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Ceramic abutments and ceramic oral implants. An update

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A focus of interest in implant dentistry is the application of ceramic materials for the fabrication of implant abutments as well as for dental implants. The ceramic materials of choice are currently alumina and zirconia. The present review discusses the available literature on the use of these ceramic materials in implant dentistry.

Ceramic abutments

Dental implants are considered an essential treatment modality. Published data have demonstrated high success rates for implants placed in partially edentulous arches for the replacement of both single teeth (42, 66, 88) and multiple teeth (87, 117, 121, 163, 200). However, the use of implants to replace missing teeth in the aesthetic zone is challenging (64, 127, 211). The restorations are subjected, especially in patients with a gummy smile or a high lip line, to direct visual comparison with the adjacent natural teeth (81, 118). Perfect three-dimensional implant positioning and well-designed superstructures are therefore essential to mimic the appearance of a natural tooth and to achieve an optimal aesthetic outcome (118, 197, 209). Dental implants and abutments are usually fabricated out of commercially pure titanium, primarily because of its well-documented biocompatibility and mechanical properties (2). However, despite numerous modifications to the fabrication and design of metal abutments, there is still the disadvantage of metallic components showing through when such abutments are used (81, 83, 85, 126). The resultant dull grayish background may give the soft tissue an unnatural bluish appearance (64, 118, 209). The presence of a gray gingival discoloration may be attributed to a thin gingival biotype that is incapable of blocking reflective light from the metallic abutment surface (64, 209). Gingival biotype switching has been suggested when using a metal abutment to increase the thickness of the gingiva; this thicker gingiva will block the reflective light from the abutment's surface from showing through and thus improve the aesthetic outcome (91, 104, 105, 192). Biotype switching, however, requires an additional surgical procedure, which is unpleasant for most patients (105). Recent years have shown a consistent trend toward aesthetic improvements in implant restorative materials and in treatment outcome. To achieve optimal mucogingival aesthetics, ceramic abutments were developed (Figs 1 and 2).

Development of ceramic abutments

The first ceramic abutment 'Ceramic Core' was introduced in 1993 in small and large diameters (not commercially available) (156, 157). The abutment was a prototype of alumina ceramic with resistance to shearing forces that reached values up to those of the metal–ceramic crowns (130). Compared to metal abutments, these new abutments offered optically favorable characteristics, low corrosion potential, high biocompatibility, and low thermal conductivity (156). On the other hand, restorations made out of such ceramic cores were weaker when compared to metal–ceramic restorations (98). Such controversies led to further investigations into new designs and materials for ceramic abutments. Custom-made ceramic abutments were fabricated using Alumina blocks (InCeram®, Vita, Bad Säckingen, Germany) and milled on a coping milling machine (Celay®, Mikrona, Spreitenbach, Switzerland) (198). The

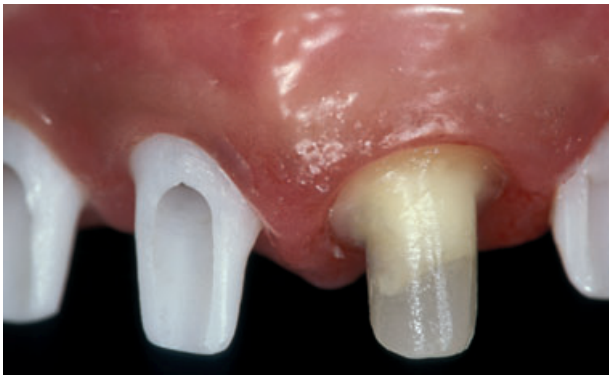

Fig. 1. Ceramic abutments (zirconia) attached to the implants intraorally. Aesthetically pleasing appearance of the soft tissue.

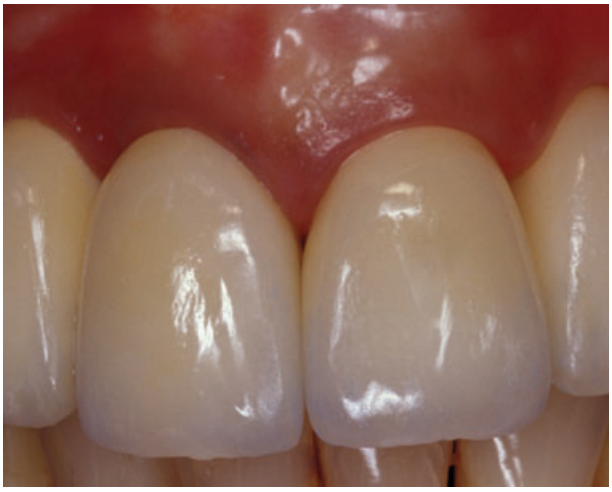

Fig. 2. The same situation as in Fig. 1 with the all-ceramic crowns cemented on to the ceramic abutments.

abutments showed improved values for resistance to fracture but they were still weaker than the CeraOne® abutments (Nobel Biocare, Göteborg, Sweden) (36, 198). Another step toward perfecting the overall aesthetic outcome was taken with the development of the customizable CerAdapt® abutment (Nobel Biocare). The abutment was made of pure, highly sintered aluminum oxide and demonstrated significantly improved resistance compared to previous abutments (13, 158). It was indicated for the fabrication of implant-supported single crowns and short-span fixed partial dentures in both anterior and premolar regions. Technically, an impression is taken at the implant level. Then, the ceramic abutment can be prepared in the dental laboratory like a die on the master cast with water-cooled rotary instruments. After a try-in of the abutment, the fabrication procedures of the restoration can be resumed, which will depend on the type and material used, following the same technique as for tooth-supported restorations. Finally, the abutment is fixed onto the implant intraorally using a CeraOne® gold screw and a torque regulator, and the final restoration can be either conventionally or adhesively cemented. Clinical studies have demonstrated high success rates of the CerAdapt® abutment (12–14). Additional attempts were made to enhance the resistance of the abutment's material by combining alumina with zirconia (136, 164). Taking advantage of computer-aided design/computer-aided manufacturing technologies, the zirconia abutment, which will be discussed later in this paper, is a recent addition to the range of ceramic abutments (209). Further design improvements led to the application of a concept in which metals were used to reinforce the ceramic abutment (24, 27). This design was intended to provide an implant abutment that presented a metal reinforcement at the implant–abutment interface and thus provided improved aesthetics combined with increased resistance to fracture (ZiReal® abutment, 3i, Palm Beach Gardens, FL, USA) (27).

Contemporary ceramic abutments

Today, the majority of implant manufacturers offer ceramic abutments. The abutments are available in pre-fabricated or customizable forms and can be prepared in the dental laboratory either by the technician or by utilizing computer-aided design/computer-aided manufacturing techniques. The materials of preference are densely sintered high-purity alumina (Al_2O_3) ceramic and yttria (Y_2O_3) -stabilized tetragonal zirconia polycrystal ceramics. These high-strength ceramics have improved mechanical properties (15, 38, 125, 180). Alumina ceramic has a flexural strength of 400 MPa, a fracture toughness value between 5 and 6 MPa/$m^{0.5}$, and a modulus of elasticity of 350 GPa (148). The yttria stabilized zirconia ceramic has twice the flexural strength of alumina ceramic (900–1400 MPa), a fracture toughness of up to 10 MPa/$m^{0.5}$, and a modulus of elasticity value of 210 GPa (38, 148). Compared to alumina ceramic, the enhanced strength of zirconia (ZrO_2) can be explained by microstructural differences, such as higher density, smaller particle size, and polymorphic mechanism against flaw propagation (38, 67). The main reason for the superior resistance of zirconia lies in the stabilizing effect of yttria, which allows the processing of zirconia in the metastable tetragonal crystalline

structure at room temperature (18°C–23°C). The tetragonal phase at room temperature allows for transformation to the monoclinic phase under stress and represents an efficient mechanism against flaw propagation. The transformation results in a compressive stress as the result of volume expansion and slows down further crack propagation, resulting in improvement of the mechanical properties (i.e. transformation toughening) (34, 38, 62).

