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CAD/CAM Ceramic Restorative Materials for Natural Teeth

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Abstract

Advances in computer-aided design (CAD) / computer-aided manufacturing (CAM) technologies and their ease of application enabled the development of novel treatment concepts for modern prosthodontics. This recent paradigm shift in fixed prosthodontics from traditional to minimally invasive treatment approaches is evidenced by the clinical long-term success of bonded CAD/CAM glass-ceramic restorations. Today, defect-oriented restorations, such as inlays, onlays, and posterior crowns, are predominately fabricated from glass-ceramics in monolithic application. The variety of CAD/CAM ceramic restorative systems is constantly evolving to meet the increased demands for highly aesthetic, biocompatible, and long-lasting restorations. Recently introduced polymer-infiltrated ceramic network CAD/CAM blocks add innovative treatment options in CAD/CAM chairside 1-visit restorations. The material-specific high-edge stability enables the CAD/CAM machinability of thin restoration margins. Full-contour zirconia restorations are constantly gaining market share at the expense of bilayered systems. Advancements in material science and bonding protocols foster the development of novel material combinations or fabrication techniques of proven high-strength zirconia ceramics. CAD/CAM applications offer a standardized manufacturing process resulting in a reliable, predictable, and economic workflow for individual and complex teeth-supported restorations. More evidence from long-term clinical studies is needed to verify the clinical performance of monolithic polymer-infiltrated ceramic network and zirconia teeth-supported minimally invasive and extensive restorations.

Keywords: computer-aided design, clinical outcomes, ceramics, prosthetic dentistry/prosthodontics, minimally invasive dentistry, aesthetics dental

Introduction

Computer-aided design (CAD) / computer-aided manufacturing (CAM) technology is one of the fastest-evolving aspects in modern restorative dentistry. The track record of CAD/CAM technology and chairside dentistry started in 1985, when Mörmann and Brandestini introduced the Cerec system.

An increasing number of chairside systems are now available (Zaruba and Mehl 2017). Intraoral scanners have become significantly better, faster, and smaller, with more intuitive design software surfaces. This virtual environment with on-screen designing and computer-assisted production with rapid prototyping, such as milling or the growing option of 3-dimensional printing possibilities, allows for the fabrication of various restorations without any physical models. Major advantages for the digital workflow over the conventional impression technique are patient's preferences as well as excellent marginal and internal fit of fixed prosthodontics (Chochlidakis et al. 2016; Gallardo et al. 2018). Due to the application of homogeneous industrial blanks and blocks, fewer material failures are likely to occur during fabrication and clinical application (Belli et al. 2017). In comparison with hand-built materials, CAD/CAM blocks reveal a decreased presence of flaws and pores, resulting in increased reliability (Zhang and Kelly 2017).

A large range of materials (Fig. 1) is currently available for the digital manufacturing process, increasing the range of indications in the field of restorative dentistry, dental implantology, orthodontics, and complex treatment-planning strategies. Hence, the decision to choose the right material for each indication has become challenging.

Consequently, the aim of this work is to review the evolution of CAD/CAD ceramic materials, to survey their respective properties, and to critically discuss the recent clinical evidence.

Evolution and State of the Art of CAD/CAM Ceramic Restorative Materials

Glass-Ceramics

Silica. The first CAD/CAM fine-structure feldspar ceramics (VITA Mark II; VITA-Zahnfabrik) evolved from traditional feldspathic ceramics and are still in clinical application (Table). The microstructural characterization of this feldspathic CAD/CAM ceramic reveals 2 crystallization patterns, with a sodium potassium aluminum silicate peak ($Al_8K_2Na_6O_34Si_9$) and a

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potassium sodium aluminum silicate peak ($AlK_{0.29}Na_{0.71}O_3Si_3$; Ramos Nde et al. 2016). The material shows a low characteristic strength (biaxial test with plate geometry σ0, 118.65 MPa; Wendler et al. 2017). The Weibull modulus of this CAD/CAM glass-ceramic, as a measure of data scatter and the material's reliability, is high (m = 19.9; Wendler et al. 2017; Fig. 1).

Leucite-Reinforced Glass-Ceramics. Empress CAD (Ivoclar-Vivadent) is a well-established ceramic derived from early generations of CAD/CAM blocks containing leucite crystals up to 40% embedded in an feldspathic glass-ceramic (Höland et al. 2007). It is a successor of the monolithic CAD/CAM block (ProCAD; Ivoclar-Vivadent) that uses a SiO_2-Al_2O_3-K_2O-Na_2O glass system for the nucleation and crystallization of leucite crystals (Höland et al. 2007). Leucite reveals a dentritical growth through surface crystallization of glass particles in powdered glass by bulky crystallization of monolithic glasses having TiO_2 and CeO_2 as nucleating agents (Höland et al. 2008). With this technique termed "dispersion strengthening" and the addition of fillers such as uniformly dispersed leucite throughout the feldspathic glass, a moderate strength increase could be achieved (Höland et al. 2008). Empress CAD exhibits a flexural strength of 185 MPa according to the manufacturer. The material shows a low characteristic strength (σ0, 187.7 MPa) but a high Weibull modulus of 16.10 (Wendler et al. 2017; Fig. 1).

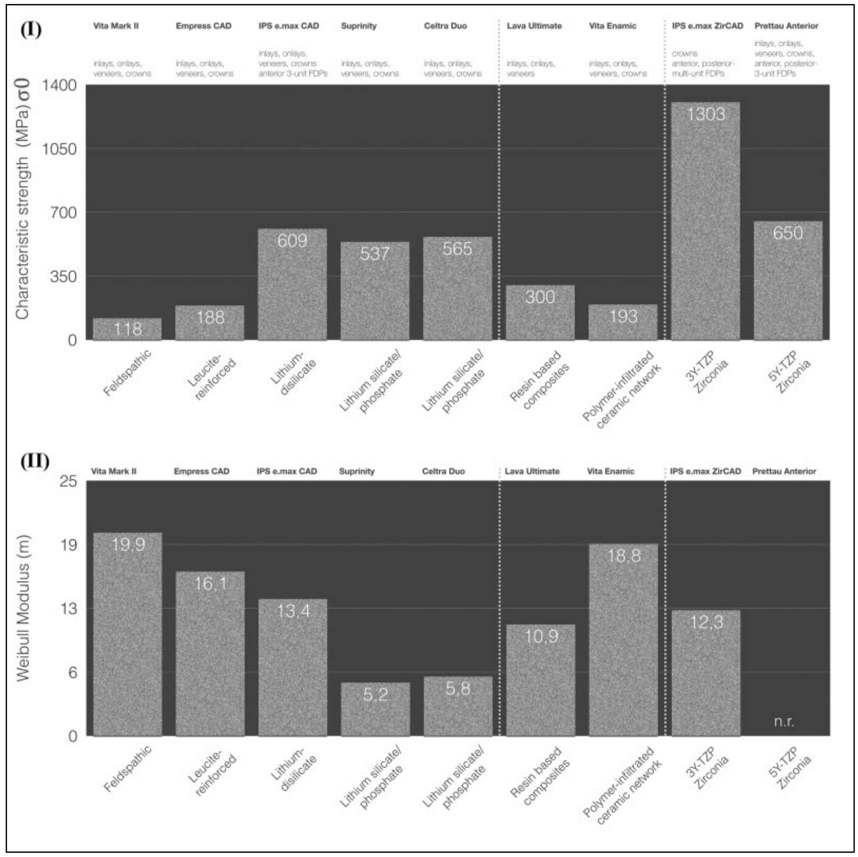

Figure 1. Overview of CAD/CAM ceramic restorative materials for natural teeth. Representative commercial CAD/CAM materials of different classes are listed with their clinical indications. Glass-infiltrated alumina ceramics and densely sintered alumina ceramics were not included in the present overview. (**I**) Data for the characteristic strength—ball-on-3-balls biaxial strength test, with specimens in rectangular plate geometry—and (**II**) Weibull modulus (m) are from Wendler et al. (2017). 3Y-TZP, 3 mol% yttria partially stabilized tetragonal zirconia polycrystal; CAD/CAM, computer-aided design/computer-aided manufacturing; FDP, fixed dental prosthesis. Flexural strength data for 5Y-TZP (5 mol% yttria partially stabilized tetragonal zirconia polycrystal), so-called translucent zirconia, is from Zhang and Lawn (2018); a Weibull modulus for 5Y-TZP is not reported (n.r.).

