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Review article

Influence of the chemical composition of monolithic zirconia on its optical and mechanical properties. Systematic review and meta-regression

María Fernanda Solá-Ruíz [a], Aitana Rico-Coderch [a,*], José María Montiel-Company [a], Carla Fons-Badal [a], Blanca Verdejo-Solá [b], Rubén Agustín-Panadero [a]

[a] Department of Stomatology, Faculty of Medicine and Dentistry, University of Valencia, Valencia, Spain

[b] Department of Medicine, Faculty of Medicine and Dentistry, Universidad Cardenal Herrera-CEU, Valencia, Spain

Abstract

Purpose: This systematic review set out to investigate the influence of chemical composition and specimen thickness of monolithic zirconia on its optical and mechanical properties. Meta-analysis and meta-regression analyzed the effects of variations in percentages of yttrium, aluminum, and specimen thickness of monolithic zirconia.

Study selection: The review followed recommendations put forward in the PRISMA checklist. An electronic search for relevant articles published up to October 2019 was conducted in the Pubmed, Cochrane, Scopus, Scielo, and Web of Science databases, with no language limits and articles published in the last 10 years. From 167 relevant articles; applying inclusion criteria based on the review's PICO question, 26 articles were selected for qualitative synthesis (systematic review) and 24 for quantitative synthesis (meta-analysis). Experimental in vitro studies published were selected and their quality was assessed using the modified Consort scale for in vitro studies of dental materials.

Results: The variables yttrium, aluminum and thickness were analyzed in random effects models, observing high heterogeneity (>75%), and finding statistically significant influences on the properties of monolithic zirconia ($p<0.05$).

Conclusion: Within the review's limitations, it may be concluded that variations in the percentage of yttrium and aluminum influence the optical and mechanical properties of monolithic zirconia, making it more or less esthetic and resistant in relation to each variable. The clinical implications of these findings can help select the most appropriate type of zirconia to meet the different clinical needs when restoring different regions (posterior or anterior).

Keywords: Monolithic zirconia, Optical properties, Mechanical properties, Yttrium, Aluminum

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1. Introduction

All-ceramic fixed dental prostheses (FDPs) were developed to improve dental esthetics, as metal-ceramic FDPs can cause a grayish halo to appear around the restoration's gingival third, despite the ceramic layering masking the metal core [1,2].

Zirconium dioxide (ZrO_2), or zirconia, has become a widely used ceramic that exists in three different crystallographic forms: monoclinic (M), tetragonal (T), or cubic (C) [3,4]. Zirconium oxide can be partially stabilized with 3 mol % yttrium oxide (3Y-TZP) giving it high strength thanks to its tetragonal crystalline phase [1,5]. But it is very opaque and so is only used to fabricate the restoration's prosthetic core, which is then covered with a conventional porcelain layering [6]. To overcome this drawback, monolithic zirconia restorations have been introduced, fabricated from a single block without porcelain layering [7].

To reduce the opacity of these new monolithic zirconia restorations, improve esthetics and overcome ceramic veneering chipping complications [8], the proportion of yttrium oxide may be increased to 5% or more. This increase means that the zirconia stabilizes as a mixture of cubic and tetragonal crystalline phases. As the proportion of cubic crystals increases, light scattering decreases from birefringent grain boundaries and residual porosities, making the material more translucent and so more esthetic. But the ceramic has less fracture resistance compared with zirconia restorations stabilized with 3 mol % yttrium oxide [9,10].

It is not only variations in yttria content that modify the properties of zirconia. Authors such as Zhang et al. [11], Tong et al. [12] or Elsaka et al. [13] have affirmed that small quantities of aluminum (Al) in the composition bring better optical properties, an increase in translucency, and a reduction in contrast ratio, but poorer mechanical properties.

The objective of this systematic review was to evaluate the in-

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***Corresponding author:** Aitana Rico-Coderch, Faculty of medicine and Dentistry (Unit of Prosthodontics and Oclusion) University of Valencia, C/Gascó Oliag, 1. 46021 Valencia, Spain.
E-mail address: aitana_rico@hotmail.com (A. Rico Coderch).

fluence of chemical composition and thickness on the optical and mechanical properties of monolithic zirconia. Meta-analysis was performed to analyze the influence of variations in the quantities of yttria and aluminum among various brands of monolithic zirconia.

2. Materials and methods

The articles were selected following the guidelines of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) checklist [14]. To prepare and structure this systematic review and meta-analysis, the focused question was elaborated by use of the PICO format (P: population, I: intervention, C: comparison, O: outcome).

P : Plates or bars of monolithic zirconia.
I : Variations in chemical composition and thickness.
C : Different brands of zirconia available on the market.
O: Optical and mechanical properties of each material.

Therefore, the main question of this study is as follows:

"What are the optical and mechanical variations in different types of monolithic zirconia resulting from variations in composition and thickness?"

2.1. Search Strategy

A thorough electronic search was conducted in the PubMed, Scopus, Web of Science, Scielo, and Cochrane databases, with no language limits and including all relevant literature published internationally during the 10 years until October 2019. The search period was from July 2019 to October 2019. The search terms applied were "zirconia," "zirconium," "phase transformation," and "translucency." The terms could not be indexed with MesH (Medical subject headings) as key terms. The Boolean operators "OR" and "AND" were applied as follows: [(zirconia) OR (zirconium)] AND (phase transformation) AND (translucency).

2.2. Selection of studies and eligibility criteria

Two reviewers (ARC and FSR) assessed the identified publications and selected them by title and abstract based on the following inclusion criteria: experimental in vitro studies investigating monolithic zirconia, in which the material's properties appear as numerical data, published during the last 10 years, regardless of language.

The final decision about inclusion of a given study was made based on full-text evaluation of potentially relevant papers by the reviewers. Those which were not in accordance with the following criteria were excluded: in vitro studies that investigated pre-colored zirconia or zirconia with esthetic covering. Reference lists of the included papers were also screened.

2.3. Data analyses

The following variables were extracted from each experimental in vitro study: author, year of publication, title, journal, sample size, the material's commercial (brand) name, composition (%), thickness (mm), translucency, contrast ratio, flexural strength (MPa), hardness (GPa), and fracture toughness (MPa m1/2).

Before quantitative synthesis (meta-analysis) was performed, the original search was brought up to date, locating three new articles. Only studies that reported mean values, standard deviation, and sample sizes were included in analysis. The data subjected to meta-analysis were combined in a random effects model. Heterogeneity was determined by p-value obtained in Q and I^2 tests, whereby heterogeneity was considered to exist when $p<0.1$ in the Q test. When the I^2 test obtained 25-50%, heterogeneity was considered to be slight; 50-75% indicated moderate heterogeneity; and >75% was considered to show high heterogeneity. Method of moments random effects models were created with optical and mechanical properties (translucency, contrast ratio, flexural resistance, fracture toughness, hardness) as dependent variables, and yttria, aluminum, and thickness as independent predictive variables. Independent variables were classified as three groups grouping values to avoid data distortion as follow: for yttria: 1 (<3%), 2 (3.1%-6%), and 3 (>6.1%); and for aluminum: 1 (<0.1%), 2 (0.11%-0.4%), 3 (>0.41%). Group 1 was always taken as the reference category. Publication bias was assessed by means of funnel plots and Duval and Tweedie's Trim and Fill method, which estimates the number of imputed missing studies and computes the difference between the effect size observed in meta-analysis and imputed effect size.

2.4. Risk of bias assessment

The quality of the studies selected for review was assessed with the modified CONSORT (Consolidated Standards of Reporting Trials) scale for in vitro studies of dental materials [15]. The following items were evaluated in each paper: (1) structured summary of trial design, methods, results and conclusions, (2a) scientific background and explanation of rationale, (2b) specific objectives and/or hypothesis, (3) the intervention for each group, including how and when it was performed, (4) completely defined, pre-specified primary and secondary measured of outcome, including how and when they were assessed, (5) how sample size was determined, (6) method used to generate the random allocation sequence, (7) mechanism used to implement the random allocation sequence, (8) who generated the random allocation sequence, (9) who was blinded after assignment to the intervention, and how, (10) Statistical methods used to compare groups for primary and secondary outcomes, (11) results of each group and estimated size of effect and its precision, (12) trial limitations, (13) sources of funding and other support, (14) where the full trial protocol can be accessed, if available. Each parameter was judged as reported (*) or not reported (empty box).

3. Results

3.1. Study selection and description studies

The initial electronic search identified 250 articles of which 83 were duplicates, leaving 167. The titles and abstracts were screened, discarding 118 works that failed to meet the inclusion criteria. A further seven articles were located in manual searches of the reference sections of these articles. The complete texts of the remaining 56 studies were screened, discarding another 30 because they did not meet the inclusion criteria (**Table 1**). The articles had to be experimental in vitro studies that talk about monolithic zirconium oxide and property values appear in removable numerical data, leaving 26 articles that underwent qualitative synthesis. Five of these were not included in quantitative synthesis as they failed to provide standard deviations. A subsequent update of the original electronic search identified three new works, which were included in meta-analysis. The selection procedure is illustrated in detail in **Figure 1**.

Table 1. Excluded articles.