Alumina abutments are composed of 99.5% pure alumina ceramic (15). These abutments provide certain aesthetic advantages when compared to the more whitish zirconia abutments (75, 210). In addition, the alumina ceramic is easier to prepare; this saves time during definitive preparation, which is usually performed intraorally (75, 210). The problems presented by alumina abutments include their radioopalescence at the time of radiographic examination and their weak resistance to fracture (13, 36, 198). In this context, it is commonly agreed that ceramic abutments should show proper resistance against the masticatory forces raised during chewing or swallowing. Several studies reported a mean loading force of approximately 206 N and maximum biting forces of up to 290 N in the aesthetic zone (71, 94). For a successful restoration, the abutment should present resistance to fracture values greater than such forces and, to guarantee long-term success, maintain this resistance for at least 5 years of clinical function. A study performed *in vitro* compared titanium-reinforced zirconia and pure alumina abutments for their outcome after chewing simulation and static loading. After fixation of the abutments and adhesive cementing of metal crowns, the specimens were exposed to 1.2 million cycles in a chewing simulator to simulate 5 years of clinical service. The median fracture loads were 294 N, 239 N, and 324 N for the zirconia, alumina, and titanium abutment groups, respectively. The authors concluded that titanium-reinforced zirconia abutments perform in a similar way to metal abutments, and can therefore be recommended as an aesthetic alternative for the restoration of single implants in the anterior region. Ceramic abutments made of alumina showed less favorable properties (30). However, clinical studies using alumina abutments demonstrated excellent aesthetic outcomes and favorable survival rates when accepted treatment concepts were followed and documented components were used (76). Recent studies have shown that alumina implant abutments, when used for the fabrication of implant-supported, short-span, fixed partial dentures, had a cumulative survival rate of 98.1% after an observation period of 5 years (12), whereas alumina abutments used for the fabrication of implant-supported, single crowns had cumulative survival rates between 93% and 100% after observation periods between 1 and 3 years (14, 76). Clinical studies on zirconia abutments confirmed that these abutments had a cumulative survival rate of 100% after observation periods between 4 and 6 years (64, 65).

Ceramic abutments can be restored using all-ceramic crown systems. The majority of clinical studies and case reports applied glass–ceramic crowns on alumina or zirconia abutments (65, 80, 145, 160, 209). In a study *in vitro*, the fracture resistance of such restorations was evaluated (210). Alumina and zirconia abutments were prepared and restored with glass–ceramic crowns and placed on Brånemark implants (Nobel Biocare, Göteborg, Sweden). No artificial aging was applied to the test specimens. The statistical analysis showed significant differences between both groups, with mean fracture load values of 280.1 N for the group with alumina abutments and 737.6 N for the group with zirconia abutments. The fracture resistance in the zirconia abutment group was more than twice that in the alumina abutment group (210). Recent developments in computer-aided design/computer-aided manufacturing techniques made it possible to use high-strength ceramics to fabricate implant-supported all-ceramic restorations (68, 75, 143, 145, 159). The combination of a high-strength ceramic abutment and a high-strength all-ceramic superstructure system would enhance the overall resistance of the restoration. Unfortunately, no clinical data on the success of such restorations are available. In two studies conducted *in vitro* by our group, the fracture resistance of different implant-supported, all-ceramic restorations was evaluated and compared after chewing simulation and static loading. Ninety-six implants with an internal connection design (Replace®, Nobel Biocare) were divided into one control group and two test groups of 32 specimens each. Implants in the control group received titanium abutments whereas the implants of the test groups received Procera alumina abutments and Procera zirconia abutments (both Nobel Biocare, Göteborg, Sweden; Fig. 3). The abutments were prepared to receive standardized maxillary central incisor all-ceramic crowns (analog tooth 21); half of each group received Procera alumina crowns while the other half received Procera zirconia crowns. The specimens were exposed to 1.2 million cycles in a chewing simulator to simulate 5 years of clinical service. The median fracture loads after aging were

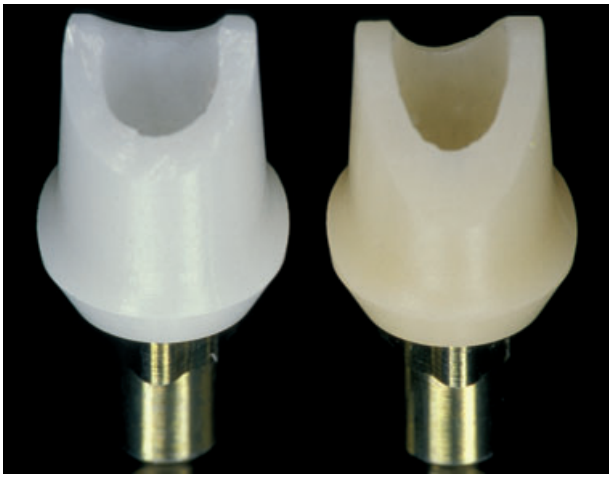

Fig. 3. Zirconia (left) and alumina (right) dental abutment with a metal base.

1454 N, 1251 N, 423 N, 241 N, 444 N, and 457 N for titanium abutment / alumina crown, titanium abutment / zirconia crown, alumina abutment / alumina crown, alumina abutment / zirconia crown, zirconia abutment / alumina crown, and zirconia abutment / zirconia crown combinations, respectively. The highest fracture resistance value was found with the titanium abutment / alumina crown combination, whereas the smallest fracture resistance was found with the alumina abutment / zirconia crown combination. We concluded that all the abutment / crown combinations tested have the potential to withstand physiological occlusal forces in the anterior region (19, 20). Compared with a previous *in vitro* study (210), it was obvious that the restorations in our study had significantly smaller values. The differences in the resistance to fracture, especially in the zirconia abutment groups, could be explained by the aging effect through environmental stresses on the abutments (abutment grinding, chewing simulator including low temperature hydrothermal degradation) (43, 48, 106, 107, 115).

Temperature peaks could alter the metastable tetragonal crystalline phase of the zirconia ceramic and there is controversy over whether this would lead to a reduction in the fracture resistance of the material (35, 48, 67, 122). Like other ceramics, zirconia is sensitive to changes in humidity and temperature, which is a particularly important issue when prosthetic applications are considered. Long-term exposure of zirconia ceramics to humidity and thermal cycling leads to a slow, low-temperature degradation of the material that might not become significant before several years have passed (128, 182, 193).

Conclusion and future developments

The diversity of contemporary materials and of methods available for the fabrication of implant-supported, all-ceramic restorations makes it difficult to select the most appropriate treatment modality. New products are constantly being added to the wide range of existing products. For example, efforts are being made to produce low-temperature, degradation-free zirconia–alumina composites for dental implant abutments (96, 97). The first short-term results are encouraging (95).

In addition to correct diagnosis and treatment planning, recognizing the properties, long-term behavior, indications, and contraindications of each material used are essential to guarantee the long-term clinical success of the restoration. Both *in vitro* and *in vivo* studies show that the indication for ceramic abutments is restricted to the fabrication of single-tooth, implant-supported all-ceramic restorations. Enhancing the resistance of the abutment will expand its application to implant-supported, all-ceramic, fixed partial dentures and restorations in the posterior region. Zirconia ceramics and abutments are being intensively investigated and are gaining in popularity. Future improvements in the ceramic will focus on its color and long-term stability. Attempts are being made to add coloring oxides to zirconia ceramic before the sintering process; this would change its whitish color and enhance the aesthetic outcome. It remains important, however, to verify the effectiveness of a suggested method before its recommendation.