Lithium Disilicate Ceramics. Significantly higher strength was achieved with a glass-ceramic by precipitating (controlled nucleation and growth) lithium disilicate crystals (Höland et al. 2008). With 2 successful precursor systems (Empress 2 and IPS e.max Press; Ivoclar-Vivadent), a lithium disilicate glass-ceramic IPS e.max CAD (Ivoclar-Vivadent) has been designed for CAD/CAM processing technology. It is derived from the SiO_2-Li_2O-K_2O-ZnO-P_2O_5-Al_2O_3-ZrO_2 system through formation and solid-state reaction (Höland et al. 2008). Lithium disilicate (LDS) ceramic reveals needle-like particles (0.5 to 4 μm) with different orientations (Höland et al. 2000). The milled LDS CAD/CAM is exposed to a 2-stage crystallization process. After sintering, the LDS CAD/CAM obtains its final flexural strength of 530 MPa according to the manufacturer. A recent study described a high characteristic strength (σ0, 609.80 MPa) and Weibull modulus (13.4; Wendler et al. 2017; Fig. 1). Hence, LDS has the highest strength in glass-ceramics, approximately 3 to 4 times the strength of other glass-rich ceramics (Wendler et al. 2017). Due to the favorable translucency and shade variety, the material can be used for monolithic restorations or as a core material coated with apatite-containing veneering ceramics (Maunula et al. 2017). The indication ranges from all kind of single-tooth and implant restorations to anterior and posterior 3-unit fixed dental prostheses (FDPs; limited to premolars; Zhang and Kelly 2017). With recent patent expiration, the variations on the LDS material have become available for other manufacturers (e.g., 3G HS; Jeneric Pentron). No scientific studies are currently available on these derivatives.

Lithium Silicate/Phosphate Glass-Ceramics. In 2013, a novel lithium silicate/phosphate (LSP) CAD/CAM material, also termed zirconia-reinforced lithium silicate glass-ceramics (VITA Suprinity, VITA Zahnfabrik; Celtra, Celtra Duo,

Table. Recent Clinical Studies on CAD/CAM Restorations by Material.

First Author (Year)	Study Design; Setting; Restoration	Material (Core/Veneering Material)	Monolithic/Layered; CAD/CAM System	Restorations, *n*	Failure/Complication				Mean ± SD Follow-up, mo	Survival Rate, %
					Secondary caries, %	Fracture, %	Loss of retention, %	Chipping, %		
Feldspathic										
Lu (2018)	Prospective; university; onlay	VITA Mark II	Monolithic; Cerec AC Bluecam / intraoral scan / Cerec MCXL	34	No secondary caries	2.9	5.8	Not reported	36	3 y: 90.7
Federlin (2014)	Prospective, split-mouth; university; PCR	VITA Mark II, RXU: without enamel etching, RXU + E: with selective enamel etching	Monolithic; Cerec 3D cast scan	68	RXU: 3	RXU: 8.8, RXU + E: 8.8	RXU: 8.8, RXU + E: 3	Not reported	36	3 y: RXU: 72.6, RXU + E: 87.6
Otto (2015)	Prospective; private practice; SC	VITA Mark II	Monolithic; CEREC 3 Redcam / intraoral scan	65 (25 endocrowns + 40 shoulder crowns)	Not reported	Shoulder crowns: 2.5; endocrowns: 4	endocrowns: 8	Shoulder crowns: 2.5	128	12 y: 90.3 (shoulder crowns. 94.9; endocrowns: 85.7)
Netjatidanesh (2015)	Retrospective; private practice; inlay / onlay	Cerec Blocks	Monolithic; Cerec AC Bluecam / intraoral scan / Cerec MCXL	102	No secondary caries	1	No loss of retention	Not reported	60	5 y: 96
Leucite-reinforced glass-ceramics										
Netjatidanesh (2015)	Retrospective; private practice; inlay / onlay	Empress CAD	Monolithic; Cerec AC Bluecam / intraoral scan / Cerec MCXL	57	No secondary caries	3.7	1.8	Not reported	60	5 y: 94.6
Lithium disilicate										
Akin (2015)	Prospective; university; SC	IPS e.max CAD	Layered; cast scan	15	No secondary caries	No fracture	No loss of retention	No chipping	24	2 y: 100
Seydler (2015)	Prospective; private practice; SC	IPS e.max CAD	Monolithic; intraoral scan Bluecam / intraoral scan / Cerec MCXL	30	No secondary caries	No fracture	No loss of retention	No chipping	26.3 ± 2.8	2 y: 100
Rauch (2018)	Prospective; university/private practice; SC	IPS e.max CAD LT	Monolithic; intraoral scan (CEREC 3)	34	7.7	3.8	3.8	No chipping	121.2 ± 2.4	10 y: 83.5
Reich (2014)	Prospective; university/private practice; FDP	IPS e.max CAD LT (+ IPS e.max Ceram)	Monolithic / cut-back; Cerec3D / intraoral scan, inLab / cast scan	32	Not reported	3.1	Not reported	6.25	46 ± 8.4	4.7 y: 93
Resin-matrix-ceramics										
Zimmermann (2017)	Prospective; university / dental students; PCR	Lava Ultimate	Monolithic; Cerec AC Bluecam / cast scan / Cerec MCXL	42	Not reported	4.8	7.1	Not reported	24	2 y: 85.7
Spitznagel (2018)	Prospective; university; inlay / PCR	VITA Enamic	Monolithic; Cerec InLab cast scan	103	No secondary caries	3.8	No loss of retention	5	36	3 y: 96.4, Inlay: 97.4 PCR: 95.6
Lu (2018)	Prospective; university; onlay	VITA Enamic	Monolithic; Cerec AC Bluecam / intraoral scan / Cerec MCXL	67	No secondary caries	1.5	1.5	Not reported	36	3 y: 97
Chirumamilla (2016)	Retrospective; private practice; SC	VITA Enamic	Monolithic; Cerec AC Bluecam / intraoral scan / Cerec MCXL	45 (31 with self-adhesive cement; 14 RMGI)	RMGI: 7.1	No fracture	RMGI: 7.1	No chipping	24	2 y: Resin cement: 96.8 RMGI: 92.9
Zirconia										
Güncü (2015)	Retrospective; university/private practice; SC	Zirconia (Lava [Anatomical] + VITA VM9)	Layered; cast scan	618	0.5	No fracture	1	1.9	60	5 y: 98.1
Nejatidanesh (2016)	Retrospective; university/private practice; SC	Zirconia (Cercon [Anatomical] + Cercon Ceram Kiss)	Layered; cast scan (CAD: Cercon)	324	No secondary caries	No fracture	6.3	8.1	60.7	5 y: 97.3
Rinke (2016)	Prospective; private practice; SC	Zirconia [Anatomical] + Cercon Ceram Kiss	Layered; cast scan (CAD: Cercon)	50	2	2	4	12	64 ± 4.8	5 y: 94
Güncü (2016)	Retrospective; university/private practice; SC	Zirconia (Lava [Anatomical] + VITA VM9)	Layered; cast scan (Lava System)	24	No secondary caries	No fracture	No loss of retention	4.2	48	4 y: 98

(continued)

Table. (continued)

