JOURNAL OF THE MECHANICAL BEHAVIOR OF BIOMEDICAL MATERIALS 61 (2016) 328–333

Available online at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/jmbbm

Short Communication

In vitro analysis of the fracture resistance of CAD–CAM monolithic zirconia molar crowns with different occlusal thickness

Roberto Sorrentino[a,*], *Clementina Triulzio*[a], *Maria Gabriella Tricarico*[a], *Giovanni Bonadeo*[a], *Enrico Felice Gherlone*[b], *Marco Ferrari*[a]

[a]*Department of Medical Biotechnologies, School of Dental Medicine, University of Siena, Viale Bracci, 53100 Siena, Italy*
[b]*Department of Dentistry, University "Vita Salute San Raffaele" of Milan, Via Olgettina 60, 20132 Milan, Italy*

ARTICLE INFO

Article history:
Received 15 February 2016
Received in revised form
6 April 2016
Accepted 8 April 2016
Available online 14 April 2016

Keywords:
Zirconia
Monolithic
Crown
CAD–CAM
Fracture resistance
Occlusal thickness

ABSTRACT

Objectives: To compare the fracture resistance and mode of failure of CAD–CAM monolithic zirconia crowns with different occlusal thickness.

Material and methods: Forty CAD–CAM monolithic zirconia crowns with different occlusal thickness were randomly distributed into 4 experimental groups: 2.0 mm (group 1), 1.5 mm (group 2), 1.0 mm (group 3) and 0.5 mm (group 4). The restorations were cemented onto human molars with a self-adhesive resin cement. The specimens were loaded until fracture; the fracture resistance and mode of failure were recorded. The data were statistically analyzed with the one-way ANOVA followed by the Fisher's Exact test with Bonferroni's correction ($p=0.05$).

Results: The fracture resistance values of all the specimens exceeded the maximum physiological occlusal loads in molar regions. All the crowns showed cohesive microcracks of the zirconia core; only 1 crown with a thickness of 0.5 mm was interested by a complete fracture.

Conclusions: The occlusal thickness of CAD–CAM monolithic zirconia crowns did not influence either the fracture resistance and the mode of failure of the restorations; the occlusal thickness of CAD–CAM monolithic zirconia crowns can be reduced up to a lower bound of 0.5 mm keeping a sufficient strength to withstand occlusal loads; CAD–CAM monolithic zirconia crowns showed sufficient fracture resistance to be used in molar regions, even in a thin configuration (0.5 mm).

---

[*] *Corresponding author.* Tel./fax: +39 0577 233117.
E-mail addresses: errestino@libero.it (R. Sorrentino), triulzio.clementina@gmail.com (C. Triulzio), marella86@hotmail.it (M.G. Tricarico), bonadeogianni@gmail.com (G. Bonadeo), gherlone.enrico@hsr.it (E.F. Gherlone), ferrarm@gmail.com (M. Ferrari).

http://dx.doi.org/10.1016/j.jmbbm.2016.04.014
1751-6161/

1. Introduction

The use of densely sintered Yttria-stabilized Tetragonal Zirconia Polycrystals (Y-TZP) onto both natural teeth and implants became more and more widespread because of its optimal mechanical properties, biocompatibility, esthetics and low wear of the antagonist dentition. Furthermore, the inherent phase transformation toughening mechanism that results in superior fracture resistance seems to limit microcrack propagation during function (Zarone et al., 2011; Ferrari et al., 2015b).

Computer Aided Design–Computer Aided Manufacturing (CAD–CAM) monolithic zirconia was developed to limit the incidence of mechanical complications due to the presence of veneering ceramic (i.e. chipping), reduce production times and improve cost-effectiveness (Zarone et al., 2011; Seydler and Schmitter, 2015).

Although the mechanical properties of zirconia exceed those of many metals, the manufacturers' guidelines suggest a minimum core thickness of 0.5 mm to avoid fractures (Zarone et al., 2011; Ferrari et al., 2015a, 2015b; Nakamura et al., 2015; Nordhal et al., 2015). Nonetheless, a minimum recommended thickness for monolithic zirconia SCs validated by scientific data has not been established yet and there is no consensus on how thin the crowns can be made (Borelli et al., 2015; Lan et al., 2015).