Advances in computer-aided design / computer-aided manufacturing technologies, which have made the fabrication procedures of ceramic abutments and implant-supported, all-ceramic restorations faster, easier, and more efficient, are playing a major role in the growing use of ceramic abutments. Future developments will make it possible to produce more resistant abutments and restorations with higher quality and lower fabrication time and costs. Here, it should be noted that the lifetime of any dental ceramic material may be limited because of accumulating damage from the oral function (90).

Ceramic implants

Forty years ago, oral implants appeared on the market for clinical use. A variety of forms, materials, and

surface treatments evolved, some more and some less for the benefit of the patients. Today, the endosseous-cylinder/screw surface textured type of implant, made from commercially pure titanium, is considered the gold standard for the fabrication of oral implants. Titanium is applied in many fields of dentistry because of its biocompatibility, high corrosion resistance (92), and good mechanical characteristics. Commercially pure titanium has been used as an implant substrate (1, 10), as well as material for implant abutments, for many years. Numerous investigations have demonstrated the reliability of this material for both mid- and long-term use (1, 28, 77, 84, 86, 116, 200). There are some concerns that titanium might provoke unwelcome host reactions, but little evidence is available (199). Tschernitschek et al. (199) found that titanium '…can also cause chemical–biological interactions. Tissue discoloration and allergic reactions in patients who have come in contact with titanium have been reported.' A small number of investigations showed increased titanium concentrations close to titanium implants (23) and in regional lymph nodes (205). An investigation reported on titanium implant failures of which more than half were, according to the authors, the result of toxic metal ions released from the superstructure (207). In an investigation evaluating tissues from patients who underwent a revision of their hip-joint replacements, Lalor et al. (113) suggested a sensitization to titanium because monoclonal antibody labeling showed macrophages and T lymphocytes in the presence of titanium particles. However, it should be mentioned that the clinical relevance of these findings is not clear. One fact, however, is that patients – perhaps because of more or less scientific reports in the lay press, which considers metals to be harmful to the body – rely on natural health and holistic medicine where a freedom of metal contamination is part of the philosophy. With implant components produced from ceramic materials, it will be possible to render the option of metal-free treatment to patients asking for such an option.

Ceramic materials are frequently used in dentistry. The application ranges from veneering material for metal substructures, through all-ceramic posts and cores towards frameworks for crowns and bridgework. Ceramics are highly biocompatible and may improve the aesthetic appearance of dental reconstructions. Furthermore, it is well-known that ceramic materials are less prone to plaque accumulation than metal substrates (47, 162, 169).

Ceramic implants in dentistry are not new. Sandhaus (166) was one of the first to report on aluminum oxide ceramic implants (CBS = the Crystalline Bone Screw). However, the Crystalline Bone Screw showed a success rate of only 25% after an average observation period of 5 years (190). In 1987, Sandhaus (167) introduced the Cerasand (Incermed, Lausanne, Switzerland) ceramic implant but unfortunately there are no long-term data on its clinical behavior. To the knowledge of the authors, neither of these ceramic implants is available on the market any more. In 1976, Schulte & Heimke (176) introduced the aluminum oxide Tübingen implant (Frialit I; Friadent, Mannheim, Germany) for immediate implant placement in the anterior area. Besides clinical reports on this implant system (29, 60, 142, 170–175, 177, 178, 204), there are also scientific data available on the long-term behavior of this system (44, 49–51, 212, 213). Investigations showed that this material integrated well into bone and soft tissue (16, 29, 212, 213). D'Hoedt (49) reported on 924 Tübingen implants in 631 patients after approximately 10 years. A success rate of 92.5% was presented since the routine phase of 1982. There was no report in that investigation on the entire success rate from 1975 until 1985. In a subsequent comparative investigation, d'Hoedt & Schulte (51) reported the results from 1982 to 1987 and showed that only two of the 448 rehabilitations were not successful; 396 rehabilitations were successful with a 95% confidence limit of 85–92% for the success rate. No information was provided for the remaining 50 samples. No clear information could be drawn on implant success rate from that investigation. However, De Wijs et al. (45) presented a clinical evaluation over a 10-year period for 127 Tübingen implants. In 101 patients, implants were placed in the maxillary incisor, canine, and premolar regions. The authors found an overall survival rate in their investigation of 87% with a mean follow-up of 4.5 years.

Since the Frialit polycrystalline aluminum oxide implant system did not meet the expectations in terms of long-term stability, it was withdrawn from the market and eventually replaced by the titanium Frialit-II system (Friadent, Mannheim, Germany).

Another aluminum oxide implant system was the Bionit implant, which was developed by Müller, Piesold, and Glien (139, 151, 153). However, there is only limited information from laboratory investigations (150, 152, 153) and no information from clinical investigations regarding the (long-term) behavior of this implant system. The authors do not know whether this implant system is still available on the market.

Much more scientific support exists for single-crystal alumina (sapphire) oral implants. Numerous

single-crystal alumina oral implants (131, 132, 134, 135) have been placed over the last 20 years in animal (7, 8, 55, 72, 131, 133, 188) and clinical (54, 56, 57, 108–111, 185–187) investigations. This material proved to be biocompatible (214). One commercially produced single-crystal oral implant was the Bioceram implant by Kyocera (Kyoto, Japan). Koth et al. (111) and Steflik et al. (187) reported 5- and 10-year results of the single-crystal sapphire (alumina) threaded cylindrical endosteal oral Bioceram implants. Twenty-eight implants were placed in the lower jaws of 17 patients. Six weeks after implant insertion, 23 implants were included into fixed prostheses as distal abutments. Twenty-one of the 23 implants could be recalled after 10 years. The authors reported a success rate of 81%. It is noteworthy that these two investigations were included in a systematic review on the survival and complication of tooth–implant-supported fixed partial dentures (114). The estimated survivals in that review were 75.7% and 64.7% after 5 and 10 years, respectively, demonstrating survival rates lower than those of titanium implants in the same review. A further report on the long-term behavior of these sapphire implants was presented by Fartash & Arvidson (54). They reported on the treatment of total or partial edentulism with fixed prosthodontics supported by Bioceram sapphire implants. The implant system performed well in the lower jaw and in partial edentulism. This investigation was also included in the above-mentioned systematic review (114); the 10-year results showed an estimated survival of 100% for combined tooth–implant reconstructions. The same investigation by Fartash & Avidson (154) was included in a second systematic review by the same group that included only implant-supported fixed partial dentures. The estimated survival for the Bioceram implants was 96.6%. The results were similar (implant-supported) or better (implant–tooth-supported) when compared to those of titanium implants.

Another report on sapphire implants (Bioceram) used to support mandibular overdentures was presented by Berge & Gronningsaeter (22). They showed the results from 30 patients who had been treated between 1984 and 1991 and reported a cumulative survival rate for the implants of 69% over a mean observation time of 11 years. The authors concluded that the long-term results with this implant system for the use of mandibular overdenture support were inferior to those with other systems.

Except for the investigation by Fartash & Avidson (54), the single-crystal alumina implant showed inferior results to titanium implants, which might be why this implant system was not as accepted as titanium implants. According to the manufacturer, the sapphire oral Bioceram implant is no longer produced.

Although it might be common sense that alumina is prone to fracture because of its brittleness, low fracture strength, and long-term aging, fracture was only mentioned once as the reason for the loss of a maxillary posterior implant in the long-term investigations mentioned above (54). Therefore, the reason for the withdrawal of some of the alumina implant systems from the market remains unclear. It can be assumed, though, that the anxieties raised by dentists that ceramic implants are prone to fracture might have played a role. There was therefore a search for tougher ceramic materials for use as an oral implant substrate instead of alumina. The ceramic of choice – it has already been in use in orthopedics since the 1990s (31, 37, 39) – seems to be zirconia. Zirconia was introduced into dentistry in the 1990s and is currently being used as the material for posts for tooth build up, for frameworks for crown and bridgework, and for implant abutments (3, 4, 9, 17, 18, 26, 27, 53, 63, 64, 78, 79, 93, 100, 112, 123, 124, 137, 147, 155, 165, 189, 191, 193–196, 202, 203, 209, 210).