YEAR	AUTHOR	TITLE	JOURNAL
2010	Paolo Baldissara, Altin Llukacej, Leonardo Ciocca, Felipe L. Valandro, Roberto Scotti.	Translucency of zirconia copings made with different CAD/CAM systems	The Journal of Prosthetic Dentistry
2011	Li Jiang, Yunmao Liao, Quianbing Wan.	Effects of sintering temperature and particle size on the translucency of zirconium dioxide dental ceramic.	J. Mater Sci: Mater Med
2012	Volkan Turp, Betul Tuncelli, Deniz Sen, Gultekin Goller.	Evaluation of hardness and fracture toughness, coupled with microstructural analysis, of zirconia ceramics stored in environments with different pH values.	Dental Materials Journal
2013	Takashi Miyazaki, Takashi Nakamura, Hideo Matsumura, Seiji Ban, Taira Kobayashi	Current status of zirconia restoration	Journal of Prosthodontic Research
2013	Mi-Jin Kim, Jin-Soo Ahn, Ji-Hwan Kim, Hae-Young Kim, Woong-Chul Kim	Effects of the sintering conditions of dental zirconia ceramics on the grain size and translucency.	The Journal of Advanced Prosthodontics
2014	Kamal Ebeid, Sebastian Wille, Amina Hamdy, Tarek Salah, Amr El-Etreby, Matthias Kern	Effect of changes in sintering parameters on monolithic translucent zirconia.	Dental Materials
2014	Yu Zhang	Making yttria-stabilized tetragonal zirconia translucent.	Dental Materials
2014	Sevcan Kurtulmus-Yilmaz, Mutahhar Ulusoy.	Comparison of the translucency of shaded zirconia all-ceramic systems.	The Journal of Advanced Prosthodontics
2015	Davor Spehar, Marko Jakovac	New Knowledge about zirconium-ceramic as a structural material in fixed prosthodontics	Acta Stomatologica Croatica
2016	Mythili Prakasam, François Weill, Eric Lebraud, Oudomsack Viraphong, Sonia Buffiére, Alain Largeteau.	Densification of 8Y-Tetragonal-Stabilized Zirconia Optoceramics with improved optical properties by Y segregation.	International Journal of Applied Ceramic Technology
2016	Ilkin Tuncel, Isil Turp, Aslihan Üsümez	Evaluation of translucency of monolithic zirconia and framework zirconia material.	The Journal of Advanced Prosthodontics
2016	Ölzem Malkondu, Neslihan Tinastepe, Ender Akan, Ender Kazazoglu	An overview of monolithic in dentistry	Biotechnology & Biotechnological Equipment
2016	Alexis Ioannidis, Andreas Bindl	Clinical prospective evaluation of zirconia-based three-unit posterior fixed dental prostheses: Up-to ten-year results.	Journal of Dentistry
2016	Kosuke Harada, Ariel J. Raigrodski, Kwok-Hung Chung, Brian D.Flinn, Sami Dogan, Lloys A. Mancl.	A comparative evaluation of the translucency of zirconias and lithium disilicate for monolithic restorations.	The Journal of Prosthetic Dentistry
2017	Mahsid Mohammadi-Bassir, Mansoure Babasafari, Mohammad Bagher Rezvani, Mahdieh Jamshidian.	Effect of coarse grinding, overglazing, and 2 polishing systems on the flexural strength, surface roughness, and phase transformation of yttrium-stabilized tetragonal zirconia.	The Journal of Prosthetic Dentistry
2017	Tariq F. Alghazzawi	The effect of extended aging on the optical properties of different zirconia materials.	Journal of Prosthodontic Research
2017	Bogna Stawarczyk, Christrine Keul, Marlis Eichberger, David Figge, Daniel Edelhoff, Nina Lümkemann.	Three generations of zirconia: From veneered to monolithic. Part II	Quintessence International
2017	Bogna Stawarczyk, Christrine Keul, Marlis Eichberger, David Figge, Daniel Edelhoff, Nina Lümkemann.	Three generations of zirconia: From veneered to monolithic. Part I	Quintessence International
2017	Bhenya Ottoni Tostes, Renato Bastos Guimaraes, Jaime Dutra Noronha-Filho, Glauco dos Santos Botelho, José Guilherme Antunes Guimaraes, Eduardo Moreira da Silva.	Characterization of conventional and high-translucency Y-TZP dental ceramics submitted to air abrasion.	Brazilian Dental Journal
2018	Sung Joon Kwon, Nathaniel C. Lawson, Edward E. McLaren, Amir H. Nejat, John O. Burgess.	Comparison of the mechanical properties of translucent zirconia and lithium disilicate.	The Journal of prosthetic dentistry
2018	Paolo Baldissara, Vinicius Felipe Wandscher, Ana Maria Estivalete Marchionatti, Candida Parisi, Carlo Monaco, Leonardo Ciocca.	Translucency of IPS e.max and cubic zirconia monolithic crowns.	The Journal of Prosthetic Dentistry
2018	Sebastian Wille, Paul Zumstrull, Victor Kaidas, Lea Katharina Jessen, Mathias Kern.	Low temperature degradation of single layers of multi-layered zirconia in comparison to conventional unshaded zirconia: Phase transformation and flexural strength.	Journal of Mechanical Behavior of Biomedical Materials
2018	M. Zhao, Y. Sun, J. Zhang, Y. Zhang.	Novel Translucent and strong submicron alumina ceramics for dental restorations.	Journal of Dental Research.
2018	Fahad Bakitian, Przemek Seweryniak, Evaggelia Papia, Christel Larsson, Per Vult von Steyern.	Effect of different semimonolithic designs on fracture resistance and fracture model of translucent and high-translucent zirconia crowns.	Clinical, Cosmetic and Investigational Dentistry.
2018	Niwut Juntavee, Surawut Attashu	Effect of sintering process on color parameters of nano-sized yttria partially stabilized tetragonal monolithic zirconia.	J Clin Exp Dent
2018	Chuin Hao Chin, Andanastuti Muchtar, Che Husna Azhari, Masfueh Razali, Mohamed Aboras.	Influences of the processing method and sintering temperature on the translucency of polycrystalline yttria-stabilized tetragonal zirconia for dental applications.	Ceramics International
2018	Hee-Kyung Kim, Sung-Hun Kim.	Effect of hydrothermal aging on the optical properties of precolored dental monolithic zirconia ceramics.	The Journal of prosthetic Dentistry
2018	Reza Shamiri, Owen Christopher Standard, Judy N.Hart, Charles Christopher Sorrell.	Optical properties of zirconia ceramics for esthetic dental restorations: A systematic reivew.	The journal of Prosthetic Dentistry
2018	Farhad Tabatabaian	Color Aspect of Monolithic zirconia restorations: A review of the literature.	Journal of Prosthodontics
2019	Adham Elsayed, Gunnar Meyer, Sebastian Wille, Matthias Kern.	Influence of the yttrium content on the fracture strength of monolithic zirconia crowns after artificial aging.	Quintessence International

*In this table, we refer to the year and the authors, as well as the title and the journal of the excluded articles of this review. Because they do not meet the inclusion criteria: They had to be experimental in vitro studies that talk about monolithic zirconium oxide and property values appear in removable numerical data.

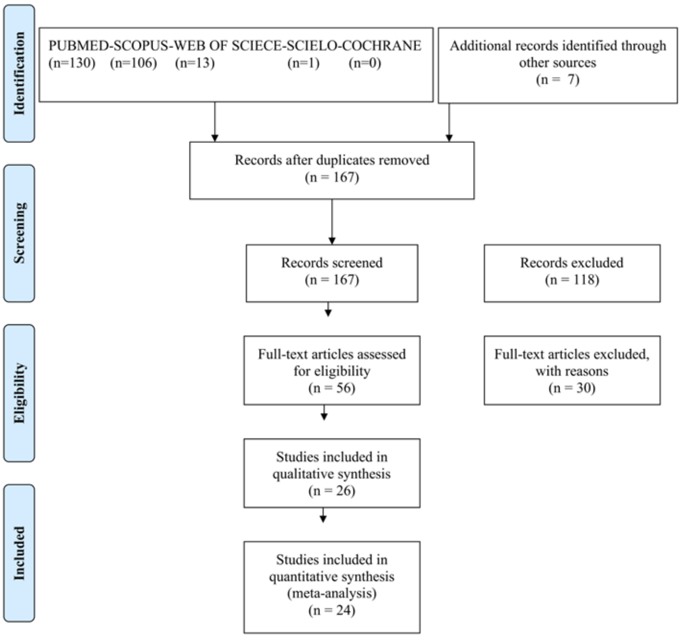

Fig. 1. Flow chat of study selection prodedure. PRISMA 2009 Flow Diagram.

The information on the material that we have used in the systematic review and meta-regression is shown in the **table 2**. In this table, we refer to the authors and years of each article, as well as the sample number, the trademark, the composition, the thickness, and the parameters of optical properties (translucency and contrast ratio) and mechanical properties (flexural strength, hardness and fracture toughness).

Within each article, various commercial brands of monolithic zirconia were compared, each presenting a different composition. Regarding composition, the proportions of yttria varied from 3% to 12%, while aluminum varied from 0.05%-1%. Only Zhang et al. (2015) [16] and Zang et al. (2016) [11] investigated the incorporation of lanthanum (La), this representing 0.2% of the composition. Some articles also investigated the presence of silica (Si), iron (Fe), hafnium (Hf), sodium (Na) and other oxides in the materials' composition, although these were in tiny proportions and were not found to influence the materials' properties. Only one study by Flinn et al. [17] evaluated the proportion of cerium (Ce) at 12% as an alternative stabilizer to yttria.

The review's main concerns were the materials' translucency (TP) and contrast ratio (CR), which varies from 0 (translucent) to 1 (opaque) [9]. Regarding the mechanical properties analyzed, fracture toughness (FT) represents the material's resistance to breakage or bending, expressed in Megapascals (MPa m1/2) [1]. Flexural resistance (FR) is the stress in a material just before it yields in a flexure test, in other words before it cracks or breaks, expressed in Megapascals (MPa). Lastly, hardness (H) measures a material's resistance to indentation. The Vickers microhardness test was employed to measure H (Vickers pyramid number), which consists of indenting an inverted diamond pyramid and applying a particular force for a period of time. H is expressed in Gigapascals (GPa).

3.2. *Methodologycal quality*

Table 3 presents the estimated risk of bias of each included study. All included papers properly presented a structured summary, specific objectives, and statistical analyses. On the other hand, the measurement of the estimation of the results for each group and its precision, and the item that refers to the limitations of the trial are only reflected in a reduced number of articles. Finally, we have not found in any article the rest of the items.

Quality assessment of the articles selected for review was performed using the modified CONSORT scale for in vitro studies of dental materials, finding moderate quality as all articles fulfilled between 7-9 items out of the scale's total of 15. The most common weakness was failure to describe how sample sizes had been determined and failure to report the randomization method used.

3.3. *Results of analyses*

In qualitative synthesis, samples sizes were very variable, and so were the form of the zirconia specimens depending on whether discs were used to evaluate optical properties or fine bars were used to test mechanical properties.

The values obtained were seen to be influenced by variations in the composition of the materials tested, differences in the percentages of yttria and aluminum. For this reason, quantitative synthesis of these parameters was performed in relation to percentages of yttria and aluminum, and the thickness of the specimens tested.