To date, few laboratory data about the mechanical predictability of monolithic zirconia crowns are available in the literature, particularly for very thin restorations (Lameira et al., 2015; Ramos et al., 2015; Bergamo et al., 2016; Mitov et al., 2016; Øilo et al., 2016; Weyhrauch et al., 2016; Zhang et al., 2016), as well as the validation of their clinical performances in the oral environment (Batson et al., 2014; Ferrari et al., 2015a; Moscovitch, 2015).

Previous in vitro investigations showed that monolithic zirconia SCs exhibited fracture loads higher than those of layered zirconia restorations (Sun et al., 2014; Lameira et al., 2015; Lan et al., 2015). Recently, an in vitro analysis reported that monolithic zirconia crowns with an occlusal thickness of 0.5 mm showed sufficient fracture resistance to withstand occlusal loads in the molar regions (Nakamura et al., 2015). Surface finishing did not affect the fracture resistance (Lameira et al., 2015) and monolithic crowns proved to be more resistant than bilayered ones after agin and mechanical cycling (Lameira et al., 2015; Ramos et al., 2015). Fracture strength was not influenced by luting agents, particularly onto implants (Weyhrauch et al., 2016); conversely, the fracture resistance was significantly affected by preparation design (Mitov et al., 2016; Øilo et al., 2016) and low temperature degradation (Mitov et al., 2016). Material and geometrical characteristics are paramount to optimize longevity of monolithic zirconia restorations (Zhang et al., 2016).

To date, very few clinical studies on zirconia restorations are available in the literature. Recent clinical investigations showed that CAD–CAM monolithic zirconia crowns presented with negligible horizontal marginal discrepancy and satisfactory clinical results (Batson et al., 2014); moreover, no mechanical complications (i.e. fracture, cracking or chipping) were observed after 68 months of function (Moscovitch, 2015).

The present in vitro study aimed at comparing the fracture resistance and mode of failure of CAD–CAM monolithic zirconia single crowns (SCs) with different occlusal thickness cemented onto human molars.

The null hypotheses stated that there was no association between the occlusal thickness and either the fracture resistance [1] and the mode of failure [2] of CAD–CAM monolithic zirconia SCs.

2. Materials and methods

2.1. *Specimen preparation*

Forty extracted human maxillary third molars were used for the study. Teeth with caries and/or previous restorations were excluded; only sound teeth with similar (±1 mm) bucco-lingual, mesio-distal and corono-apical dimensions were included in the study. Dental plaque, calculus and external debris were removed with an ultrasonic scaler. In order to simulate the oral environment, the teeth were stored in an incubator at 37 °C in 90% relative humidity until the execution of the mechanical tests.

Each tooth was embedded in a block of self-curing acrylic resin (Caulk Orthodontic Resin, Dentsply caulk, Milford, DE, USA) surrounded by a stainless steel cylinder with the long axis perpendicular to the base of the block, leaving 1 mm of the root exposed. In order to dissipate the heat generated during the polymerization of the resin, the specimens were continuously moistened with water spray. A thin layer of polyvinylsiloxane impression material (Flexitime, Heraeus Kulzer, Hanau, Germany) was applied on dental roots to simulate the periodontal ligament.

Each tooth was covered with a powder for digital scanning (Cerec Optispray, Sirona Dental, Salzburg, Austria) and three-dimensionally (3D) scanned by means of a laboratory optical digital scanner (GC Aadva Lab Scan, GC, Tokyo, Japan). The 3D shape of each tooth was digitized, so as to use it for the fabrication of CAD–CAM monolithic crowns (Fig. 1).

Standardized tooth preparations were performed with high-speed diamond rotary cutting burs under constant water cooling, according to the following geometry: 1 mm axial reduction, 0.7 peripheral rounded minichamfer shoulder placed 0.5 mm above the cemento-enamel junction, 12° of total occlusal convergence; all preparation angles were rounded. The 40 M were randomly divided into 4 groups of 10 specimens each and different occlusal thickness preparation were performed as follows: 2.0 mm (group 1), 1.5 mm (group 2), 1.0 mm (group 3) and 0.5 mm (group 4).

As previously described, each abutment tooth was scanned and digitized and 40 monolithic zirconia SCs were designed by means of a dedicated CAD software (Exocad DentalCAD, Exocad GmbH, Darmstadt, Germany). The monolithic zirconia restorations of group 1, 2, 3 and 4 presented with an occlusal thickness of 2.0, 1.5, 1.0 and 0.5 mm respectively (Fig. 2).

