Original Article

Clinical evaluation of monolithic zirconia crowns: a failure analysis of clinically obtained cases from a 3.5-year study

Shoko Miura^{a,b,*}, Shinobu Yamauchi^c, Shin Kasahara^b, Yusuke Katsuda^b, Masanori Fujisawa^a, Hiroshi Egusa^b

^a Division of Fixed Prosthodontics, Department of Restorative & Biomaterials Sciences, Meikai University School of Dentistry, Sakado, Japan

^b Division of Molecular and Regenerative Prosthodontics, Tohoku University Graduate School of Dentistry, Sendai, Japan

^c Department of Biomaterials, Nihon University School of Dentistry at Matsudo, Japan

Abstract

Purpose: The primary purpose of this study was to examine the clinical performance of monolithic zirconia single crowns in terms of short-term failure or complications. The secondary purpose was to detect the originating flaws of clinically failed monolithic zirconia crowns to find the causes of failure.

Methods: A short-term prospective cohort study based on record evaluation and clinical examination of patients treated with tooth-supported monolithic zirconia crowns was performed in the Department of Fixed Prosthodontics, Tohoku University Hospital, Japan. The crowns were prepared during the follow-up period from April 2014 to July 2018. The 3.5-year cumulative success and survival rates were set as primary endpoints. Fractures of the crown or fragments were inspected under a scanning electron microscope for descriptive fractography.

Results: During the study period, 40 monolithic zirconia crowns were placed. Four crowns experienced clinical complications, including: 1) fracture of the crown (two crowns), 2) abrasion of the crown (one crown), and 3) fracture of the antagonist tooth (one crown). The estimated Kaplan-Meier 3.5-year success and survival rates were 90.5% (95% confidence interval [CI]: 73.1–97.1) and 92.8% (95% CI: 74.1–98.3), respectively. Fractography revealed that all fractures were initiated from the wear phase on the occlusal surface.

Conclusions: The results of this study suggest that the molar application of monolithic zirconia crowns requires detailed attention to interocclusal clearance and the restoration of the antagonist tooth.

Keywords: Y-TZP, CAD/CAM, Fractography, Risk factor, Digital dentistry

Received date: 26 December 2019 , Accepted date: 29 April 2020, J-STAGE Advance published date: 9 September 2020

1. Introduction

In the early 2000s, the first-generation of yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) was introduced to provide frameworks for porcelain-veneered restorations [1], whose major complication was porcelain chipping (cohesive failure) especially for porcelain-veneered zirconia crowns [2–6]. In recent years, monolithic zirconia fixed dental prostheses have gained prominence as a metal-free treatment option that involves the use of second-generation Y-TZP (3Y-TZP), which was allowed for improved translucency; the alumina content was reduced and the sintering temperature increased in order to reduce porosities and increase the grain size [6]. In the molar region, it became possible to fabricate fixed dental prostheses on tooth crowns using 3Y-TZP without porcelain veneering ceramics; hence, patients' selection of monolithic

zirconia restoration has further increased. Additionally, monolithic zirconia restoration does not have the disadvantage of porcelain chipping. It also allows lesser tooth preparation, as it requires little interocclusal clearance; this has driven down manufacturing costs [6,7]. However, the fracture rate of a monolithic zirconia crown fabricated at a dental laboratory and investigated up to 7.5 years from 2010 to 2017 was reported to be 0.54% [8]. This fracture rate was lower than 1.4%, which was previously reported in a 3.5-year investigation of posterior computer-aided design and computer-aided manufacturing (CAD/CAM) all-ceramic restorations [9]. There is limited information available regarding the clinical outcomes of these restorations [6,10,11] and the long-term clinical performance has not been clarified.