3.3.1. *Translucency*

Eleven articles were included in meta-analysis of translucency, combining 40 estimations of translucency in relation to variations in the materials' composition (yttria and aluminum) and thickness by means of a random effects model. Mean translucency was estimated

Table 2. Two-way ANOVA.

AUTHOR/ YEAR	SAMPLE N°	TRADE MARK	COMPOSITION (%)	THICKNESS (MM)	TRANSLUCENCY	CONTRAST RATIO	FLEXURAL RESISTANCE (MPA)	HARDNESS (GPA)	FRACTURE TOUGHNESS (MPA M1/2)
Flinn/ 2012 [17]	20 FR	3Y-TZP	3% Y 0.25% Al	1.2			1740 ± 151		
	20 FR	ATZ	3% Y 0.2% Al	1.2			1093 ± 51		
	30 FR	12Ce-TZP	12% Ce	1.2			495 ± 11		
Kohorst/ 2012 [27]	10 FR	Lava Zirconia	3% Y	0.2			1156 ± 87.6		
	10 FR	Zirkozahn	4-6% Y <1% Al 0.02% Si 0.01% Fe	0.2			1406 ± 243		
	10 FR	Zirprime	3-6% Y <0.5% Al 0.02% Si 0.02% Fe	0.2			1126 ± 92.4		
Stawarczyk/ 2013 [25]	10 CR 22 FR	Ceramill ZI	4.5-5.6% Y ≤ 5% Hf ≤0.5%Al ≤1% otros	0.7		0.77 ± 0.02	1281.1 ± 230		
Zhang/ 2015 [16]	6 T 6 CR 10 FR 10 H 10 FT	3Y-E (control)	3% Y 0.25% Al	0.53 ± 0.01	15.9 ± 0.3	0.61 ± 0.01	648 ± 36	12.96 ± 0.07	3.4 ± 0.1
	6 T 6 CR 10 FR 10 H 10 FT	3Y-0.2La-0.1Al	3% Y 0.2% La 0.1% Al	0.53 ± 0.01	20.9 ± 0.5	0.48 ± 0.01	651 ± 77	12.78 ± 0.16	3.4 ± 0.1
	6 T 6CR 10 FR 10 H 10 FT	3Y-0.2La-0.25Al	% Y 0.2% La 0.25% Al	0.53 ± 0.01	22.6 ± 0.6	0.52 ± 0.01	730± 111	13.20 ± 0.12	3.3 ± 0.1
Ersoy/ 2015 [30]	20 FR	In-Coris IZ	4.5-6% Y ≤5% Hf ≤0.5% Al ≤0.5% otros				662.1 ± 77.8		
	20 FR	In-Coris TZI	99% Zr+Hf+Y 5.2%Y 0.35% Al				622.3 ± 82.7		
Vichi/ 2016 [21]	10 T 10 CR 20 FR	IPS e.max Zir-CAD	6.5-8%Y ≤5%Hf ≤1%Al	1	11.48 ± 0.53	0.75 ± 0.01	1157 ± 100		
	10 T 10 CR 20 FR	InCoris ZI	4.5-6% Y ≤5% Hf ≤0.5% Al ≤0.5% otros	1	12.64 ± 0.93	0.74 ± 0.02	1160 ± 108		
	10 T 10 CR 20 FR	InCoris TZI	99% Zr+Hf+Y 5.2%Y 0.35% Al	1	14.05± 0.31	0.68 ± 0.01	1098 ± 118		
	10 T 10 CR 20 FR	In-Ceram YZ	5% Y <3% Hf <1% Al y Si	1	13.78 ± 0.28	0.70 ± 0.01	1120 ± 96		
	10 T 10 CR 20 FR	In Ceram YZ HT	4-6%Y <3%Hf <1%Al	1	14.44 ± 0.34	0.68 ± 0.01	1106 ± 97		
Stawarczyk/ 2016 [23]	15 CR 15 FR	Zenostar	4.5-6%Y <5%Hf <0.1% Al+otro	0.5 ± 0.005		0.57 ± 0.01	632 ± 172		
	15 CR 15 FR	DD Bio ZX2 hoch transluzent	<6% Y ≤ 0.15% Al <1% otros	0.5 ± 0.005		0.62 ± 0.01	718 ± 149		
	15 CR 15 FR	Ceramill Zolid	8.9-9.5%y <5%Hf <0.5%Al <1% otros	0.5 ± 0.005		0.57 ± 0.01	618 ± 114		
	15 CR 15 FR	InCoris TZI	99% Zr+Hf+Y 5.2%Y 0.35% Al	0.5 ± 0.005		0.57 ± 0.01	628 ± 128		

Table 2. continued.

Stawarczyk/ 2016 [23]	15 CR 15 FR	Ceramill ZI - control	4.5-5.6% Y ≤ 5% Hf ≤0.5%Al	0.5 ± 0.005		0.77 ± 0.01	917 ± 178		
Zhang/ 2016 [11]	6 T 6 CR 10 FR 10 H 8 FT	TZ-3YE	3% Y 0.25% Al	0.53 ± 0.01	15.9 ± 0.3	0.61 ± 0.01	997 ± 202	13.19 ± 0.07	6.6 ± 0.61
	6 T 6 CR 10 FR 10 H 8 FT	Zpex	3%Y 0.05% Al ≤0.02% Si	0.55 ± 0.01	18.9 ± 0.9	0.55 ± 0.02	854 ± 92	13.39 ± 0.001	6.9 ± 0.98
	6 T 6 CR 10 FR 10 H 8 FT	Zpex Smile	5%Y 0.05% Al ≤0.02% Si	0.54 ± 0.01	30.1 ± 2.3	0.36 ± 0.03	485 ± 78	13.39 ± 0.19	4.8 ± 0.58
	6 T 6 CR 10 FR 10 H 8 FT	3Y-0,25Al-0.2La	3%Y 0.25% Al 0.2% La	0.53 ± 0.01	20.9 ± 0.5	0.52 ± 0.01	651 ± 77	13.19 ± 0.49	6.4 ± 0.28
	6 T 6 CR 10 FR 10 H 8 FT	3Y-0.1Al-0.2La	3%Y 0.1% Al 0.2% La	0.53 ± 0.01	22.6 ± 0.6	0.48 ± 0.01	730 ± 110	13.29 ± 0.12	7.0 ± 0.47
Tong/ 2016 [12]	10 FR 10 H 10 FT	Zpex	3% Y ≤ 0.1% Al	1			990 ± 39	13.10 ± 0.02	3.24 ± 0.10
	10 FT 10 H 10 FT	TZ-3YS-E	3% Y 0.1-0.4% Al	1			1416 ± 33	12.88 ± 0.02	3.63 ± 0.12
	10 FR 10 H 10 FT	TZ-3Y-E	3% Y 0.1-0.4% Al	1			1076 ± 32	13.19 ± 0.03	3.21 ± 0.14
Nakamura/ 2016 [28]	5 H 5 FT	Zr1450	94.6% Zr+Hf 5.3%Y 0.14% Si <0.01% Al	1				11.41 ± 0.33	11.21 ± 1.24
	5 H 5 FT	Zr1500	94.6% Zr+Hf 5.3%Y 0.14% Si <0.01% Al	1				11.47 ± 0.28	11.35 ± 0.88
	5 H 5 FT	TZI	99% Zr+Hf+Y 5.2%Y 0.35% Al	1				11.75 ± 0.29	10.02 ± 1.19
Muñoz/ 2017 [31]	12 FR	Prettau Anterior	<12%Y 1%Al 0.02%Si 0.01%Fe 0.04% Na	1.2			853.5 ± 123.2		
	12 FR	Prettau Posterior	4-6%Y <1%Al 0.02%Si 0.01%Fe 0.02%Na	1.2			1162.6 ± 150.3		
	12 FR	ICE Zirkon	4-6%Y <1%Al 0.02%Si 0.01%Fe 0.04%Na	1.2			1048.1 ± 131.3		
De Souza/ 2017 [29]	11 FR 13 H	ZC-IPS E-max Zircad	86-93%Zr 6.5-8%Y ≤5%Hf ≤1%Al	1.2±0.2			892.4 ± 111.8	10.47 ± 0.71	
Carrabba/ 2017 [24]	10 CR 15 FR	Aadva ST	94.8% Zr 3%Y 0.2%Al	1.0 ± 0.1		0.74 ±0.01	1215 ± 190		
	10 CR 15 FR	Aadva EI	95%Zr 3% Y	1.0 ± 0.1		0.69 ± 0.01	983 ± 182		

Table 2. continued.

