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Journal of Prosthodontic Research 57 (2013) 236–261

Journal of Prosthodontic Research

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Review

Current status of zirconia restoration

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Received 27 August 2013; received in revised form 6 September 2013; accepted 6 September 2013
Available online 18 October 2013

Abstract

During the past decade, zirconia-based ceramics have been successfully introduced into the clinic to fabricate fixed dental prostheses (FDPs), along with a dental computer-aided/computer-aided manufacturing (CAD/CAM) system. In this article (1) development of dental ceramics, (2) the current status of dental CAD/CAM systems, (3) CAD/CAM and zirconia restoration, (4) bond between zirconia and veneering ceramics, (5) bond of zirconia with resin-based luting agents, (6) surface finish of zirconia restoration and antagonist enamel wear, and (7) clinical evaluation of zirconia restoration are reviewed.

Yttria partially stabilized tetragonal zirconia polycrystalline (Y-TZP) showed better mechanical properties and superior resistance to fracture than other conventional dental ceramics. Furthermore, ceria-stabilized tetragonal zirconia polycrystalline and alumina nanocomposites (Ce-TZP/A) had the highest fracture toughness and had resistance to low-temperature aging degradation. Both zirconia-based ceramics have been clinically available as an alternative to the metal framework for fixed dental prostheses (FDPs). Marginal adaptation of zirconia-based FDPs is acceptable for clinical application. The most frequent clinical complication with zirconia-based FDPs was chipping of the veneering porcelain that was affected by many factors. The mechanism for the bonding between zirconia and veneering ceramics remains unknown. There was no clear evidence of chemical bonding and the bond strength between zirconia and porcelain was lower than that between metal and porcelain.

There were two alternatives proposed that might avoid chipping of veneering porcelains. One was hybrid-structured FDPs comprising CAD/CAM-fabricated porcelain parts adhering to a CAD/CAM fabricated zirconia framework. Another option was full-contour zirconia FDPs using high translucent zirconia. Combined application of silica coating and/or silane coupler, and 10-methacryloyloxydecyl dihydrogen phosphate is currently one of the most reliable bonding systems for zirconia. Adhesive treatments could be applied to luting the restorations and fabricating hybrid-structured FDPs. Full-contour zirconia FDPs caused concern about the wear of antagonist enamel, because the hardness of Y-TZP was over double that of porcelain. However, this review demonstrates that highly polished zirconia yielded lower antagonist wear compared with porcelains. Polishing of zirconia is possible, but glazing is not recommended for the surface finish of zirconia.

Clinical data since 2010 are included in this review. The zirconia frameworks rarely got damaged in many cases and complications often occurred in the veneering ceramic materials. Further clinical studies with larger sample sizes and longer follow-up periods are required to investigate the possible influencing factors of technical failures.

Keywords: Dental CAD/CAM; FDPs; Zirconia; Polishing; Friction; Antagonist wear; Full contour

Contents

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1883-1958/$ – see front matter
http://dx.doi.org/10.1016/j.jpor.2013.09.001

1. Introduction

Developments in routine dental practice, including prosthodontic treatments, are often driven by the introduction of new dental materials and processing technologies. Dental prostheses such as crowns, fixed dental prostheses (FDPs), and removable dental prostheses are fabricated from a variety of dental materials using a range of dental laboratory processes. Because of the popularity of osseo-integrated implants, the application of fixed prostheses has expanded, even in the edentulous situation.

Development of both casting gold alloys and precision dental casting technologies has contributed to the application of metallic prostheses. However, because of the recent demand from patients for esthetics and biosafety, metal-free prostheses have been desired. Both new dental materials and new processing technologies are required to meet these patient demands.

During the past decade, new dental ceramic materials such as glass ceramics, poly-crystalline alumina, and zirconia-based ceramics have been successfully introduced into the clinic, along with new processing technology, i.e. computer-assisted fabrication systems [dental computer-assisted design/computer-assisted manufacturing (CAD/CAM)].

In this article we discuss: (1) development of dental ceramics, (2) the current status of dental CAD/CAM systems, (3) CAD/CAM and zirconia restoration, (4) the bond between zirconia and veneering ceramics, (5) bond of zirconia with resin-based luting agents, (6) surface finish of zirconia restoration and antagonist enamel wear, and (7) clinical evaluation of zirconia restoration.

2. Development of dental ceramics

Porcelain has been used in dentistry for 100 years. Esthetics is the major advantage of porcelain, and brittleness is its weakest point for load-bearing restorations. The conventional powder build-up and firing process was innovative but is still very technically sensitive. Therefore, porcelain-fused-to-metal (PFM) restorations to make ‘‘metal-ceramic restorations’’ has been the first choice of prostheses to satisfy requirements for esthetics, durability, and fit to the abutments [1,2].

Two main types of all-ceramic FDP systems are proposed. The first system involves using a single material for full-contour crowns. Reinforced glassy materials were successfully used to make single crowns for anterior and premolar regions. Recently, polycrystalline zirconia with improved translucency has been used for full-contour crowns in the molar region [3].

Table 1
Classification of ceramics for fixed prostheses by intended clinical use (ISO 6872:2008).

Class	Recommended clinical indications	Mechanical and chemical properties	
		Flexural strength minimum (mean), MPa	Chemical solubility maximum, $\mu g\ cm^{-2}$
1	(a) Esthetic ceramic for coverage of a metal or a ceramic substructure	50	100
	(b) Esthetic-ceramic: single-unit anterior prostheses, veneers, inlays, or onlays		
2	(a) Esthetic-ceramic: adhesively cemented, single-unit, anterior or posterior prostheses	100	100
	(b) Adhesively cemented, substructure ceramic for single-unit anterior or posterior prostheses	100	2000
3	Esthetic-ceramic: non-adhesively cemented, single-unit, anterior or posterior prostheses	300	100
4	(a) Substructure ceramic for non-adhesively cemented, single-unit, anterior or posterior prostheses	300	2000
	(b) Substructure ceramic for three-unit prostheses not involving molar restoration		
5	Substructure ceramic for three-unit prostheses involving molar restoration	500	2000
6	Substructure ceramic for prostheses involving four or more units	800	100

The second system is to fuse esthetic ceramics, such as porcelain and other glassy materials, to frameworks made of high-strength ceramics instead of alloys. Dense sintered polycrystalline zirconia-based material is promising for frameworks of FDPs [4–6].

The mechanical properties of brittle ceramics are characterized by fracture toughness and flexural strength [7] (Table 1). Conventional porcelain is a partially glassy material; its fracture toughness is approximately 1.0 MPa $m^{1/2}$ and flexural strength is approximately 100 MPa. This material is not suitable for load-bearing molar restorations. Initially, porcelain was reinforced by dispersing crystals within it. Aluminous porcelain was widely available. Since the conventional powder build-up and firing procedure is sensitive to technique, new, easier-to-work-with ceramic materials were needed. To respond to this demand, castable and pressable ceramics were developed and are available for single esthetic restorations. In addition, prefabricated reinforced glass ceramic blocks are available for milling using a CAD/CAM device. These materials have fracture toughnesses from 1.5 to 3.0 MPa $m^{1/2}$. However, these ceramics are still only available for single restorations.

Another type of ceramic includes alumina and other fine ceramic powders that are porously sintered; the pores are then infiltrated with glass to give "glass-infiltrated ceramics," with fracture toughnesses from 3 to 5 MPa $m^{1/2}$. These materials have been applied to fixed partial dentures, but the prognosis was not satisfactory.

Finally, industrial dense polycrystalline ceramics such as alumina, zirconia, and alumina-zirconia composites are currently available for use with CAD/CAM technology via a networked machining center. In particular, yttrium partially stabilized tetragonal zirconia polycrystalline (Y-TZP) shows better mechanical properties and superior resistance to fracture. Y-TZP has a high fracture toughness, from 5 to 10 MPa $m^{1/2}$, and a flexural strength of 900–1400 MPa [8,9].

When a crack initiates on the surface of Y-TZP, the stress concentration at the top of the crack causes the tetragonal crystal to transform into a monoclinic crystal, with associated volumetric expansion. In the vicinity of a propagating crack, the stress-induced transformation leads to compressive stress that shields the crack tip from the applied stress and enhances the fracture toughness [10].

Ceria-stabilized tetragonal zirconia polycrystalline (Ce-TZP) showed much higher fracture toughness of 19 MPa $m^{1/2}$ but lower flexural strength and hardness than Y-TZP. Ce-TZP has not been applied in the dental field. Ce-TZP/alumina nanocomposites (Ce-TZP/A) were developed to improve Ce-TZP [11]. Ce-TZP/A consists of nanometer-sized Al_2O_3 particles that are dispersed within the Ce-TZP grains and grain boundaries, and nanometer-sized Ce-TZP particles that are dispersed within the alumina grains and grain boundaries. This homogeneous dispersion of alumina in the Ce-TZP matrix suppresses grain growth and increases hardness, flexural strength, and hydrothermal stability of tetragonal zirconia while preserving its toughness [11]. Ce-TZP/A is the toughest dental ceramic material available, with a fracture toughness of 19 MPa $m^{1/2}$, and a flexural strength of 1400 MPa [12]. Y-TZP suffers from low-temperature aging degradation (LTAD) caused by phase transformation, whereas Ce-TZP/A has complete resistance to LTAD [13].

These improved characteristics are expected to expand the clinical application of dental ceramics to not only all-ceramic restorations, but also other fields such as the abutment of implants, implant bodies, and removable denture bases and parts.

3. CAD/CAM and zirconia restoration

3.1. The current status of dental CAD/CAM

CAD/CAM technology was introduced into dentistry, and FDPs could be fabricated using a series of steps, as shown in Fig. 1. The intraoral abutment was scanned by an intraoral digitizer to obtain an optical impression. Digitized data were reconstructed as 3-D graphics on the monitor and the optimal morphology for the FDPs was virtually designed on the monitor. Real FDPs were fabricated by milling a block using a numerically-controlled machine.

Since there were difficulties in digitizing the intraoral abutment accurately using a direct intraoral scanner, we decided to prepare a conventional stone model to begin the CAD/CAM process for the fabrication of crowns, especially for

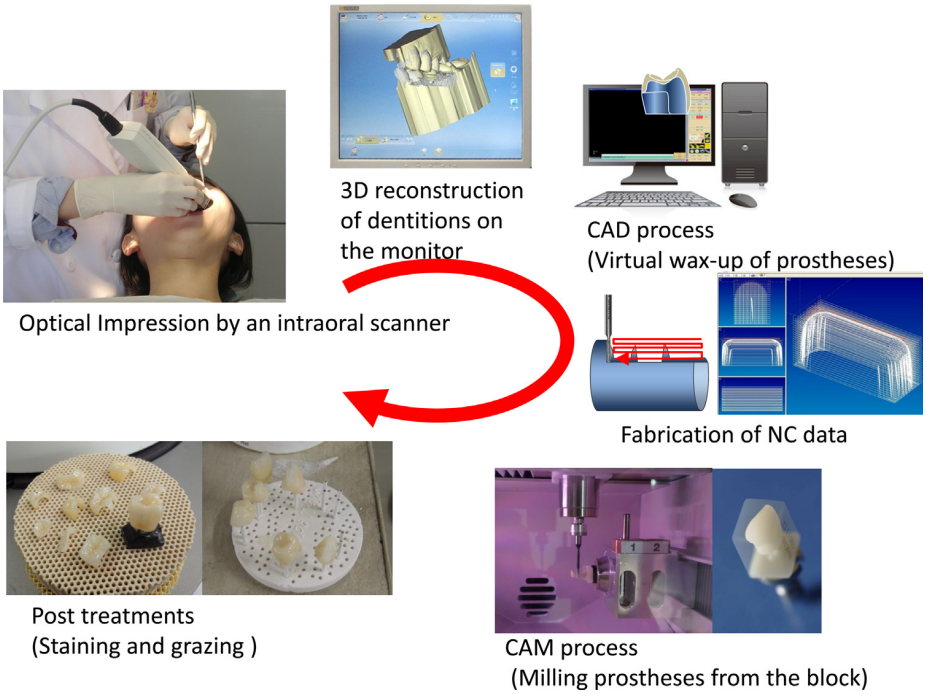

Fig. 1. A process of digital fabrication system of FDPs.

Table 2
Current dental CAD/CAM systems available in the world market.