First Author (Year)	Study Design; Setting; Restoration	Material (Core / Veneering Material)	Monolithic/ Layered; CAD/ CAM System	Restorations, *n*	Failure/Complication				Mean ± SD Follow-up, mo	Survival Rate, %
					Secondary caries, %	Fracture, %	Loss of retention, %	Chipping, %		
Monaco (2017)	Prospective; university; SC	Zirconia (IPS e.max ZirCAD + ZirPress)	Layered; cast scan	45	No secondary caries	2.2	No loss of retention	6.7	65.7	5 y: 97.73
Dogan (2017)	Prospective; university; SC	Zirconia (Lava + Lava Ceram)	Layered; cast scan (Lava System)	20	No secondary caries	No fracture	No loss of retention	Not reported	58.7	5 y: 100
Seydler (2015)	Prospective; private practice; SC	IPS e.max ZirCAD + IPS. e.max CAD	Layered; Bluecam / intraoral scan / Cerec MCXL)	30	No secondary caries	No fracture	No loss of retention	No chipping	25.3 ± 1.4	2 y: 100
Sasse (2014)	Prospective; university; RBFDP	Zirconia + IPS e.max Ceram	Layered; cast scan (Cerec inLab)	42	2.4	No fracture	4.8	No chipping	61.8	6 y: 100
Sailer (2014)	Retrospective; university; RBFDP	IPS e.max ZirCAD / Cerion Straumann + Initial GC	Layered; cast scan (Cerec inLab / Ethkon, Cares Straumann)	15	Not reported	No fracture	13.3	No chipping	53.3	4 y: 100
Kern (2017)	Retrospective; university; RBFDP	Zirconia	Layered; cast scan	108	Not reported	No fracture	6.5	2.7	92.2 ± 33	10 y: 98.2
Solá-Ruíz (2015)	Prospective; university; FDP	Lava + Lava Ceram	Layered; cast scan (Lava System)	27	7.4	No fracture	7.4	14.8	84	7 y: 88.8
Ioannidis (2016)	Prospective; university; FDP	VITA In-Ceram 2000YZ + Vitadur Alpha	Layered; cast scan (inLab)	59	3.5	No fracture	Not reported	28	75.6 ± 22.8	6.3 y: 94.7; 10 y: 85.0
Naenni (2015)	Prospective; university; FDP	IPS e.max ZirCAD [Anatomical] + IPS e.max ZirPress or IPS e.max Ceram	Pressed / layered; cast scan (inEOS + inLab)	40	Not reported	No fracture	No loss of retention	33.2; ZirPress: 40 IPS e.max Ceram: 20	36.8 / 34.9	3 y: 100
Zenthöfer (2015)	Prospective; university; FDP	Lava [Anatomical] + LavaCeram	Layered; cast scan (Lava System)	11	No secondary caries	No fracture	No loss of retention	20	36	3 y: 100
Moscovitch (2015)	Case series; private practice; SC	Zirconia (Prettau + VITA VM9)	Monolithic / facially layered; cast scan	236	Not reported	No fracture	Not reported	No chipping	2 to 68	5.6 y: 100
Bömicke (2017)	Prospective; university; SC	Zirconia (Cercon ht) + Cercon Ceram Kiss	Monolithic (MZC) / partially layered (PZC); cast scan (CAD: D700 / D800 3Shape)	162 (90 MZC, 72 PZC)	MCZ: 1.2	No fracture	MZC: 2.4; PZC: 1.5	PZC: 1.5	35.1 ± 6.3	3 y: 98.5 MZC: 100; PZC: 98.5

CAD/CAM: computer-aided design / computer-aided manufacturing; FDP: fixed dental prosthesis; PCR: partial coverage restoration; RBFDP: resin-bonded fixed dental prosthesis; RMGI: resin-modified glass ionomer; SC: single crown.

Dentsply-Sirona), was introduced. The monolithic Suprinity blocks are provided in a metasintered stage to facilitate grinding, and the later piece is subjected to a final crystallization firing. The Celtra blocks are available in a precrystallized (Celtra CAD) or fully sintered (Celtra Duo) stage. Inlays, onlays, veneers, and crowns are indications for LSP (Belli et al. 2017).

The lithium silicate glass containing ZrO_2 uses diphosphorous pentoxide (P_2O_5) as a nucleation agent for crystallization of metasilicate (Belli et al. 2017). According to the manufacturer, LSP ceramics contain 10% by weight of dispersed zirconia particles embedded in a fine-grained glass matrix of 500 to 800 nm.

A recent microstructural and phase characterization revealed that both materials have very similar microstructures, constituted of mainly 2 crystal phases. However, the size of the Li_2SO_3 phase, which appeared to have grown larger in Celtra Duo (up to ~1 µm in length) than in Suprinity (~0.5 µm), is significantly different (Belli et al. 2017).

The manufacturer states that the flexural strength averages 360 MPa. A recent study showed that both materials reveal a characteristic strength that is in an intermediate range in comparison with silicate ceramics and zirconia ($\sigma 0$: Celtra Duo, 565.87 MPa; Suprinity, 537.03 MPa; Wendler et al. 2017; Fig. 1). Similar fracture toughnesses of LSP were observed when compared with LDS. Hence, the addition of ZrO_2 to lithium metasilicate and disilicate did not result in an increased strength or higher resistance to crack propagation as compared with LDS (Ramos Nde et al. 2016). Yet, a low Weibull modulus (~5.5) was described for Suprinity and Celtra Duo, indicating material-dependent strength-limiting defects of wide size distribution (Fig. 1). Multiple cracking and surface pitting were observed in scanning electron microscope evaluation throughout the specimen surface. Thermal incompatibility between phases and related high local residual stresses that are relieved upon cooling by means of microcracking are possible reasons (Wendler et al. 2017). In addition, damage induced to the presintered block by diamond-coated grinding instruments during machining is another source of concern (Chavali et al. 2017).