Carrabba/ 2017 [24]	10 CR 15 FR	Aadva NT	91% Zr 5.5%Y	1.0 ± 0.1		0.65 ± 0.01	539 ± 66		
Camposilvan/ 2018 [32]	10 CR	Aadva ST	3% y 0.2%Al	1			0.74 ± 0.01		
	10 CR	Aadva EI	3% Y 0.05% Al	1			0.70 ± 0.01		
	10 CR	Aadva NT	5.5%Y 0.05% Al	1			0.62 ± 0.01		
	10 CR	Katana UTML	>6%Y	1			0.69 ± 0.0		
Yan/ 2018 [26]	10 CR 10 TP 10 FR	Zpex	3%Y 0.05% Al ≤0.02% Si	1.0 ± 0.2	24.0 ± 0.1	0.48 ± 0.00	904 ± 57		
	10 CR 10 TP 10 FR	Zpex 4	4% Y 0.05% Al	1.0 ± 0.2	24.2 ± 0.6	0.47 ± 0.01	749 ± 29		
	10 CR 10 TP 10 FR	Zpex Smile	5%Y 0.05% Al ≤0.02% Si	1.0 ± 0.2	29.7 ± 0.4	0.37 ± 0.00	593 ± 90		
Mao/ 2018 [19]	3 CR 3 TP 10 FR	Zpex Smile	5%Y 0.05% Al ≤0.02% Si	1	32.81 ± 1.42	0.34 ± 0.02	324 ± 57		
	3 CR 3 TP 10 FR	Zpex	3%Y 0.05% Al ≤0.02% Si	1	16.35 ± 0.99	0.48 ± 0.004	990 ± 39		
Inokoshi/ 2018 [33]	5 TP	Katana HT	4%Y	0.5	29.5 ± 0.9				
	5 TP	Katana STML	4.8%Y	0.5	34.2 ± 0.7				
	5 TP	Katana UTML	5.4%Y	0.5	36.7 ± 1.8				
	5 TP	Zpex Smile	5%Y 0.05% Al ≤0.02% Si	0.5	33.1 ± 0.7				
Juntavee/ 2018 [34]	15 FR	Y-TZP, VITA YZ HT	4-6% Y 1.5-2.5% Hf 0-0.3% Al	1.5			1604.1±139.5		
Nassary/ 2018 [18]	10 TP 15 FR 15 FT	Ceramill Zolid	8.9-9.5%y <5%Hf <0.5%Al	1.0 ± 0.05	38.3 ± 0.3		557 ± 88		3.56 ± 0.47
	10 TP 15 FR 15 FT	CopraSmile	70-90%Zr 5-10%Y 0.5-1%Al	1.0 ± 0.05	37.1 ± 0.3		507 ± 69		3.34 ± 0.56
	10 TP 15 FR 15 FT	DD cubeX	<10%Y <0.01%Al ≥99% Zr + Hf	1.0 ± 0.05	37.3 ± 0.3		490 ± 83		3.64 ± 0.71
	10 TP 15 FR 15 FT	NOVAZIR MaxT	86-94% Zr 5.8-9.7% Y <0.5% Fe <0.5%Al <2%Er	1.0 ± 0.05	33.1 ± 0.5		540 ± 86		3.69 ± 0.88
	10 TP 15 FR 15 FT	Priti multidisc ZrO2	94.1-94.6% Zr+Hf 4.6-5.9%Y <0.4% Al	1.0 ± 0.05	37.6 ± 0.5		493 ± 119		3.34 ± 0.72
	10 TP 15 FR 15 FT	StarCeram Z-smile	8.5-9.6% Y <0.5%Hf <0.1%Al <0.1%Fe <0.1%Er	1.0 ± 0.05	33.6 ± 0.2		498 ± 104		3.77 ± 0.72
Sen/ 2018 [22]	10 TP 10 CR 10 FR	Vita YZ HT	4-6% Y 1.5-2.5% Hf 0-0.3% Al	1.0 ± 0.05	17.49 ± 0.38		1170 ± 63		
	10 TP 10 CR 10 FR	Prettau Zirkonzahn	4-6% Y 0-1% Al 0.02% Si	1.0 ± 0.05	16.05 ± 0.36		1254 ± 64		
	10 TP 10 CR 10 FR	Prettau Anterior Zirkonzahn	8-12% Y 0-1% Al 0.02% Si	1.0 ± 0.05	20.8 ± 0.89		803 ± 92		
Walczak/ 2019 [20]	30 CR 30 TP 30 FR	Cercon ht White	5%Y <3%Hf <1%Si	0.52 ± 0.01	11.72 ± 1.61	0.76 ± 0.03			

Table 2. continued.

Walczak/ 2019 [20]	30 CR 30 TP	BruxZir Solid	5.1%Y <3%Hf <0.5%Al <0.02%SI <0.01% Fe <0.04%Na	0.50 ± 0.01	11.66 ± 0.73	0.76 ± 0.01			
	30 CR 30 TP	Zenostar T0	4.5-6%Y <5%Hf <0.1% Al+otro	0.52 ± 0.01	12.96 ± 0.89	0.74 ± 0.18			
	30 CR 30 TP	Lava Plus	<5%Hf 5-6%Y 0.01%Al	0.52 ± 0.02	10.59 ± 0.72	0.79 ± 0.14			
Elsaka/ 2019 [13]	30 CR 30 TP 30 FR 30 H 30 FT	Ceramill Zolid FX	8.9-9.5%y <5%Hf <0.5%Al <1% otros	1	19.41 ± 0.49	0.56 ± 0.02	676 ± 49.75	11.36 ± 0.61	3.7 ± 0.27
	30 CR 30 TP 30 FR 30 H 30 FT	Prettau Anterior	<12%Y <1%Al 0.02%Si 0.01%Fe 0.04%Na	1	16.83 ± 0.41	0.74 ± 0.03	569.5 ±51.19	5.41 ± 0.26	1.72 ± 0.12
	30 CR 30 TP 30 FR 30 H 30 FT	Zenostar T0	<5%Hf >4.5-6%Y <1%Al+otros	1	15.88 ± 0.45	0.76 ± 0.03	960.1 ±70.22	7.09 ± 0.40	4.7 ± 0.34
Alshamrani/ 2019 [35]	5 TP 15 FR	Ceramill Zolid FX	3% Y 0-0.5% Al 1-5% Hf	1.5	12.95 ±1.45		712.45 ± 77.04		
	5 TP 15 FR	IPS e.max Zircad	5% Y 0-0.5% Al 1-5% Hf	1.5	21.43 ± 0.55		339.77 ± 88.08		
Zhang/ 2019 [36]	6 CR 20 FR	Zpex	3%Y 0.05% Al ≤0.02% Si	0.5		0.54 ± 0.02	908 ±44		
	6 CR 20 FR	Zpex4	4% Y 0.05% Al	0.5		0.47 ± 0.01	928 ± 82		
	6 CR 20 FR	ZpexSmile	5%Y 0.05% Al ≤0.02% Si	0.5		0.36 ± 0.01	534 ± 56		

*In this table, we refer to the authors and years of each article, as well as the sample number, the trademark, the composition, the thickness and the parameters of optical and mechanical properties. The meaning of the abbreviations is as follows: FR (flexural resistance), CR (contrast ratio), T(translucency), H (hardness), FT (fracture toughness), Y (Ytrium), Al (Aluminum), Ce (Cerio), Hf (Hafnium), La (Lanthanum), Zr (zirconium), Si (Silicon), Fe (iron), Na (Sodium)"

to be 22.49 with a 95% confidence interval (CI) between 19.85 and 25.13. Meta-analysis found high heterogeneity: I^2 = 99.98 and Q = 200614.10 (p< 0.001).

A methods of moments random effects model was created to estimate translucency (p=0.003; R^2=0.26), in which yttria, aluminum, and thickness were predictive variables. The effect of yttria on translucency was found to be significant, increasing translucency (coefficient = 14.93) when the proportion of yttria was over 6.1%. Aluminum was also found to have a significant effect, reducing translucency (coefficient = -8.81) when its proportion was >0.41%. Material thickness did not show any influence on translucency (**Table 4**; **Fig. 2-3**).

3.3.2. Contrast ratio

Meta-analysis of contrast ratio included 12 articles, combining 38 estimations of contrast ratio in relation to variations in composition (yttria and aluminum) and thickness using a random effects model. It was estimated that contrast ratio was 0.62 with a 95% confidence interval between 0.58 - 0.65. Meta-analysis found high heterogeneity (I^2 = 99.90: Q = 36358.38; p<0.001).

A methods of moments random effects model was created to estimate contrast ratio (p<0.001; R^2=0.5) with yttria, aluminum and thickness as predictive variables, finding that the percentage of yttria significantly reduced contrast ratio (coefficient = -0.13) when its proportion was over 6.1. The percentage of aluminum also has a significant effect, increasing contrast ratio (coefficient = 0.07) when it was between 0.11% and 0.4%, and when it was >0.41% (coefficient = 0.20). Thickness was not found to exert any influence on contrast ratio (**Table 5**; **Fig. 4-5**).

3.3.3. Flexural resistance

Twenty articles that investigated FR were included in meta-analysis, combining 61 estimations in relation to variations in the test materials' composition (yttria and aluminum) in a random effects model. It was estimated that FR was 858.98MPa with a 95% confidence interval between 781.92 MPa and 936.04 MPa. Meta-analysis exhibited high heterogeneity (I^2 = 99.77; Q = 25801.29; p < 0.001).

Table 3. The quality of the studies selected for review was assessed with the modified CONSORT.

STUDIES	1	2a	2b	3	4	5	6	7	8	9	10	11	12	13	14
Flinn et al [17]	*	*	*	*	*	*					*		*		
Kohorst et al.[27]	*	*	*	*	*	*					*				
Stawarczyk et al [25]	*	*	*	*	*	*					*	*	*		
Zhang et al [16]	*	*	*	*	*	*					*				
Ersoy et al [30]	*	*	*	*	*	*					*		*		
Vichi et al [21]	*	*	*	*	*	*					*				
Stawarczyk et al [23]	*	*	*	*	*	*					*	*			
Zhang et al [11]	*	*	*	*	*	*					*	*			
Tong et al [12]	*	*	*	*	*	*					*				
Nakamura et al [28]	*	*	*	*	*	*					*				
Muñoz et al [31]	*	*	*	*	*	*					*		*		
De Souza et al [29]	*	*	*	*	*	*					*				
Carrabba et al [24]	*	*	*	*	*	*					*				
Camposilva et al [32]	*	*	*	*	*	*					*		*		
Yan et al [26]	*	*	*	*	*	*					*				
Mao et al [19]	*	*	*	*	*	*					*				
Inokoshi et al [33]	*	*	*	*	*	*					*		*		
Juntavee et al [34]	*	*	*	*	*	*					*	*			
Nassary et al [18]	*	*	*	*	*	*					*	*	*		
Sen et al [22]	*	*	*	*	*	*					*	*	*		
Walczak et al [20]	*	*	*	*	*	*					*				
Elsaka et al [13]	*	*	*	*	*	*					*				
Alshamrani et al [35]	*	*	*	*	*	*					*	*	*		
Zhang et al [36]	*	*	*	*	*	*					*				

: 1) Structured summary. 2a) Scientific background. 2b) Specific objectives and/ or hypotheses. 3) The intervention for each group, including how and when it was administrered. 4) Pre-specified primary and secondary measures ofautcome. 5) How sample size was determined. 6) Method used to generate the random allocation sequence. 7) Mechanism used to implement the random allocation sequence. 8) Who generated the random allocation sequence. 9) Who was blinded after assignment to intervention, and how. 10) Statistical methods used to compare groups for primary and secondary outcomes. 11) The estimated size of the effect and its precision. 12) Trial limitations. 13) Sources of funding and other support. 14) Where the full trial protocol can be accessed, if available.

A method of moments random effects model ($p < 0.001$; $R^2=0.30$) was used to estimate flexural resistance with yttria and aluminum as predictive variables, in which the percentage of yttria was found to have a significant effect on FR, reducing FR (coefficient = -230.86 MPa) when concen trations were between 3.1% and 6%, and when the percentage was over 6.1% (coefficient = -489.30 MPa). Aluminum also had a significant effect, ncreasing FR (coefficient = 314.22 MPa) when the proportion was over 0.41%. (**Table 6**; **Fig. 6-7**).