CAD/CAM system (Company)	Scanner	Milling machine	Prostheses				Materials					Central production center
			Inlay	Veneer	Crown	Bridge	Resin	Titanium	Porcelain	Alumina	Zirconia	
Everest & Arctica (KaVo electrotechnical work GmbH)	Original	Original	○	○	○	○		○	○		○	○
Lava (3 M ESPE Dental AG)	Original & OEM	Original			○	○		○	○		○	○
Procera (Nobel Biocare Germany GmbH)	Original & OEM	Original		○	○	○		○	○	○	○	○
Cercon smart ceramics (DeguDent GmbH)	Original & OEM	Original			○	○					○	○
CEREC AC (Sirona Dental of system GmbH)	Original	Original	○	○	○	○			○		○	○
Hint-ELs system (Hint-ELs DentaCAD systems)	Original	Original	○		○	○	○	○	○		○	?
Aadva system (GC)	Original & OEM	Original	○	○	○	○	○	○	○	○	○	○
C-Pro system (Panasonic dental)	OEM	Original			○	○				Nano-composite		○
Katana (Kuraray noritake dental)	OEM	OEM			○	○					○	○
ZENO® Tec System (Wieland)	OEM	OEM			○	○					○	○

dental laboratory use. Different digitizers such as a contact probe, laser beam with position sensitive detector sensor, and laser with a CCD camera were developed. In addition, sophisticated CAD software and compact dental CAD/CAM machines were developed. Both metallic and ceramic restorations were fabricated by the second-generation CAD/CAM systems [14].

Later, networked CAD/CAM systems were available, and all-ceramic frameworks using industrial dense sintered polycrystalline alumina were available in the clinic. Since these

high-strength industrial ceramics were not available to the conventional dental laboratory, the application of networked CAD/CAM, located in a processing center, was a tremendous innovation in the history of dental technology. Such networked production systems are currently being introduced by a number of companies worldwide. Currently, the production of zirconia frameworks is the most popular use of this approach in the world market (Table 2).

The application of CAD/CAM is currently limited to laboratory processing. For example, even if the zirconia framework is fabricated using a CAD/CAM process in the machining center, final restorations are completed by dental technicians veneering conventional porcelain using conventional manual dental technology. Nevertheless, there are advantages to the introduction of CAD/CAM, such as the introduction of new, safe, esthetic, and durable materials, an increase in the efficiency of laboratory processing, earlier function of restoration, and better quality control of restorations, for improved fit, mechanical durability, and predictability.

Furthermore, the veneering part of zirconia all-ceramic FDPs was also fabricated by a CAD/CAM process from a block of glassy materials. A new fabrication system for digital veneering was introduced [15].

Because of the rapid progress in new technologies, especially optical technology, new intraoral digitizers are available. Information about these systems is still limited, and their manipulation and digitizing accuracy seem to be unclear at present. However, rapid progress in technology will ensure that taking the optical impressions will become practical in the clinic in the near future.

3.2. Application of zirconia-based ceramic FDPs using CAD-CAM process

Zirconia-based ceramics, especially Y-TZP, are clinically available as an alternative to metal frameworks for FDPs [16,17]. The fabrication of Y-TZP frameworks can be performed by milling a solid block using CAD/CAM procedures and either of two systems [18].

In the first system, frameworks with final dimensions can be milled directly from fully sintered dense ceramic blocks using a CAD/CAM-controlled grinding machine. This system has the advantage of a superior fit, because no shrinkage is involved in the process, but has the disadvantage of inferior machining associated with wear of the tool.

In the second system, frameworks with enlarged dimensions can be milled from partially-sintered blocks or green blocks, again using CAD/CAM-controlled grinding machines, followed by post-sintering at high temperature (using an electric furnace) to obtain a framework with final dimensions and sufficient strength. This system is currently popular for fabricating zirconia frameworks using the main CAD/CAM systems available in the world market. However, although this system has the advantage of easy machinability without wear on the tools and chipping of the material, the dimensions of the frameworks must be adjusted to compensate for extensive sintering shrinkage during the post-sintering process, so that the final frameworks fit well.

Fit of the FDPs to the abutment, especially marginal adaptation, is one of the determining factors for the long-term clinical success of dental prostheses [19]. Clinical evaluation showed that the margin fit of zirconia-ceramic FDPs fabricated by the current CAD/CAM systems was similar to that of conventional metal ceramic restorations [20].

There were a number of publications evaluating the fit of the FDPs fabricated by CAD/CAM systems. However, because of the rapid progress and remodeling of the CAD/CAM systems currently available in the clinic, it is difficult to judge the degree of fit of FDPs produced by each system. Laboratory studies suggested marginal adaptation of 3-unit and 4-unit zirconia-ceramic FDPs consisting of frameworks fabricated using commercially-available CAD/CAM systems was acceptable for clinical application [21–23].

However, the discrepancy of the margin of the crown adjoined to the pontic was increased by the sintering shrinkage of the bulky pontic in the case of 3-unit and 4-unit frameworks. Therefore, we must beware of distortion of zirconia-based FDPs with long span units when using partially-sintered blocks or green blocks [24].

The survival and complication rates of zirconia-based and metal ceramic FDPs indicate that the most frequent technical complication with zirconia-based FDPs was chipping of the veneering porcelain [25,26]. There are many factors affecting chipping of veneering porcelain on zirconia-based ceramic frameworks, including adequate framework design to support the veneering porcelain, adequate handling in the dental laboratory, and further developments in the mechanical properties and application techniques of the veneering porcelain [27].

It was difficult to design a complicated support form using a CAD process, compared with the simpler manual method of making a wax-pattern. However, because of rapid progress in computer hardware and software, sophisticated CAD processes are available to design adequate frameworks using current CAD/CAM systems.

Each manufacturer recommends surface treatment of the zirconia framework (such as sandblasting and heat treatments) prior to porcelain fusing. However, the effect of surface treatments on the bonding strength of porcelain to zirconia is still controversial. There are differences in the thermal expansion coefficients and firing temperatures among the commercial veneering porcelain products for zirconia frameworks; this implies that the different products have different powder compositions. Improvement is needed in the compatibility of the thermal expansion coefficients, and this improvement will probably involve optimizing the powder composition [28].

Ce-TPZ/A is the toughest ceramic material currently available for FDPs. The thickness of Ce-TPZ/A frameworks can be reduced to 0.3 mm, compared with 0.5 mm for Y-TZP frameworks. Therefore, the amount of tooth preparation required for FDPs can be reduced when using the Ce-TPZ/A frameworks [29]. Y-TZP has a problem of LTAD caused by

phase transformation from the tetragonal to the monoclinic structure [13]. However, Ce-TPZ/A showed complete resistance to LTAD [30]. Therefore, Ce-TPZ/A ceramic frameworks can be exposed to the oral environment with a lingual supporting structure similar to that of conventional metal frameworks.

Although Y-TZP and Ce-TPZ/A are tougher than conventional dental ceramics, veneering porcelain and glassy ceramics are as brittle as conventional porcelain. After the veneering material is placed and baked onto the frameworks in a manual process such as powder build-up and firing, it contains many internal defects that may decrease the resistance to debonding and chipping. Therefore, it seems reasonable to find another solution for applying veneering porcelain automatically.

New hybrid structures have been proposed for FDPs. An example of this type of structure is CAD/CAM-fabricated porcelain veneering with parts adhering to CAD/CAM-fabricated zirconia-based ceramic frameworks [31]. In this system, all parts of the FDPs are fabricated by the CAD/CAM process, without manual steps. A reliable adhesive treatment for both parts can be performed in a laboratory, not in a patient's mouth. Adhesive treatments also improve the durability of porcelain. Even if porcelain suffers from chipping during function, repair is easy using the remaining material as a template.

One ultimate solution for the chipping of veneering porcelain is to not use porcelain. Therefore, the opacity of Y-TZP was improved and monolithic full-contour zirconia FDPs were introduced [3]. However, there was concern about wear of the opposing enamel, because the hardness of Y-TZP was over double that of porcelain. According to the current studies, polished zirconia appears to be wear-friendly with opposing enamel, even after simulated aging [32–34]. We need standardized polishing procedures for full-contour zirconia FDPs in both laboratories and clinics. We also need careful observation of the long-term performance to make this application clinically popular.

In this article, the current state and future prospects of zirconia-based new ceramics and their application to FDPs in conjunction with dental CAD/CAM systems are reviewed. Porcelain fused to CAD/CAM-fabricated zirconia frameworks appears to be a promising option in the clinic. However, there are two alternatives that may avoid chipping of veneering porcelains. One is hybrid-structured FDPs comprising CAD/CAM-fabricated porcelain veneering parts adhering to a CAD/CAM-fabricated zirconia framework. Another option is full-contour zirconia FDPs. Both are promising because sensitive manual porcelain work is replaced by digital procedures, although we still need longer clinical evaluations to prove the usefulness of these new options.

4. The bond between zirconia and veneering ceramics

4.1. Zirconia and veneering ceramics

One of the specialized ways of using zirconia in dentistry is to fabricate zirconia frames upon which tooth-colored veneering ceramic is bonded. At present, there are two widely used methods of securing ceramic onto zirconia frames: the layering technique and the press technique. In the layering technique, porcelain powder is applied onto the zirconia frame before firing. In the press technique, the lost wax technique is used to create the restoration. A homogeneous ceramic ingot is heated and then forced under pressure into a wax-formed void. The layering technique is usually used for PFM crowns. It results in excellent esthetics, but several firings are required in order to reproduce the desired color and shape [35]. The virtue of the press technique is easy shaping, however, it is hard to reproduce the desired color because the ceramic ingot used for this technique has only a single color.

For both the layering technique and the press technique, the coefficient of thermal expansion of the veneering ceramic is set to be the same as or slightly lower than that of zirconia. This is because a large difference in the coefficient of thermal expansion between a zirconia frame and veneering ceramic will cause residual stress on the crown, thus resulting in reduced reliability of the restoration [36]. There are some studies comparing the layering technique with the press technique, however, many reports argue that the dislodgement or fracture of veneered ceramics is more affected by frame design than differences in molding techniques [37–39].

4.2. Mechanism and evaluation of integration

Metal-to-porcelain integration of PFM crowns is apparently attained through both mechanical and chemical bonding. Mechanical bonding occurs because porcelain fills the irregularities in the metal surface; this is also called the interlocking effect. Compressive stress caused when the porcelain cools appears to produce this interlocking effect. On the other hand, chemical bonding is the bond between oxygen atoms contained in the porcelain and an oxide film containing tin oxide and indium oxide on the metal frame's surface.

However, there is no clear evidence demonstrating the presence of chemical bonding between zirconia and veneering ceramics, although there is one report [40] suggesting such a bond. It is thus assumed that mechanical bonding plays the major role in the zirconia-to-porcelain integration of zirconia-based restorations.

The bond strength between metal and porcelain is usually evaluated in two ways: a three-point bending test using a thin plate-shaped metallic specimen onto which porcelain is fired, and a shear test using a metallic specimen onto which a disk of porcelain is fired. There are many reports of using a shear test to evaluate the bond strength between zirconia and ceramic (Fig. 2). There is an international standard (ISO9693) for the method of evaluating the bond strength between metal and porcelain using a bending test, and PFM restorations in clinical use are required to have a bond strength of 25 MPa or more [41]. Although there have not been many reports [42–44] concerning the evaluation of zirconia-to-porcelain integration using a bending test (ISO9693), all of those reported that the bond strength was 25 MPa or more. In experiments where the

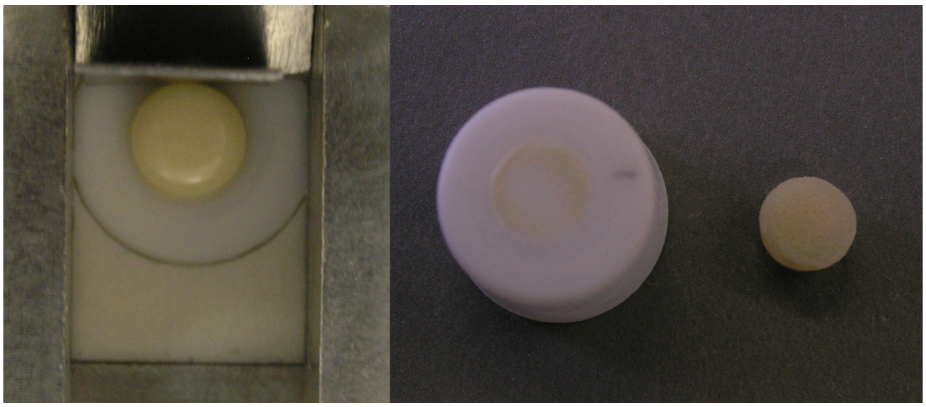

Fig. 2. Shear bond test and the specimens [41].