The monolithic zirconia crowns were designed according to the original shape of each specimen (Fig. 3).

A cement layer of 70 μm and 50 μm was simulated at level of the intaglio surface and of the minichamfer shoulder respectively.

The internal surface of each crown was sandblasted with 50 μm Al_2O_3 powder at 1 bar. The SCs were cleaned with steam for 60 s. A dual-cure self-adhesive universal resin cement (G-Cem LinkAce, GC, Tokyo, Japan) was used to lute the restorations. The crowns were seated onto the abutment teeth with finger pressure and then 5 kg were applied onto each crown for 5 min by means of a dedicated cementation appliance. Cement excess was removed with a microbrush and each surface was light-cured for 40 s with a LED curing unit (Elipar S10, 3M ESPE, Seefeld, Germany). A layer of glycerin gel was applied on the margin of each crown to block oxygen inhibition and polymerization was completed for 40 s on each surface.

2.2. *Load to fracture test*

A universal loading machine (Triaxial Tester T400 Digital, Controls srl, Cernusco, Italy) was used to statically load the specimens. Load to fracture was performed using a 1.0 mm stainless steel hemispherical tip placed in the occlusal fossa. The experimental load was applied at a crosshead speed of 1 mm/min in a direction parallel to the longitudinal axis of the tooth (Fig. 4).

All samples were loaded until fracture and the maximum breaking loads were recorded in Newtons (N) by a computer

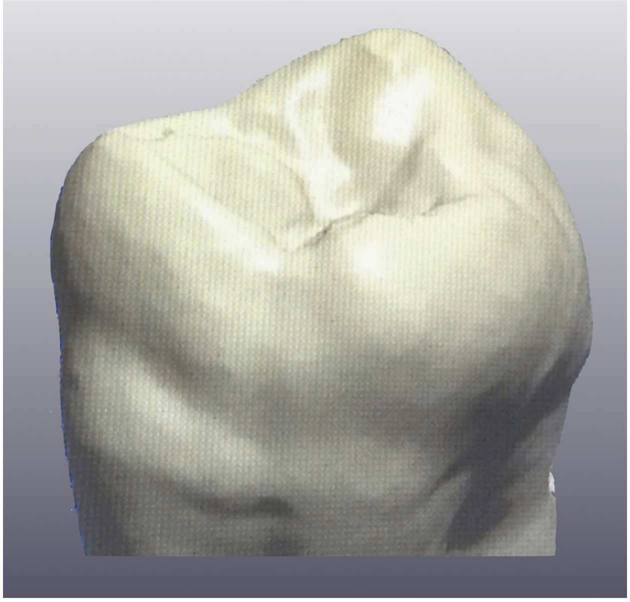

Fig. 1 – Anatomy digitization: 3D scanning of the original anatomy of a specimen.

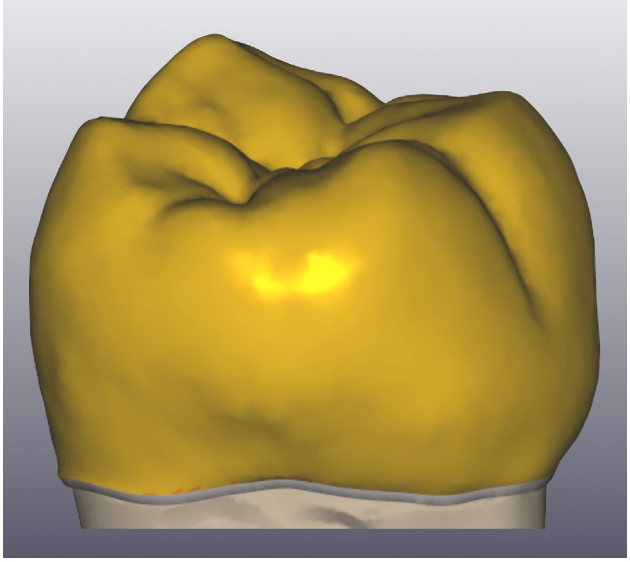

Fig. 3 – CAD finalization: monolithic zirconia single crown designed in accordance with the original digitized anatomy.