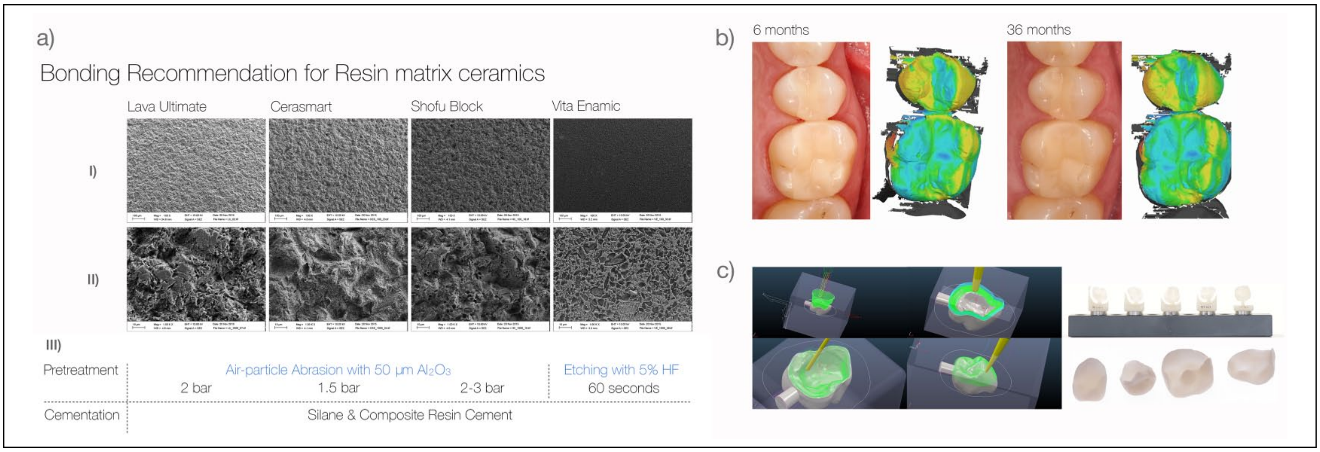

Figure 2. Clinical recommendations, behavior, and advantages of resin-matrix-ceramics. (**a**) Recommended adhesive bonding protocol for resin-matrix-ceramics. Scanning electron microscope pictures with respective recommended pretreatments at magnifications of (I) 100× and (II) 1,000×. At 100× for the resin-based composites Lava Ultimate, Cerasmart, and Shofu Block, a uniformly rough surface caused by alumina air-particle abrasion can be observed. At a higher magnification of 1,000×, minor cracks, cutting edges, small pores, and material-specific grains are evident. A different surface texture can be noticed for the hydrofluoric acid–pretreated polymer-infiltrated ceramic network (PICN) material. At low magnification, a clear etching pattern is visible. The partly dissolved glass phase and a polymeric network phase are perceptible. The enlarged pores and roughened surface subsequently allow a penetration of the bonding systems and enable a permanent adhesive interface. (III) Suggested pretreatment protocol for resin-based composites with air-particle abrasion (50-µm Al_2O_3) at a moderate pressure and 5% hydrofluoric (HF) acid etching for the PICN material. Consequently, all resin-matrix-ceramics should be pretreated with a silane and bonded with an adhesive resin cement. (**b**) Three-dimensional evaluation of 2 PICN inlays after 6 and 36 mo (FDI 25, 26) of clinical function. Matching and superimposition (Geomagic Qualify; 3D Systems) of 6-mo and 3-y recall resin model with color-coded distance display (dark blue color indicates surface loss vs. baseline scan). (**c**) The PICN material-specific high-edge stability enables the CAD/CAM machinability of thin restoration margins. The computer-aided manufacturing of a minimally invasive onlay restoration in the milling preview is displayed in the software (PowerMill Pro 2016; Autodesk). Minimally invasive onlay and full veneer restorations milled from PICN (milling unit: Ultrasonic Linear 20; DMG Mori AG). Smooth and intact margins can be notified.

Resin-Matrix-Ceramics

Resin-matrix-ceramics (RMCs) form a novel group of CAD/CAM ceramic restorative materials, which were developed to combine the positive advantages of polymers, which are not brittle, with ceramics resulting in superior aesthetics (Coldea et al. 2013). There is still an ongoing controversy in the literature about the correct classification of this novel material group. RMCs are also termed as “hybrid ceramic” or “nanoceramics” due to marketing reasons or insurance reimbursement policies, especially in North America (Mainjot et al. 2016). However, these commercial names do not reflect the correct material-specific chemical composition.

Based on their microstructure and industrial polymerization mode, RMCs can be subdivided to 1) high-temperature polymerized resin-based composites (RBCs; CAD/CAM) with dispersed fillers and a predominately organic phase and 2) high-temperature/high-pressure polymer-infiltrated ceramic network (PICN) materials with a predominately inorganic phase (Coldea et al. 2013; Mainjot et al. 2016).

Resin-Based Composites (CAD/CAM). Lava Ultimate (LU) was released as a CAD/CAM machinable block (3M-ESPE) in 2011. It is based on the polymerizable resin composite Filtek Supreme Ultra (3M) and contains dispersed nanometric colloidal silica and ZrO_2 spherical particles in agglomerated and nonagglomerated form (80% wt, 65% vol) embedded in a dimethacrylate resin (Belli et al. 2017). LU exhibits a ceramic/polymer ratio of 80%/20% wt (Wendler et al. 2017). It has a flexural strength of 200 MPa and a dentin-like modulus of elasticity of 12 GPa (Lauvahutanon et al. 2014). The materials showed a comparatively low characteristic strength ($\sigma 0$: 300.64 MPa) in a recent study (Wendler et al. 2017). The Weibull modulus is ~10 (Fig. 1). The Young’s modulus for LU is much lower when compared with VITA Enamic (VE; Belli et al. 2017).

Cerasmart (GC-Corp), Shofu Block HC (Shofu-Inc.), and Brilliant Crios (Coltene) are novel RBCs with a homogeneous and evenly distributed ceramic network. Flexural strengths up to 230 MPa have been reported (Lauvahutanon et al. 2014). RBCs are indicated for veneers, inlays, onlays, single crowns (SCs), and implant crowns (except LU). For resin bonding, RBCs should be pretreated through air-particle abrasion and application of a universal bonding agent (Fig. 2; Spitznagel et al. 2016).

PICN Materials. Recent studies showed that this material (VITA Enamic; VITA-Zahnfabrik) is composed of a PICN containing urethane dimethacrylate and triethylene glycol dimethacrylate cross-linked polymers and a fine open porous feldspathic ceramic structure network (86% wt, 75% vol; Coldea et al. 2013). Both networks interpenetrate each other to combine the positive characteristics of ceramics and composites. Microstructure characterization confirmed that the PICN is amorphous (both phases) with no evidence of crystallization (Ramos Nde et al. 2016). With an E-modulus of ~30 GPa (34.7 GPa; Ramos Nde et al. 2016), VE exhibits properties between enamel and dentin. The Young's modulus of VE is approximately 3-fold higher when compared with LU. The continuous interpenetrating inorganic phase is responsible for the stiffening of the VE material (Belli et al. 2017). According to the manufacturer's data, the material has a flexural strength of 160 MPa. A recent study showed that the characteristic strength (σ0, 193.45 MPa,) is low but the Weibull modulus is high ~18 (Wendler et al. 2017; Fig. 1). Due to the dual network structure, crack propagation is mitigated by the interlinked polymer network (Coldea et al. 2013). VE can be used for all types of single-tooth and implant-crown restorations (Coldea et al. 2013). In vitro results show that 2-body wear, gloss, and roughness is comparable to human enamel (Mainjot et al. 2016). Hydrofluoric acid etching in combination with silane is recommended as a surface pretreatment prior to bonding (Fig. 2; Spitznagel et al. 2016).

Oxide Ceramics

Zirconia Ceramics. In the early 1990s, CAD/CAM technology made zirconia widely available in dentistry. Hence, the material's properties are well known and are described briefly. The material, characterized by a dense monocrystalline homogeneity, possesses low thermal conductivity, low corrosion potential, and good radio-opacity. Due to a phenomenon called "transformation toughening," zirconia reveals unsurpassed flexural strength values (900 to 1,200 MPa) and a high fracture toughness (9 to 10 $MPa{\cdot}m^{1/2}$; Denry and Kelly 2008). A recent study confirmed its very high characteristic strength (σ0: 1,303.21 MPa) and Weibull modulus (~12.30; Wendler et al. 2017; Fig. 1). Zirconia, specifically yttria-stabilized zirconia polycrystal (Y-TZP), was developed as a core material to eliminate bulk fracture of restorations. Hence, the range of applications has been expanded from single crowns and short-span FDPs to multiunit and full-arch zirconia frameworks as well as to complex implant superstructures to support fixed and removable prostheses (Zhang and Lawn 2018). The majority of currently available CAD/CAM systems shape blocks of partially sintered zirconia prior to densification. Enlarged frameworks are then sintered to their full strength, as accompanied by shrinkage of approximately 25% to the desired dimensions (Belli et al. 2017). Press and, most dominantly, hand-layer veneering techniques are used to apply the respective veneering ceramic.

Most recently, functionally graded glass/zirconia/glass structures (Zhang and Kim 2009; Zhang and Lawn 2018) are being explored in high–load bearing areas.

CAD/CAM veneering techniques. Advanced CAD/CAM systems are now able to design and manufacture separate monolithic core and veneer layers that can then be joined with adhesive or sintering methods (Schubert et al. 2017). The VITA-Rapid-Layer-Technology (VITA-Zahnfabrik) uses a CAD/CAM silicate ceramic veneer (Vitablocks-Triluxe, VITA-Zahnfabrik) and a CAD/CAM zirconia core (VITA-YZ-cubes; VITA-Zahnfabrik) that are adhesively bonded.