3.3.4. Fracture toughness

Six articles were included in meta-analysis of fracture toughness, combining 23 estimations in relation to variations in composition (yttria and aluminum) in a random effects model. Mean FT was estimated to be 4.90 MPa m1/2 with a 95% confidence interval between 4.46 MPa m1/2 – 5.34 MPa m1/2. Meta-analysis showed high heterogeneity ($I^2 = 99.73$; $Q = 8204.84$; $p < 0.001$).

A method of moments random effects model ($p < 0.001$; $R^2=0.29$) estimated FT with percentages of yttria and aluminum as predictive variables, finding that yttria had a significant effect on FT so that it increased (coefficient = 3.65 MPa m1/2) when the percentage was between 3.1% and 6%. Aluminum also showed a significant effect, reducing FT (coefficient = -1.69 MPa m1/2) when its percentage was over 0.41%. (**Table 7**; **Fig. 8-9**).

3.3.5. Hardness

The last meta-analysis included six articles that investigated hardness, combining 19 estimations of HV in relation to variations in composition (percentages of yttria and aluminum) using a random effects model. Mean HV was estimated to be 11.76 GPa with a 95% confidence interval between 11.49 GPa – 12.03 GPa. Meta-analysis showed high heterogeneity ($I^2 = 99.96$; $Q = 46530.44$; $p < 0.001$).

The methods of moments random effects model ($p = 0.001$; $R^2 = 0.77$) was created to estimate hardness, with percentages of yttria and aluminum in the materials' composition as predictive variables. Yttria had a significant effect on hardness, reducing HV (coefficient = -1.31) when its concentration was 3.1%-6% (coefficient = -1.48 GPa) and when it was over 6.1%. Aluminum was also found to have a significant influence, reducing hardness when the percentage was over 0.41% (coefficient = -3.90 GPa). (**Table 8**; **Fig. 10-11**).

3.3.6. Publication Bias

Funnel plots are showed in **Figure 12, 13, 14 and 15**. Translucency shows symmetrical data distribution, suggesting that there

Table 4. Method of moments random effects metaregression analysis of translucency. *p<0.05. Yttria category of reference 1 (<3), aluminum category 1 (<0.1).

	Coefficient	95% lower	95% upper	P- value
Intercept	17.1	7.81	26.39	<0.001
Yttria (%): (3.1-6)	3.05	-3.88	9.98	0.389
Yttria (%): (>6.1)	14.93	5.91	23.94	0.001*
Aluminum (%): (0.11-0.4)	-1.59	-8.4	5.23	0.649
Aluminum (%): (>0.41)	-8.81	-15.63	-1.99	0.011*
Thickness (mm)	4.13	-6.11	14.37	0.429

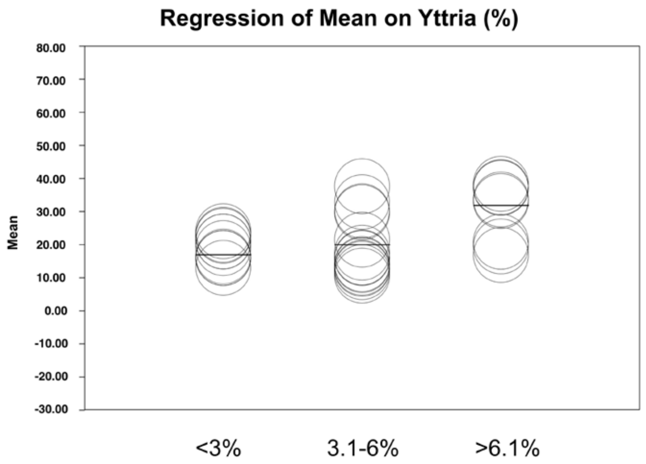

Fig. 2. Scatter-plots of Meta-regression analysis of translucency with Yttria (%).

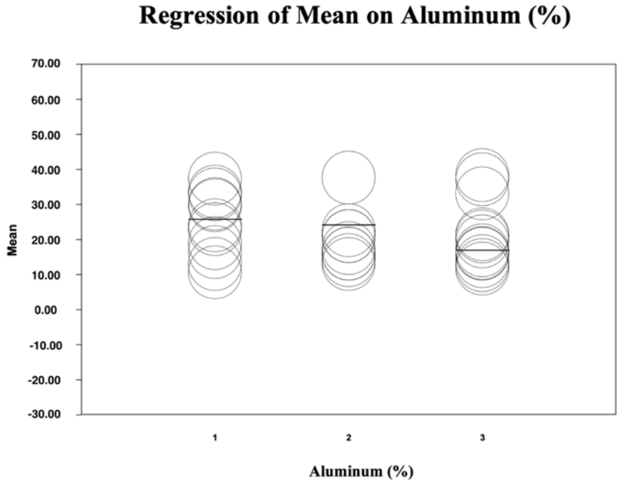

Fig. 3. Scatter-plots of Meta-regression analysis of translucency with Aluminum (%).

Table 5. Method of moments random effects metaregression analysis of contrast ratio. *p<0.05. Reference category for yttria 1 (<3) and for aluminum 1 (<0.1).

Covariate	Coefficient	95% lower	95% upper	P- value
Intercept	0.47	0.36	0.57	<0.001
Yttria (%): (3.1-6)	-0.002	-0.07	0.07	0.965
Yttria (%): (>6.1)	-0.13	-0.26	-0.003	0.045*
Aluminum (%): (0.11-0.4)	0.07	0.01	0.14	0.037*
Aluminum (%): (>0.41)	0.2	0.12	0.29	<0.001*
Thickness (mm)	0.1	-0.02	0.23	0.103

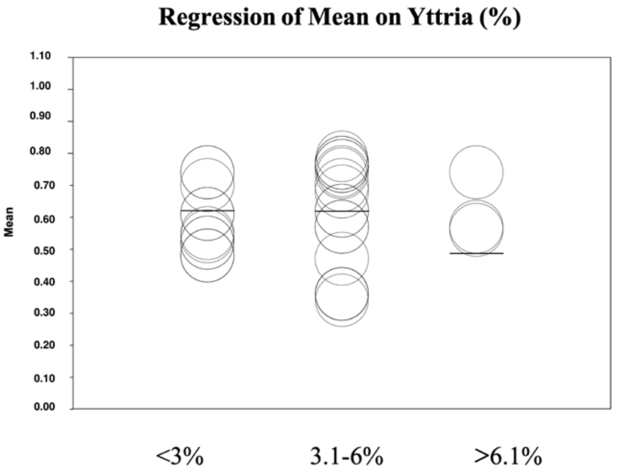

Fig. 4. Scatter-plots of Meta-regression analysis of Contrast ratio with Yttria (%).

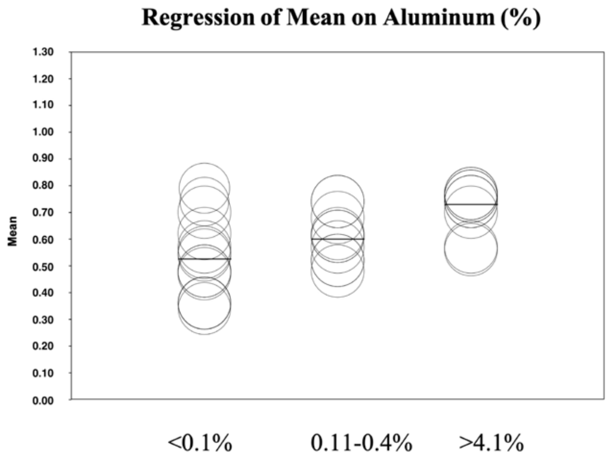

Fig. 5. Scatter-plots of Meta-regression analysis of Contrast ratio with Aluminum (%).

Table 6. Method of moments random effects analysis of flexural resistance. *p<0,05. Reference category for yttia 1 (<3) and for aluminum 1 (<0.1).

Covariate	Coefficient	95% lower	95% upper	P- value
Intercept	0.47	0.36	0.57	<0.001
Yttria (%): (3.1-6)	-0.002	-0.07	0.07	0.965
Yttria (%): (>6.1)	-0.13	-0.26	-0.003	0.045*
Aluminum (%): (0.11-0.4)	0.07	0.01	0.14	0.037*
Aluminum (%): (>0.41)	0.2	0.12	0.29	<0.001*
Thickness (mm)	0.1	-0.02	0.23	0.103

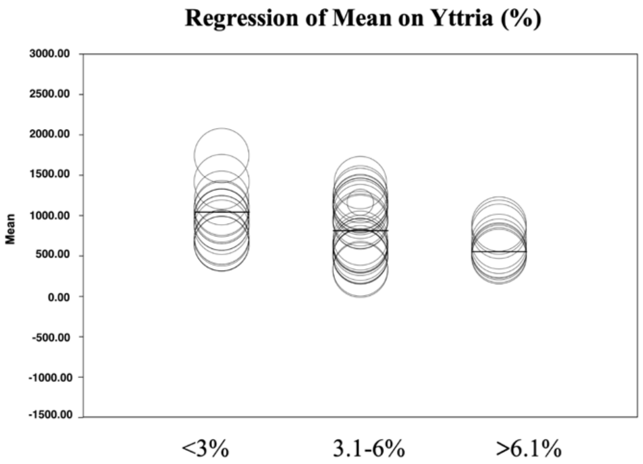

Fig. 6. Scatter-plots of Meta-regression analysis of Flexural resistance with Yttria (%).

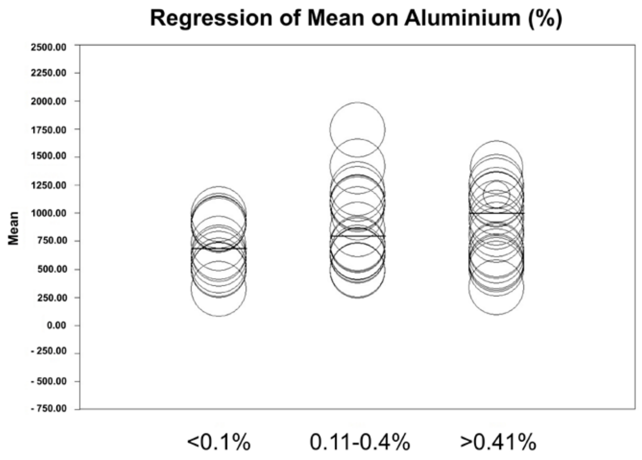

Fig. 7. Scatter-plots of Meta-regression analysis of Flexural resistance with Aluminum (%).