Table 3
Shear bond strength with different surface treatments (MPa).

Authors (Year) [Ref]	Control	Sandblast	Other treatment
Nakamura et al. (2009) [61]	22.0	27.8–44.3[a]	–
Fischer et al. (2010) [57]	27.0	23.9	–
Kim et al. (2011) [58]	32.0	36.6[a]	27.8 (porcelain liner)
Teng et al. (2012) [62]	39.1	46.1[a]	47.2[a] (powder coating)
Liu et al. (2013) [63]	24.8	31.3[a]	32.1[a] (laser irradiation)

[a] Represent significant differences against control (no treatment) [57].

bond strength between metal and porcelain and that between zirconia and porcelain were compared, it has been reported that the bond strength between metal and porcelain is greater than that between zirconia and porcelain [45,46].

4.3. Factors affecting bond strength

4.3.1. Veneering ceramic

It is known that the strength of the bond between zirconia and veneering ceramic varies greatly with the type of veneering ceramic used [47–49]. This is probably because different veneering ceramics have different coefficients of thermal expansion, causing a mismatch in the coefficient of thermal expansion between zirconia and the veneering ceramic being used [50].

In the layering technique, the number of firings may affect the bond strength. It is reported that, between three to five firings, the greater the number of firings the higher the bond strength [51,52]. However, one report argues that more than six firings will reduce the bond strength [53]. It is also reported that some types of veneering porcelain show changes in crystalline structure as the number of firings is increased beyond a certain number [35], and thus it is preferable to avoid increasing the number of firings unduly.

In addition, some researchers have reported that the cooling rate after firing will also affect the bond strength of ceramic-veneered zirconia restorations [54–56], and thus the cooling rate needs to be set properly to suit the type of porcelain used. It is generally thought that using a porcelain liner at the start of veneering does not lead to improvement in bond strength [57–59].

4.3.2. Zirconia

Sandblasting is the most widely-used surface treatment method in dentistry. For porcelain-veneered zirconia restorations, the purpose of sandblasting is to produce irregularities on the zirconia to enhance the mechanical bonding between zirconia and veneering ceramic. It has in fact been reported that sandblasting produces changes in the surface topography and surface roughness of zirconia [60].

However, concerning the effectiveness of sandblasting zirconia, some researchers state that this improves the bond strength of porcelain to zirconia [58,61–63], but others maintain that it does not affect the bond strength [40,59,64] (Table 3). This difference is probably because the effect on the zirconia surface varies greatly according to the type, size, and injection pressure of the abrasive particles and also because sandblasting provokes a local tetragonal to monoclinic (*t–m*) transformation [65].

Monoclinic crystal zirconia transformed by milling or sandblasting can be returned to tetragonal crystals by heat-treating at 1000–1100 °C for 5–10 min. It is reported that such heat treatment does not affect the ceramic to zirconia bond [42]. Furthermore, some reports state that powder coating [62] or laser irradiation of the zirconia surface is effective in improving bond strength.

Bonding between zirconia and veneering ceramics is still in many respects a mystery, including the mechanism involved, partly because this procedure is peculiar to dentistry. Basic

Table 4
Bonding of zirconia with resin-based luting systems.

Adherend material	Bonding/luting systems	Results	Authors (Year) [Ref]	Comments from the authors
Zirconia bracket	Prismafil, Heliosit (light-cured), Delfic (chemically-cured)	Heliosit, Delphic > Prismafil	Springate and Winchester (1991) [66]	All specimens failed at the bracket-adhesive interface. Highly opaque appearance may adversely affect bonding with light-cured adhesives
Yttrium oxide partially stabilized (YPS) zirconia	Kevloc, Rocatec, Clearfil FII, Dyract Cem, Panavia EX (with MDP), Panavia 21 EX (with MDP), Twinlook	Panavia EX, Panavia 21 EX > others	Kern and Wegner (1998) [67]	MDP in the two composites is effective for bonding the YPS zirconia
Zirconia	Alumina blasting, HF treating, grinding with diamond burs, Panavia 21, Twinlook, Superbond C&B	Washing with hydrofluoric acid had no significant influence on bond strength	Dérand and Dérand (2000) [83]	Superbond showed a bond strength reasonably acceptable for clinical use
Zirconia post material	Panavia 21, C&B Metabond, Biscore	Panavia 21 > Biscore > C&B Metabond	O'Keefe et al. (2000) [68]	Panavia 21 is effective for bonding the zirconia prefabricated post material
In-Ceram Zirconia	Particle abrasion with alumina, 10% HF for 20 s	Particle abrasion of In-Ceram Zirconia did not change the morphologic characteristics	Borges et al. (2003) [84]	Hydrofluoric acid etching of In-Ceram Zirconia and Procera did not change their morphologic microstructure
InCeram-Zirconia, Frialit	PyrosilPen flame treatment, silane, luting composite	Empress II, InCeram-Alumina > Frialit > InCeram-Zirconia	Janda et al. (2003) [73]	PyrosilPen is an effective method for treating zirconia to obtain bonding to luting composites
Glass infiltrated zirconia	Hydrofluoric acid etching, airborne particle abrasion, tribochemical silica coating, composite material	Acid etched glass ceramics 26.4-29.4, glass infiltrated alumina ceramics 5.3-18.1, zirconia 8.1 MPa	Özcan and Vallittu (2003) [74]	Silica coating with silanization increased the bond strength for glass infiltrated zirconia compared to that of airborne particle abrasion
Procera AllZirkon	Clearfil SE Bond/Porcelain Bond Activator, Single Bond/Ceramic Primer, Panavia F, Rely X ARC	Silane/phosphate bonding agent was effective for both systems	Blatz et al. (2004) [78]	A bonding/silane coupling agent containing MDP can achieve superior long-term bond strength to Procera AllZirkon with two luting agents
Cerapost (Zirconia)	Sandblasting and HF etching, Alloy Primer, Metalprimer II, Silane, CoJet Sand, ParaPost Cement, Panavia F	Bonding of both resin cements to zirconia posts was improved by Cojet treatment	Sahafi et al. (2004) [75]	Air abrasion with silica acid-modified alumina (CoJet Sand) improved bonding to zirconia of two cements
Lava (zirconia ceramic crown)	Four resin-cement systems, a compomer, a glass-ionomer cement, a resin-modified glass-ionomer cement, and a self-adhesive resin	Superbond C&B (+ Rocatec) specimens showed the highest median retentive strength	Ernst et al. (2005) [76]	The compomer-cement, the resin-modified glass-ionomer cement, and the self-adhesive resin luting agent had the same level of retentive quality as the resin luting agents
Lava (97% zirconia stabilized with yttria)	Fleck's zinc cement, Fuji I, Ketac-Cem, Fuji Plus, Fuji Cem, RelyX Luting, RelyX ARC, Panavia F, Variolink II, Compolute, RelyX Unicem	Resin cement 9.7, 12.7 MPa	Piwowarczyk et al. (2005) [77]	When using the Rocatec system, the highest values were found for one of the resin cements
Cercon	CoJet system (tribochemical silica coating), Clearfil Liner Bond 2V (MDP)/Porcelain Bond Activator (silane), Panavia F	The MDP/silane mixture increased the shear bond strength to zirconia	Atsu et al. (2006) [79]	CoJet system and the application of an MDP-containing bonding/silane coupling agent mixture increased the bond strength between zirconia and Panavia F
Cercon smart ceramics (tetragonal zirconia polycrystals, TZP)	Rocatec-system to sandblasted TZP, Ketac-Cem, Nexus, RelyX Unicem, Superbond C&B, Panavia F, Panavia 21	RelyX Unicem, Superbond C&B, Panavia F, and Panavia 21 gave superior results	Lüthy et al. (2006) [69]	The strongest bond to zirconia was obtained with Panavia 21

Table 4 (*Continued*)

Adherend material	Bonding/luting systems	Results	Authors (Year) [Ref]	Comments from the authors
Lava	Left untreated, airborne-particle abraded, Rocatec tribochemical silica/silane, ground and polished, RelyX ARC, RelyX Unicem, Panavia F, RelyX Luting	Rocatec generally yielded the highest long-term shear bond strength	Blatz et al. (2007) [80]	Airborne-particle abrasion combined with a resin composite containing MDP or tribochemical silica/silane coating combined with the tested resin luting agents provides superior long-term bond strengths
Katana (YPS zirconia)	Rocatec Soft, Espe Sil, Epricord, RelyX ARC	The silica-coating of YPSZ ceramics by tribochemical modification was not efficient, given the higher mechanical toughness of the densely sintered ceramics	Tanaka et al. (2008) [81]	Stable shear bond strength was achieved on silica-coated YPSZ ceramics with the cooperative interaction of phosphate monomer and silane coupling
Cercon smart ceramics (tetragonal zirconia polycrystals, TZP)	Alumina blasting, tribochemical silica coating, no treatment, Calibra, Clearfil Esthetic Cement, RelyX Unicem	Bond strength of Clearfil Esthetic Cement to zirconia was significantly higher than that of others, regardless of the surface treatment	de Oyagüe et al. (2009) [70]	The luting system with MDP (Clearfil Esthetic Cement) is recommended to bond zirconia
Katana (YPS zirconia)	Acryl Bond, All Bond II Primer B, Alloy Primer, Estenia Opaque Primer, Eye Sight Opaque Primer, M.L. Primer, MR. Bond, Super-Bond Liquid, tri-n-butylborane (TBB)-initiated acrylic resin	The highest post-thermocycling bond strength was obtained with the use of Alloy Primer and Estenia Opaque Primer	Nakayama et al. (2010) [82]	Application of Alloy Primer or Estenia Opaque Primer, containing MDP, is recommended for bonding the zirconia material with TBB-initiated acrylic resin
Katana (YPS zirconia)	Ceramic Primer, Monobond Plus, Clearfil Esthetic Cement, Clearfil SA Cement, Panavia F2.0, Variorink II	Clearfil SA Cement and Panavia F2.0 showed durable post-thermocycling bond strength	Koizumi et al. (2012) [71]	Application of resin-based luting and priming agents containing MDP provide better bond strength to zirconia than do other systems
In-Ceram Zirconia	No treatment, sandblasting, CoJet + silane, CoJet + Alloy Primer, glaze + 9.6% HF etching 60 s + silane, Panavia F2.0	The highest tensile bond strength for the enamel surfaces was obtained in group; glaze + HF etching + silane	Saker et al. (2013) [72]	Adhesion of zirconia to enamel and dentin can be improved when the specimens are glazed, etched, and silanized, or sandblasted, primed, and cemented with Panavia

research in this field and development of a reliable clinical procedure will be necessary in the future.

5. Bonding of zirconia with resin-based luting agents

5.1. Adhesive bonding to zirconia

Adhesive behavior of zirconia was primarily evaluated as bonding between orthodontic brackets and adhesive resin. Springate and Winchester [66] assessed two light-curing composite resins and a chemically curing composite resin for bonding a zirconia bracket material. The result showed that one of the light-curing materials exhibited statistically lower bond strength than the other two materials. The authors pointed out that the opaque appearance of the zirconia negatively affects bonding with light-curing luting agents. Their results suggested selection of chemically curable resin-based luting agents for cementing zirconia restorations. Table 4 summarizes the reports concerning bonding of zirconia with resin-based luting agents.

5.2. Resin-based luting systems with methacryloyloxydecyl dihydrogen phosphate

Kern and Wegner [67] assessed bonding of an yttrium oxide partially stabilized (YPS) zirconia ceramic using varying bonding systems. Their results demonstrated effectiveness of two luting agents containing a hydrophobic phosphate monomer, 10-methacryloyloxydecyl dihydrogen phosphate (MDP), for bonding to the zirconia. Several researchers thereafter reported that composite materials containing MDP enhanced bond strength to zirconia prefabricated post material [68], tetragonal zirconia polycrystals (TZP) [69,70], YPS zirconia [71], and In-Ceram zirconia [72]. Oyagüe et al. [70] reported that a phosphate monomer-containing luting system is recommended to bond zirconia and surface treatments are not necessary.

5.3. Surface modifications of zirconia

Techniques for modifying zirconia surface mechano-chemically with inorganic silicon compounds followed by

Table 5
Diamond rotary instruments and polishing pastes.