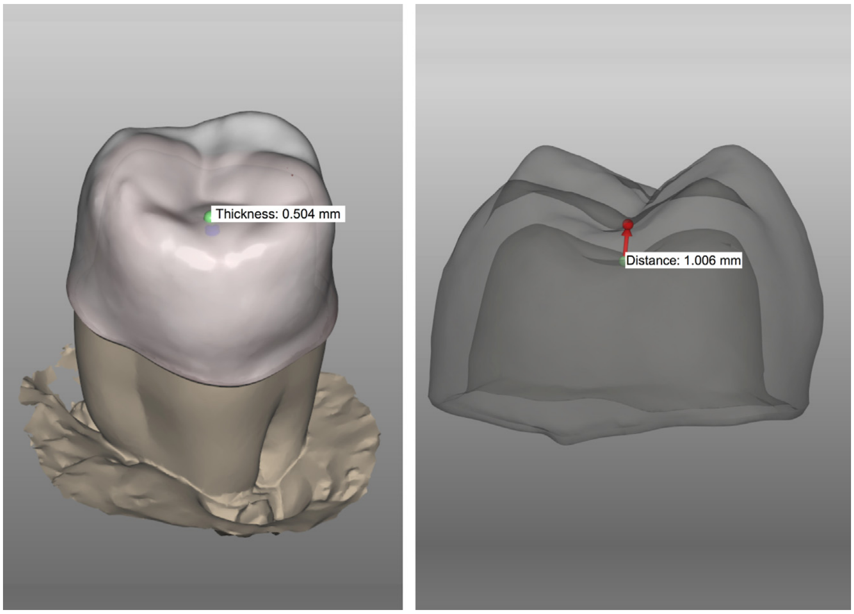

Fig. 2 – CAD process: occlusal thickness and distance measurements.

(Digimax Plus, Controls srl, Cernusco, Italy) connected to the loading machine. The failure mode was visually evaluated using a stereomicroscope at 10 × magnification (Zeiss OpMi1, Zeiss, Oberkochen, Germany); and in case of fracture, the fracture pattern was examined using a scanning electron microscope (Jeol, Tokyo, Japan).

2.3. *Statistical analysis*

The recorded data were statistically analyzed with a dedicated software (SPSS 13.0, SPSS Inc., Chicago, IL, USA). The Kolmogorov–Smirnov test was used to verify the normality of data distribution. The fracture values were analyzed with the one-way ANOVA; in order to verify whether statistically significant differences were found among the experimental groups, the Fisher's Exact test was applied. In all the analyses the level of significance was set at $\alpha<0.05$ with Bonferroni's correction.

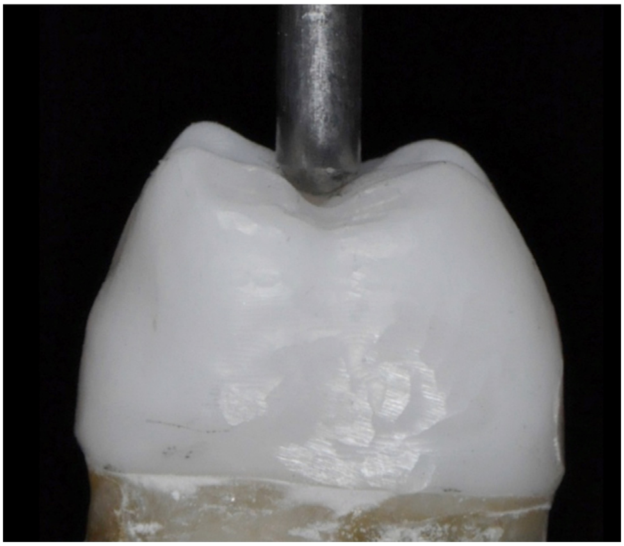

Fig. 4 – Static load at fracture: axial load direction and application.

3. Results

In the present study, the survival rate of molar CAD–CAM monolithic zirconia SCs was 100% in the experimental groups 1, 2 and 3 and 90% in group 4.

The highest fracture resistance values were reported in group 1 while the lowest were noticed in group 4 (Table 1).

All the crowns showed cohesive microcracks of the zirconia in the occlusal region, particularly at level of the load application area (Fig. 5); only 1 crown in group 4 was interested by a complete fracture (Fig. 6).

No statistically significant differences between groups were evidenced either for the fracture strength ($p>0.05$) and the failure mode ($p>0.05$) (Fig. 7).