Table 7. Method of moments random effects metarregresion analysis of fracture toughness. *p<0.05. Yttria category of reference 1 (<3), for aluminum 1 (<0.1).

Covariate	Coefficient	95% lower	95% upper	P- value
Intercept	4.89	4.09	5.68	<0.001
Yttria (%): (3.1-6)	3.65	2.54	4.75	<0.001*
Yttria (%): (>6.1)	-0.44	-1.56	0.69	0.445
Aluminum (%): (0.11-0.4)	-0.37	-1.3	0.56	0.434
Aluminum (%): (>0.41)	-1.69	-2.82	-0.56	0.003*

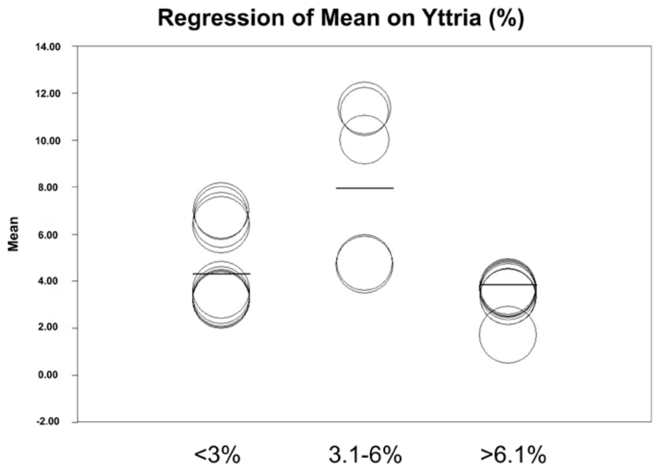

Fig. 8. Scatter-plots of Mean-regression analysis of Fracture toughness with Yttria (%).

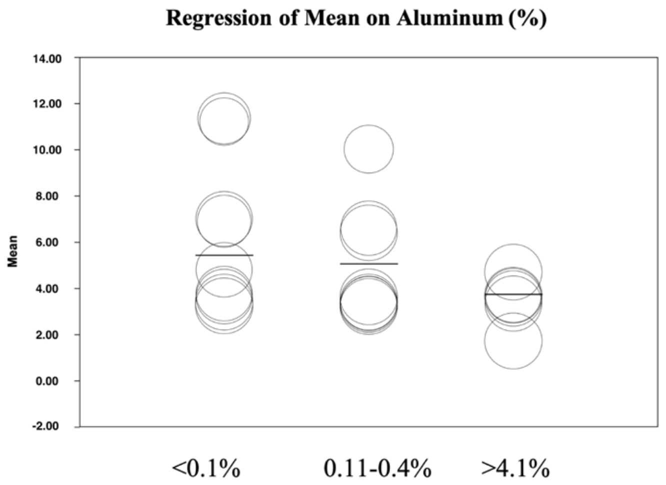

Fig. 9. Scatter-plots of Mean-regression analysis of Fracture toughness with Aluminum (%).

Table 8. Method of moments random effects metaregresion analysis of hardness. *p<0.05. yttria category of reference 1 (<3), for aluminum 1 (<0.1).

Covariate	Coefficient	95% lower	95% upper	P- value
Intercept	4.89	4.09	5.68	<0.001
Yttria (%): (3.1-6)	3.65	2.54	4.75	<0.001*
Yttria (%): (>6.1)	-0.44	-1.56	0.69	0.445
Aluminum (%): (0.11-0.4)	-0.37	-1.3	0.56	0.434
Aluminum (%): (>0.41)	-1.69	-2.82	-0.56	0.003*

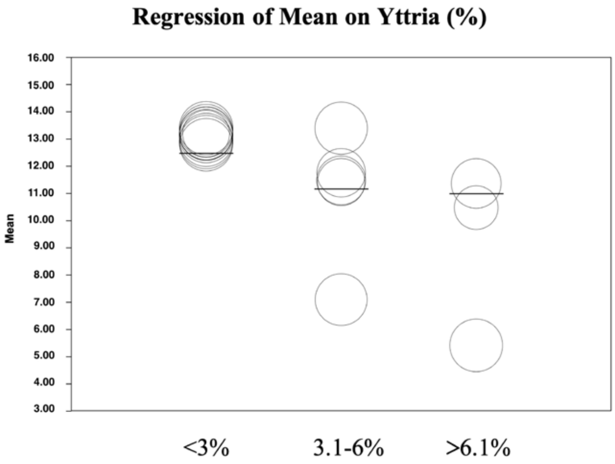

Fig. 10. Scatter-plots of Meta-regression analysis of Fracture hardness with Yttria (%)

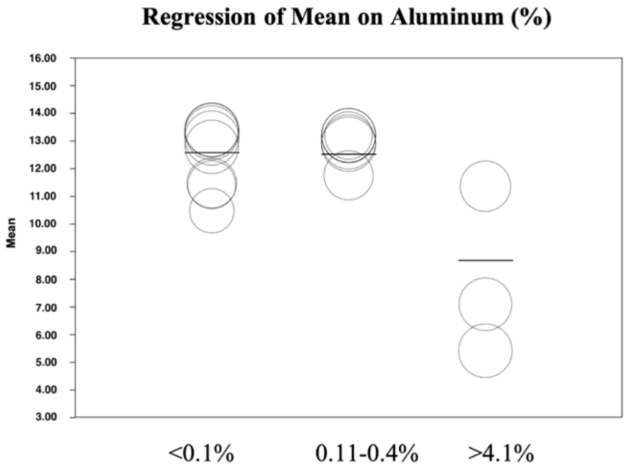

Fig. 11. Scatter-plots of Meta-regression analysis of Fracture hardness with Aluminum (%)

was no publication bias. The Trim and Fill method added two imputed studies obtaining a new estimation of mean translucency of 23.13, which was not significantly different from the estimation obtained in meta-analysis (22.49). Contrast ratio shows symmetrical data distribution, suggesting that there was no publication bias. Trim and Fill added four new imputed studies, obtaining a new estimated mean contrast ratio of 0.60, which did not differ significantly from the estimation obtained in meta-analysis (0.62). For Flexural resistance, Trim and Fill did not need to impute additional articles, so estimation upheld the mean FR value of 858.98 MPa. Fracture toughness showed that data distribution was symmetrical, suggesting that there was no publication bias. Trim and Fill did not add imputed studies, so the estimation of mean FT remained at 4.90 MPa m1/2. The funnel plot of Harness shows that data distribution was symmetrical, suggesting no publication bias. Trim and Fill added 4 imputed studies generating an estimated mean FT of 11.25 GPa, which did not differ greatly from the estimation obtained in meta-analysis (11.76 GPa).

4. Discussion

This systematic review was conducted to evaluate the influence of variations in the composition (percentages of yttria and aluminum) of monolithic zirconia on its optical and mechanical properties. The review compared various in vitro experimental studies, each testing different types of commercially available monolithic zirconia. The studies were carefully selected to obtain a sample that was as uniform as possible in order to facilitate synthesis of the results.

4.1. Translucency

Among the articles selected for review, 11 studied the translucency of monolithic zirconia, making it possible to combine 40 estimations of TP in zirconia samples with variations in composition (percentages of yttria and aluminum) and thickness. Meta-regression analysis found that yttria caused a significant increase in TP when its concentration was >6.1%, as shown in the study by Nassary et al. [18] in which all the brands of zirconia tested exhibited TP values of between 33.1 ± 05 (Nova zirMax T) and 38.3 ± 0.3 (Ceramill Zolid), with yttria percentages ranging between 6% and 10%. Mean translucency in meta-analysis was 22.49, while in studies by Zang et al. [16] and Mao et al. [19] TP values were 15.9 ± 0.3 and 16.35 ± 0.99 respectively for 3% yttria. A progressive increase in TP was observed when the percentage of yttria rose above 3%, but these findings were not statistically significant.

Variations in the proportion of aluminum were also found to have a significant effect, reducing the TP of monolithic zirconia when the percentage is >0.41%, as shown in the study by Walczak et al. [20] which evaluated BruxZir Solid, finding it to be the brand exhibiting the lowest TP value (11.66 ± 0.73), approximately half the mean TP obtained in the review. This effect concurs with findings reported by Vichi et al. [21], Sen et al. [22], and Elsaka et al. [13].

Regarding the thickness of the test specimen, the method of moments random effects model showed that TP increases as thickness increases, but the data obtained were not statistically significant.

4.2. Contrast ratio

Twelve of the articles included in the review studied contrast ratio, producing 38 estimations which showed that variations in the percentage of yttria cause reductions in CR, becoming significant when yttria was >6.1%. This was shown in the study by Elsaka et al. [13], and also in Stawarczyk et al, [23]. But when percentages of yttria were between 3% and 6.1% the effects on CR were not statistically significant, although the study by Zhang et al. [11] was notable, obtaining a CR of 0.36 ± 0.03 with the brand ZpexSmile with 5% yttria, while Mao et al. [19] obtained 0.34 ± 0.02 testing the same brand;

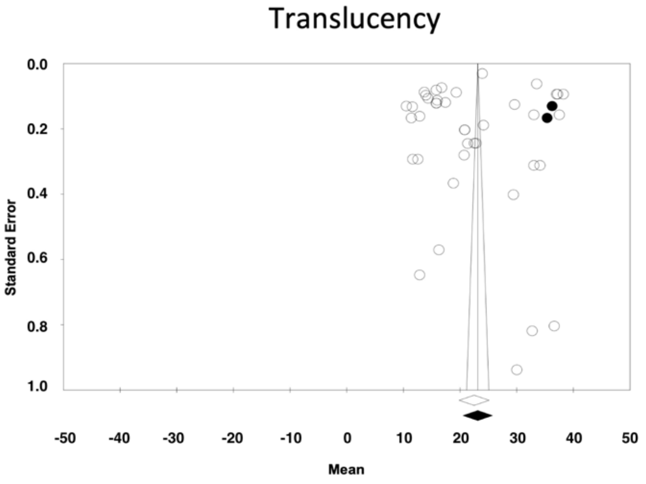

Fig. 12. Funnel Plot of Translucency.