Cell culture testing of zirconia

Since zirconia is of certain interest in orthopedics and implant dentistry, its biocompatibility towards bone and soft connective and epithelial tissue is essential. To determine the biocompatibility or interactions at the biomaterial–tissue interface studies *in vitro* using cell cultures provide an important tool (Fig. 4A, B) (138). Advantages of such studies include the isolated, homogeneous nature of the culture system, a defined temporal course of events, relatively limited expense, the reproducible growth of multiple cultures, and reduced animal morbidity and mortality (40).

While early *in vitro* studies were performed with zirconia in powder form, co-cultured mostly with fibroblasts or lymphocytes – well-summarized in the reviews by Piconi et al. (148, 149) – newer experiments focused on osteoblasts and compact zirconia substrates (Table 1). Josset et al. (89) tested proliferation, and total protein and DNA content of human osteoblasts on zirconia and alumina disks with reference to control cells cultured on glass coverslips (89). They found that neither material altered the cell ploidy or the cell growth rate, which was in accordance with the absence of any inducing effect on DNA synthesis or proliferation. *In vitro* studies using

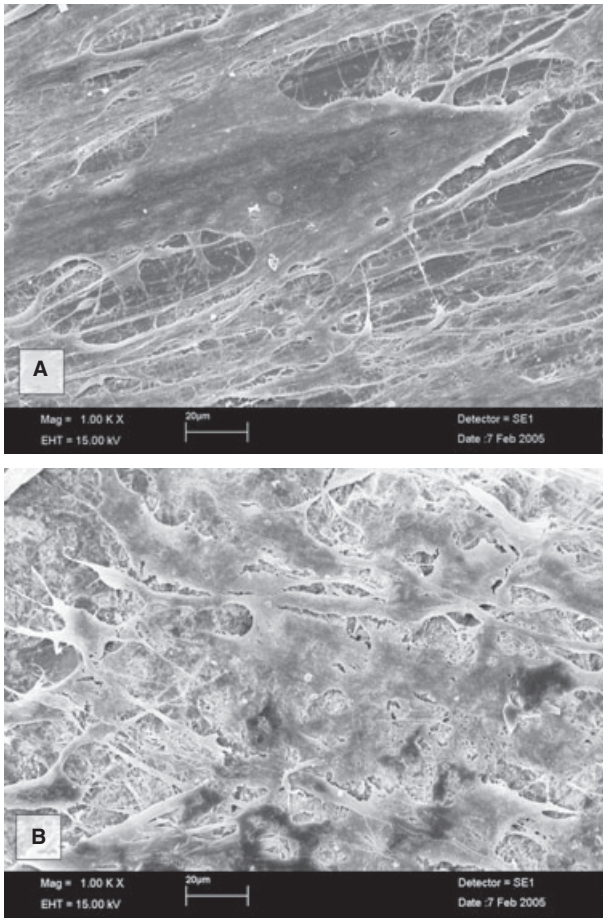

Fig. 4. Scanning electron microscopy images of primary human osteoblasts cocultured with zirconia; (A) machined substrate surface, (B) rough, air-borne particle abraded substrate surface.

human osteoblasts are considered to be of particular interest because these cells are involved in the tissue reaction at the implant site in patients (129, 161). The effect of zirconia, alumina, and titanium on the expression and secretion of the matrix metalloproteinases MMP-2, MMP-9 and their natural tissue inhibitors TIMP-1 and TIMP-2 by primary human osteoblasts was studied by Oum'hamed et al. (146). Matrix metalloproteinases (MMPs) are a family of proteolytic enzymes that are capable of degrading all the major components of the extracellular matrix (140). Their activities can be regulated by natural specific inhibitors (tissue inhibitors of metalloproteinases, TIMPs). A balance between MMPs and TIMPs is necessary for many physiological processes and an imbalance can result in a number of pathological events (32, 46, 141). MMPs play an important role in the development of osteolysis and implant loosening (120, 141). Zirconia did not have a significant effect on MMP-2 messenger RNA expression and even decreased MMP-9 expression. Whereas TIMP-2 levels were very low in this experiment, TIMP-1 increased to a maximum level at 48–72 hours. In their biomolecular study Carinci et al. (33) determined the genetic effect of zirconia on an osteoblast-like cell line (MG63) using microarray slides with 19,200 different oligonucleotides. Several genes were identified of which the expression was either up- or down-regulated. It was shown that zirconia was able to modulate immunity, vesicular transport, and cell cycle regulation. The authors suggested that the regulation of immunity may positively affect the foreign body reaction *in vivo*, allowing for a close apposition of bone, as found in histological studies (5, 6, 52, 82, 168, 179). Furthermore, it was concluded that the regulation of vesicular transport and cell cycle mechanisms might produce modifications in the turnover of extracellular matrix and in the proliferation of osteoblasts. Using another approach, the effect of zirconia surface property modification on human fetal osteoblasts was analyzed (69, 70). Carbon dioxide laser treatment was applied on magnesia partially stabilized zirconia (69) and yttria partially stabilized zirconia (70). The surface of the magnesia partially stabilized zirconia was roughened and the polar component of the surface energy was enhanced by the laser treatment, resulting in an increased number of cells attaching and spreading compared to the untreated control. In contrast, the surface of yttria partially stabilized zirconia was smoothed by carbon dioxide laser irradiation. Nevertheless, cell attachment was also increased, probably as a result of surface energy enhancement, i.e. alterations in the wettability characteristics. A recent investigation evaluated differently roughened yttrium-stabilized tetragonal zirconia polycrystal samples using the CAL72 osteoblast-like cell line (21). This investigation showed that there was no difference in cell proliferation between the different materials and surfaces later in the culture. From their results the authors concluded that the yttrium-stabilized tetragonal zirconia polycrystal material used might be an appropriate substrate for the proliferation and spreading of osteoblastic cells.

Further studies *in vitro* are required to understand the behavior of osteoblasts on zirconia substrates more comprehensively. So far, little is known about the effects of zirconia on gene / extracellular matrix protein expression patterns (183) and healing-specific enzyme kinetics. Since surface topography has proven to be one of the key factors in bone–titanium integration (208), this may be another field that needs to be addressed in future studies.

Table 1. Summary of cell culture studies involving compact zirconia substrates

Reference	Material	Cell type	Test	Main findings
Josset et al. (89)	Zirconia Alumina Glass	Primary human osteoblasts	Cell proliferation Total protein synthesis Cell morphology Evidence of osteoblastic proteins Carcinogenicity (DNA image cytometry Ag-NORs quantification)	No adverse response
Oum'hamed et al. (146)	Zirconia Alumina Titanium	Primary human osteoblasts	Expression analysis of MMP-2, MMP-9, TIMP-1, TIMP-2	No effect on MMP-2, decrease of MMP-9, increase of TIMP-1
Carinci et al. (33)	Zirconia	Osteoblast-like MG63 cells	Gene expression analysis (DNA microarray)	Modulation of immunity, vesicular transport, and cell cycle regulation
Hao et al. (69)	Zirconia* (MgO-PSZ)	Human fetal osteoblast cells (hFOB 1.19)	Surface analysis Cell proliferation Cell adhesion	Increase of cell attachment and spreading by surface treatment
Hao et al. (70)	Zirconia* (Y-PSZ)	Human fetal osteoblast cells (hFOB 1.19)	Surface analysis Cell adhesion	Increase of cell attachment by surface treatment
Bächle et al. (21)	Zirconia (Y-TZP)	CAL72 osteoblast-like cells	Cell proliferation Cell morphology Cell-covered surface area	No adverse response Similar cell proliferation of different substrates

*Carbon dioxide laser irradiation.