4. Discussion

According to the results of the present investigation, both the null hypotheses were accepted, since there were no statistically significant differences in the fracture resistance [1] and

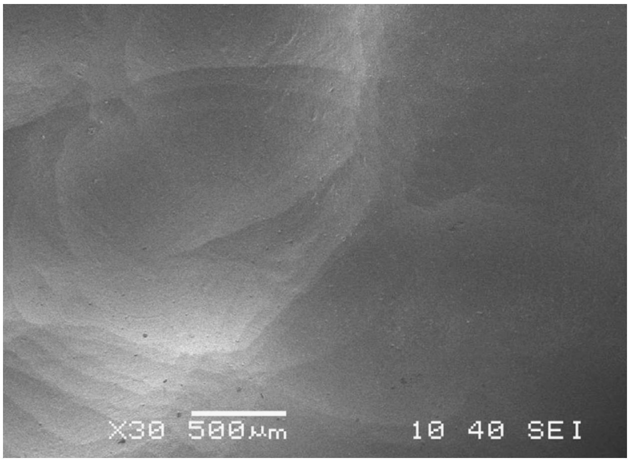

Fig. 5 – Zirconia chipping: SEM image of a cohesive microcrack of the zirconia core in the occlusal region at level of the load application area (group 1).

Table 1 – Load at fracture.

n	GROUP 1 (2.0 mm)		GROUP 2 (1.5 mm)		GROUP 3 (1.0 mm)		GROUP 4 (0.5 mm)	
	Fracture load (N)	Failure mode	Fracture load (N)	Failure mode	Fracture load (N)	Failure mode	Fracture load (N)	Failure mode
1	1602.24	R	1818.98	R	1870.88	R	1866.13	R
2	1719.21	R	1769.56	R	1163.83	R	2140.31	R
3	1621.09	R	1391.32	R	1322.59	R	747.54	U
4	1720.40	R	1737.85	R	1974.43	R	1647.95	R
5	1644.12	R	691.30	R	2048.64	R	2156.06	R
6	1791.61	R	1206.91	R	1352.07	R	1353.16	R
7	1732.58	R	1872.28	R	1603.73	R	1489.45	R
8	1735.17	R	1668.44	R	2020.96	R	1424.63	R
9	1693.02	R	1773.74	R	1596.61	R	956.33	R
10	1603.68	R	1609.99	R	1595.63	R	1355.59	R

Load at fracture (in Newtons) and failure patterns (R: restorable, U: unrestorable) of the experimental specimens.

mode of failure [2] of CAD–CAM monolithic zirconia SCs in relation to the occlusal thickness.

From a clinical viewpoint, the recorded cohesive occlusal microcracks have to be considered repairable, since they could be polished intraorally without impairing function.

Monolithic zirconia crowns showed higher fracture resistance than bilayered ones (Lameira et al., 2015; Ramos et al., 2015) and the geometrical properties of the material could improve the reliability of the restorations (Zhang et al., 2016). The thickness of all-ceramic crowns influence the fracture strength of restorations (Sun et al., 2014). Although most investigations reported that thicker zirconia copings showed higher fracture strength (Sun et al., 2014), recent in vitro analyses demonstrated that an occlusal thickness of 0.5 mm allowed monolithic zirconia crowns to withstand occlusal forces in the molar areas (Nakamura et al., 2015; Seydler and Schmitter, 2015). In accordance with these findings, the recorded fracture values of all the experimental groups exceeded both the physiological (50–250 N) and parafunctional (500–900 N) occlusal loads in molar regions (Ferrario et al., 2004). In accordance with previous investigations (Nordhal et al., 2015), the results of the present analysis suggested the possibility to reduce crown thickness when fabricating monolithic Y-TZP crowns, reducing the invasiveness of the preparation and saving a valuable amount of dental tissues (Nordhal et al., 2015).

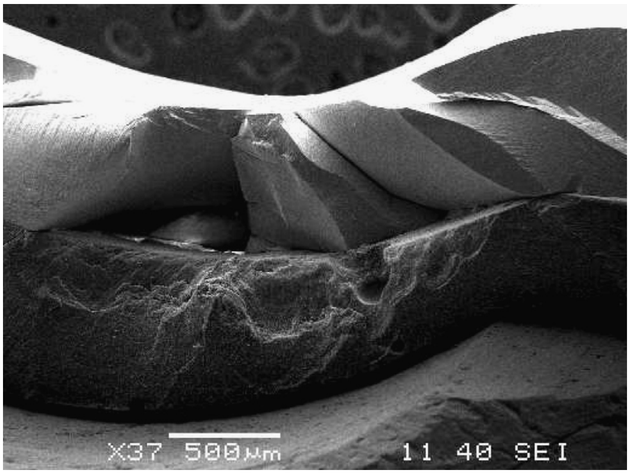

Fig. 6 – Zirconia failure: cross–sectional SEM image of a complete fracture of the zirconia starting from the load application area (group 4).