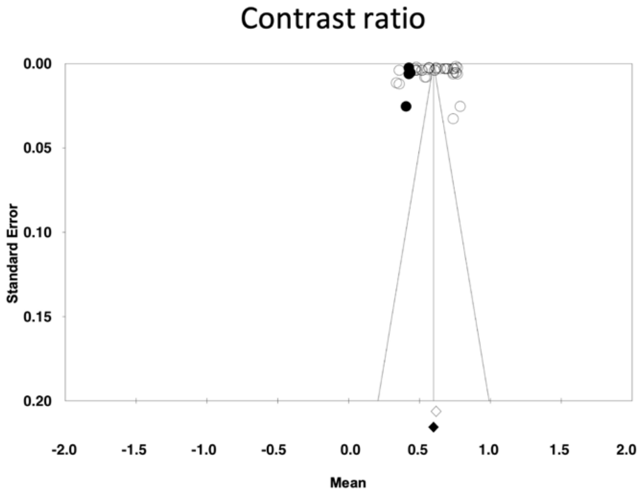

Fig. 13. Funnel Plot of Contrast ratio.

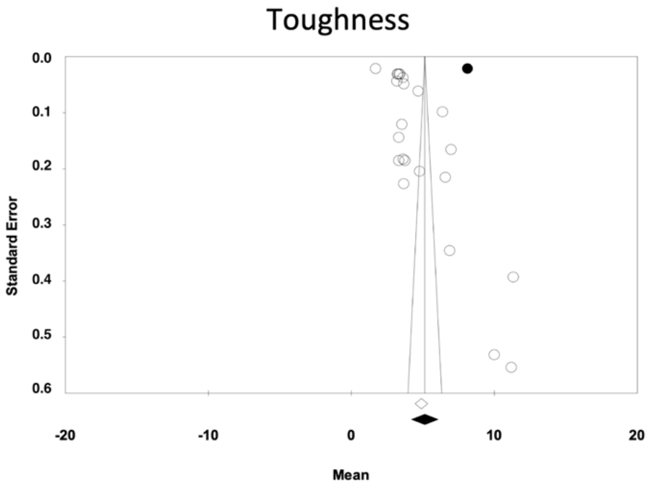

Fig. 14. Funnel Plot of Toughness.

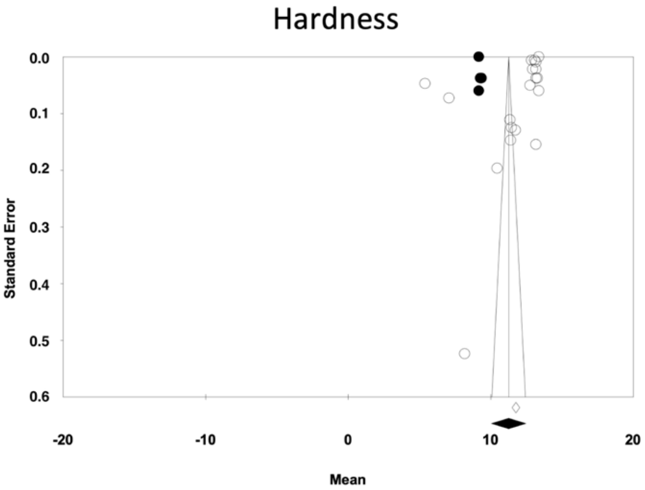

Fig. 15. Funnel Plot of Hardness.

these studies presented values lower than 0.62, the overall mean CR obtained in the review.

It was also found that aluminum had a significant effect on CR when the percentage was between 0.11% and 0.4%, as observed in the study by Carrabba [24] obtaining a CR of 0.74 ± 0.01 testing the brand Aadva ST with a percentage of 0.2%, the study by Vichi [21] obtaining 0.68 ± 0.01 CR with 0.35% aluminum in the brand Coris ZI, and Stawarczyk et al. [23] obtaining 0.62 ± 0.01 with 0.15% aluminum in DD Bio ZX2 High Translucent. When the proportion of aluminum is >0.4% this also had a significant effect on CR as shown in studies by Stawarczyk et al. [25], Walczak et al. [20], and Vichi et al. [21].

Regarding the thickness of the specimens, it was found that contrast ratio increased as thickness increased but without statistical significance.

4.3. *Flexural resistance*

The method of moments random effects model included 20 articles investigating flexural resistance, from which 61 estimations were extracted, finding that different percentages of yttria had significant effects on the materials' FR, reducing resistance when percentages were between 3.1% and 6%, in other words, decreasing as the proportion of yttria rose. For example, the study by Mao [19] compared the brand ZpexSmile with 5% yttria obtaining 324 ± 57 MPa compared with 990 ± 39 MPa obtained with Zpex with 3% yttria. Zhang et al. [11], Nassary et al. [18] and Yan et al. [26] also confirmed this effect. While yttria percentages of 3.1%-6% were found to have a statistically significant effect on FR, proportions over 6.1% also reduced resistance, as shown by Nassary et el. [18] who compared various brands of zirconia, obtaining a value of 557 ± 88 MPa for the brand Ceramill Zolid with percentages of yttria between 8.9% and 9.5%, almost 300 MPa less than the mean estimated in the present review (858.98 MPa).

The proportion of aluminum was also found to have a significant effect on FR, which was seen to increase significantly when the percentage was above 0.41%. For example, Kohorst et al. [27] obtained mean FR of 1406 ± 243 MPa when aluminum was <1% as in the brand Zirkozahn, while Stawarczyk et al. [25] obtained 1281 ± 230 MPa with 0.5% aluminum, similar to findings reported by Sen et al. [22].

4.4. Fracture toughness

Six of the articles reviewed studied fracture toughness, providing 23 estimations of using brands of zirconia with varying compositions. Variations in the percentage of yttria had a statistically significant effect on FT, whereby FT increased when the percentage was between 3.1% and 6%, as shown by Nakamura [28] who obtained values of 10.02 ± 1.19 MPa m1/2 with the brand inCoris TZI (5.2% yttria), while the overall mean FT obtained in the present review was 4.90 MPa m1/2.

Aluminum was also seen to have a significant effect on FT, but unlike yttria FT decreased when the percentage of aluminum was >0.41%. This was shown by Elsaka et al. [13] in which all the brands of zirconia tested had percentages of aluminum >0.41% obtaining FT of 3.7 ± 0.27 MPa m1/2 when aluminum represented 0.5% in Ceramill Zolid FX and 1.72 ± 0.12 when aluminum increased to 1% in the brand Prettau Anterior. These findings were reaffirmed in the study by Nassary et al. [18].

4.5. Hardness

Six articles that included data on hardness were included in meta-analysis, combining 19 estimations of materials of varying composition. Yttria was found to have a significant effect on HV, which was reduced for percentages between 3.1% and 6% and percentages >6.1%. Elsaka et al. [13] found that percentages between 4.5% and 6% obtained an HV value of 7.09 ± 0.40 GPa with the brand Zenostar T0, and 5.41 ± 0.26 GPa at a percentage <12% with Prettau Anterior, compared with overall mean HV obtained in the review of 11.76 GPa, similar to values reported by Nakamura et al. [28] and de Souza et al. [29].

The percentage of aluminum was also found to have a significant effect on HV, which decreased when the amount of aluminum was >0.41%. Elsaka et al. [13] reported this decrease in specimens with high proportions of aluminum, obtaining HV of 5.41 ± 0.26 GPa with the brand Prettau Anterior containing 1% aluminum, and 7.09 ± 0.4 GPa with Zenostar T0 containing the same percentage.

Nevertheless, the process was subject to certain limitations as no similar studies or reviews were located with which to compare the present findings, and methods employed in the works reviewed varied so that some data could not be included in analysis.

In addition, it was decided not to include in the review studies that evaluated the influence of thermochemical variations on the properties of monolithic zirconia because there were few studies that referred to the temperature parameter, and in which temperature was studied, temperature parameters ranged from 1400-1600ºC and good results were obtained from the properties. Concluding that if the temperature values are between 1450-1550ºC there are no significant differences in the values obtained from the chemical and mechanical properties.

Despite these limitations, the review has produced relevant information. In vitro experimental studies of dental materials are needed to determine their properties before they can be used satisfactorily in subsequent in vivo research and clinical practice.

5. Conclusion

Despite the limitations to which meta-analysis and meta-regression were subject, the following may be concluded:

- A percentage >6.1% yttria produces a significant increase in translucency. Percentages of aluminum > 0.41% cause a statistically significant reduction in translucency.
- Percentages of yttria > 6.1% produce a statistically significant reduction in contrast ratio. Aluminum at percentages between 0.11% and 0.4% or > 0.41% provoke increases in contrast ratio.
- Variations in specimens' thickness did not have any significant effect on translucency or contrast ratio.
- Flexural resistance underwent a significant reduction when the percentage of yttria was between 3.1% and 6% or >6.1%. However, when the percentage of aluminum was >0.41% this caused a statistically significant increase in flexural resistance.
- Fracture toughness increased significantly with percentages of yttria between 3.1% and 6%, in contrast to aluminum which significantly reduced fracture toughness when percentages were >0.41%.
- Hardness was affected when the percentage of yttria was between 3.1% and 6% or >6.1%, undergoing statistically significant reductions. Percentages of aluminum >0.41% also caused a reduction in hardness.

Based on these conclusions, a series of clinical indications may be affirmed regarding the selection of types of monolithic zirconia for restoring different regions:

1. The monolithic zirconia of choice for use in anterior teeth requires good esthetic properties and acceptable mechanical performance, and so will have a higher proportion of yttria as stabilizer (>6.1%) and reduced percentages of aluminum in its composition (<0.11%).
2. In posterior regions, mechanical properties are required that will resist higher occlusal forces while providing adequate esthetics, and so zirconia with lower percentages of yttria (≤3%) and higher percentages of aluminum (>0.41%) are recommended.

Further research is needed to determine a clear protocol for selecting the right monolithic zirconia composition for each clinical situation.

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Conflicts of interest

The authors declare no conflict of interest.