Some researchers have reported that fractography may optimize the methods of processing and designing restorative materials and its components. Additionally, by providing information regarding the loading conditions based on the fracture pattern recognition, the causes of clinical failure can be identified and reduced [12,13]. Furthermore, fractographic analyses of ceramic crowns fractured during clinical use can reveal the fracture origin, fracture path, and perhaps the reason for fracture [14]. Hence, the use of fractography has increasingly been applied in both in vitro lab-scale specimens and in vivo ceramic

* Corresponding author at: Department of Restorative & Biomaterials Sciences, Meikai University School of Dentistry, 1-1 Keyakidai, Sakado, Saitama, 350-0283, Japan.
E-mail address: miuras@dent.meikai.ac.jp (S. Miura).

restorations [13]. Conversely, zirconia is harder than either enamel or feldspar porcelain; hence, antagonist tooth wear or damage is a concern following the placement of monolithic zirconia prosthetics [15]. Moreover, several concerns remain regarding 1) tooth preparation, design, and interocclusal clearance, 2) restoration materials for the antagonist tooth, 3) clinical prognosis, and 4) long-term chemical stability [6,11,15]. Currently, the information on the clinical performance of monolithic zirconia crowns is insufficient, and their long-term prognosis remains unknown. To establish a long-term prognosis for the monolithic zirconia restoration methods, it is necessary to identify the early potential problems. Therefore, the primary purpose of this study was to examine the clinical performance of monolithic zirconia single crowns in terms of short-term failure or complications. The second purpose was to evaluate the fracture origins when there was a fracture of the crown to detect the originating flaws of clinically failed monolithic zirconia single crowns to find the causes of failure.

2. Materials and Methods

A short-term prospective cohort study based on record evaluation and clinical examination of patients treated with tooth-supported monolithic zirconia single crowns was performed in the Department of Fixed Prosthodontics of Tohoku University Hospital in Japan. Informed consent was obtained from all patients. The study was approved by the Research Ethics Committee of Tohoku University, Graduate School of Dentistry (approval number: 26-17). Five dentists who had more than 5 years of clinical experience supervised the check-up based on the protocol or clinical procedure for crown treatment. The crowns were prepared during the follow-up period from April 2014 to July 2018 (52 months).

The inclusion criteria were as follows: age >18 years, need for crown treatment in the permanent teeth, pre-prosthetic treatment completion, low caries activity, good oral hygiene, regular dental check-ups. The exclusion criteria were the presence of dental implants and not visiting the hospital or clinic for dental maintenance by the end of the study period.

Prior to prosthetic treatment, all patients received full-mouth periodontal examination and underwent periodontal, endodontic, and care treatment, where necessary. All patients were thoroughly instructed by a dedicated dental hygienist to brush their teeth. Following the aforementioned initial management and the standard procedures, crowns were placed using 3Y-TZP to fabricate monolithic zirconia crowns. The preparation design was based on monolithic zirconia restorations suggested by the manufacturer (a chamfer margin with a minimal occlusal reduction of 0.5 mm and an axial reduction of at least 0.5 mm [11,16]. Appropriateness for the tooth preparation was judged using a silicone index. In addition, wax or silicone bite registration materials were used for measuring the interocclusal reduction. Impressions were made using silicone rubber (Examixfine, Exahiflex: GC Corp., Tokyo, Japan) and self-wetting hybrid polysiloxane impression materials (Fusion II: GC Corp.). Crowns were manufactured from 3Y-TZP blocks (cercon ht, Dentsply Sirona, York, PA, USA; Shofu disk ZR-SS, Shofu Inc., Kyoto, Japan; inColis TZI, Dentsply Sirona) using a dental CAD/CAM system (cercon smart ceramics, Dentsply Sirona; shofu S-WAVE, Shofu Inc.; cerec inlab, Dentsply Sirona) in the hospital dental laboratory and two private dental laboratories. After performing trial fitting and adjustment in the oral cavity, the crowns were returned to the dental laboratory for final polishing with solid polish (Zircon-Brite, Dental Ventures of America Inc., Corona, CA, USA) or were stained and grazed. Then, the crown was placed. Prior to crown cementation, the abutment surface was cleaned by scraping with an ultrasonic scaler and brushing with a tooth surface cleaning brush to remove residual provisional cement. Air-particle abrasion with 50–70 μ m aluminum oxide (Zest Anchors LLC, Escondido, CA, USA; Hi Aluminas, Shofu Inc.) or silica-coating sandblasting (Cojet Sand, 3M ESPE, Maplewood, MN, USA) was used for surface treatment of the inner crown surface.