Several variables could affect the results of static investigations, such as sample storage, die material, cementation technique and crosshead speed, and this could explain the heterogeneity of data reported in the literature. Although fracture strength was not influenced by luting agents (Weyhrauch et al., 2016), in the present investigation, all the specimens were kept hydrated prior to testing and were luted onto natural teeth with a dual-cure self-adhesive universal resin cement to simulate a real clinical situation. The formation of an adhesive "monoblock" (Tay and Pashley, 2007) probably contributed to increase fracture strength, letting the cement act as an elastic stress adsorber and compensating for the stiffness of the zirconia core. This could strengthen the restorative system, allowing to dissipate the occlusal loads on the entire intaglio surface of the crowns. Similarly to previous investigations, the samples were experimentally fractured at a crosshead speed of 1 mm/min.

Although dynamic testing could give information about the resistance to fatigue loads, static axial load tests still represent the first step to investigate the resistance to fracture of dental materials (Sun et al., 2014). Nonetheless, such an approach would give information about the ultimate strength of the materials that is useful to optimize the geometry of restorations but it is worth remembering that clinical failures mainly occur because of fatigue. Consequently, the results achieved with static testing have to be integrated with those obtained from dynamical tests. Recent in vitro analyses showed that monolithic zirconia crowns proved to be more resistant than bilayered ones after agin and mechanical cycling (Lameira et al., 2015; Ramos et al., 2015).

It is not possible to apply laboratory information directly to clinical recommendations, since the clinical scenario is never completely simulated in in vitro tests (Anusavice et al., 2007). As a consequence, the results of the present investigation have to be validated clinically since only a static perpendicular force was simulated.

5. Conclusions

Within the limitations of the present in vitro study, the following conclusions can be drawn:

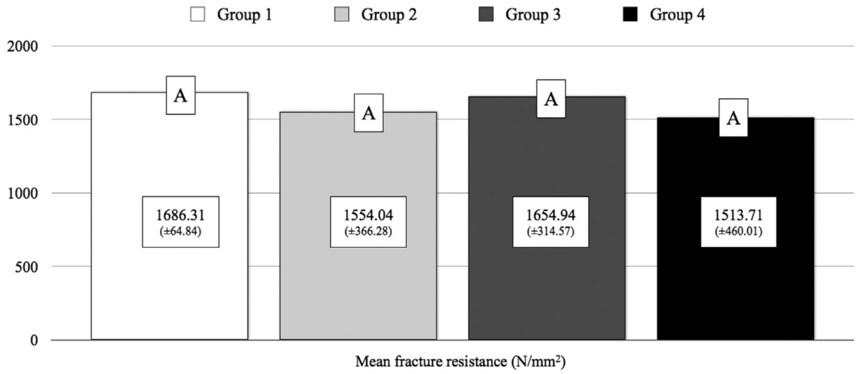

Fig. 7 – Mean fracture load values (in Newtons) ± Standard deviations of the experimental specimens and statistical significance (same letters indicate no statistically significant differences).

1. The occlusal thickness of CAD–CAM monolithic zirconia crowns did not influence either the fracture resistance and the mode of failure of the restorations;
2. The occlusal thickness of CAD–CAM monolithic zirconia crowns can be reduced up to a lower bound of 0.5 mm keeping a sufficient strength to withstand occlusal loads;
3. CAD–CAM monolithic zirconia crowns showed sufficient fracture resistance to be used in molar regions, even in a thin configuration (0.5 mm).

As it agrees with the results of previous investigations, the present research can be considered a confirmative study on the possibility to use monolithic zirconia CAD–CAM crowns in posterior areas even in very thin thicknesses.

Further clinical investigations will be necessary to validate the results of the present study under functional loading.

Acknowledgments

The authors would like to thank GC Europe (Leuven, Belgium) for the technical support and the fabrication of the CAD–CAM monolithic zirconia crowns (Aadva Zirconia, GC Europe, Leuven, Belgium) used in the present investigation.

