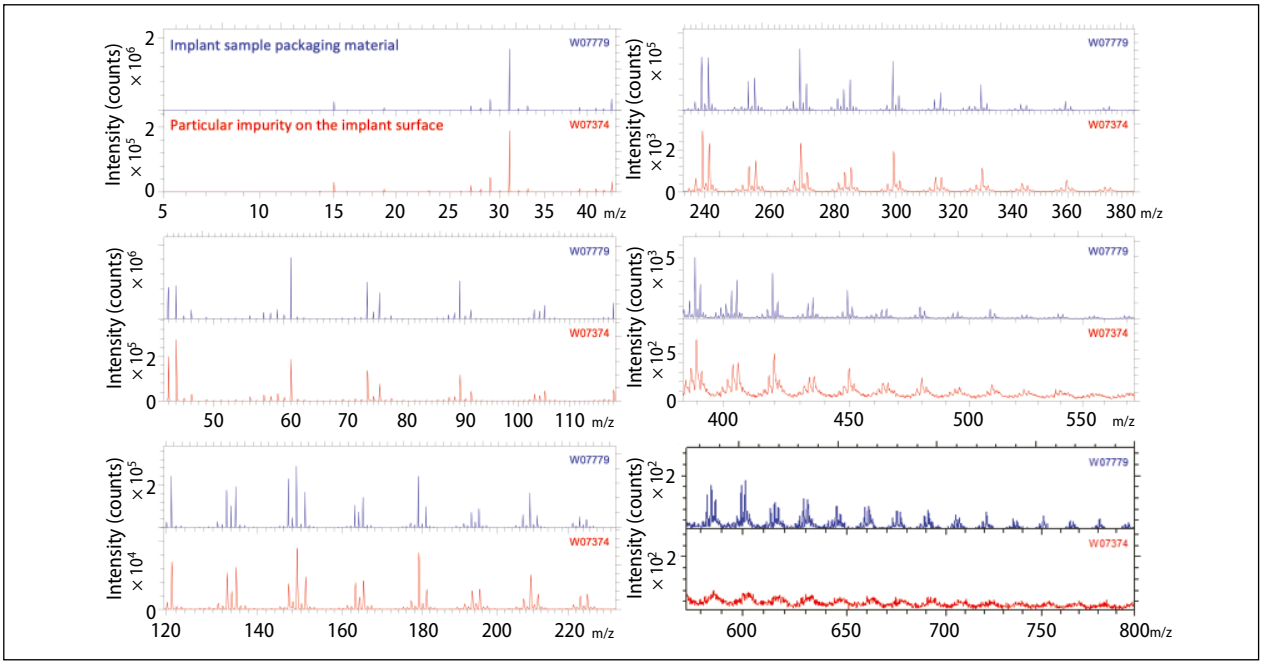


Fig 13 Comparison of ToF-SIMS spectra (blue = packaging material as seen in Fig 11, red = impurity on the implant surface as seen in Fig 12), primary ion Bi3+, 30 keV; both materials are chemically identical and consist of polyacetal (extract from test report A28710b, with permission of Tascon).