	Name(Manufacturer)	Composition of abrasives	Composition of binder
Grinding rotary instrument	SinterDia (Shofu)		Metal sintering
	Diamond Point FG (Shofu)	Diamond (C)	Metal plating (Ni, Cr)
	VitrifiedDia (Shofu)		Glass
	Aadva point Zr (GC)	Diamond (C), Corundum (Al_2O_3), Anatase (TiO_2)	
	CeramDia (Morita)	Diamond (C), Corundum (Al_2O_3), Anatase (TiO_2), Zinc oxide (ZnO)	Artificial rubber
	Pro-tec diamond point (Kuraray Noritake Dental)	Diamond (C), Corundum (Al_2O_3), Rutile (TiO_2)	
	Porcelain Hi-glaze (Dedeco)	Diamond (C), Rutile (TiO_2)	
	Name (Manufacturer)	**Composition of abrasives**	**Polishing instrument**
Polishing paste	DirectDia Paste (Shofu)	Diamond (C), Anatase (TiO_2), Glycerin	Super-snap buff disk
	Diapolisher Paste (GC)	Diamond (C), Zinc oxide (ZnO), Glycerin	Felt, Brush, PTC cup
	DuraPolish Dia (Shofu)	Diamond (C), Pumice (SiO_2), wax	Felt
	Zircon-Brite (DVA)	Diamond (C), Corundum (Al_2O_3), Pumice (SiO_2), wax	Felt, Brush
	Zirkopol (Feguramed)	Diamond (C), Corundum (Al_2O_3), Pumice (SiO_2), wax	
	Pearl Surface Z (Kuraray Noritake Dental)	Diamond (C), Silicon carbide (SiC), wax	Brush

Table 6
Studies on wear of antagonist against zirconia.

Author (Year)	Materials	Antagonist	Condition	Results	References
Kumar et al. (1991)	Zirconia (Y-PSZ), Alumina, and xSUS316L	Polyethylene cylinder $\phi = 4$ mm or 9 mm	Unidirectional wear (3 MPa load, 60 mm/s, total 30–40 km) and reciprocating wear (3.45 MPa, 50 mm sliding distance, 60 cycles/min, 1,300,000 times) in lubricant fluid medium (distilled water, human blood plasma, physiological saline solution)	Different lubricant fluid media had little effect on the polyethylene wear against ceramic counterfaces, but were prominent against SUS316L metal. Y-PSZ ceramic may be a biomaterial potentially suitable for low friction arthroplasty because of its better wear resistant properties and high strength	[102]
Tambra et al. (2003)	Polished zirconia, surface treated zirconia, and Type 4 gold alloy	Human enamel	Rotation, 500 g load, 60 cycles/min, 10,000 cycles	The zirconia caused greater enamel wear than did the gold control	[103]
Culver et al. (2008)	Cercon, Lava, Empress, MZ100, and Z100	Human enamel	Modified Leinfelder wear testing machine, 75 N load, 20,000 cycles in Slurry (15 g of $\phi = 50$ μm PMMA beads and 9 g of water)	Cercon and Lava showed larger enamel loss than others	[104]
Shar et al. (2010)	Polished and glazed zirconia	Human enamel	Modified Leinfelder wear testing machine, 75 N load, 1.2 Hz, 10,000 cycles in Slurry ((15 g of $\phi = 50$ μm PMMA beads and 9 g of water)	Polished zirconia showed larger enamel loss than glazed one	[105]
Jung et al. (2010)	Glazed, polished zirconia, polished porcelain veneered zirconia	Human enamel	Chewing simulator, 240,000 cycles	The antagonist wear of three CAD/CAM full contour zirconia ceramics was significantly less than that of the veneering ceramic	[106]
Albashaireh et al. (2010)	e.max ZirCAD, e.max Press, Empress Esthetic, e.max ZirPress, e.max Ceram	Zirconia balls $\phi = 6$ mm	Dual-axis mastication simulator, 300,000 mastication cycles	Wear was of the fatigue type, and was significantly lowest in the zirconia specimens tested	[107]
Sorensen et al. (2011)	Omega 900, Empress, Bovine enamel, d. sign, Lava, Aquarius, Empress 2	Human enamel	OHSU oral wear simulator, 20 and 70 N load, 50,000 times in slurry (poppy seeds/PMMA beads)	Polished Lava showed small enamel loss and nearly the same with that of Gold alloy (Aquarius)	[108]

Table 6 (*Continued*)

Author (Year)	Materials	Antagonist	Condition	Results	References
Basunbul et al. (2011)	Polished and glazed Wieland zirconia, polished Ceramco 3, polished Mark II	Human enamel	400 g load, 6 mm reciprocating moving, 60,000 and 600,000 cycles in water	Polished zirconia caused significantly less wear to enamel than either the glazed zirconia, Ceramco porcelain and Cerec Mark II. The polished zirconia remained unchanged, but the glazed zirconia showed significant loss of the glazed layer	[109]
Preis et al. (2011)	Five zirconia and four veneering porcelains	Steatite sphere $\phi = 3$ mm or enamel	Chewing simulator, 50 N load, 120,000 cycles (1.6 Hz, lateral movement 1 mm, mouse opening 2 mm)	Antagonist wear against zirconia was found to be lower than wear against porcelain	[32]
Kuretzky et al. (2011)	Rough, polished, glazed, and veneered Lava zirconia and e.max CAD	Steatite balls $\phi = 6$ mm	Longitudinal moving notch device, 5 and 50 N load, path length 32 mm, 72 cycles/min for 120 min	Polished zirconia showed the least wear after abrading with a steatite sphere	[110]
Yang et al. (2012)	Zirkonzahn Y-TZP (polished, stained, stained then glazed), Acura Y-TZP, Wieland Y-TZP, a feldspathic porcelain	Human enamel	Chewing simulator, 240,000 cycles	Antagonist wear of three Y-TZP was significantly less than veneering porcelain because the surface character of Y-TZP is relatively homogeneous. Zirkonzahn with staining and glazing was significantly more abrasive than the other Y-TZP without glazing	[111]
Janyavula et al. (2013)	Polished, glazed, polished then reglazed, and porcelain veneered Lava, molar enamel	Human enamel	University of Alabama wear testing device, 10 N load, 20 cycles/min, 400,000 cycles in 33% glycerin solution	Highly polished zirconia is more desirable than the glazed zirconia	[112]
Kontos et al. (2013)	Zirconia (a)was only fired, (b) sandblasted, (c) ground, (d) polished, and (e) glazed	Steatite balls $\phi = 6$ mm	Pin-on-disk, 45°, 5 N load, 5000 cycles, water	Polished zirconia seems to have the lowest wear on the antagonist, in contrast with the other kinds of surface treatment	[113]
Stawarczyk et al. (2013)	Mechanically and manually polished, glazed, spray glazed, and veneered zirconia, and a base alloy	Human enamel	Chewing simulator, 49 N load, 1,200,000 cycles (1.7 Hz, horizontal distance 2 mm) and thermal stress (5–50 °C every 120 s)	Polished zirconia showed lower wear rate on enamel antagonists as well as within the material itself but developed higher rate of enamel cracks	[114]

application of silane monomers have been introduced. Janda et al. [73] compared bonding performance of silica, alumina, and two zirconia ceramic materials treated with a flame treatment and silane priming. The results showed that the silica and alumina ceramics showed higher bond strength than the zirconia ceramic materials, although the flame treatment was effective for all ceramic materials. Özcan and Vallittu [74] evaluated the effect of mechanical and chemical retentive systems on bonding zirconia. The results showed the effectiveness of silica coating and subsequent silane treatment on bonding to glass infiltrated zirconia. Sahafi et al. [75] confirmed the effectiveness of a tribochemical coating system on bonding to zirconia post material. Ernst et al. [76], Piwowarczyk et al. [77], and Lüthy et al. [69] reported usefulness of another tribochemical coating system for bonding zirconia.

5.4. Silica/silane and MDP

It is also reported that combined application of silica coating, silane, and MDP is currently one of the most reliable bonding systems for zirconia [78–81]. Blatz et al. [78] demonstrated effectiveness of a silane/phosphate bonding agent for cementing zirconia restorative material. This procedure does not necessarily require another mechano-chemical treatment before application of the silane/phosphate bonding agent. Tanaka et al. [81], however, concluded that stable bond strength was achieved on Rocatec-coated Katana zirconia with the cooperative interaction of phosphate monomer and silane, which was analyzed by means of X-ray photoelectron spectroscopy. This bonding mechanism is substantially the same mechanism as bonding to feldspathic porcelain with silane/MDP bonding agent.

5.5. Unfilled luting agent

Bonding to zirconia of unfilled acrylic luting agent was not particularly excellent [68]. This weak point, however, has been improved by application of a tribochemical coating [76]. Nakayama et al. [82] evaluated bonding between an YPS zirconia and a tri-n-butylborane (TBB)

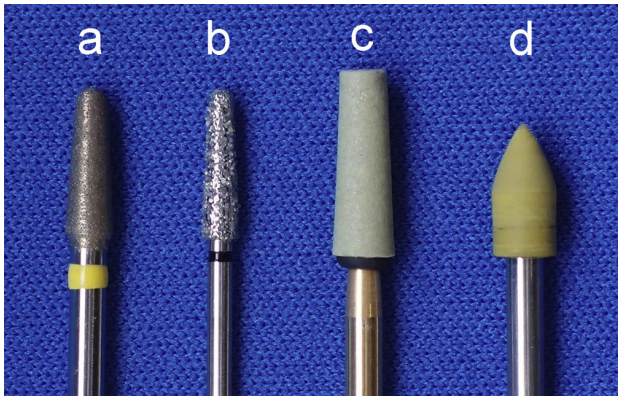

Fig. 3. Diamond rotary instruments. (a) SinterDia HP30R; (b) Super Course SC106RD; (c) VitrifiedDia HP20; (d) CeramDia SF.

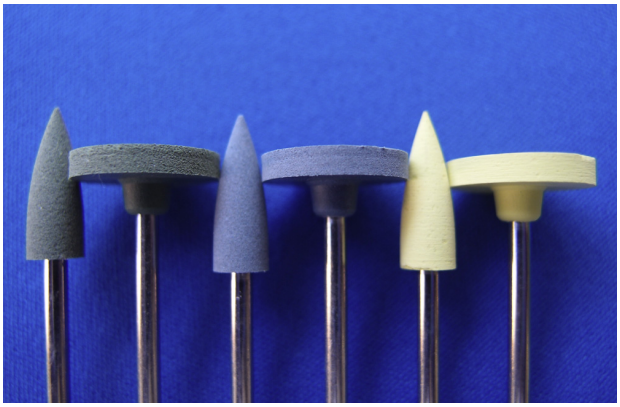

Fig. 4. Diamond rotary instruments, Dodeco Hi-glaze diamond polishing kit.

Fig. 5. Diamond polishing pastes. (a) DirectDia paste; (b) Diapolisher paste; (c) Zircon-Brite; (d) Zirkopol; (e) Dura-PolishDia; (f) Pearl Surface Z.

initiated luting agent in combination with eight primers. Among them, application of either the Alloy Primer or the Estenia Opaque Primer (Kuraray), both of which contain MDP, exhibited durable bonding between the zirconia and the TBB-initiated luting agent.

5.6. Mechanical retention

Etching zirconia with acidic etchant is currently difficult [83,84]. Although a reliable mechanical retentive system between resin material and zirconia is unachievable, laboratory

and clinical studies on macro mechanical as well as mechano-chemical retention of zirconia is being continued.

6. Surface finish of zirconia restorative and antagonist enamel wear

Various ceramics have been used as dental restoratives. In terms of mechanical strength [30,85–87] and physical properties [88–90], there is no doubt the superiority of zirconia. When zirconia is used for esthetic dental restoratives such as crowns and bridges, it is generally veneered with feldspathic porcelain, because zirconia has an insufficient translucency. However, the strength of the veneering porcelain is not enough to act as dental restoratives, especially for posterior teeth. It is known that the clinical failure has been reported to be mostly due to chipping of porcelain [91,92]. Recently, high translucent zirconia has been introduced into dentistry [93,94]. It can be used as all zirconia restoratives, so-called "Full Contour", without covering the veneering porcelain, indicating its zirconia surface is exposed to the oral cavity. Then, the wear of opposing teeth is an important and interesting issue. In order to prevent wear of the antagonist enamel, the mirror polishing is undertaken in the dental laboratory and in the oral cavity for occlusal adjustment. On the other hand, some dentists misunderstand that the enamel opposing to zirconia restoratives is easy to wear because of the hardness of zirconia. Furthermore, effects of the glazing on zirconia are uncertain whether this coating is effective on the prevention of antagonist wear or not. Veneering porcelains have also come to be questioned about the antagonist wear. Recent studies on wear of antagonist enamel demonstrated mostly that adequate surface finish of zirconia restoratives resulted in the least wear of antagonist enamel among various dental materials. These results suggest that the antagonist enamel wear is significantly affected by the degree of surface finish. This review outlines the method for surface finish of zirconia restoratives and their effects on the wear of antagonist enamel.