REFERENCES

Anusavice, K.J., Kakar, K., Ferree, N., 2007. Which mechanical and physical testing methods are relevant for predicting the clinical performance of ceramic-based dental prostheses?Clin Oral Implant. Res. 18, 218–231.

Batson, E.R., Cooper, L.F., Duqum, I., Mendonca, G., 2014. Clinical outcomes of three different crown systems with CAD/CAM technology. J. Prosthet. Dent. 112, 770–777.

Bergamo, E., da Silva, W.J., Cesar, P.F., Del Bel Cury, A.A., 2016. Fracture load and phase transformation of monolithic zirconia crowns submitted to different aging protocols. Oper. Dent. [Epub ahead of print].

Borelli, B., Sorrentino, R., Goracci, C., Amato, M., Zarone, F., Ferrari, M., 2015. Evaluating residual dentin thickness following various mandibular anterior tooth preparations for zirconia full-coverage single crowns: an in vitro analysis. Int. J. Periodontics Restor. Dent. 35, 41–47.

Ferrari, M., Vichi, A., Zarone, F., 2015b. Zirconia abutments and restorations: from laboratory to clinical investigations. Dent. Mater. 31, e63–e76.

Ferrari, M., Sorrentino, R., Cagidiaco, C., Goracci, C., Vichi, A., Gherlone, E., Zarone, F., 2015a. Short-term clinical performance of zirconia single crowns with different framework designs: 3-year clinical trial. Am. J. Dent. 28, 235–240.

Ferrario, V.F., Sforza, C., Zanotti, G., Tartaglia, G.M., 2004. Maximal bite forces in healthy young adults as predicted by surface electromyography. J. Dent. 32, 451–457.

Lameira, D.P., Buarque e Silva, W.A., Andrade e Silva, F., De Souza, G.M., 2015. Fracture strength of aged monolithic and bilayer zirconia-based crowns. Biomed Res. Int.http://dxdoi.org/10.1155/2015/418641 [Epub ahead of print].

Lan, T.H., Liu, P.H., Chou, M.M., Lee, H.E., 2015. Fracture resistance of monolithic zirconia crowns with different occlusal thicknesses in implant prostheses. J. Prosthet. Dent.http://dxdoi.org/10.1016/j.prosdent.2015.06.021 [Epub ahead of print].

Mitov, G., Anastassova-Yoshida, Y., Nothdurft, F.P., von See, C., Pospiech, P., 2016. Influence of the preparation design and artificial aging on the fracture resistance of monolithic zirconia crowns. J. Adv. Prosthodont. 8, 30–36.

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

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

Nordhal, N., Vult von Steyern, P., Larsson, C., 2015. Fracture strength of ceramic monolithic crown systems of different thickness. J. Oral Sci. 57, 255–261.

Øilo, M., Kvam, K., Gjerdet, N.R., 2016. Load at fracture of monolithic and bilayered zirconia crowns with and without a cervical zirconia collar. J. Prosthet. Dent.http://dxdoi.org/10.1016/j.prosdent.2015.11.017 [Epub ahead of print].

Ramos, G.F., Monteiro, E.B., Bottino, M.A., Zhang, Y., Marques de Melo, R., 2015. Probability of three designs of zirconia crowns. Int. J. Periodontics Restor. Dent. 35, 843–849.

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

Sun, T., Zhou, S., Lai, R., Liu, R., Ma, S., Zhou, Z., Longquan, S., 2014. Load-bearing capacity and the recommended thickness of dental monolithic zirconia single crowns. J. Mech. Behav. Biomed. Mater. 35, 93–101.

Tay, F.R., Pashley, D.H., 2007. Monoblocks in root canals: a hypotetical or a tangible goal. J. Endod. 33, 391–398.

Weyhrauch, M., Igiel, C., Scheller, H., Weibrich, G., Lehmann, K.M., 2016. Fracture strength of monolithic all-ceramic crowns on titanium implant abutmentsInt. J. Oral Maxillofac Implant. Titan. Implant 31, 304–309.

Zarone, F., Russo, S., Sorrentino, R., 2011. From porcelain-fused-to-metal to zirconia: clinical and experimental considerations. Dent. Mater. 27, 83–96.

Zhang, Y., Mai, Z., Barani, A., Bush, M., Lawn, B., 2016. Fracture-resistant monolithic dental crowns. Dent. Mater. 32, 442–449.