The appropriate inner crown surfaces with 10-methacryloyloxydecyl dihydrogen phosphate primers (Clearfil Ceramic Primer, Kuraray Noritake Dental Inc., Tokyo, Japan; AZ primer, Shofu Inc.; Ceramic Primer II, GC Corp.) were performed before cementation according to the manufacturer's instructions. Each type of adhesive resin cement (Panavia V5, Kuraray Noritake Dental Inc.; Resicem, Shofu Inc.; Unicem 2, 3M ESPE) and resin modified glass ionomer cement (Fujiluting EX, GC Corp.) were used for placing the crown. The study started at the time of cementation with a definitive luting agent (ie., baseline/entry point). Clinical problems with prosthetic placement, abutment teeth, and antagonist teeth were assessed at the start of the placement and during maintenance. The endpoint of the study was the appearance of technical or biological problems, such as clinically visible cracks or fractures and debonding of the crown. The data were analyzed using the Fisher's exact test to assess possible associations with the presence of crown complications. The 3.5-year cumulative success and survival rates were set as primary endpoints, and the Kaplan-Meier method was further used for analysis. Statistical analysis was conducted using JMP Pro14.2.0 (SAS Institute Inc., Cary, NC, USA). In this study, a "successful crown" was defined as an intact crown without any complication. "Surviving crowns" included those that had been used at the follow-up visit, regardless of dislodging or minor fracture.

When there was a loss of crown retention due to a clinical problem, the crown was retrieved from the patient. The crown or fragments of the crown were cleaned in ethanol in an ultrasonic bath to remove organic debris and contaminants; then, all specimens were Pt-coated and inspected under a scanning electron microscope (JSM-6390LA, JEOL, Tokyo, Japan) for descriptive fractography. The interpretation of fracture patterns was based on the descriptions by Scherrer et al. [13], particularly to determine the origin and direction of the crack propagation.

3. Results

3.1. Clinical results

Thirteen patients (mean age, 53.1 $\pm$ 12.0 years; gender, four men and nine women) participated in this study, and 40 monolithic zirconia crowns were provided in total. The crowns were placed between April 2014 and September 2017. The mean follow-up time was 2.0 $\pm$ 1.0 years (range 0.1–4.3 years). All patients continuously responded to a request to attend a recall every 3 to 6 months. Only one crown was placed with resin modified glass ionomer cement; the rest of the crowns were placed with resin cement. During this period, clinical complications were found in four crowns, and the details were as follows: 1) fracture of the crown (two crowns), 2) abrasion of the crown (one crown), and 3) fracture of the antagonist tooth (one crown) (Tables 1, 2). Of the four cases of failure, three (cases 1, 3, and 4) were treated by the same clinician (S. M.) and the four crowns fabricated by different dental technicians. The crown fractures occurred 0.8 and 1.5 years after placement and propagated medio-distally and bucco-lingually from the central occlusion region, respectively (Figs. 1, 2). The fractured crowns had a minimum thickness of approximately 0.6 mm, and the antagonist teeth had been restored with a metal inlay and monolithic zirconia crown. In the case of crown abrasions, loss of retention of the crown was caused by the wear of the crown placed in the lower left of the first molar (Fig. 3). Its antagonist tooth was a natural tooth. In case 4, chipping of the antagonist tooth occurred 0.1 year after crown placement (Fig. 4). In this case, a metal partial-coverage crown was placed on the antagonist teeth. Three of these were placed on the rearmost tooth. The location of the crown "maxilla/mandible" exerted a statistically significant effect on the incidence of complications as analyzed using the Fisher's exact test (Table 1). The estimated Kaplan-Meier 3.5-year success and survival rates of the 40 monolithic zirconia crowns were 90.5% (95% confidence interval [CI]: 73.1–97.1) and 92.8% (95% CI: 74.1–98.3), respectively (Fig. 5).