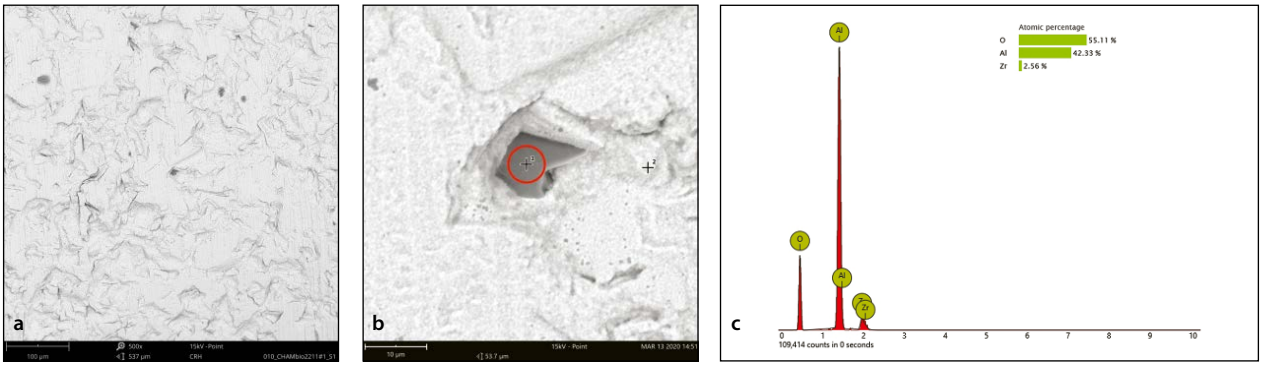


Fig 14 SEM/EDS analysis of the BioWin!/Standard Zirkon Implantat (Champions-Implants/ZV3). *(a)* SEM 500×, *(b)* SEM 5,000× with marked spots for EDS analysis; *(c)* differential EDS spot measurement of a single particle (5 to 10 µm) showed signals of aluminum and oxygen.

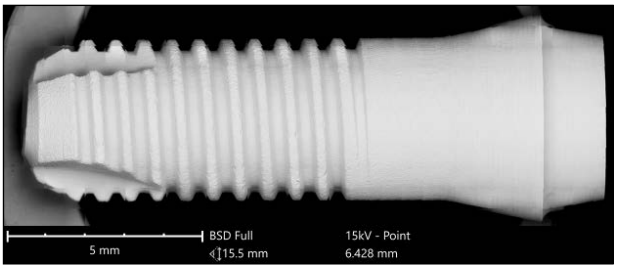


Fig 15 SEM mapping image of the BioWin!/standard zirconium implant (Champions-Implants/ZV3).

a survival rate of 96.5%.[26] vitaclinical sent a requested documentation summary. None of the other manufacturers responded to emails.

The webpage of the ZiBone implant system (www.zibone.com) provided links to six case presentations but no scientific documentation. The webpage of the W implant system (www.tavdental.com) contained links to six case presentations and 19 publications, but none of these were clinical trials, and none evaluated the W implant system. The webpage of Standard Zirkon Implant (www.zv-3.com) contained links to eight publications. Three of these were user guides, three were in vitro trials of titanium and/or zirconia particles, and one was a review on peri-implantitis. Only one undated, unpublished abstract evaluated the implant system.

The webpage of ceramic.implant (www.vitaclinical.com) listed 13 publications. The webpage also contained links to a documentation summary, which was ordered online. Four clinical trials were identified here. These were all, however, evaluations of the same cohort of patients. The latest was a 3-year follow-up of 60

Table 1 Surface Roughness of Five Selected Ceramic Implant Types

	S_{sk} (SD)	S_z µm	S_a µm	S_{al} µm	S_{tr}	S_{dr} %	S_{ds} 1/µm²
Champions-Implants/ZV3	−0.721 (2.09)	47.612 (27.94)	1.178 (0.33)	6.386 (1.76)	0.812 (0.09)	83.007 (87.32)	0.25 (0.01)
TAV Dental	0.167 (1.51)	66.542 (74.58)	1.244 (0.75)	8.369 (2.54)	0.749 (0.09)	95.273 (191.67)	0.282 (0.01)
vitaclinical	−1.184 (0.91)	17.421 (8.31)	0.727 (0.09)	7.067 (0.58)	0.819 (0.09)	22.038 (5.59)	0.25 (0.02)
COHO/ZiBone	−0.653 (2.08)	74.343 (75.52)	1.681 (0.74)	6.802 (2.16)	0.638 (0.22)	118.293 (148.45)	0.233 (0.02)
Z-Systems	0.619 (3.66)	81.697 (58.16)	1.884 (1.54)	3.561 (2.09)	0.561 (0.29)	261.028 (295.40)	0.267 (0.02)

patients with 71 implants and a survival rate of 98.5%.[27] Of the four available in vitro trials, two trials evaluated zirconia implants from vitaclinical. In addition, there was a link to case reports, but that webpage contained no information.