6.1. Grinding and polishing of zirconia restoratives

As described above, in order to prevent wear of the antagonist enamel, the mirror polishing is undertaken in the dental laboratory and in the oral cavity for occlusal adjustment. Previously, we reported a comparative study on mirror polishing methods of the zirconia surface [64,95]. Based on this study, the grinding and mirror-polishing manner for zirconia are described first. Table 5 shows name, manufacturer name, the composition of the grinding rotary instruments, and polishing pastes available for zirconia.

6.1.1. Grinding rotary instruments

The hardness of zirconia is high (H_V 1,160–1,300), but lower than alumina (H_V 1,800–2,200) and diamond (H_V 10,200). Therefore, zirconia can be easily processed by the instruments coated with diamond abrasive grains. As shown in Table 6, the grinding rotary instruments for zirconia contain diamond abrasives in high density which are fixed with metal, glass, and artificial rubber to a stainless steel shaft. Figs. 3 and 4 show some examples of diamond rotary instruments.

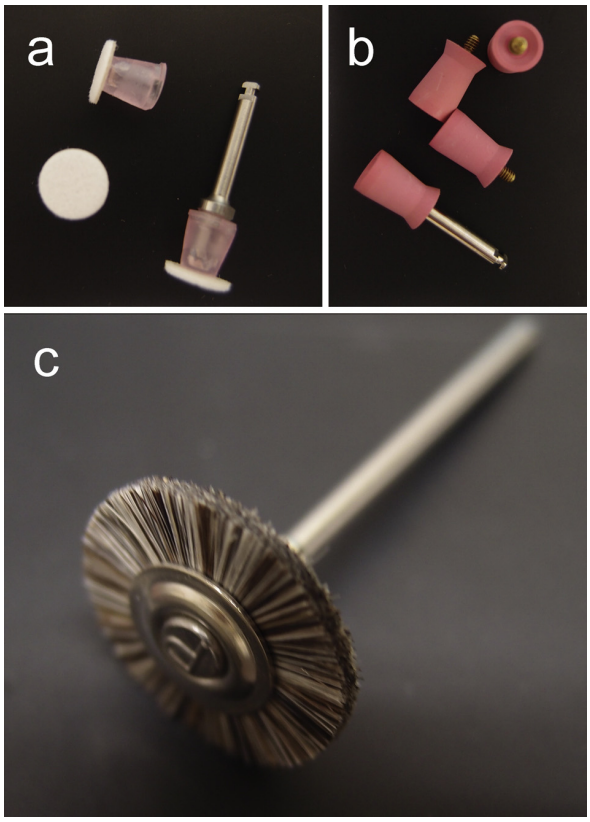

Fig. 6. Polishing cups and brush. (a) Super snap buff disk; (b) PTC cup; (c) Robinson brush.

Generally, diamond rotary instruments fix diamond abrasive grains to the stainless steel shaft with a nickel-chromium plating. "Super Course" fixes twice-size diamond grains (100–300 μm) than usual ones by the plating, resulting in almost double grindability than usual ones. On the other hand, "SinterDia" fixes diamond grains by sintering of metal to a stainless steel shaft. Consequently, it possibly results in preventing diamond grains falling off into the high-density packing, indicating high grindability and durability [96].

"VitrifiedDia" fixes diamond grains with glass. "Aadva Point Zr", "CeramDia", and "Porcelain Hi-glaze" fix diamond grains and other oxides such as corundum (Al_2O_3) and anatase or rutile (TiO_2) with artificial rubber. Diamond grain sizes of "CeramDia" M, F, and SF are 100–200, 30–60, and 3–6 μm, respectively [97].

It has been confirmed that larger diamond grains show higher grindability for zirconia [98]. However, the surface roughness is also large. Therefore, the rotary instrument should be changed sequentially from a large to small grain size of the diamond abrasives of the instrument. Consequently, this manner results in a fast and homogeneous smooth surface, and enables a fast move to the next step, i.e. polishing.

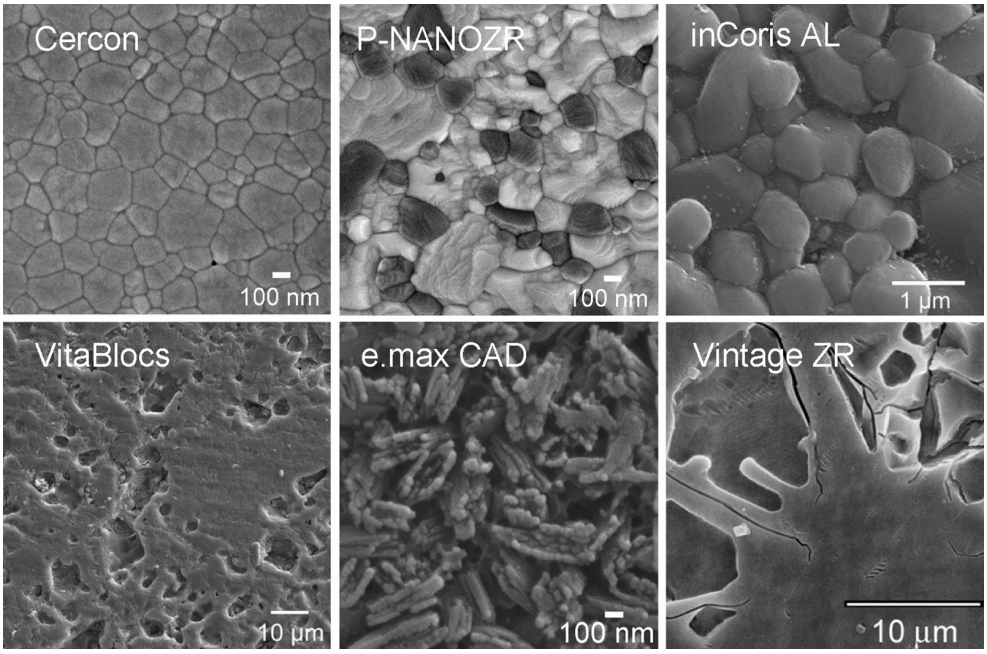

Fig. 7. Scanning electron micrograph of six types of dental ceramics.

6.1.2. Diamond polishing paste

Fig. 5 shows some examples of polishing pastes for zirconia. The diamond pastes mainly contain diamond grains (1–6 μm) and fine other oxides (less 0.5 μm) such as anatase (TiO_2), corundum (Al_2O_3), zinc oxide (ZnO), and Pumice (SiO_2) [97]. These diamond pastes are usually used to polish with plastic or rubber cone and soft brush (Fig. 6). "Super snap buff disk" consists of TiO_2 and polyester. "PTC Cup" consists of TiO_2, ZnO, and artificial rubber. "Robinson brush" consists of hard fibers such as horse hair or soft fibers such as sheep hair. "DirectDia paste" and "Diapolisher paste" can be applied to the mirror polishing with plastic or rubber cone after occlusal adjustment in the oral cavity. Other pastes are used mainly with Robinson brush in laboratories.

6.1.3. Polishing of dental ceramics

The surface roughness of the ground and polished ceramic is largely governed by the microstructure of the ceramic. And, a variety of materials have been used as dental ceramics.

In our previous study, we measured the surface roughness of seven types of dental ceramics finished with three diamond grinding instruments and two diamond pastes [64,95].

Fig. 7 shows scanning electron micrographs of dental ceramics used in the study. Cercon is a Y-TZP (yttria-stabilized tetragonal zirconia type) having a high density sintered body of about 0.3 μm grain size after the final firing at 1350 °C. Although not shown, "ZENOSTAR" is also a Y-TZP fired at 1450 °C, and classified to high translucent type having a particle size of about 0.4 μm. "P-NANOZR" has an interpenetrated intragranular nanostructure, in which either nanometer-sized Ce-TZP (ceria-stabilized tetragonal zirconia) or Al_2O_3 particles locate within submicron-sized Al_2O_3 or Ce-TZP grains, respectively. The average grain size of this composite was about 0.5 μm. This material design makes it possible to strengthen the 10 mol% Ce-TZP matrix with 30 vol% Al_2O_3 [11,99]. "inCoris AL" is a high-density sintered body having a particle size of 1 μm after the final firing at 1500°C [100]. "Vitablocs" is a CAD/CAM block containing about 30 vol% feldspar crystal (Sanidin) grains of 2–10 μm dispersed in the glass [99]. "e.max CAD" is a CAD/CAM block containing about 70 vol% elongated lithium disilicate grains of about 1.5 μm dispersed in the glass [100]. "Vintage ZR" is a feldspathic veneering porcelain for zirconia, consisting of about 4.5 wt% leucite crystal of 5–10 μm, dispersed in the glass [101].

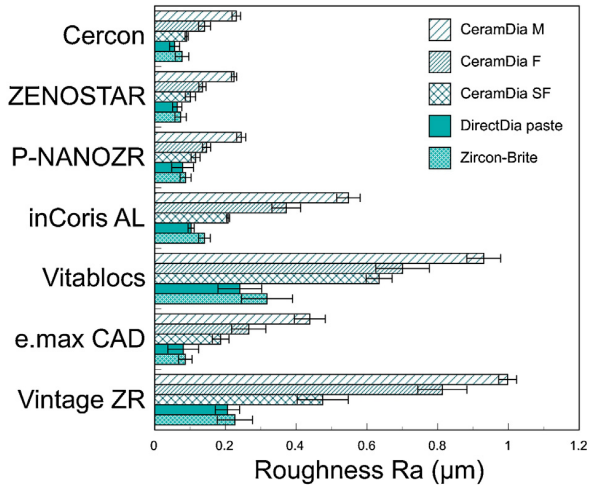

Fig. 8. Surface roughness of seven types of dental ceramics finished with three types of diamond rotary instruments and two types of diamond polishing pastes.

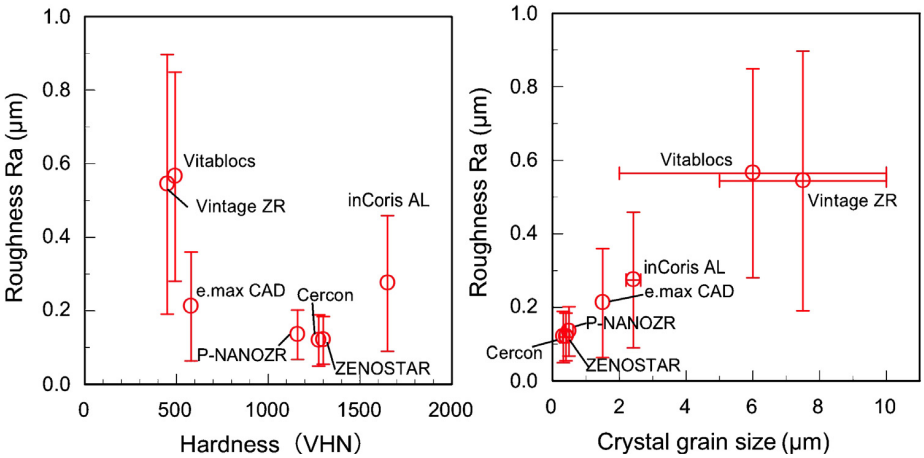

Fig. 9. Relation between average surface roughness and hardness (left) and between average surface roughness and crystal grain size (right) of seven dental ceramics finished with three types of diamond grinding bar and two types of diamond polishing pastes.