Table 1. Baseline characteristics of study subjects according to the clinical complications in monolithic zirconia crowns using Fisher's exact test (n=40).

Characteristic		Total (%)	Complication		p value *
			Yes (%)	No (%)	
Gender	Men	6 (15.0%)	2 (33.3%)	4 (66.7%)	0.0997
	Women	34 (85.0%)	2 (5.9%)	32 (94.1%)	
Age	<60	27 (67.5%)	2 (7.4%)	25 (92.6%)	0.5839
	≥60	13 (32.5%)	2 (15.4%)	11 (84.6%)	
Location of the crown	Maxilla	24 (60.0%)	0 (0.0%)	24 (100.0%)	0.0199
	Mandible	16 (40.0%)	4 (25.0%)	12 (75.0%)	
	Anterior	2 (5.0%)	0 (0.0%)	2 (100.0%)	0.2057
	Premolar	17 (42.5%)	0 (0.0%)	17 (100.0%)	
	Molar	21 (52.5%)	4 (19.1%)	17 (80.9%)	
	Not distal-most tooth	31 (77.5%)	2 (6.5%)	29 (93.5%)	
	Distal-most tooth	9 (22.5%)	2 (22.2%)	7 (77.8%)	
Abutment material	Dentin	24 (60.0%)	1 (4.2%)	23 (95.8%)	0.2425
	Resin	13 (32.5%)	3 (23.1%)	10 (76.9%)	
	Metal	3 (7.5%)	0 (0.0%)	3 (100.0%)	
Antagonist tooth characteristics	Natural tooth	5 (12.5%)	1 (20.0%)	4 (80.0%)	0.8007
	Inlay	9 (22.5%)	1 (11.1%)	8 (88.9%)	
	Crown	24 (60.0%)	2 (8.3%)	22 (91.7%)	
	Removable partial denture	2 (5.0%)	0 (0.0%)	2 (100.0%)	

*Fisher's exact test in each characteristic category

Table 2. Characteristics of clinical complications in monolithic zirconia crowns

	Case 1 (Fig. 1)	Case 2 (Fig. 2)	Case 3 (Fig. 3)	Case 4 (Fig. 4)
Tooth number	#37	#36	#36	#37
Gender	Woman	Man	Man	Woman
Age (years)	65.3	62.2	41.0	42.6
Complication	Crown fracture	Crown fracture	Crown abrasion	Cracking of antagonist tooth
Time to event (years)	1.5	0.8	3.5	0.1
Abutment tooth condition	Vital	Resin core with metal post	Resin core without post	Resin core with fiber post
Cement	Resin cement	Glass-ionomer modified resin cement	Resin cement	Resin cement
Antagonist tooth	Metal inlay	Monolithic zirconia crown	Natural tooth	Metal partial-coverage crown
Distal-most tooth	Yes	No	No	Yes
Parafunctional activity	Clenching	None	Bruxism	None
Zirconia material	cercon ht	inColis TZI	cercon ht	cercon ht
Clinical intervention	Replacement with monolithic zirconia crown after additional tooth preparation	Replacement with monolithic zirconia crown after additional tooth preparation	Replacement with metal-ceramic crown after additional tooth preparation	Treatment for antagonist tooth with monolithic zirconia crown

3.2. Descriptive fractographic analysis

The incidences of fracture and abrasion in cases 1, 2, and 3 were analyzed to identify the origin of the crown and the direction of crack propagation.

3.2.1. Case 1: crown fracture in the left mandibular second molar (tooth #37)

The fracture showed by a compression curl was observed in the region close to the abutment tooth (Fig. 1-f). Thus, the fracture was assumed to have started on the occlusal surface of the opposite side. It was presumed that the crack progressed through the thin occlusal region until it broke the crown completely.

3.2.2. Case 2: crown fracture in the left mandibular first molar (tooth #36)

Two remarkable aspects of case 2 were: (1) The main crack traversing from the occlusal groove toward the abutment tooth (Fig.