Ag-NOR, argyrophilic nuclear organizer region; MgO-PSZ, magnesia partially stabilized zirconia; MMP, matrix metalloproteinase; TIMP, tissue inhibitor of metalloproteinases; Y-PSZ, yttria partially stabilized zirconia; Y-TZP, yttria partially stabilized zirconia.

Zirconia oral implants

Zirconia was applied relatively early as a coating material for oral implants in animal investigations. In 1975, Cranin et al. (41) used zirconia flame-spray-deposition-coated Vitallium implants in beagle dogs. They showed that five of nine zirconia-coated implants were surrounded by connective tissue and that the results were not satisfactory. In a histological interface analysis of titanium and zirconium bone implants, Albrektsson et al. (11) observed a fibrous, tissue-free zone with a 20- to 40-nm thick proteoglycan layer at the titanium implants. At a distance of approximately 100 nm, collagen bundles were detected. The proteoglycan zone at the zirconia-coated implants showed a thickness of 30–50 nm and the collagen fibers were further apart from zirconia compared to titanium. From these two earlier investigations, it could be concluded that zirconia might not be an adequate alternative to titanium for implant fabrication. Further investigations in the early 1990s (73, 74) compared the biocompatibility of alumina, zirconia, and stainless steel in dogs. In several experiments it was shown that the affinity of bone towards the different materials was not different. However, the authors reported on thin intervening fibrous membranes between the bone and the implants. There was no detailed description of the kind of soft tissue that was found.

In a histomorphometric study in rats, Fini et al. (58) evaluated implants of different materials placed in the femur (hydroxyapatite, titanium alloy, yttrium partially stabilized zirconia, alumina, and two biological glasses). In non-ovariectomized rats there were no significant differences regarding the affinity index of bone towards the different implant materials (hydroxyapatite 77.0%, zirconium 58.2%, titanium alloy 61.2%).

Summarizing the results of later investigations, it seems that the bone integration of zirconia has im-

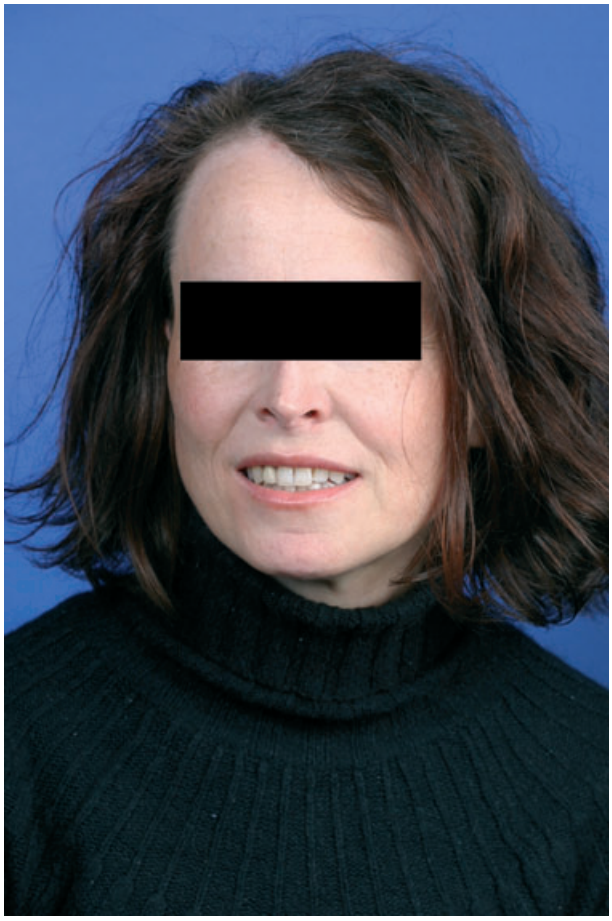

Fig. 5. En-face photograph of a patient participating in the clinical investigation on zirconia implants.

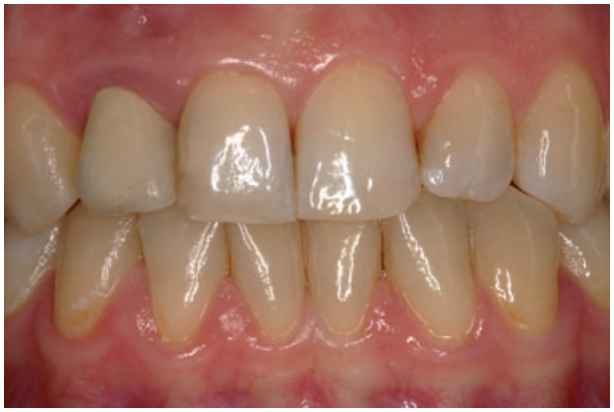

Fig. 6. Overview (retracted lips). Tooth 12 (FDI nomenclature) is restored with an insufficient crown which had to be re-cemented several times.

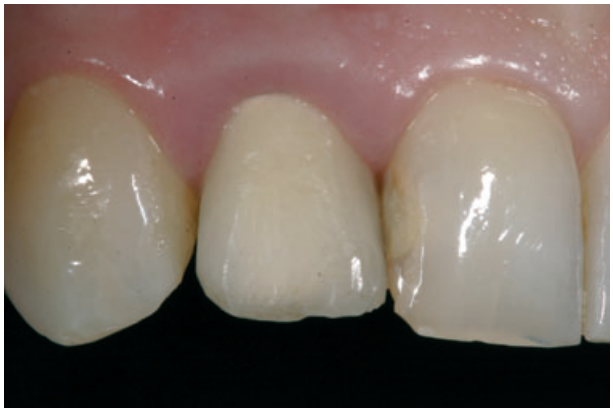

Fig. 7. Close-up of Fig. 6. Marginal gingival inflammation is visible. The papillae towards the neighboring teeth are present.

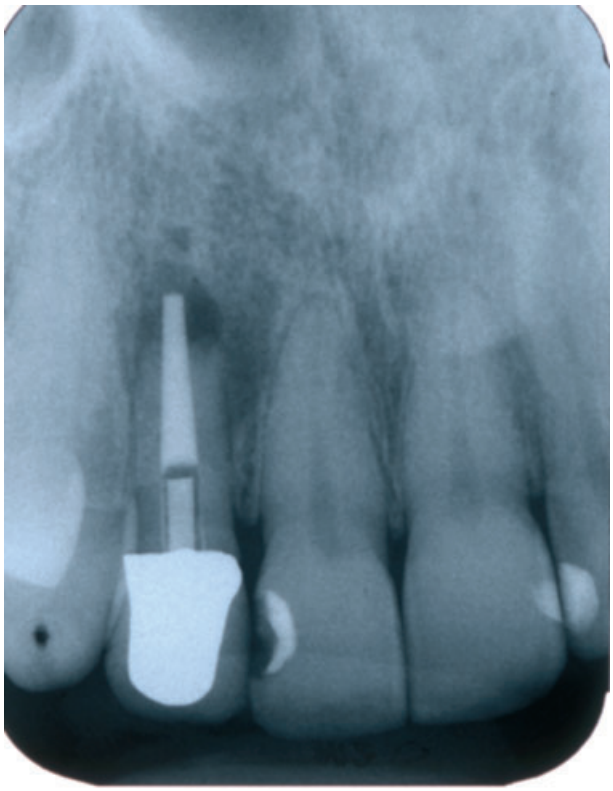

Fig. 8. A periapical radiograph showing an apical radiolucency (result of an apicectomy) as well as a transdental fixation. The crown is insufficiently attached to the tooth with an endodontic post.

proved and is no longer different to that of titanium (59, 119, 168, 179). This might be because of refinements made in the preparation and production of zirconia materials.