Sintering a CAD/CAM-milled LDS veneer (IPS e.max CAD) with a low-fusing glass onto the zirconia coping (IPS e.max ZirCAD) was introduced for SCs and 3-unit FDPs (Schubert et al. 2017).

Monolithic Zirconia. Monolithic zirconia restorations refined with superficial glazing are increasingly used (Moscovitch 2015; Bömicke et al. 2017). The mechanical stability of monolithic zirconia for crown and FDPs was demonstrated in many in vitro studies (Zhang and Lawn 2018).

Traditionally, sintering of zirconia is a time-consuming process. To meet the demand for time and cost-effective chairside 1-visit CAD/CAM restorations, novel speed and super-speed sintering protocols (Speedfire; Dentsply-Sirona) have been developed. The effect of speed sintering on the flexural strength of monolithic Y-TZP was investigated (Fig. 3) and showed that no significant difference was observed (Kaizer et al. 2017).

The metastability of tetragonal-zirconia increases the susceptibility to aging in the presence of moisture. This aging phenomenon is known as low-temperature degradation (LTD) and was described many years ago (Kobayashi et al. 1981). There is currently no clear relationship between LTD and failure predictability when zirconia is used in dentistry. Long-term clinical studies are needed to determine the effect of LTD on monolithic zirconia.

Translucent Zirconia. To overcome the problem of veneer chipping, some progress has been made in improving the translucency of Y-TZP by reducing porosity, decreasing grain size, and eliminating the addition of alumina. Many manufacturers (e.g., BruxZir-Solid-Zirconia, Glidewell; InCoris-TZI, Dentsply-Sirona; Prettau-Anterior, Zirkonzahn) introduced a somewhat more translucent CAD/CAM zirconia block for crowns and FDPs (Zhang and Lawn 2018; Fig. 3).

In addition, so-called cubic zirconia materials were launched for monolithic application. An optically isotropic cubic zirconia phase is introduced into an ordinarily tetragonal material (e.g., DD CubeX^2, Dental-Direkt; ZpexSmile, TosoCorp). In contrast to the traditional dental tetragonal zirconia, these translucent ceramic materials are significantly weaker and more brittle and cannot be considered an alternative for the strong but more opaque Y-TZP. The flexural strength of the aforementioned ceramic reveals 600 to 700 MPa and is only half of that of Y-TZP (Zhang and Lawn 2018; Fig. 1). The mechanical integrity and its susceptibility to LTD have to be elaborated.

Minimally Invasive CAD/CAM Restorations

Scientific data on minimally invasive restorations such as CAD/CAM veneers are still scarce. A recent in vitro study revealed that minimally invasive anterior veneers can be fabricated from LDS and leucite-reinforced glass-ceramics at a thickness of 0.5 mm. However, ultrathin veneers (0.3 mm) could be milled only from LDS but not leucite-reinforced

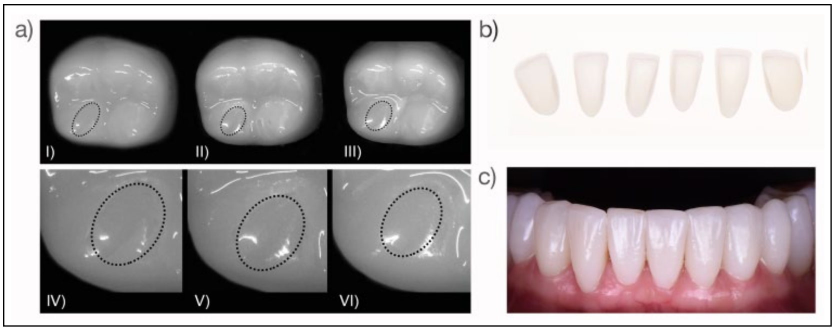

Figure 3. In vitro and clinical behavior as well as advantages of translucent zirconia ceramics. (**a**) Monolithic translucent 3Y-TZP crowns (InCoris TZI; Dentsply Sirona) under optical microscope (SZH 10; Olympus) after 5-y clinical chewing simulation with steatite antagonist (1.2 million sliding cycles at 198 N). The dashed circle indicates the dynamic loading area. (I, IV) Super speed sintered (1,580 °C, total sinter time: 10 min). (II, V) Speed sintered (1,510°C, total sinter time: 1 h (III, VI) Long term sintered (1,510 °C, total sinter time: 4 h). Material loss is limited to the removal of the glaze layer, with only minor superficial damage to the zirconia. (**b**, **c**) Monolithic translucent 5Y-TZP veneer restorations (Prettau Anterior; Zirkonzahn); note the high light transmission of these 0.5- to 0.7-mm-thin veneer restorations. Favorable aesthetic clinical outcomes were obtained. 3Y-TZP, 3 mol% yttria partially stabilized tetragonal zirconia polycrystal; 5Y-TZP, 5 mol% yttria partially stabilized tetragonal zirconia polycrystal.

glass-ceramics (Maunula et al. 2017). For the posterior dentition, CAD/CAM bonded veneers are increasingly applied. Nonretentive preparation designs ranging from 0.4 to 0.6 mm at the fissure and 1.0 to 1.3 mm at the cups tip are suggested (Schlichting et al. 2016). On many occasions even no preparation is needed—for example, with significant loss of the vertical dimension of occlusion due to erosive wear (Schlichting et al. 2016). High fracture loads surpassing physiologic chewing forces were described for these minimally invasive restorations when fabricated from LDS, LSP, and PICN, irrespective of the application of fatigue (Al-Akhali et al. 2017; Yazigi et al. 2017).

Conservative monolithic zirconia molar crowns (0.5-mm occlusal thickness; Nakamura et al. 2015) and posterior 3-unit FDPs (0.6-mm occlusal thickness; Bömicke et al. 2016) also showed high fracture resistance.

Machinability of CAD/CAM Materials

The machinability ("tool penetration rate for a given applied force") of LU (3.21 mm/min) and VE (2.53 mm/min) was significantly greater when compared with LDS (1.12 mm/min) or LSP (0.80 mm/min; Chavali et al. 2017). The material brittleness was directly correlated with the degree of marginal chipping. The ceramic-based materials LDS and LSP revealed edge chipping (Chavali et al. 2017). The high strength of LDS and brittleness of its glassy phase make it difficult to machine during shaping and adjustments with diamond burs (Song et al. 2016). Surface roughness for machined LDS was comparable to that of other glass-ceramics (Song et al. 2016). In this context, the power output of the milling spindels in a mill is related to torque and tool spindles to guarantee high-precision processing of all areas of the workpiece (Kurbad 2017). Hence, the CAD software and milling unit should be modified to match the power of the mill with the machinability of the material. Besides the innovations in material science, novel devices for chairside milling are being developed for faster fabrication times with protocols that are adjusted to the respective CAD/CAM material (Chavali et al. 2017; Kurbad 2017; Fig. 2).

Clinical Evidence: Recent Clinical Trials

An electronic database search (MEDLINE via PubMed, Cochrane Library) for English-language clinical trials published between January 1, 2014, and December 1, 2017, pertaining to the clinical performance of CAD/CAM materials on teeth was performed to provide a comprehensive overview and limit bias in the selection and assessment of the dental literature. A combination of MeSH terms and free-text words was used: *computer-aided design, digital, CAD/CAM, ceramics, dental porcelain, polymers, crowns, dental prosthesis, fixed dental prosthesis, inlays, survival, survival rate, longevity, clinical trials, clinical studies or follow-up studies*. The following inclusion criteria were applied: 1) clinical studies related to CAD/CAM ceramic restorative material restorations on teeth; 2) human clinical trials with 1 of the following study designs—prospective, retrospective, randomized controlled, or case series; 3) studies with a dropout rate <25%; and 4) clinical studies with a mean follow-up time of at least 2 y in function. Manual search complemented the electronic search.