2-d), and (2) the twist hackles starting from the main crack (Fig. 2-f). These results indicated that the main fracture occurred first in the thin region on the occlusal groove. The fracture appearing by the twist hackles was considered a secondary event occurring after the main fracture, indicating that the contact loading or impact on the occlusal surface was the cause of this fracture.

3.2.3. Case 3: crown abrasion in the left mandibular first molar (tooth #36)

A hole with excessive wear was observed on the occlusal surface (Fig. 3). Traces of wear were clearly observed. It can be concluded that the fracture (hole) was caused by contact wear of the antagonist tooth.

Discussion

The 3.5-year cumulative success and survival rates of monolithic zirconia crown treatment were 90.5% and 92.8%, respectively. These results were

Fig. 1. Case 1: crown fracture in the left mandibular second molar (tooth #37). The two fragments of the retrieved fracture of the crown (a, b, mesio-distal view) and scanning electron microscope images of fragments of the crown (c–f). The compression curl was observed in the region close to the abutment tooth (white arrow).

Fig. 2. Case 2: crown fracture in the left mandibular first molar (tooth #36). The two fragments of the retrieved fracture of the crown (a, b, bucco-lingual view) and scanning electron microscope images of fragments of the crown (c–f). The main crack traversing from the occlusal groove toward the abutment tooth (d). The twist hackles starting from the main crack (f).

Fig. 3. Case 3: crown abrasion in the left mandibular first molar (tooth #36). Occlusal view (a), internal view (b), scanning electron microscope images of the crown (c–f). Traces of wear were recognized clearly (d, e, f).

Fig. 4. Case 4: cracking of antagonist tooth in the left mandibular second molar (tooth #37). After placement of the crown. (a: lateral view, b: occlusal view), chipping of the antagonist tooth (white arrow, c: lateral view, d: occlusal view).

Fig. 5. The Kaplan-Meier curves present the cumulative success and survival rates (red line: success rate, blue line: survival rate).

similar to those of previous studies showing that the cumulative survival success rate at 3.5-years was 91.5 % [11]. Additionally, the 1- to 3-year prognostic report of a monolithic zirconia crown placed on a natural tooth reported a survival rate of 100% and no technical and biological failure [10]. As there are few clinical studies on monolithic zirconia restoration, its long-term prognosis is still unknown. A high incidence of technical problems appeared in this study; however, no biological complications were noted. Furthermore, all the failures occurred in the cases where crowns were placed on molars. A previous study had also reported that for fractures occurring in all-ceramic crowns, the fracture locations were on molar teeth [17]. In the porcelain-veneered zirconia all-ceramic single crowns, there was a high risk of porcelain chipping with posterior teeth [4]. Therefore, it was believed that the crown fracture was caused by insufficient interocclusal clearance and the crowns were refabricated

after preparation. Although the manufacturer's recommended minimum clearance (0.6–0.8 mm) [18] was achieved in this study, fracture of the crowns occurred. In the two cases of crown fracture, the thicknesses were approximately 0.6 mm by the measurement of the broken fragments. However, in a prospective study with a prognosis of 1–3 years, no problems were reported, even when the crown thickness was set to a minimum of 0.5 mm [10]. Reduced preparation of the abutment tooth is an advantage of monolithic zirconia restoration, and less invasive treatment became possible [7]; however, it must be understood that insufficient interocclusal clearance might lead to the failure of monolithic zirconia restoration. Furthermore, a report evaluating the effect of molar monolithic zirconia crowns on the wear of antagonist teeth found that there was no difference between these crowns and the veneering ceramic crown and no problem in the clinical application [19]. Stober et al. examined the