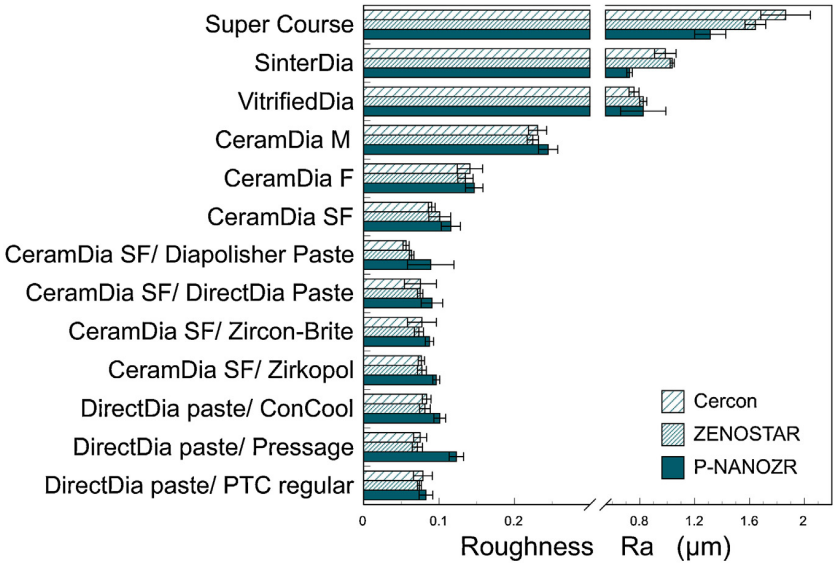

Fig. 10. Surface roughness of three types of dental zirconia finished with 13 types of grinding and polishing condition.

Fig. 8 shows the surface roughness Ra of seven types of dental ceramics after grinding and polishing. Polishing with diamond pastes such as DirectDia paste and Zircon-Brite was undertaken after grinding sequentially with CeramDia M, F, and SF. According to the size of diamond grains of the grinding rotary instruments, the surface roughness decreased in all the dental ceramics. The roughness was further reduced by the following polishing. In particular, three zirconia products (Cercon, ZENOSTAR, and P-NANOZR) showed the minimum roughness after each grinding and polishing. On the other hand, Vitablocs and Vintage ZR showed large roughness. Fig. 9 shows the relation between the average surface roughness of seven dental ceramics after three grindings and two polishings shown in Fig. 6 and the Vickers hardness of each ceramic (left), and relation between the average surface roughness and the average size of crystal grains (right). The surface roughness after grinding and polishing was independent of the hardness, but strongly depended on the crystal grain size. It has been suggested that the surface roughness of dental ceramics after grinding and polishing depend highly on the microstructure. Therefore, it is concluded that zirconia can be polished to a smooth surface due to the homogeneous and fine microstructure.

6.1.4. *Polishing of zirconia*

Fig. 10 shows the surface roughness of three types of dental zirconia finished with 13 types of grinding and polishing. Super Course, SinterDia, VitrifiedDia, and CeramDia M, F, and SF are grinding rotary instruments. Super Course, SinterDia, and VitrifiedDia showed large surface roughness, greater than 1 μm. On the other hand, CeramDia M, F, and SF showed relatively low roughness. It possibly depends on the diamond

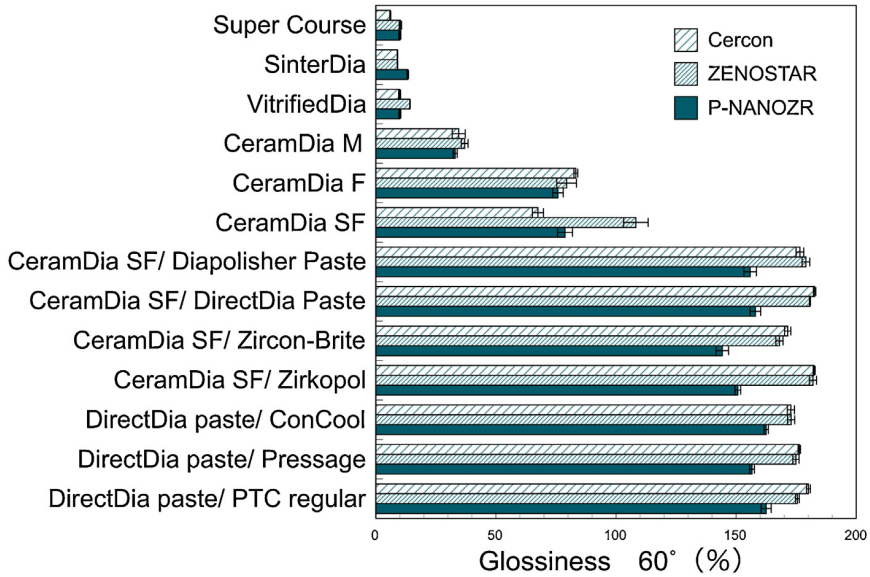

Fig. 11. Glossiness of three types of dental zirconia finished with 13 types of grinding and polishing condition.

grains fixed with artificial rubber. Polishing with diamond pastes such as Diapolisher paste, DirectDia paste, Zircon-Brite, and Zirkopol was undertaken after grinding sequentially with CeramDia M, F, and SF. The polishing made a further smooth surface, and there were no significant differences in type of zirconia and in type of diamond polishing paste. ConCool, Pressage, and PTC regular are cleaning pastes for professional mechanical tooth cleaning (PMTC) operations. The polishing with these pastes after polishing with DirectDia paste showed no change in the surface roughness.

Fig. 11 shows the glossiness at 60° of the same specimens shown in Fig. 8. The glossiness increased with decreasing the size of diamond grains of grinding rotary instruments and increased more with further polishing. However, PMTC pastes showed no remarkable change. Because diamond is not included in the PMTC pastes which are composed of abrasive grains of silica, it means that the PMTC operation is not affected on both surface roughness and gloss of zirconia restoratives mounted as full contours in the oral cavity, indicating no interference with maintenance of good oral hygiene.

Fig. 12 shows the correlation between the glossiness and the surface roughness. The glossiness increased steeply with decreasing roughness to less than 0.3 μm. It means that the final gloss of zirconia restoratives is determined whether the final polishing is enough or not.

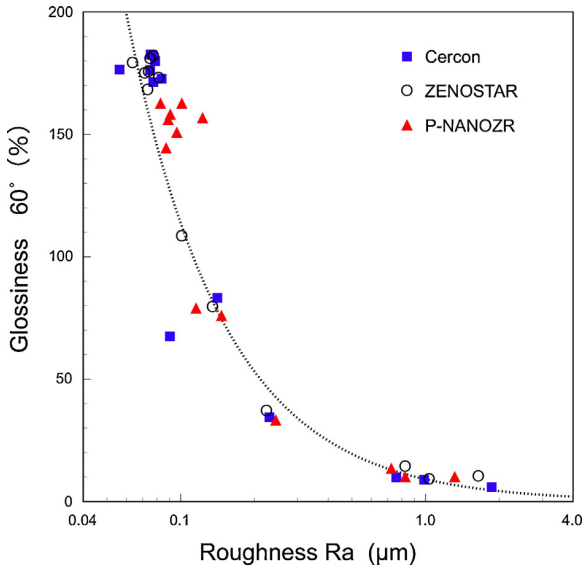

Fig. 12. Relation between surface roughness and glossiness of three types of dental zirconia finished with 13 types of grinding and polishing condition.

6.2. *Studies on the wear of antagonist against zirconia*

Table 6 shows the summary of antagonist wear test studies on zirconia in the past two decades [102–114].

6.2.1. *Friction study in arthroplasty*

Studies on the wear against zirconia have been conducted for more than 20 years in the field of orthopedics. A variety of materials have been used in the femoral head and cup of artificial hip joints and research interest has been paid to wear of the combination of various materials of these. The first interest of antagonist wear against zirconia was concern to the wear of femoral cups made of high-density polyethylene.

In 1991, Kumar et al. [102] employed three types of materials (zirconia, alumina, and stainless steel) and two types of wear test (unidirectional rotary motion and reciprocating motion) in three types of lubricant fluid (distilled water, human blood plasma, and physiological saline solution). They demonstrated that different lubricant fluid media had little

effect on the polyethylene wear against ceramic counterfaces, but were prominent against SUS316L metal. They concluded that Y-PSZ ceramic is a biomaterial potentially suitable for low-friction arthroplasty because of its better wear-resistant properties and high strength. It was confirmed that soft antagonists such as polyethylene rarely wear on zirconia, although zirconia is quite hard. This fact implies that the hardness of the materials is independent on the susceptibility of antagonist wear.

6.2.2. Wear studies using enamel in the 2000s

Zirconia began to spread to the dental field in the 2000s and entered the mature stage in the 2010s. With the development of peripheral technology of zirconia, the conclusion about the antagonist wear against zirconia crown restoration has changed.

At the International and American Association for Dental Research (IADR) 2003, Tambra et al. [103] reported that zirconia caused greater enamel wear than did the IV gold control, although the polished zirconia caused less wear to the enamel abrader than the processed zirconia. They described that the surface was mirror-polished with diamond paste. However, the polishing method and the smoothness of zirconia were not indicated.

At the American Association for Dental Research (AADR) 2008, Culver et al. [104] determined the wear of premolar enamel against five types of materials (Cercon, Lava, Empress, MZ100, and Z100) using a modified Leinfelder wear testing machine. They reported that zirconia (Cercon and Lava) caused more enamel loss than composite resins (MZ100 and Z100) and leucite-containing glass (Empress).

At the AADR 2010, Shar et al. [105] determined the wear of premolar enamel against polished and glazed zirconia using a modified Leinfelder wear testing machine. They reported that the polished zirconia showed larger enamel loss than the glazed one.

The polishing conditions of these reports were unclear. In the 2010s, various polishing materials and instruments for zirconia have been introduced and the conclusion began to change.

6.2.3. Wear studies using enamel in the 2010s

In 2010, Jung et al. [106] measured enamel loss against three types of surface-treated zirconia (Zirkonzahn Prettau). They reported that the enamel loss on the mirror-polished zirconia was significantly less than those of glazed and porcelain-veneered ones. On the other hand, Albashaireh et al. [107] measured the loss of five dental ceramics (e.max ZirCAD, e.max Press, Empress Esthetic, e.max ZirPress, e.max Ceram) against zirconia balls using dual-axis mastication simulator. They demonstrated that the degree of antagonistic tooth wear was less in zirconia than feldspathic dental porcelain, representing that the zirconia may be more beneficial in terms of antagonistic tooth wear (Fig. 13).

At the IADR 2011, Sorensen et al. [108] measured the enamel wear against seven types of materials (Omega 900, Empress, Bovine enamel, d. sign, Lava, Aquarius, and

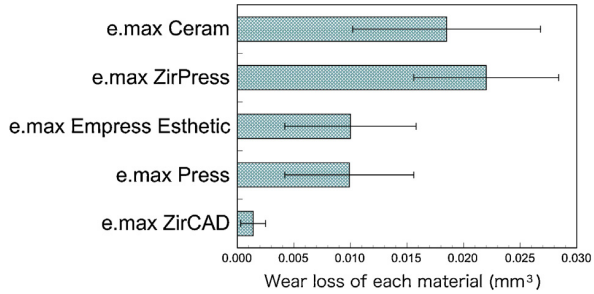

Fig. 13. Wear loss of five dental ceramics against zirconia ball (ϕ = 6 mm) after 300,000 mastication cycles.
Graphing of the data in [107].

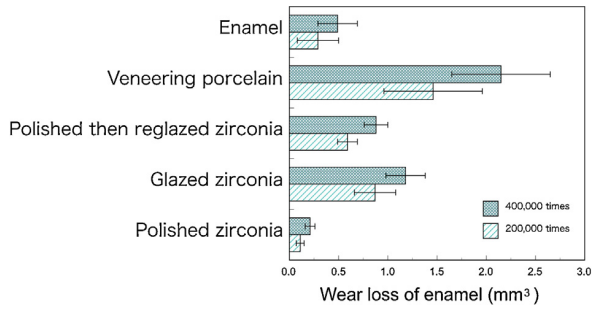

Fig. 14. Wear loss of enamel against four different surface treated zirconia and enamel after 400,000 chewing cycles.
Graphing of the data in [112].

Empress 2) using the Oregon Health & Science University (OHSU) oral wear simulator. They reported that the polished Lava showed small enamel loss similar to that of gold alloy (Aquarius). At the same meeting, Basunbul et al. [109] reported the enamel wear of four types of materials. They demonstrated that polished Wieland zirconia caused significantly less wear to enamel than the glazed Wieland zirconia, Ceramco porcelain, and Cerec Mark II. They concluded that the polished zirconia remained unchanged, but the glazed zirconia showed significant loss of the glazed layer.

At the IADR 2012, Yang et al. [111] measured the enamel wear against Zirkonzahn Y-TZP (polished, stained, stained then glazed), Acura Y-TZP, Wieland Y-TZP, a feldspathic porcelain using the University of Alabama wear-testing device. They demonstrated that the antagonist wear of the three Y-TZP products was significantly less than veneering porcelain because the surface character of Y-TZP is relatively homogeneous, and Zirkonzahn with staining and glazing was significantly more abrasive than the other Y-TZPs without glazing.