The initial search resulted in 570 records. After title and abstract analysis, 51 publications were retrieved for full-text analysis. A total of 26 articles were finally included for data extraction. The Table scrutinizes the current available clinical evidence of CAD/CAM ceramic restorative materials.

Glass-infiltrated alumina ceramics and densely sintered alumina ceramics, which are no longer in use, were not included in the present review.

Glass-Ceramics

Silica. Recent studies report excellent marginal integrity for CAD/CAM chairside fabricated glass-ceramic restorations (Nejatidanesh et al. 2015; Otto and Mormann 2015; Lu et al. 2018). The clinical long-term performance with high survival rates is well documented for CAD/CAM fabricated glass-ceramic inlays, onlays, and crowns (Table; Federlin et al. 2014; Otto and Mormann 2015; Otto 2017; Lu et al. 2018).

The adequate preparation design and proper adhesive cementation protocol are crucial for the long-term success of these restorations (Federlin et al. 2014; Nejatidanesh et al. 2015). Nowadays, nonretentive preparation designs in combination with reduced ceramic thicknesses allow a minimally invasive treatment approach (Ahlers et al. 2009). Due to this treatment modality and the fabrication of CAD/CAM restorations in a single treatment session, endodontic complications decreased significantly and are rarely reported in the present literature (Nejatidanesh et al. 2015; Otto and Mormann 2015). Also, secondary caries has become a rare biological complication (Federlin et al. 2014; Nejatidanesh et al. 2015; Otto and Mormann 2015; Lu et al. 2018; Table).

Leucite-Reinforced Glass-Ceramics. Long-term data are presently available only for minimally invasive restorations. Favorable survival rates of 95% after 5 y have been reported (Nejatidanesh et al. 2015). Tooth vitality played a significant role: ceramic fracture occurred significantly more often in nonvital than in vital teeth (Nejatidanesh et al. 2015). No secondary caries was observed, and the color match was significantly better when compared with feldspathic-based CAD/CAM systems (Nejatidanesh et al. 2015).

Lithium Disilicate Ceramics. CAD/CAM LDS crowns showed high clinical survival rates for chairside fabrication: 100% after 2 y (Akin et al. 2015; Seydler and Schmitter 2015) and 83.5% after 10 y (Rauch et al. 2018). Promising results are also available for CAD/CAM monolithic LDS 3-unit FDPs, with survival rates of 93% after 4.7 y (Reich et al. 2014), with limited technical and biological complications. However, adequate dimension of the connectors is crucial for the clinical success of LDS FDPs. Clinical long-term studies on minimally invasive LDS restorations are needed.

Lithium Silicate/Phosphate Glass-Ceramics. No clinical study that met the inclusion criteria of this search could be identified, as the material was only recently introduced. Preliminary data revealed a success rate of 96.7% for LSP restorations after 12 mo (Zimmermann, Koller, Mehl, and Hickel 2017). However, future studies need to address the long-term performance of LSP glass-ceramics.

Resin-Matrix-Ceramics

Resin-Based CAD/CAM Composites. Preliminary data on LU partial-coverage restorations (PCRs) revealed a survival rate of 85.7% after 2 y. Two tooth fractures (4.8%) and 3 debondings (7.1%) were observed. However, it has to be noted that dental students performed the restorations (Zimmermann, Koller, Reymus, et al. 2017). Clinical long-term data are lacking to date. The degradation and discoloration behavior of the RBCs needs to be addressed in further research. No clinical study on other RBC materials could be identified.

PICN Materials. Chairside fabricated PICN crowns revealed 2-y survival rates of 96.8% for resin composite cementation and 92.9% for resin-modified glass ionomer cementation (Chirumamilla et al. 2016). Promising results are also available for PICN minimally invasive restorations: the 3-y survival rates were 97.4% for inlays and 95.6% for PCRs (Fig. 2; Spitznagel et al. 2018). Similar results with survival rates of 97% after 3 y were also reported for PICN PCRs (Lu et al. 2018). This clinical data revealed that PICN is susceptible toward cementation failure if the material-specific recommendations are not followed. Deterioration of the PICN surface was observed (Chirumamilla et al. 2016; Spitznagel et al. 2018); hence, further clinical long-term data have to be awaited.

Oxide Ceramics

Zirconia Ceramics

Layered restorations. Anterior zirconia single-retainer resin-bonded fixed dental prostheses exhibited excellent clinical outcomes, with survival rates of 100% to 98.2% after 4 to 10 y (Sailer and Hammerle 2014; Sasse and Kern 2014; Kern et al. 2017). Loss of retention is still the most common failure.

Clinical zirconia framework failure rates are much lower than those reported for silicate-based frameworks but cannot be entirely excluded (Table). However, the clinical success of veneered zirconia restorations is predominately limited by the poor performance of the veneering ceramic. The low thermal conductivity of the zirconia core results in a large temperature gradient in the veneer layer upon cooling. Hence, residual thermal stresses become locked into the material system, leading to fractures within the veneering ceramic (Naenni et al. 2015). Veneer fracture rates are reported at 1.9% to 8.1% for SCs after 4 to 5 y (Güncü et al. 2015; Nejatidanesh et al. 2016; Monaco et al. 2017) and 14.8% to 40% for FDPs after 3 to 10 y (Naenni et al. 2015; Solá-Ruíz et al. 2015; Zenthöfer et al. 2015; Ioannidis and Bindl 2016). Anatomic Y-TZP core design and slow-cooling veneer application protocols could reduce the incidence of veneer failures (Zhang and Lawn 2018). However, press veneer application did not result in superior performance of the veneering ceramic when compared with the traditional hand-layer veneering (Naenni et al. 2015). Chairside occlusal adjustment is a major concern. Significantly higher chipping incidence due to the deterioration of the ceramic surface was observed after occlusal grinding (Bömicke et al. 2017).

CAD/CAM veneering techniques. A 2-y evaluation revealed 100% survival for CAD/CAM veneered crowns with no biological or technical complications. However, increased occlusal substance removal (1.8 mm) is necessary for the CAD/CAM veneering technique, which represents a major limitation (Seydler and Schmitter 2015).

Monolithic restorations. Preliminary clinical studies showed that monolithic or minimally veneered (no feldspathic veneer in function) zirconia appeared as a viable treatment option. The evidence on monolithic zirconia crowns and FDPs restorations is presently low (Table). The available studies showed that all monolithic zirconia restorations exhibited a 100% survival rate after 36 to 68 mo (Moscovitch 2015; Bömicke et al. 2017). No fractures, cracks, or chipping within the monolithic zirconia material was observed.

Concerns with respect to the wear behavior could be eliminated when the zirconia surface is well polished and glazed

(Stober et al. 2014). The wear rates of monolithic zirconia crown restorations are in consensus with other clinical studies on all-ceramic restorations (Lohbauer and Reich 2017). However, increased surface roughness due to intraoral adjustment will affect the wear rate. Hence, a perfect polish is a prerequisite for a suitable wear resistance of zirconia and the opposing antagonists (Bömicke et al. 2017; Esquivel-Upshaw et al. 2018).

Translucent zirconia. No clinical studies on novel translucent zirconia materials are currently available.