wear of antagonist teeth during the 2-year evaluation period and found that the wear of enamel vs zirconia was twice as high as that of enamel vs enamel, but no difference was reported with other ceramic materials [15]. In contrast, it has been reported that the depth of enamel wear caused by monolithic zirconia and composite resin was significantly lower than the corresponding caused by ceramic glass and enamel [20]. As there are still controversial reports on this issue, a long-term follow-up is necessary to evaluate the wear of the antagonist teeth. In case 3, the enamel on the antagonist tooth caused a hole in the monolithic zirconia crown due to abrasion. In this case of abrasion of the crown placed on the mandibular left first molar, it was the distal-most tooth in the dental arch (actual last molars) because the second and third molars had a scissors bite. The reason was attributed to the lower coefficient of friction in zirconia material than in enamel [21]. Thus, excessive occlusal pressure was applied and the occlusal crown was thinned because of insufficient interocclusal clearance. Bruxism was also considered to be a cause. A study by Kitaoka et al. reported that a crack occurred in the antagonist enamel encased with composite resin inlay one year after placement [22]. In case 4, after the crown was placed on the mandibular left second molar, which is the distal-most molar, a fracture of the cusp opposing a metal partial-coverage crown on the antagonist teeth occurred within a few weeks. Therefore, when applying crowns on distal-most teeth, it is important to pay attention to the restoration and the occlusal contact of the antagonist tooth when the latter has already been partially restored.

It has been observed that all fractures were initiated from the wear phase on the occlusal surface (Case 1, 2 and 3). Fractures generally start at a worn surface that has been burdened by occlusal load from the antagonist teeth [23]. Wear can, then, lead to microcracks, which negatively influence the mechanical strength. As a rule, the location of the fracture origin is important, since it will determine the factor that first caused the fracture and how the crack will propagate [12,24]. The most common fracture origins of alumina crowns are split into two or more pieces with the fractures usually starting at margins and propagating because of hoop stresses in the crown walls [25]. However, it was hard to find the fracture origin in fragments of case 1 because of the cement sticking in the occlusal region of the fracture surface. The finding of twist hackles in case 2 indicates the direction of local crack propagation [26]. The crack was generated by change in the stress field or caused by leaning the axis of principal stress of the primary crack, which crosses through the fracture surface [12,26]. Many studies have reported that the major concern with the use of monolithic zirconia for restoration is the abrasion of antagonist teeth because of its hardness and surface roughness [20,27], as opposed to that of a zirconia crown. However, the monolithic zirconia crown in case 3 revealed the possibility that a fracture may occur because of excessive wear when the occlusal thickness of the crown is not sufficient. According to other *in vitro* studies, a monolithic zirconia crown with 0.3–0.5 mm occlusal thickness can be used in the molar region to ensure fracture resistance [7,28,29]. The minimum thickness of a crown that can be manufactured is approximately 0.5 mm. Although, it is not mandatory to adjust the amount of interocclusal clearance at 0.5 mm, an abutment tooth that fully considers the clearance amount with the antagonist tooth is required.

Despite the excellent fracture resistance of the material, the monolithic zirconia crowns in this study demonstrated that they might carry a risk of fractures and abrasion because of the thin occlusal thickness design. Therefore, the application of a monolithic zirconia crown in the molar region requires attention to the antagonist tooth and occlusion. Particularly for application to the last molar, the interocclusal clearance and restoration of the antagonist tooth should be fully examined. Actually, the cusp may be cracked when the antagonist tooth has already been partially restored. Additionally, parafunctional activity is reported to have a high prevalence of complications, and manufacturers often recommend monolithic zirconia restorations for this indication [6]. However, it has been reported that the failure rate of single-unit monolithic zirconia restorations was not as high

as expected in this sample including patients with parafunctional habits [6]. In some cases, night guards should be considered to prevent from such troubles. In this study, there was significant statistical difference between the maxilla and mandible. To discuss this result as a prognostic factor, we should accumulate a larger number of cases and evaluate them further by conducting a multivariate analysis.

Clinicians might be able to reduce failures by considering several risk factors, such as the restoration of antagonist teeth, parafunctional activity, and the securement of interocclusal clearance. However, it should be noted that this study was limited by the low number of cases analyzed and the short observation time. As only 40 crowns were analyzed, we could not make an objective evaluation of the risk factors associated with crown complications; this should be considered in future prospective long-term clinical studies.