References

[1] Agustín-Panadero R, Román-Rodríguez JL, Ferreiroa A, Solá-Ruíz MF, Fons-Font A. Zirconia in fixed prosthesis. A literature review. J Clin Exp Dent 2014;6. https://doi.org/10.4317/jced.51304, PMID:24596638

[2] Malkondu Ö, Tinastepe N, Akan E, Kazazoğlu E. An overview of monolithic zirconia in dentistry. Biotechnol Biotechnol Equip 2016;30:644–52. https://doi.org/10.1080/13102818.2016.1177470.

[3] Špehar D, Jakovac M. New Knowledge about Zirconium-ceramic as a Strcutrual material in fixed prosthodontics. Acta Stomatol Croat 2015;49:137–44. https://doi.org/10.15644/asc49/2/7, PMID:27688396

[4] Fons, A. Solá, M.F. Martínez, A. Casas J. Clasificación actual de las cerámicas dentales. RCOE 2001;6:645–56.

[5] Martínez-Rus, F. Pradíes-Ramiro, G. Suárez-García M et al. Dental ceramics: Classification and selection criteria. RCOE 2007;12:253–63.

[6] Agustín-Panadero R, Fons-Font A, Román-Rodríguez JL, Granell-Ruíz M, Solá-Ruíz MF, Del Rio-Highsmith J. Zirconia versus metal: A preliminary comparative analysis of ceramic veneer behavior. Int J Prosthodont 2012;25:294–300. PMID:22545261

[7] Tabatabaian F. Color Aspect of Monolithic Zirconia Restorations: A Review of the Literature. J Prosthodont 2019;28:276–87. https://doi.org/10.1111/jopr.12906, PMID:29801196

[8] Shahmiri R, Standard OC, Hart JN, Sorrell CC. Optical properties of zirconia ceramics for esthetic dental restorations: A systematic review. J Prosthet Dent 2018;119:36–46. https://doi.org/10.1016/j.prosdent.2017.07.009, PMID:28927925

[9] Miyazaki T, Nakamura T, Matsumura H, Ban S, Kobayashi T. Current status of zirconia restoration. J Prosthodont Res 2013;57:236–61. https://doi.org/10.1016/j.jpor.2013.09.001, PMID:24140561

[10] Stawarczyk B, Keul C, Eichberger M, Figge D, Edelhoff D, Lümkemann N. Three generations of zirconia: From veneered to monolithic. Part I. Quintessence Int (Berl) 2017;48:369–80. https://doi.org/10.3290/j.qi.a38057, PMID:28396886

[11] Zhang F, Inokoshi M, Batuk M, Hadermann J, Naert I, Van Meerbeek B, et al. Strength, toughness and aging stability of highly-translucent Y-TZP ceramics for dental restorations. Dent Mater 2016;32:e327–37. https://doi.org/10.1016/j.dental.2016.09.025, PMID:27697332

[12] H. Tong, C. Tanaka, M. Kaizer et al. Characterization on three commercial Y-TZP ceramics produced for their high-translucency, high-strength and high-surface area. Ceram Int 2016;42:1077–85. https://doi.org/10.1016/j.ceramint.2015.09.033, PMID:26664123

[13] Elsaka SE. Optical and Mechanical Properties of Newly Developed Monolithic Multilayer Zirconia. J Prosthodont 2019;28:e279–84. https://doi.org/10.1111/jopr.12730, PMID:29239067

[14] Julian Higgins, James Thomas, Jackie Chandler, Miranda Cumpston, Tianjing Li, Matthew Page VW. Cochrane handbook for systematic reviews of interventions version 6.0. Cochrane,. 2019. https://doi.org/10.1002/14651858.ED000142, PMID:31643080

[15] Faggion CM. Guidelines for reporting pre-clinical in vitro studies on dental materials. J Evid Based Dent Pract 2012;12:182–9. https://doi.org/10.1016/j.jebdp.2012.10.001, PMID:23177493

[16] Zhang F, Vanmeensel K, Batuk M, Hadermann J, Inokoshi M, Van Meerbeek B, et al. Highly-translucent, strong and aging-resistant 3Y-TZP ceramics for dental restoration by grain boundary segregation. Acta Biomater 2015;16:215–22. https://doi.org/10.1016/j.actbio.2015.01.037, PMID:25662163

[17] Flinn BD, Degroot DA, Mancl LA, Raigrodski AJ. Accelerated aging characteristics of three yttria-stabilized tetragonal zirconia polycrystalline dental materials. J Prosthet Dent 2012;108:223–30. https://doi.org/10.1016/S0022-3913(12)60166-8, PMID:23031728

[18] Nassary Zadeh P, Lümkemann N, Sener B, Eichberger M, Stawarczyk B. Flexural strength, fracture toughness, and translucency of cubic/tetragonal zirconia materials. J Prosthet Dent 2018;120:948–54. https://doi.org/10.1016/j.prosdent.2017.12.021, PMID:29807742

[19] Mao L, Kaizer MR, Zhao M, Guo B, Song YF, Zhang Y. Graded Ultra-Translucent Zirconia (5Y-PSZ) for Strength and Functionalities. J Dent Res 2018;97:1222–8. https://doi.org/10.1177/0022034518771287, PMID:29694258

[20] Walczak K, Meißner H, Range U, Sakkas A, Boening K, Wieckiewicz M, et al. Translucency of Zirconia Ceramics before and after Artificial Aging. J Prosthodont 2019;28:e319–24. https://doi.org/10.1111/jopr.12771, PMID:29527778

[21] Vichi A, Sedda M, Fabian Fonzar R, Carrabba M, Ferrari M. Comparison of contrast ratio, translucency parameter, and flexural strength of traditional and “augmented translucency” zirconia for CEREC CAD/CAM system. J Esthet Restor Dent 2016;28:S32–9. https://doi.org/10.1111/jerd.12172, PMID:27113296

[22] Sen N, Sermet IB, Cinar S. Effect of coloring and sintering on the translucency and biaxial strength of monolithic zirconia. J Prosthet Dent 2018;119:308.e1-308.e7. https://doi.org/10.1016/j.prosdent.2017.08.013, PMID:29150133

[23] Stawarczyk B, Frevert K, Ender A, Roos M, Sener B, Wimmer T. Comparison of four monolithic zirconia materials with conventional ones: Contrast ratio, grain size, four-point flexural strength and two-body wear. J Mech Behav Biomed Mater 2016;59:128–38. https://doi.org/10.1016/j.jmbbm.2015.11.040, PMID:26751707

[24] Carrabba M, Keeling AJ, Aziz A, Vichi A, Fabian Fonzar R, Wood D, et al. Translucent zirconia in the ceramic scenario for monolithic restorations: A flexural strength and translucency comparison test. J Dent 2017;60:70–6. https://doi.org/10.1016/j.jdent.2017.03.002, PMID:28274651

[25] Stawarczyk B, Özcan M, Hallmann L, Ender A, Mehl A, Hämmerlet CHF. The effect of zirconia sintering temperature on flexural strength, grain size, and contrast ratio. Clin Oral Invest 2013;17:269–74. https://doi.org/10.1007/s00784-012-0692-6, PMID:22358379

[26] Yan J, Kaizer MR, Zhang Y. Load-bearing capacity of lithium disilicate and ultra-translucent zirconias. J Mech Behav Biomed Mater 2018;88:170–5. https://doi.org/10.1016/j.jmbbm.2018.08.023, PMID:30173069

[27] Kohorst P, Borchers L, Strempel J, Stiesch M, Hassel T, Bach FW, et al. Low-temperature degradation of different zirconia ceramics for dental applications. Acta Biomater 2012;8:1213–20. https://doi.org/10.1016/j.actbio.2011.11.016, PMID:22138551

[28] Nakamura T, Nakano Y, Usami H, Wakabayashi K, Ohnishi H, Sekino T, et al. Translucency and low-temperature degradation of silica-doped zirconia: A pilot study. Dent Mater J 2016;35:571–7. https://doi.org/10.4012/dmj.2015-274, PMID:27477222

[29] De Souza GM, Zykus A, Ghahnavyeh RR, Lawrence SK, Bahr DF. Effect of accelerated aging on dental zirconia-based materials. J Mech Behav Biomed Mater 2017;65:256–63. https://doi.org/10.1016/j.jmbbm.2016.08.023, PMID:27595931

[30] Ersoy NM, Aydoğdu HM, Değirmenci BÜ, Çökük N, Sevimay M. The effects of sintering temperature and duration on the flexural strength and grain size of zirconia. Acta Biomater Odontol Scand 2015;1:43–50. https://doi.org/10.3109/23337931.2015.1068126, PMID:28642900

[31] Muñoz EM, Longhini D, Antonio SG, Adabo GL. The effects of mechanical and hydrothermal aging on microstructure and biaxial flexural strength of an anterior and a posterior monolithic zirconia. J Dent 2017;63:94–102. https://doi.org/10.1016/j.jdent.2017.05.021, PMID:28591620

[32] Camposilvan E, Leone R, Gremillard L, Sorrentino R, Zarone F, Ferrari M, et al. Aging resistance, mechanical properties and translucency of different yttria-stabilized zirconia ceramics for monolithic dental crown applications. Dent Mater 2018;34:879–90. https://doi.org/10.1016/j.dental.2018.03.006, PMID:29598882

[33] Inokoshi M, Shimizu H, Nozaki K, Takagaki T, Yoshihara K, Nagaoka N, et al. Crystallographic and morphological analysis of sandblasted highly translucent dental zirconia. Dent Mater 2018;34:508–18. https://doi.org/10.1016/j.dental.2017.12.008, PMID:29325861

[34] Juntavee N, Attashu S. Effect of different sintering process on flexural strength of translucency monolithic zirconia. J Clin Exp Dent 2018;10:e821–30. https://doi.org/10.4317/jced.54749, PMID:30305883

[35] Alshamrani AA, De Souza GM. Effect of ionizing radiation on mechanical properties and translucency of monolithic zirconia. J Biomed Mater Res 2019:1–9. https://doi.org/10.1002/jbm.b.34458, PMID:31410974

[36] Zhang F, Reveron H, Spies BC, Van Meerbeek B, Chevalier J. Trade-off between fracture resistance and translucency of zirconia and lithium-disilicate glass ceramics for monolithic restorations. Acta Biomater 2019;91:24–34. https://doi.org/10.1016/j.actbio.2019.04.043, PMID:31034947