In 2013, Janyavula et al. [112] measured the loss of molar enamel of four types of surface-treated zirconia (Lava). They concluded that highly polished zirconia is more desirable than glazed zirconia (Fig. 14). Furthermore, Stawarczyk et al. [114] measured the enamel loss of three types of surface-treated zirconia (ZENOTEC Zr Bridge Translucent) and a base alloy (Denta NEM, CoCr alloy) using a chewing

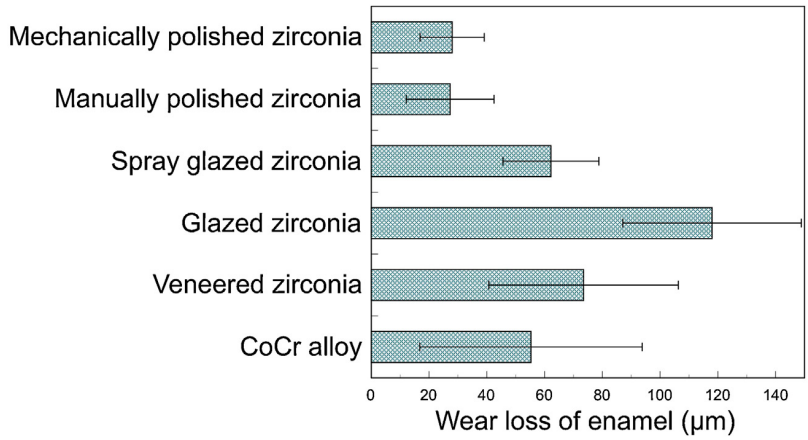

Fig. 15. Wear loss of enamel against five different surface-treated zirconia and a CoCr alloy after 1,200,000 chewing cycles. Graphing of the data in [114].

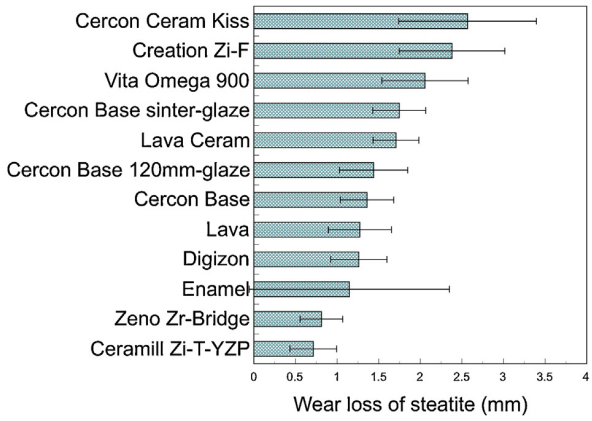

Fig. 16. Wear loss of steatite balls ($\phi = 3$ mm) against five zirconia and four veneering porcelains after 1,200,000 chewing cycles. Graphing of the data in [32].

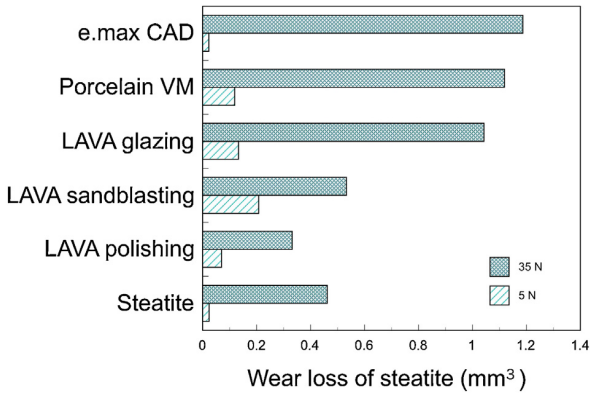

Fig. 17. Wear loss of steatite balls ($\phi = 6$ mm) against four surface treated zirconia and e.max CAD after 120-min longitudinal moving at 72 cycles/min Graphing of the data in [110].

simulator. They reported that the polished zirconia showed a lower wear rate on enamel antagonists as well as within the material itself (Fig. 15).

6.2.4. Wear studies using steatite

On the other hand, there were no reliable clinical reports because of large variation of measurement values and conditions. As a substitute for human enamel, steatite ($MgO{\cdot}SiO_2$) has been frequently used as an antagonist material due to similar wear behavior to human enamel [115–118]. In 2011, Preis et al. [32] measured the loss of steatite and enamel of five zirconia and four veneering porcelains using a chewing simulator. They reported that antagonist wear against zirconia was lower than the wear against porcelain (Fig. 16). Kuretzky et al. [110] measured the enamel loss against four kinds of surface-treated zirconia (rough, polished, glazed, and veneered Lava) and e.max CAD using a longitudinal moving notch device. They demonstrated that the polished zirconia showed the least wear after abrading with a steatite sphere (Fig. 17).

In 2013, Kontos et al. [113] measured the loss of steatite against five types of surface-treated zirconia using a chewing simulator. They concluded that the polished zirconia seems to have the lowest wear on the antagonist, in contrast to the other types of surface treatment (sandblasted, ground, and glazed) (Fig. 18).

According to these studies on antagonist wear, it is summarized as follows.

- A smooth surface of zirconia can be obtained with adequate polishing, because the microstructure of zirconia is fine and homogeneous. Highly polished zirconia shows the least wear of antagonist among various dental materials.
- Glazed zirconia shows higher wear loss than that of polished zirconia, although the surface of glazed zirconia is smooth before wear testing. Because the thin glaze layer (ca. 100 μm) disappears after a period of function, consequently a rough surface appears, which can act aggressively as an abrasive surface [107,113].

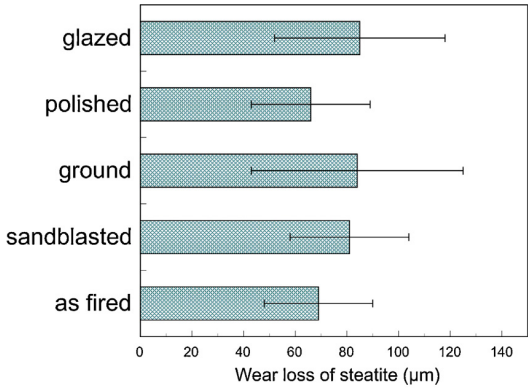

Fig. 18. Wear loss of steatite balls ($\phi = 6$ mm) against five surface-treated zirconia after 5000 cycles.
Graphing of the data in [113].

- Porcelain-veneered zirconia shows higher wear loss than that of polished zirconia, because porcelain consists of a feldspathic glass and leucite crystal grains (ca. 10 μm). The glass easily disappears after wear such as mastication, consequently large leucite grains are exposed and act as abrasive materials.

6.3. Prevention of antagonist enamel wear against zirconia restoratives

When dental zirconia is used as the full contour, the wear of antagonist enamel is a concern because zirconia is very hard. However, it is a misunderstanding. This review describes the method for surface finishing of zirconia restoratives and its effect on the wear of antagonist enamel. The correlation between hardness and wear is small [97]. The wear strongly depends on the homogeneity and particle size of the microstructure of the restorative material. Because zirconia has a fine uniform structure, it is suitable for mirror polishing by using appropriate polishing materials and instruments containing fine diamond particles. There is no need to fear the wear of the enamel of opposing teeth against zirconia restoratives. Vice versa, the wear of antagonist enamel is large when the surface roughness of zirconia restoratives is large. Therefore, when zirconia restoratives are ground for occlusal correction, their surface should be sufficiently mirror-polished. Furthermore, glazing is not recommended for the surface finish of zirconia.

7. Clinical evaluation of zirconia restoration

7.1. Clinical outcome

To date, PFM restorations remain the most widely and successfully used options for FPDs since their failure rates are often low (8–10% within 10 years). Overall, the clinical survival rates of FPDs are between 72% and 87% after 10 years, between 69% and 74% after 15 years, and 53% after 30 years [4,119,120]. However, as is well-known, the metals used in PFM restorations have the potential to cause allergic or toxic reactions within soft or hard tissue. Also, PFM is known to cause graying of the gingival margin because of metal show-through.

The increased use of ceramics for restorative procedures and demand for improved clinical performance has led to the development and introduction of several new ceramic restorative materials and techniques. PFM restorations became available for dentistry in the 1960s followed by Dicor glass ceramics (Dentsply Intl, York, PA, USA), the castable Fluormica Glass-Ceramic in the 1980s, the installation of systems such as VITABLOCS® MARK II for CEREC® (Vita), In-Ceram® ALUMINA (Vita), and IPS Empress (Ivoclar-Vivadent) etc. of the early 1990s. Y-TZP-based systems are a recent addition to the high-strength, all-ceramic systems used for crowns and fixed partial dentures [121,122]. CAD/CAM-produced Y-TZP-based systems are in considerable demand in esthetic and stress-bearing regions. The highly esthetic nature of zirconia with its superior physical properties and biocompatibility makes it an effective restorative system to meet the demands of modern patients [123–125]. Currently, endowing a removable knob to the dental prosthesis apparatus has made it possible to treat temporary cementation. Clinical fractures of all-ceramic crowns and FPDs have rarely been identified.

Crowns are reported to spoil from the cavital cementation surface, which is opposite the chewing surface whereas all-ceramic FPDs spoil at their connectors [126–128]. The past decade has seen the unprecedented introduction of a myriad of all-ceramic crown systems. Many of these systems have been criticized for their failure in restorations. It has been reported that the survival rates for all-ceramic restorations range from 88% to 100% after 2–5 years in service and up to 97% after 5–15 years of service [129–138]. Although all-ceramic restorations have improved considerably, zirconia is undoubtedly the best all-ceramic restoration available. Since the end of the 1990s a form of partially stabilized zirconia has been promoted as being suitable for dental use because of its excellent strength and superior fracture resistance as a result of numerous clinical and basic scientific studies [4,139]. To gain the strength benefits of the core material, the core-veneer bond strength must be of adequate strength and toughness to transmit functional stresses from the esthetic veneer to the underlying framework. CAD/CAM-produced zirconia was first introduced to Japan around 2005. Numerous clinical studies have evaluated zirconia ceramic restorations and concluded that chipping or fracturing of the veneering porcelain are observed at a relatively high rate in posterior zirconia-based ceramic restorations. Factors that are considered during the fabrication of restorations include differences in the coefficient of thermal expansion, undesirable heating and cooling rates between the veneering porcelain and the porcelain framework, and unfavorable shear forces between the zirconia framework and layering material [54,140–142]. Several aspects of zirconia dental restorations require investigation in randomized controlled clinical trials. The most common complaints are chipping of the veneer surface or framework fracture (Fig. 19). Clinical

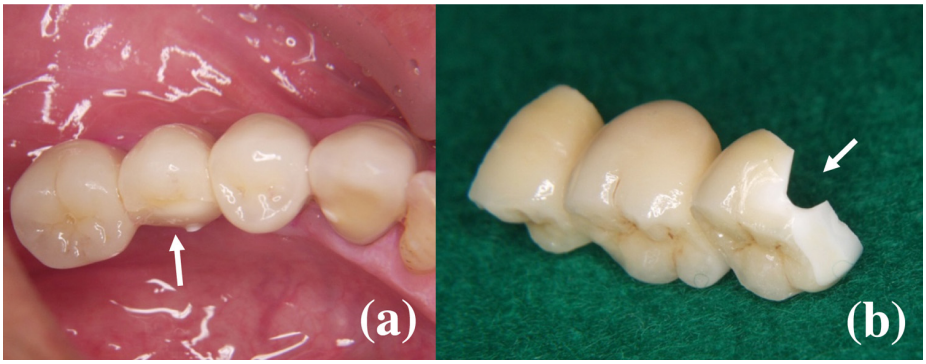

Fig. 19. (a) Chipping of the ceramic veneer. (b) Framework fracture in the second upper left molar distal buccal.

Table 7
Clinical performance of zirconia fixed restorations.