5. Conclusion

Considering the limitation of the study period, our results suggest that the molar application of monolithic zirconia crowns requires detailed attention to interocclusal clearance and whether the antagonist tooth has been partially restored. As the success and survival rates were as high as 90%, monolithic zirconia crowns could be an effective fixed dental prosthetic treatment option for restoration in the molar region.

Funding

This work was supported by Grant-in Aid for Scientific Research (C:17K11739) from the Japan Society for the Promotion of Science.

Ethical approval

This study was performed following a protocol approved by the Research Ethics Committee of Tohoku University, Graduate School of Dentistry (approval number: 26-17).

Conflicts of interest

The authors declare that they have no conflicts of interest.

Informed consent

Informed consent of patients to conduct this study was obtained verbally and in writing. This study was a prospective, non-interventional clinical study without the need for formal consent in accordance with the ethical standards of the institutional and/or national research committee.

Acknowledgments

We are grateful to the Tohoku University Hospital dental technicians for their valuable support to accomplish this work. The authors thank Dr. Takashi Ohi for providing us with helpful comments on this study, as well as colleagues in our department for their invaluable assistance in conducting the study.

References

- [1] Blatz MB, Chiche G, Bahat O, Roblee R, Coachman C, Heymann HO. Evolution of Aesthetic Dentistry. *J Dent Res* 2019;98:1294-304.
- [2] Sailer I, Makarov NA, Thoma DS, Zwahlen M, Pjetursson BE. All-ceramic or metal-ceramic tooth-supported fixed dental prostheses (FDPs)? A systematic review of the survival and complication rates. Part I: Single crowns (SCs). *Dent Mater* 2015;31:603-23.
- [3] Stawarczyk B, Keul C, Eichberger M, Figge D, Edelhoff D, Lunkemann N. Three generations of zirconia: From veneered to monolithic. Part I. *Quintessence Int* 2017;48:369-80.