Regarding Z-Systems, 27 publications and seven case reports were identified through the manufacturer's Scientific Evidence Brochure online (https://zsystems.com). Seven of these were not available in full text, and 16 evaluated titanium implants, zirconia implants other than Z-Systems, or were in vitro trials, case reports, or reviews. Thus, four clinical trials evaluating zirconia implants from Z-Systems were identified by the manufacturer with 93% survival of 189 implants over 1 year,[28] 87.5% survival of 40 implants over 1 year,[29] 100% survival of 51 implants over 2.5 years,[30] and 100% survival of 106 implants over 1 year.[31] Another 3-year study of the Z-implant system revealed a survival of 82.5% of 170 implants.[32] Of the seven available in vitro trials, two evaluated zirconia implants from Z-Systems.

The PubMed search revealed a medium-term follow-up of zirconia implants from Z-Systems presenting a 2- to 5-year follow-up of 34 patients with 66 implants with a survival rate of 98%.[33] The search process identified four systematic reviews.[15,18,34,35] A further two clinical trials were identified in these reviews: a 1-year trial evaluating 60 patients with 71 ceramic implants from vitaclinical with a survival of 98.3%,[36] and one long-term trial presenting an up to 7-year follow-up of 60 patients with 71 implants from Z-Systems with a survival rate of 77.3%.[37] However, it must be pointed out that the latter study referred to the 3rd generation of Z-Systems implants (Z-Look3). The diameter-reduced versions of this implant, manufactured until 2011, often developed fractures in the clinical follow-up. The 5th-generation type tested in this study (Z5) has a laser-structured surface replacing the previous models' sandblasted surface.

DISCUSSION

The investigated implants varied in the level of surface contamination. Champions-Implants (ZV3) and Z-Systems implants were generally rather clean, with only some aluminum oxide particles on their surfaces. No systemic contamination could be found. The vitaclinical implant displayed a pattern of organic contamination that most likely originated from the package of the implant. The TAV Dental W implant revealed organic impurities all over one sample with metallic ions detectable at different places. Other samples showed possible aluminum sodium silicates. ZiBone ceramic implants varied from one implant to the other. Organic contaminations were found on two of the implants, whereas the third specimen was relatively clean.

This raises a good question as to what a "clean" implant is after the outcome of this study. In a study carried out by the University of Mainz, Germany, Beger et al analyzed five zirconia implants of different brands (only one sample per manufacturer) by SEM and concluded that none of the examined samples was contaminated.[38] It must be critically noted that only selected areas were captured with very high magnifications, and, thus, a general overview was not performed, as seen in the material-contrast SEM mapping images in this article. In order to make reliable statements about the cleanliness of implants, it should always be ensured that the entire implant body anchored in the bone is used as the basis for analysis.

The analysis of a single sample can only give an indication of the production quality of an implant manufacturer on a specific production date. A single residue-free implant sample is, first and foremost, a positive result. The identification of a contaminated implant, on the other hand, may indicate production problems that could affect more than just this one random finding. Thus, only the repeated testing of individual samples over a more extended period or the testing of several samples from different batches— as in this study—can reveal alterations in manufacturing quality. Consistency of the production quality of medical devices cannot be measured if only a single sample is used as a benchmark for testing.

Thresholds for particulate implant contaminations in the lower micrometer range were described in a consensus paper published for the first time in 2017.[39] If these

given standards are applied to the impurities found in this study, implants from Z-Systems and Champions-Implants (ZV3) can be classified as clean with respect to particles in the SEM-given range of magnification. Regarding the other implant systems in this study, this applies only and with restrictions to the COHO system, but for none of the test specimens analyzed from vitaclinical and TAV Dental. In this study, ToF-SIMS has proven to be a suitable technique for a detailed description and an additional chemical classification of implant surface impurities. Chemical substances can be determined with a lateral resolution < 100 nm and a depth resolution < 1 nm. The combination of the two analytical techniques used in this study, SEM/EDS and ToF-SIMS, is not only of academic value. By determining the exact nature of the contamination, manufacturers can derive concrete indications of the technical cause and initiate quality assurance measures to avoid such contaminants in the future.

The present study has not dealt with the question of any clinical relevance of contaminations detected within this thesis. However, the present analyses showed that it is technically possible to produce zirconia implants that are largely residue-free.