Perspectives

Nowadays, the subtractive approach is the most current basis for CAD/CAM systems in dentistry. Additive manufacturing, also known as 3-dimensional printing, builds a material layer by layer directly from 3-dimensional digital data without the use of expensive molds and tooling, which are required for the conventional milling technique. Whereas direct deposition printing/jetting of dental ceramics showed major limitations (Silva et al. 2011), stereolithography/digital light procession appears promising (Osman et al. 2017). A recent study revealed sufficient dimensional accuracy of digital light procession–printed zirconia discs and implants (Osman et al. 2017). The mechanical properties exhibited flexural strength values (943 MPa) comparable to that of milled zirconia (800 to 1,000 MPa). Also the Weibull modulus (5.3 to 13) was in line with the reported values for current Y-TZP (4.31 to 21.59). Cracks and porosities present challenges inherent to the layering technique and sintering process of the printed parts. Modifying the sintering parameters and altering the grain size will be future fields for research in exploring the additive manufacturing of ceramic-based materials.

Conclusions

Time efficiency, predictability, and economically interesting treatment options are of great importance in current dentistry.

The clinical long-term success of CAD/CAM fabricated glass-ceramic restorations is well proven. Monolithic CAD/CAM high-strength LDS glass-ceramics reveal high levels of long-term survival for crowns and FDPs. Preliminary clinical data on PICN minimally invasive restorations as well as SCs appear promising. No clinical evidence is currently available on LSP. Problems of zirconia restorations due to fractures within the veneering ceramic could mostly be solved with a trend toward full-contour application for the high–load bearing areas. However, long-term clinical data on the monolithic zirconia treatment approach still need to be awaited. Substantial research on the clinical performance of translucent zirconia CAD/CAM restorations is needed.

Author Contributions

F.A. Spitznagel, contributed to conception, design, and data analysis, drafted and critically revised the manuscript; J. Boldt, contributed to data analysis, drafted and critically revised the manuscript; P.C. Gierthmuehlen, contributed to conception, design, and data analysis, drafted and critically revised the manuscript. All authors gave final approval and agree to be accountable for all aspects of the work.

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References

Ahlers MO, Morig G, Blunck U, Hajto J, Probster L, Frankenberger R. 2009. Guidelines for the preparation of CAD/CAM ceramic inlays and partial crowns. Int J Comput Dent. 12(4):309–325.

Akin A, Toksavul S, Toman M. 2015. Clinical marginal and internal adaptation of maxillary anterior single all-ceramic crowns and 2-year randomized controlled clinical trial. J Prosthodont. 24(5):345–350.

Al-Akhali M, Chaar MS, Elsayed A, Samran A, Kern M. 2017. Fracture resistance of ceramic and polymer-based occlusal veneer restorations. J Mech Behav Biomed Mater. 74:245–250.

Belli R, Wendler M, de Ligny D, Cicconi MR, Petschelt A, Peterlik H, Lohbauer U. 2017. Chairside cad/cam materials: part 1. Measurement of elastic constants and microstructural characterization. Dent Mater. 33(1):84–98.

Bömicke W, Rammelsberg P, Stober T, Schmitter M. 2017. Short-term prospective clinical evaluation of monolithic and partially veneered zirconia single crowns. J Esthet Restor Dent. 29(1):22–30.

Bömicke W, Rues S, Hlavacek V, Rammelsberg P, Schmitter M. 2016. Fracture behavior of minimally invasive, posterior, and fixed dental prostheses manufactured from monolithic zirconia. J Esthet Restor Dent. 28(6):367–381.

Chavali R, Nejat AH, Lawson NC. 2017. Machinability of CAD-CAM materials. J Prosthet Dent. 118(2):194–199.

Chirumamilla G, Goldstein CE, Lawson NC. 2016. A 2-year retrospective clinical study of enamic crowns performed in a private practice setting. J Esthet Restor Dent. 28(4):231–237.

Chochlidakis KM, Papaspyridakos P, Geminiani A, Chen CJ, Feng IJ, Ercoli C. 2016. Digital versus conventional impressions for fixed prosthodontics: a systematic review and meta-analysis. J Prosthet Dent. 116(2):184–190.e12.

Coldea A, Swain MV, Thiel N. 2013. Mechanical properties of polymer-infiltrated-ceramic-network materials. Dent Mater. 29(4):419–426.

Denry I, Kelly JR. 2008. State of the art of zirconia for dental applications. Dent Mater. 24(3):299–307.

Dogan S, Raigrodski AJ, Zhang H, Mancl LA. 2017. Prospective cohort clinical study assessing the 5-year survival and success of anterior maxillary zirconia-based crowns with customized zirconia copings. J Prosthet Dent. 117(2):226–232.

Esquivel-Upshaw JF, Kim MJ, Hsu SM, Abdulhameed N, Jenkins R, Neal D, Ren F, Clark AE. 2018. Randomized clinical study of wear of enamel antagonists against polished monolithic zirconia crowns. J Dent. 68:19–27.

Federlin M, Hiller KA, Schmalz G. 2014. Effect of selective enamel etching on clinical performance of CAD/CAM partial ceramic crowns luted with a self-adhesive resin cement. Clin Oral Investig. 18(8):1975–1984.

Gallardo YR, Bohner L, Tortamano P, Pigozzo MN, Lagana DC, Sesma N. 2018. Patient outcomes and procedure working time for digital versus conventional impressions: a systematic review. J Prosthet Dent. 119(2):214–219.

Güncü MB, Cakan U, Aktas G, Guncu GN, Canay S. 2016. Comparison of implant versus tooth-supported zirconia-based single crowns in a split-mouth design: a 4-year clinical follow-up study. Clin Oral Investig. 20(9):2467–2473.

Güncü MB, Cakan U, Muhtarogullari M, Canay S. 2015. Zirconia-based crowns up to 5 years in function: a retrospective clinical study and evaluation of prosthetic restorations and failures. Int J Prosthodont. 28(2):152–157.

Höland W, Rheinberger V, Apel E, van't Hoen C. 2007. Principles and phenomena of bioengineering with glass-ceramics for dental restoration. J Eur Ceram Soc. 27(2):1521–1526.

Höland W, Schweiger M, Frank M, Rheinberger V. 2000. A comparison of the microstructure and properties of the IPS Empress 2 and the IPS Empress glass-ceramics. J Biomed Mater Res. 53(4):297–303.

Höland W, Schweiger M, Watzke R, Peschke A, Kappert H. 2008. Ceramics as biomaterials for dental restoration. Expert Rev Med Devices. 5(6):729–745.

Ioannidis A, Bindl A. 2016. Clinical prospective evaluation of zirconia-based three-unit posterior fixed dental prostheses: up-to ten-year results. J Dent. 47:80–85.

Kaizer MR, Gierthmuehlen PC, Dos Santos MB, Cava SS, Zhang Y. 2017. Speed sintering translucent zirconia for chairside one-visit dental restorations: optical, mechanical, and wear characteristics. Ceram Int. 43(14):10999–11005.

Kern M, Passia N, Sasse M, Yazigi C. 2017. Ten-year outcome of zirconia ceramic cantilever resin-bonded fixed dental prostheses and the influence of the reasons for missing incisors. J Dent. 65:51–55.

Kobayashi K, Kuwajima H, Masaki T. 1981. Phase change and mechanical properties of ZrO2-Y2O3 solid electrolyte after aging. Solid State Ionics. 3–4(4):489–493.

Kurbad A. 2017. A new milling machine for computer-aided, in-office restorations. Int J Comput Dent. 20(2):201–213.

Lauvahutanon S, Takahashi H, Shiozawa M, Iwasaki N, Asakawa Y, Oki M, Finger WJ, Arksornnukit M. 2014. Mechanical properties of composite resin blocks for CAD/CAM. Dent Mater J. 33(5):705–710.

Lohbauer U, Reich S. 2017. Antagonist wear of monolithic zirconia crowns after 2 years. Clin Oral Investig. 21(4):1165–1172.

Lu T, Peng L, Xiong F, Lin XY, Zhang P, Lin ZT, Wu BL. 2018. A 3-year clinical evaluation of endodontically treated posterior teeth restored with two different materials using the CEREC AC chair-side system. J Prosthet Dent. 119(3):363–368.