- [4] Miura S, Kasahara S, Yamauchi S, Okuyama Y, Izumida A, Aida J, et al. Clinical evaluation of zirconia-based all-ceramic single crowns: an up to 12-year retrospective cohort study. *Clin Oral Investig* 2018;22:697-706.
- [5] Tanner J, Niemi H, Ojala E, Tolvanen M, Narhi T, Hjerpe J. Zirconia single crowns and multiple-unit FDPs—An up to 8 -year retrospective clinical study. *J Dent* 2018;79:96-101.
- [6] Koenig V, Wulfman C, Bekaert S, Dupont N, Le Goff S, Eldafrawy M, et al. Clinical behavior of second-generation zirconia monolithic posterior restorations: Two-year results of a prospective study with Ex vivo analyses including patients with clinical signs of bruxism. *J Dent* 2019;103:229.
- [7] Jang GW, Kim HS, Choe HC, Son MK. Fracture strength and mechanism of dental ceramic crown with zirconia thickness. *Procedia Engineering* 2011;10:1556-60.
- [8] Sulaiman TA, Abdulmajeed AA, Delgado A, Donovan TE. Fracture rate of 188695 lithium disilicate and zirconia ceramic restorations after up to 7.5 years of clinical service: A dental laboratory survey. *J Prosthet Dent* 2019.
- [9] Belli R, Petschelt A, Hofner B, Hajto J, Scherrer SS, Lohbauer U. Fracture Rates and Lifetime Estimations of CAD/CAM All-ceramic Restorations. *J Dent Res* 2016;95:67-73.
- [10] Worni A, Katsoulis J, Kolgeci L, Worni M, Mericske-Stern R. Monolithic zirconia reconstructions supported by teeth and implants: 1- to 3-year results of a case series. *Quintessence Int* 2017;48:459-67.
- [11] Gunge H, Ogino Y, Kihara M, Tsukiyama Y, Koyano K. Retrospective clinical evaluation of posterior monolithic zirconia restorations after 1 to 3.5 years of clinical service. *J Oral Sci* 2018;60:154-8.
- [12] Pang Z, Chughtai A, Sailer I, Zhang Y. A fractographic study of clinically retrieved zirconia-ceramic and metal-ceramic fixed dental prostheses. *Dent Mater* 2015;31:1198-206.
- [13] Scherrer SS, Lohbauer U, Della Bona A, Vichi A, Tholey MJ, Kelly JR, et al. ADM guidance-Ceramics: guidance to the use of fractography in failure analysis of brittle materials. *Dent Mater* 2017;33:599-620.
- [14] Quinn JB, Quinn GD, Kelly JR, Scherrer SS. Fractographic analyses of three ceramic whole crown restoration failures. *Dent Mater* 2005;21:920-9.
- [15] Stober T, Bermejo JL, Schwindling FS, Schmitter M. Clinical assessment of enamel wear caused by monolithic zirconia crowns. *J Oral Rehabil* 2016;43:621-9.
- [16] Rinke S, Fischer C. Range of indications for translucent zirconia modifications: clinical and technical aspects. *Quintessence Int* 2013;44:557-66.
- [17] Goodacre CJ, Bernal G, Rungcharassaeng K, Kan JY. Clinical complications in fixed prosthodontics. *J Prosthet Dent* 2003;90:31-41.
- [18] Sulaiman TA, Abdulmajeed AA, Donovan TE, Cooper LF, Walter R. Fracture rate of monolithic zirconia restorations up to 5 years: A dental laboratory survey. *J Prosthet Dent* 2016;116:436-9.
- [19] Mundhe K, Jain V, Pruthi G, Shah N. Clinical study to evaluate the wear of natural enamel antagonist to zirconia and metal ceramic crowns. *J Prosthet Dent* 2015;114:358-63.
- [20] Sripetchdanond J, Leevailoj C. Wear of human enamel opposing monolithic zirconia, glass ceramic, and composite resin: an in vitro study. *J Prosthet Dent* 2014;112:1141-50.
- [21] Zurek AD, Alfaro MF, Wee AG, Yuan JC, Barao VA, Mathew MT, et al. Wear Characteristics and Volume Loss of CAD/CAM Ceramic Materials. *J Prosthodont* 2019;28:e510-e8.
- [22] Kitaoka A, Akatsuka R, Kato H, Yoda N, Sasaki K. Clinical Evaluation of Monolithic Zirconia Crowns: A Short-Term Pilot Report. *Int J Prosthodont* 2018;31:124-6.
- [23] Moraguez OD, Wiskott HW, Scherrer SS. Three- to nine-year survival estimates and fracture mechanisms of zirconia- and alumina-based restorations using standardized criteria to distinguish the severity of ceramic fractures. *Clin Oral Investig* 2015;19:2295-307.
- [24] Belli R, Scherrer SS, Lohbauer U. Report on fractures of trilayered all-ceramic fixed dental prostheses. *Case Studies in Engineering Failure Analysis* 2016;7:71-9.
- [25] Oilo M, Quinn GD. Fracture origins in twenty-two dental alumina crowns. *J Mech Behav Biomed Mater* 2016;53:93-103.
- [26] Scherrer SS, Quinn GD, Quinn JB. Fractographic failure analysis of a Procera AllCeram crown using stereo and scanning electron microscopy. *Dent Mater* 2008;24:1107-13.
- [27] Ludovichetti FS, Trindade FZ, Werner A, Kleverlaan CJ, Fonseca RG. Wear resistance and abrasiveness of CAD-CAM monolithic materials. *J Prosthet Dent* 2018;120:318 e1- e8.
- [28] Nakamura K, Harada A, Inagaki R, Kanno T, Niwano Y, Milleding P, et al. Fracture resistance of monolithic zirconia molar crowns with reduced thickness. *Acta Odontol Scand* 2015;73:602-8.
- [29] Tsuyuki Y, Sato T, Nomoto S, Yotsuya M, Koshihara T, Takemoto S, et al. Effect of occlusal groove on abutment, crown thickness, and cement-type on fracture load of monolithic zirconia crowns. *Dent Mater J* 2018;37:843-50.