Having said this, there is currently a lack of precise knowledge of the type and the amount of contaminations that may disturb clinical function. Titanium implants result in an elevated immune response.[40] It is known that adding ligatures to titanium implants in experimental situations causes an elevation of the immune response,[41] and it has been assumed that the accidental presence of cement particles in the soft tissues may likewise result in further immune activation and a shift to marginal bone resorption with immediate cessation if the cement is removed in time.[6] However, if cement particles are not removed, they may shift the immune reaction to rejection of the implant.[6] Yet, there is no proof if such an unfortunate reaction may occur to impurities on implant surfaces as well. Future research will show whether this shift in the immune reactions from demarcation of bone to rejection[42] may occur as a reaction to specific surface impurities that can range from biocompatible remnants to potential toxic contaminants.

In the patients' interest, it should always be assumed that undeclared foreign substances and contaminations may lead to undesirable biologic effects—as long as they are not proven harmless and do not adversely affect the process of osseointegration. This so-called "Precautionary Principle" should always be the guideline for any medical treatment. It is noteworthy that all systems evaluated in this study were CE marked or had FDA approval. The lack of clinical studies in peer-reviewed journals does not seem to be relevant for the approval of marketing, nor does the lack of surface cleanliness. In the authors' opinion, a critical analysis of these aspects should clearly be included in a more stringent future analysis prior to the marketing of oral implant systems.

The overall S_a values of the five included ceramic implants showed that four of them were moderately rough, whereas one, the vitaclinical, was minimally rough. With metallic implants, these levels of roughness were documented with 10-year clinical outcomes and survival rates between 95% and 99%.[43] Metallic implants demonstrated a couple of percent better early clinical results for moderately rough implants[44] compared with minimally rough ones. Whether a similar difference in results exists for ceramic implants is currently unknown. Claimed evidence that some ceramic implants tested in animals displayed similar results for minimally or moderately rough surfaces must be taken with a grain of salt, since animal results may not mimic clinical outcomes and, furthermore, since no spatial information about implant surfaces was presented by Gahlert et al.[16] This does not necessarily mean that ceramic implants with minimal surface roughness will not function adequately. In cases with titanium implants, Jemt[45] found approximately 3% poorer 1-year results with minimally rough machined surfaces compared with moderately rough TiUnite surfaces, a difference that was in a similar range with the same implants at 10 years of follow-up.[43] It must be pointed out that the article by Beger et al[38] reported a moderately rough surface topography of vitaclinical implants in conflict with the findings of the present study. The most likely reason for this discrepancy is a methodologic one; Beger et al[38] did not report which parts of the implants were analyzed or whether they used any filtering, whereas the present evaluations are based on the carefully described approach by Wennerberg and Albrektsson.[21]

With respect to clinical documentation, one might argue that using the product name as a search term in the database search will not yield complete information on a specific implant system, as product names are not always included as tags for abstracts, keywords, etc. However, the scope of the present paper was not to perform a systematic review of specific implants. It is argued that manufacturers should be able to provide information on published data regarding their products. To further improve the present search, searches were added of recently published, high-quality systematic reviews on clinical trials of zirconia implants. An additional finding was that not only is clinical data lacking, but among the in vitro trials cited, only a minority were tests investigating the manufacturers' implants.

CONCLUSIONS

The results of this study suggest that there is the possibility of a relatively clean surface in ceramic implants. This should be the objective for all ceramic implants. The authors cannot conclude any specific clinical consequences caused by the types of contamination described in this article.

Surfaces of Champions-Implants (ZV3) and Z-Systems implants were relatively clean, whereas the other investigated surfaces of vitaclinical, TAV Dental, and ZiBone implants all displayed organic contaminations on their surfaces.

Whereas four of the investigated ceramic implants showed a moderately rough implant surface, one of them—the vitaclinical ceramic.implant—had minimal surface roughness.

With respect to the clinical recording of results, three ceramic designs, the vitaclinical, ZV3, and Z-Systems, had clinical trials documented for up to 3 years of follow-up, with results varying between 82.5% and 100% survival. TAV Dental W and ZiBone implant systems lacked properly conducted clinical recording of results.

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