Authors [Ref] (Year)	Materials	Type of restorations	Mean time	Sample size	Framework complication	Veneer complication	Survival rate, %
Philipp et al. [144] (2010)	Nanozir, Hint-Els	3 unit FPDs	1 year	8	0	0	100
Roediger et al. [145] (2010)	Cercon smart ceramics: Degudent	3–4 unit FPDs	4 years	99	1	13	98.9
Vigolo et al. [146] (2011)	Procera:Nobel Biocare	Single crowns	5 years	20	0	2	79
	LAVA:3M ESPE	Single crowns	5 years	20	0	1	85
Sorrentino et al. [147] (2012)	Procera:Nobel Biocare	3 unit FPDs	5 years	48	0	3	100
Örtorp et al. [148] (2012)	Procera:Nobel Biocare	Single crowns	5 years	216	0	6	88.3
Kern et al. [149] (2012)	In-Ceram Zirconia:Vita	3–4 unit FPDs	5 years	20	3	Unknown	90
Salido et al. [150] (2012)	LAVA:3M ESPE	4 unit FPDs	4 years	17	3	5	76.5
Pelaez et al. [151] (2012)	LAVA:3M ESPE	3 unit FPDs	4 years	20	0	2	95
Rinke et al. [152] (2012)	CerconBase:Degudent	3–4 unit FPDs	7 years	97	5	23	83.4

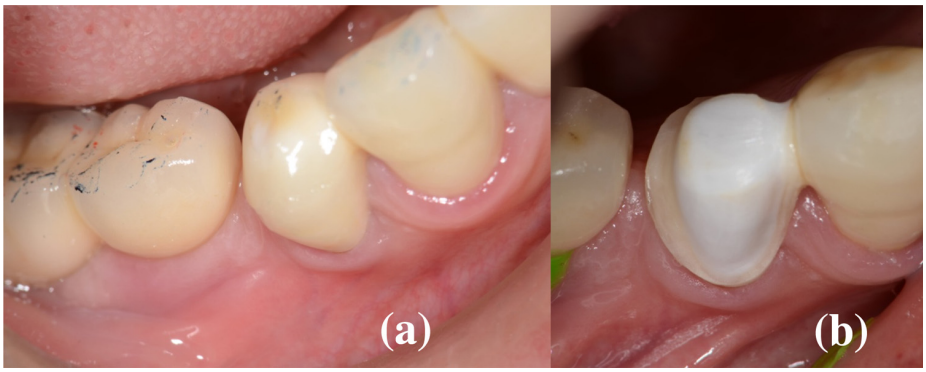

Fig. 20. (a) Chipping of the ceramic veneer of FPDs (the lower right first premolar). (b) Preparation for abutment tooth of repair.

achievements up to 2009 have been reported in other review articles [25,143]. In this review, clinical data from 2010 are listed in Table 7 [144–152]. The zirconia core rarely gets damaged in many cases and the complication often occurs in the ceramic material. Zirconia, a white crystalline oxide of zirconium, has high mechanical strength, toughness, corrosion resistance, and excellent biocompatibility with a significant reduction of plaque [153,154]. Although zirconia degradation at low temperatures is a progressive and spontaneous phenomenon, the introduction of stabilized zirconia has created a real possibility and promise for the application of ceramics in dental reconstructions [155]. Marchack et al. [156] eliminated the porcelain coverage of zirconia copings and frameworks to reduce the incidence of chipping or fracturing of the porcelain veneer. A technique to custom design strong milled ceramic cores for all-ceramic crowns has been presented. The most common technical complication of zirconia-based restorations is fracturing of the veneering ceramic with or without exposing the zirconia framework. Some recommendations for optimizing the fabrication process of zirconia-based FPDs have been published and include modification of the firing protocol. This might reduce the chipping rate and can therefore be recommended. Paolo Vigolo et al. [146] showed that

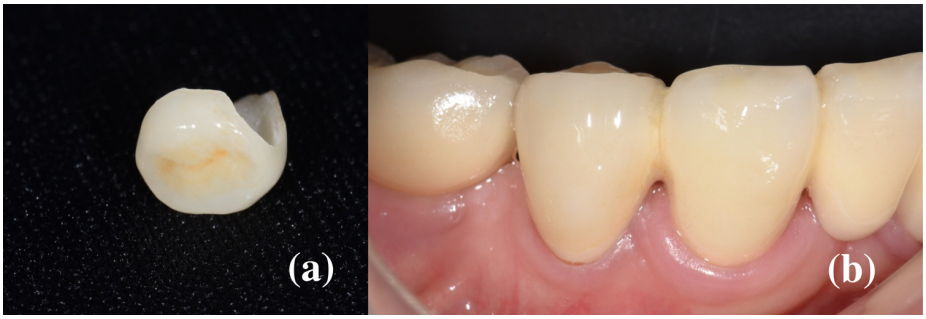

Fig. 21. (a) Custom-made press ceramic shell (occlusal view). (b) Buccal view of 3 years after repair.

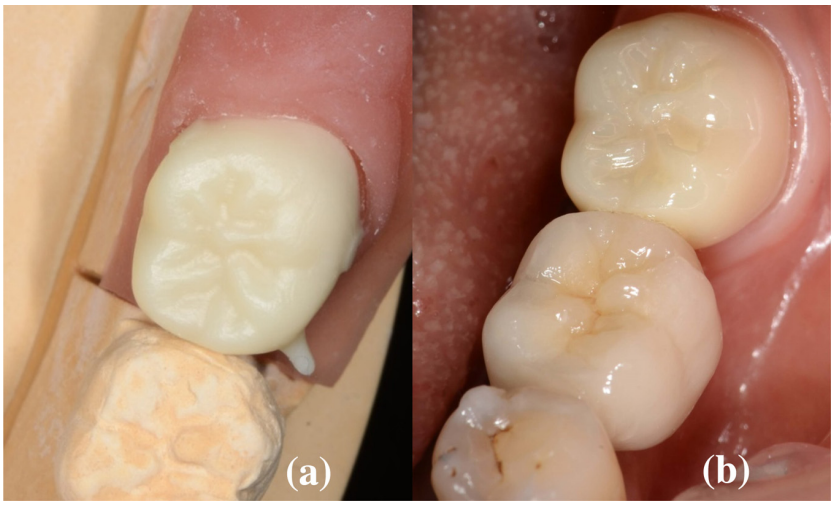

Fig. 22. (a) Cercon ht, fully contoured crown, made possible by nanotechnology, before polishing. (b) Occlusal view of the Cercon ht, fully contoured crown (second lower left molar).

zirconia-ceramic FDP groups tend to give more frequent clinical problems such as extended fracturing of the veneering ceramic. All clinical and technical variables related to the use of zirconia-ceramic FDPs generated with CAD/CAM systems should be carefully considered before all treatment procedures. On the other hand, along with the development of ceramics for building on zirconia, lithium disilicate glass-ceramic frameworks have been invented. As dentistry continues to evolve, new technologies and materials are continually being offered to the dental profession. Lithium disilicate glass-ceramic frameworks with impressive esthetic properties create long-lasting all-ceramic restorations. Used successfully in the fabrication of single-tooth restorations, lithium disilicate now forges new paths and it eliminates the need for metal and zirconia frameworks. Single zirconia crowns veneered with overpressed ceramics exhibit a lower fracture load. Lithium disilicate enables users to fabricate tooth- or implant-supported posterior bridge restorations with an outstanding overall strength [15,157–159]. It can also be applied to the repair of zirconia-based FPDs that chip off during the press-technique. It is repaired by the abutment tooth preparation process, impression taking, wax up, pressing with the disilicated lithium, and finally installing the repaired shell (Figs. 20 and 21).

Fig. 23. Shade infiltration before the sintering process.

7.2. The future prospect of zirconia restorations

Developed from the clinically proven formula for a Cercon base yttria-stabilized zirconia material, Cercon ht (Dentsply Intl., York, PA, USA) represents the new zirconia generation with outstanding translucency for highly esthetic restorations and requires no porcelain build-up. Recently, some zirconia applied as the base material has been

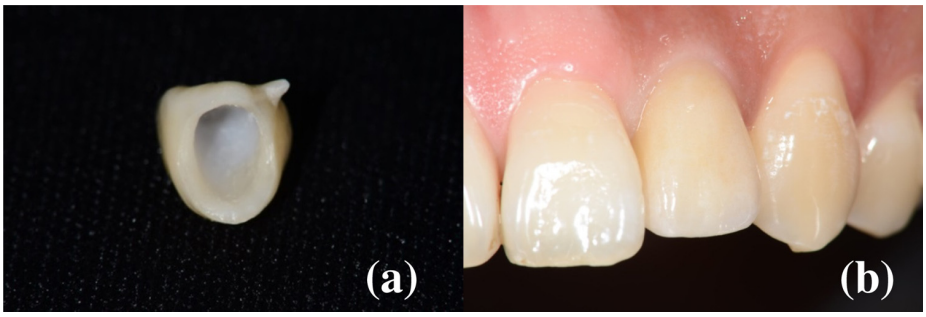

Fig. 24. (a) Inside view of the Cercon ht, fully contoured crown. (b) Labial view of the Cercon ht, fully contoured crown (upper left lateral incisor).

developed as semitransparent so that glass sintering can replicate the natural color of a tooth (Figs. 22–24). Zirconia is used exclusively for crowns and FPDs without using veneer ceramics or press ceramics. It has a high flexural strength of over 1200 MPa with excellent veneering characteristics. In dental ceramics, zirconia has proven to be a durable, reliable framework material capable of inhibiting crack growth and preventing catastrophic failure. Clinical studies have shown that zirconia is abrasive to the opposing dentition and it causes excessive wear of the tooth structure. Other in vivo studies are in progress and have demonstrated that polished zirconia yielded high wear resistance and lower antagonistic wear compared to porcelains. On the other hand, new zirconia generation materials leave the surfaces of the antagonists smooth, precisely like natural enamel [160]. There is still much to learn about zirconia and the production of zirconia copings and frameworks. Further studies with larger sample sizes and longer follow-up periods are required to investigate the possible influencing factors of technical failures.

8. Conclusion

Y-TZP had higher mechanical properties and superior resistance to fracture but had insufficient translucency. Therefore, porcelain has been generally veneered on the framework of Y-TZP. Because of the recent rapid progress of dental CAD/CAM technologies including the performance of scanners, CAD software, and net-worked machining centers, Y-TZP frameworks with clinically acceptable fit were successfully fabricated using the current commercially available CAD/CAM systems.

Both the layering and press techniques with conventional manual work were available for bonding porcelain to the frameworks. Different from the metal-to-porcelain integration of the conventional PFM restoration systems, mechanical bonding mainly contributed to the zirconia-to-porcelain bonding.

Recent clinical studies reported that chipping or fracturing of veneering porcelain was observed at a relatively higher rate in zirconia-based FPDs than conventional PFM systems. There were many factors affecting the failure and included the matching of the coefficient of thermal expansion of both materials, the adequate framework design to support the veneering porcelain, and the adequate handling of both materials in the dental laboratory. Therefore, the framework material with superior mechanical properties and the alternative application of techniques for the veneering materials were introduced.

Ce-TZP/A appeared to be a promising material, because of extremely higher fracture toughness and resistance to LTAD, and was suitable for fabricating frameworks with a lingual supporting structure similar to that of conventional PFM frameworks.

In addition, there were two alternative application techniques of veneering materials. One was hybrid-structured FDPs comprising CAD/CAM-fabricated porcelain veneering parts adhering to a CAD/CAM-fabricated zirconia framework. In this system, all parts of the FDPs were fabricated by the CAD/CAM process without manual steps. A reliable adhesive treatment for both parts was performed in a laboratory. Combined application of silica coating and/or silane coupler, and MDP monomer in the priming agents is currently one of the most reliable adhesive systems of zirconia.

Another alternative solution was to not use porcelain. The opacity of Y-TZP was improved and full-contoured zirconia FPDs without veneering porcelain were introduced into the clinic. However, there was concern about the wear of the opposing enamel and other antagonist materials because the hardness of Y-TZP was over double that of porcelain. According to the current studies, highly polished zirconia showed the least wear of antagonists among various dental materials including enamel. However, the wear of antagonist enamel became large when the surface roughness of zirconia restoration was large. Therefore, surface finishing and polishing procedure of zirconia full-contoured restorations was critical for obtaining clinical success.

Because of the rapid development of both materials and processing technologies, application of zirconia-based FPDs seemed promising. However, dentists and dental technicians must collaborate and perform the proper clinical procedures even if the CAD/CAM can neglect some parts of the conventional manual work. We still need longer clinical evaluations to prove the usefulness of zirconia-based FDPs especially with new options.

Conflict of interest

Authors have no conflict of interest concerning the present manuscript.

Acknowledgments

The present study was partially supported by the Grant-in-Aid for General Science Research from the Japan Society for the Promotion of Science. The authors would like to thank Dr Sakakibara, T. (Aichi Gakuin University) for the measurement of polishing and grinding properties of zirconia.

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