Akagawa et al. (6) were the first to report the use of oral implants made of zirconia in beagle dogs. In their experiment they evaluated loaded (1 week after implant placement) and unloaded zirconia dental implants. Histology was performed 3 months after implant placement. The authors reported that no implant was mobile and no fracture occurred during the experiment. Direct bone apposition to the implant could be observed in both treatment groups. The bone-to-implant contact ratio was 81.9% for the

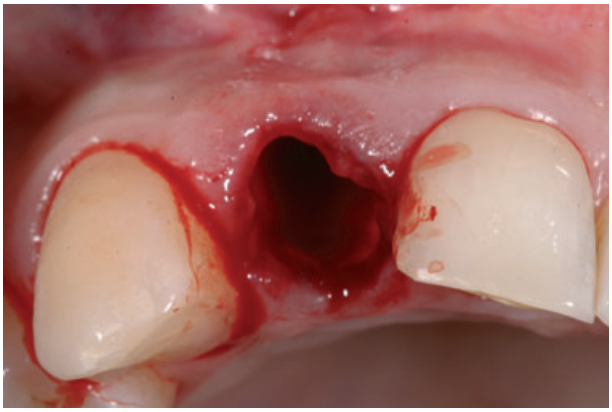

Fig. 9. The tooth was extracted with caution so as not to damage the soft and hard tissues. After tooth extraction, there was an alveolar defect of the buccal bone, which was treated according to the guided bone regeneration principle and with a soft connective tissue graft in the same session (treatment not shown).

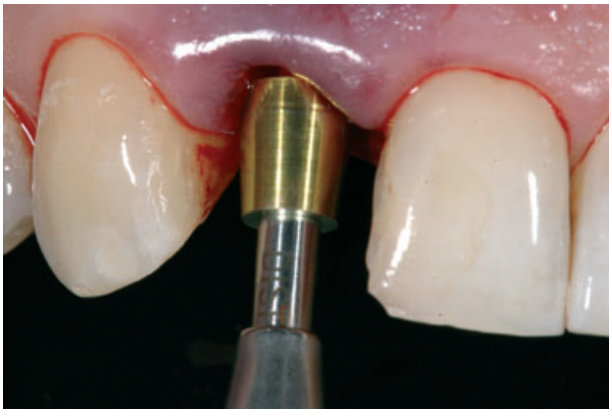

Fig. 10. Initial drilling with a 2-mm twist drill and a direction aid.

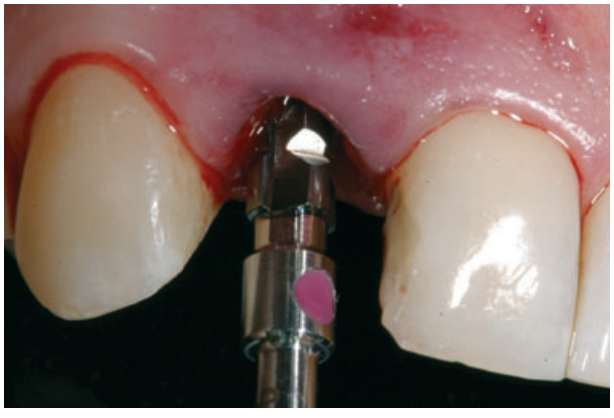

Fig. 11. Subsequent enlargement of the implant osteotomy with the respective drills.

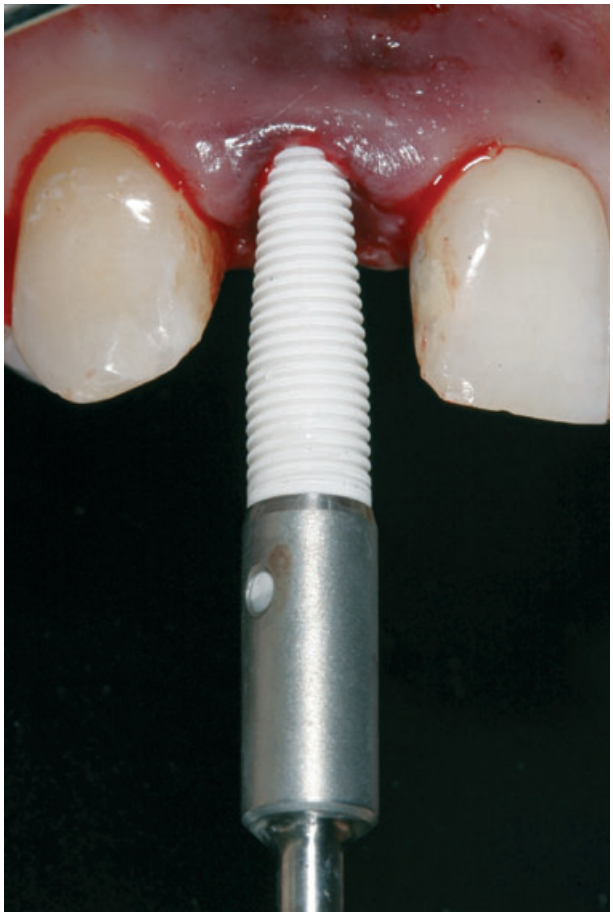

Fig. 12. Insertion of the ceramic implant.

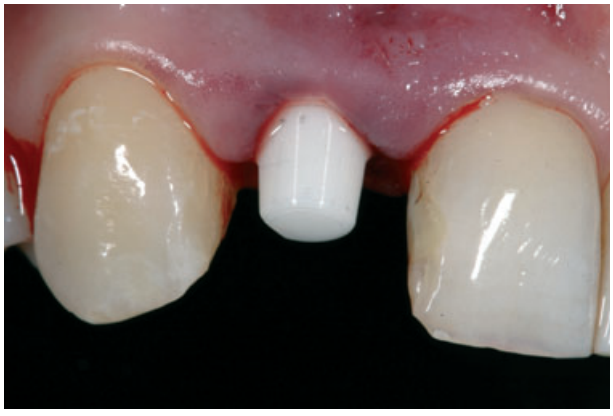

Fig. 13. Placement of the implant to the correct depth so that only the implant head is visible.

nonloaded implants and 69.8% for the loaded group and the loaded group showed more loss of marginal bone than the nonloaded group. Unfortunately, no titanium control group was included for comparison. In a second investigation, Akagawa et al. (5) compared entirely implant-borne reconstructions with implant–tooth-connected restorations in monkeys. Again, implants fabricated from partially stabilized zirconia were inserted into the mandibles of eight monkeys and 3 months later three different types of superstructures were provided (single crowns on

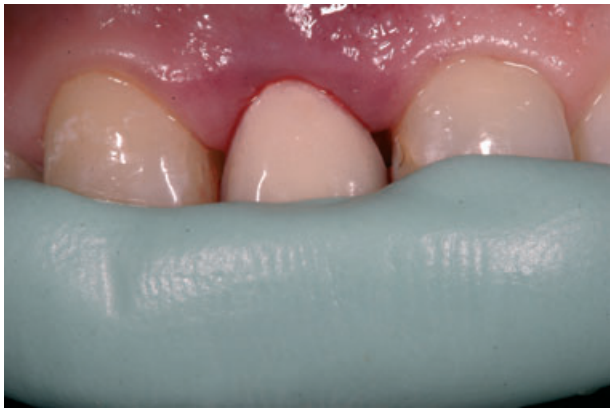

Fig. 14. Adaptation of the temporary to the clinical situation and subsequent relining.