Mainjot AK, Dupont NM, Oudkerk JC, Dewael TY, Sadoun MJ. 2016. From artisanal to CAD-CAM blocks: state of the art of indirect composites. J Dent Res. 95(5):487–495.

Maunula H, Hjerppe J, Lassila LLV, Narhi TO. 2017. Optical properties and failure load of thin CAD/CAM ceramic veneers. Eur J Prosthodont Restor Dent. 25(2):86–92.

Monaco C, Llukacej A, Baldissara P, Arena A, Scotti R. 2017. Zirconia-based versus metal-based single crowns veneered with overpressing ceramic for restoration of posterior endodontically treated teeth: 5-year results of a randomized controlled clinical study. J Dent. 65:56–63.

Moscovitch M. 2015. Consecutive case series of monolithic and minimally veneered zirconia restorations on teeth and implants: up to 68 months. Int J Periodontics Restorative Dent. 35(3):315–323.

Naenni N, Bindl A, Sax C, Hammerle C, Sailer I. 2015. A randomized controlled clinical trial of 3-unit posterior zirconia-ceramic fixed dental prostheses (FDP) with layered or pressed veneering ceramics: 3-year results. J Dent. 43(11):1365–1370.

Nakamura K, Harada A, Inagaki R, Kanno T, Niwano Y, Milleding P, Ortengren U. 2015. Fracture resistance of monolithic zirconia molar crowns with reduced thickness. Acta Odontol Scand. 73(8):602–608.

Nejatidanesh F, Amjadi M, Akouchekian M, Savabi O. 2015. Clinical performance of CEREC AC Bluecam conservative ceramic restorations after five years—a retrospective study. J Dent. 43(9):1076–1082.

Nejatidanesh F, Moradpoor H, Savabi O. 2016. Clinical outcomes of zirconia-based implant- and tooth-supported single crowns. Clin Oral Investig. 20(1):169–178.

Osman RB, van der Veen AJ, Huiberts D, Wismeijer D, Alharbi N. 2017. 3D-printing zirconia implants; a dream or a reality? An in-vitro study evaluating the dimensional accuracy, surface topography and mechanical properties of printed zirconia implant and discs. J Mech Behav Biomed Mater. 75:521–528.

Otto T. 2017. Up to 27-years clinical long-term results of chairside Cerec 1 CAD/CAM inlays and onlays. Int J Comput Dent. 20(3):315–329.

Otto T, Mormann WH. 2015. Clinical performance of chairside CAD/CAM feldspathic ceramic posterior shoulder crowns and endocrowns up to 12 years. Int J Comput Dent. 18(2):147–161.

Ramos Nde C, Campos TM, Paz IS, Machado JP, Bottino MA, Cesar PF, Melo RM. 2016. Microstructure characterization and SCG of newly engineered dental ceramics. Dent Mater. 32(7):870–878.

Rauch A, Reich S, Dalchau L, Schierz O. 2018. Clinical survival of chair-side generated monolithic lithium disilicate crowns: 10-year results. Clin Oral Investig. 22(4):1763–1769.

Reich S, Endres L, Weber C, Wiedhahn K, Neumann P, Schneider O, Rafai N, Wolfart S. 2014. Three-unit CAD/CAM-generated lithium disilicate FDPS after a mean observation time of 46 months. Clin Oral Investig. 18(9):2171–2178.

Rinke S, Kramer K, Burgers R, Roediger M. 2016. A practice-based clinical evaluation of the survival and success of metal-ceramic and zirconia molar crowns: 5-year results. J Oral Rehabil. 43(2):136–144.

Sailer I, Hammerle CH. 2014. Zirconia ceramic single-retainer resin-bonded fixed dental prostheses (RBFDPs) after 4 years of clinical service: a retrospective clinical and volumetric study. Int J Periodontics Restorative Dent. 34(3):333–343.

Sasse M, Kern M. 2014. Survival of anterior cantilevered all-ceramic resin-bonded fixed dental prostheses made from zirconia ceramic. J Dent. 42(6):660–663.

Schlichting LH, Resende TH, Reis KR, Magne P. 2016. Simplified treatment of severe dental erosion with ultrathin CAD-CAM composite occlusal veneers and anterior bilaminar veneers. J Prosthet Dent. 116(4):474–482.

Schubert O, Nold E, Obermeier M, Erdelt K, Stimmelmayr M, Beuer F. 2017. Load bearing capacity, fracture mode, and wear performance of digitally veneered full-ceramic single crowns. Int J Comput Dent. 20(3):245–262.

Seydler B, Schmitter M. 2015. Clinical performance of two different CAD/CAM-fabricated ceramic crowns: 2-year results. J Prosthet Dent. 114(2):212–216.

Silva NR, Witek L, Coelho PG, Thompson VP, Rekow ED, Smay J. 2011. Additive CAD/CAM process for dental prostheses. J Prosthodont. 20(2):93–96.

Solá-Ruíz MF, Agustin-Panadero R, Fons-Font A, Labaig-Rueda C. 2015. A prospective evaluation of zirconia anterior partial fixed dental prostheses: clinical results after seven years. J Prosthet Dent. 113(6):578–584.

Song XF, Ren HT, Yin L. 2016. Machinability of lithium disilicate glass ceramic in in vitro dental diamond bur adjusting process. J Mech Behav Biomed Mater. 53:78–92.

Spitznagel FA, Scholz KJ, Strub JR, Vach K, Gierthmuehlen PC. 2018. Polymer-infiltrated ceramic CAD/CAM inlays and partial coverage restorations: 3-year results of a prospective clinical study over 5 years. Clin Oral Investig. 22(5):1973–1983.

Spitznagel FA, Vuck A, Gierthmuhlen PC, Blatz MB, Horvath SD. 2016. Adhesive bonding to hybrid materials: an overview of materials and recommendations. Compend Contin Educ Dent. 37(9):630–637.

Stober T, Heuschmid N, Zellweger G, Rousson V, Rues S, Heintze SD. 2014. Comparability of clinical wear measurements by optical 3D laser scanning in two different centers. Dent Mater. 30(5):499–506.

Wendler M, Belli R, Petschelt A, Mevec D, Harrer W, Lube T, Danzer R, Lohbauer U. 2017. Chairside CAD/CAM materials: part 2. Flexural strength testing. Dent Mater. 33(1):99–109.

Yazigi C, Kern M, Chaar MS. 2017. Influence of various bonding techniques on the fracture strength of thin CAD/CAM-fabricated occlusal glass-ceramic veneers. J Mech Behav Biomed Mater. 75:504–511.

Zaruba M, Mehl A. 2017. Chairside systems: a current review. Int J Comput Dent. 20(2):123–149.

Zenthöfer A, Ohlmann B, Rammelsberg P, Bomicke W. 2015. Performance of zirconia ceramic cantilever fixed dental prostheses: 3-year results from a prospective, randomized, controlled pilot study. J Prosthet Dent. 114(1):34–39.

Zhang Y, Kelly JR. 2017. Dental ceramics for restoration and metal veneering. Dent Clin North Am. 61(4):797–819.

Zhang Y, Kim JW. 2009. Graded structures for damage resistant and aesthetic all-ceramic restorations. Dent Mater. 25(6):781–790.

Zhang Y, Lawn BR. 2018. Novel zirconia materials in dentistry. J Dent Res. 97(2):140–147.

Zimmermann M, Koller C, Mehl A, Hickel R. 2017. Indirect zirconia-reinforced lithium silicate ceramic CAD/CAM restorations: preliminary clinical results after 12 months. Quintessence Int. 48(1):19–25.

Zimmermann M, Koller C, Reymus M, Mehl A, Hickel R. 2017. Clinical evaluation of indirect particle-filled composite resin CAD/CAM partial crowns after 24 months. J Prosthodont [epub ahead of print 19 Apr 2017] in press. doi:10.1111/jopr.12582