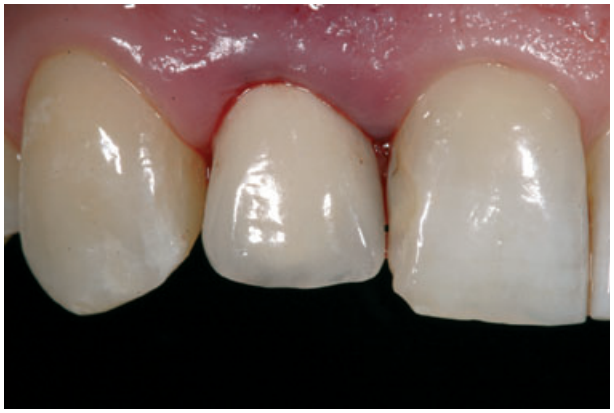

Fig. 15. The provisional is cemented with temporary cement at the end of session.

implants, implant-borne connected restorations, or implant–tooth-supported reconstructions). Clinically, there were no differences between the groups. Histology was performed after 12 and 24 months. Direct bone apposition was observed in all groups. Histomorphometry showed bone-to-implant contact between 66 and 81%. In general, there was no significant difference between the different treatment groups.

Our group was the first to compare loaded titanium implants with loaded zirconia implants in the same model (103). Twelve custom-made titanium and 12 zirconia implants were inserted in the upper anterior jaw of six monkeys. Six months after implant installation single crowns were fabricated and inserted on all implants. Five months after crown installation (i.e. the loading time) the implants, with their soft and hard tissues, were harvested and evaluated microscopically. No implant was lost over the observation period. There were no statistically significant differences in the soft tissues around the titanium and zirconia implants and no differences in respect to the

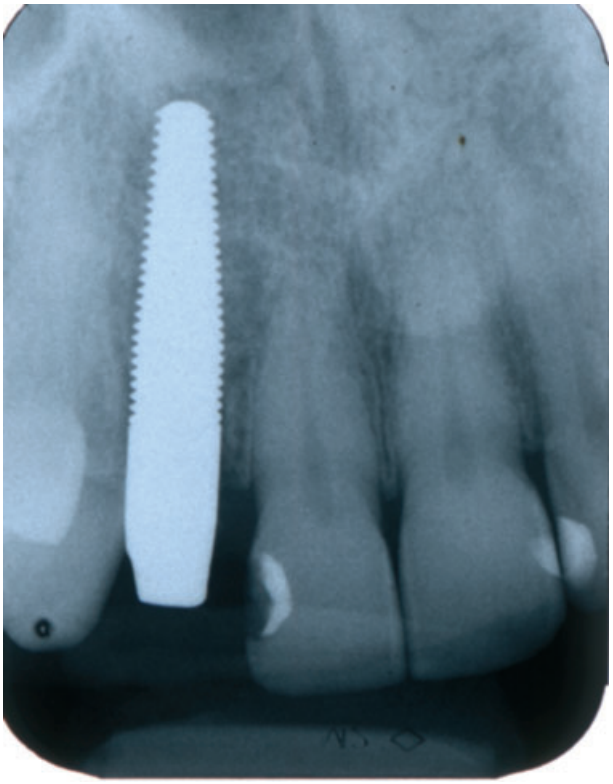

Fig. 16. Standardized periapical radiograph after implant placement showing the implant position in the mesiodistal and apicocoronal direction.

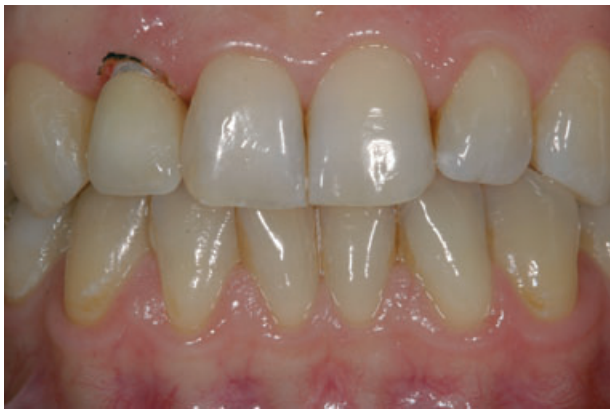

Fig. 17. Clinical appearance 13 weeks after installation of implant. Marginal soft tissue overgrowth made it necessary for a minor gingivectomy to be performed at the periimplant mucosal margin.

bone-to-implant contact between the two materials (titanium 72.9%; zirconia 67.4%). The surface treatments used to change the surface topography for the titanium implants included air-borne particle abrasion and acid etching. The zirconia implants, however, were only air-borne particle abraded because acid etching had no effect on zirconia (unpublished data). So far, air-borne particle abrasion has been the

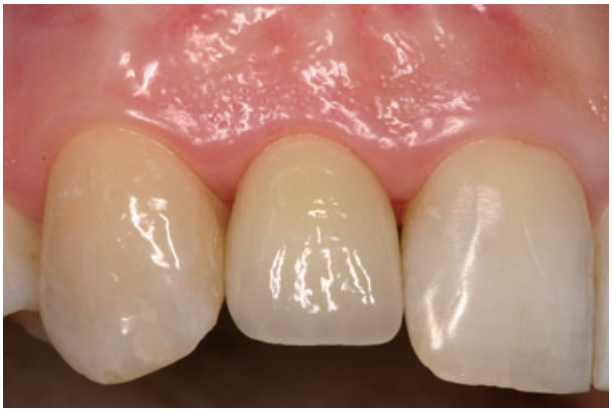

Fig. 18. Close-up of the final restoration with the clinical appearance of the red and white aesthetics. Slight recession of the interdental papillae can be observed.

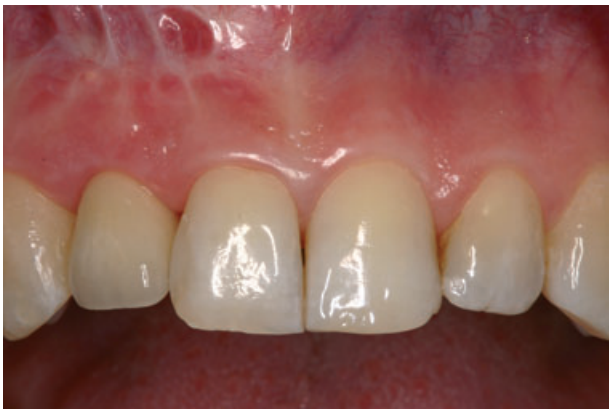

Fig. 19. Situation with retracted lips. The dental and soft tissue symmetry is not perfect when tooth 12 is compared to tooth 22 but the overall result is satisfactory.

method of choice for increasing the surface roughness of zirconia. However, Sennerby et al. (181) developed a technique that was different to air-borne particle abrasion to achieve a porous surface. They coated zirconia implants with slurry containing zirconia powder and a pore-former. While sintering the coating the pore-former was burned and a porous surface was the result. Their topographic analyses showed that the zirconia implant surface modified in this way resembled the well-known TiUnite® surface (Nobel Biocare, Goteborg, Sweden). The authors installed threaded zirconia implants with either a machined surface or one of two surface modifications into the tibia and femur of rabbits. Oxidized titanium implants served as controls. Removal torque tests showed higher values for the surface-modified zirconia implants than for the titanium implants. The lowest values were found for the machined zirconia implants. However, no significant differences regarding bone-to-implant contact and bone area

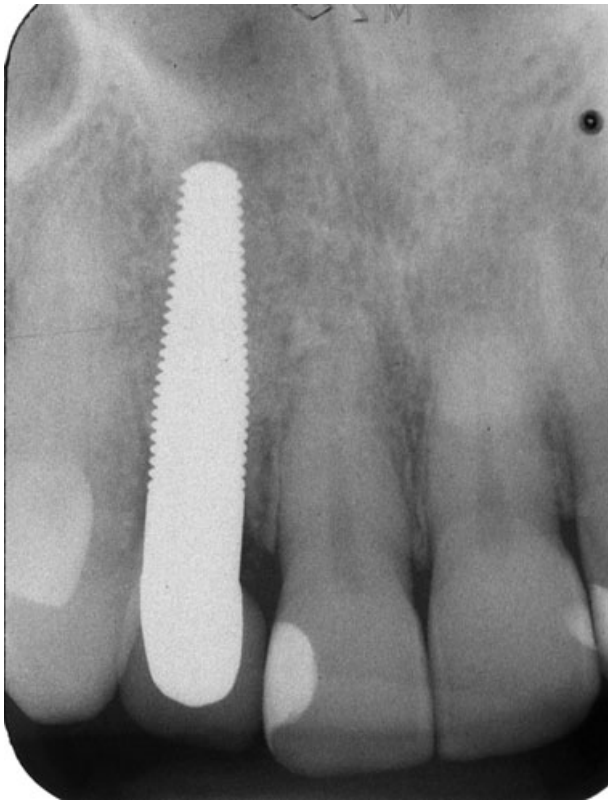

Fig. 20. Standardized periapical radiograph after crown placement.

filling could be observed between the different treatment groups. Another two animal investigations showed that zirconia implants undergo osseointegration and that a rough surface is of benefit (61, 184).

Biomechanical investigations on zirconia oral implants are rare in the literature. In a three-dimensional finite element analysis, the stress distribution patterns of implants made of commercially pure titanium and yttrium partially stabilized zirconia were analyzed. Two three-dimensional finite element analysis models of a maxillary incisor with Re-Implant (Hagen, Germany) implants (99) were made, surrounded by cortical and cancellous bone. A porcelain-fused-to-metal crown for the commercially pure titanium implant and a ceramic crown for the yttrium partially stabilized zirconia implant were modeled and the stress levels were calculated according to von Mises criteria. Yttrium partially stabilized zirconia implants had similar stress distribution to commercially pure titanium implants (102). In another investigation by our group on biomechanical behavior, two groups of two-piece zirconia implants were tested in the artificial mouth (101). The implants restored with Procera crowns seemed possibly to fulfill the biomechanical

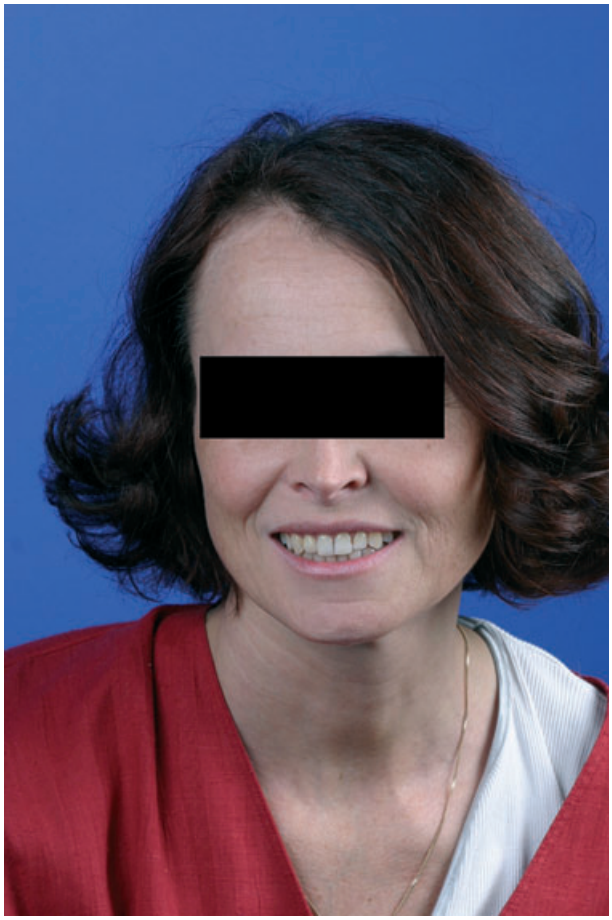

Fig. 21. Final facial photograph shows a harmonic smile.

requirements for anterior teeth, showing mean fracture loads of the crowns of 575.7 N when not artificially loaded and 555.5 N when aged in a chewing simulator for 1.2 million cycles. Further testing *in vitro* (i.e. artificial mouth) mimicking long-term clinical service would surely be of benefit to obtain additional information on the long-term fatigue behavior of zirconia implants.

Although there have been reports of problems with zirconia (e.g. increased fracture rate of hip prosthesis), which occurred some years ago in orthopedics (34, 206), the zirconia production process for medical applications is currently one of the best-controlled fabrication processes in industry. High reproducibility and constant production chains seem to ensure a high quality of zirconia products for medical applications so zirconia appears to be the ceramic material of choice for metal-free reconstructions in implant dentistry.

However, regarding the clinical use of zirconia oral implants, scientific information is lacking. To the authors' knowledge there are only two clinical patient case reports using zirconia implants and two retrospective observational case series published in the international literature. The first report on the application of a zirconia implant – crown system in a patient dated from 2004 (100). The authors used a custom-made two-piece dental implant to replace a left upper central incisor. After an unloaded healing period of 6 months, abutment connection was performed using a pre-fabricated zirconia abutment, which was cemented to the implant with Panavia (Kuraray, Osaka, Japan). The implant was subsequently restored with a zirconia-based single crown. A second report presented a patient case in which eight, one-piece zirconia implants had been placed. After implant placement the patient had to wear a protective splint over a 6-month period for 24 hours a day. After that time the implants were restored with zirconia crowns (201). There was, however, no follow-up presented on either of the two reports.

Two clinical retrospective case series were reported by the developers of two different zirconia ceramic implant systems (25, 144). However, because of bias the scientific value of these reports is questionable. Furthermore, the authors did not clearly state the aim of their investigation nor the inclusion or exclusion criteria used. No additional parameters (radiographic bone remodelling, soft tissue health, mobility) were evaluated. The only result that was reported was the 'survival' rate in per cent. The level of evidence in these two clinical reports might therefore be regarded as very low.

There are currently five zirconia implant systems commercially available. Sandhaus, again, was the first to develop a zirconia implant system in 1987: the SIGMA implant system (Incermed, Lausanne, Switzerland). Further zirconia implant systems are the Ceraroot system (Ceraroot, Barcelona, Spain), the White Sky system (Bredent Medical, Senden, Germany), the z-systems implant system (z-systems, Konstanz, Germany), and the zit-z ceramic implant system (Ziterion GmbH, Uffenheim, Germany). However, there are no data on the histological and biomechanical behavior of these different implant systems in the international literature. Furthermore, no scientific short-, middle- or long-term clinical data on the above-mentioned zirconia implant systems can be found.

The only prospective ongoing clinical evaluation on zirconia implants of which the authors are aware is on a one-piece yttria-stabilized tetragonal zirconia polycrystal reinforced with alumina implant with an implant surface modification similar to that presented by Sennerby et al. (181). This investigation is

being performed at the Department of Prosthodontics at the University of Freiburg, Germany. So far, 92 patients have received 119 implants: 65 patients received one implant (Figs 5–21) and 27 patients received two implants each for a three-unit bridge. All implants were immediately temporized with composite temporary crowns or bridges. After an observation time of up to 1 year four implants have so far been lost, giving a cumulative survival rate of 96.6%. Besides clinical measurements, aesthetic measurements are also being performed, and bone modeling / remodeling will be evaluated using standardized radiographs.

Since the clinical use of zirconia implants lacks scientific support, the authors do not currently recommend their use. Prospective clinical investigations are needed before these implant systems can be recommended for clinical use.

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