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Translucency of chairside monolithic zirconias using different sintering ovens: An *in vitro* investigation

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A R T I C L E I N F O

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A B S T R A C T

Objective: To evaluate the translucency of several monolithic zirconias (MZ) processed in various sintering ovens designed for single-visit, chairside use.
Methods: Discs ($n = 40$) from zirconia blocks were fabricated for each MZ at manufacturer-recommended minimal thicknesses, as provided in each material's instructions for use: IPS e.max ZirCAD LT (ZLT); CEREC Zirconia+ (CZ+); 3M Chairside (3M); KATANA Zirconia (KT). Groups ($n = 10$) were sintered following manufacturer instructions for each oven: CEREC SpeedFire, Ivoclar CS4, Ivoclar CS6, and Ivoclar S2 (laboratory furnace control). Specimens were highly polished on one side and glazed on the other. Each side was measured with a spectrophotometer against white and black backgrounds to determine translucency parameter (TP) and contrast ratio (CR) values. Results for TP and CR for each material and oven combination were compared with a linear mixed model. Oven precision was evaluated using the Kruskall-Wallis test.
Results: Glazed specimens were more translucent than polished ones ($p < 0.001$). ZLT and CZ+ were more translucent than 3M and KT regardless of the sintering oven ($p < 0.01$). Several oven/material combinations reached or exceeded the S2 oven TP: CS4 with CZ+ and 3M; CS6 with ZLT and KT ($p < 0.01$). SpeedFire was significantly less precise ($p < 0.05$) and produced lower TP values for ZLT, CZ+, and KT ($p < 0.01$). Results for TP and CR were highly correlated.
Conclusions: MZ surface finish, material thickness, and oven used all had a significant effect on translucency. Some chairside-oriented solutions produced results with translucency equal to conventionally processed zirconia.
Clinical significance: The translucency of a ceramic restoration is an important factor in determining its esthetics. Clinicians desiring the most esthetic outcomes with monolithic zirconia should be aware of the significant effects that surface finishing, material thickness, and the sintering oven used can have on restoration translucency.

1. Introduction

The robust development of digital technologies and newer restorative materials have significantly shifted clinical practices over the last 15 years [1]. The excellent esthetic and mechanical properties of lithium disilicate and monolithic zirconia (MZ) have made them increasingly popular for clinicians who wish to provide their patients with minimally invasive, metal-free restorations [2]. Since its introduction into the market in 2009, the use of MZ for indirect restorations has rapidly increased. Trends in laboratory production [1] and clinician preferences [3] indicate that most indirect restorations today are conventionally cemented MZ crowns. These restorations are made via computer-aided design/computer-aided manufacturing (CAD/CAM), typically milled in a pre-sintered state and then sintered in a furnace.

Laboratory survey data indicates that technical complications such as chipping and fracturing are exceedingly low for 3 mol % yttria tetragonal polygon zirconia (3Y-TZP) over up to 7.5 years [4]. 5-year clinical data confirms this, with biological complications and de-cementations the primary reasons for failure [5,6]. *In vitro* data [7] and results from recent prospective clinical trials [5,6] indicate that 3Y-TZP crowns have sufficient resistance to fracture at a minimum thickness of 0.5 mm – 0.7 mm. One of the drawbacks of 3Y-TZP is its lack of translucency, making it less esthetic than glass ceramics for crown restorations [2,8,9].

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Restoration esthetics are often evaluated in terms of value, hue, and chroma [10]. Value, which is the perceived brightness of the restoration, has long been recognized as the most important for matching the esthetics of surrounding teeth [10]. The translucency/opacity of a restoration is a primary determinant of its value [11]. The relative translucency of dental materials is generally quantified using either translucency parameter (TP) or contrast ratio (CR) [12]. While TP and CR measure different things, they have a strong inverse correlation for esthetic restorations [13,14], though CR loses sensitivity as material opacity increases [15]. Previous studies have established human perceptibility thresholds for these values, specifically ΔTP >1.33 for translucency parameter (CIELAB) [16] and a range of ΔCR >0.04 (experienced dental faculty threshold) - ΔCR >0.09 (dental student threshold) for contrast ratio [17]. For ceramic materials, translucency decreases as material thickness increases [18,19]

Manufacturers have improved MZ esthetic properties in recent years with increasing yttria content and the amount of cuboidal phase of zirconia contained in the material [9]. The use of 4 mol % yttria partially stabilized zirconia (4Y-PSZ) or 5 mol % yttria partially stabilized zirconia (5Y-PSZ) requires more material thickness than 3Y-TZP to resist fracture [7,20]. As yttria content increases and less tetragonal phase of zirconia is present, MZ loses strength and fracture toughness [21]. 5Y-PSZ has been documented to have a similar fracture toughness to lithium disilicate while being significantly less translucent and potentially less mechanically reliable [8]. No five-year prospective clinical data is currently available for 4Y- and 5Y-PSZ restorations. Laboratory data indicates they might require a minimal thickness of at least 1.2 mm [7,20], while a recent review [21] suggests a minimum thickness of at least 1.5 mm for 5Y-PSZ.

Previous investigations have shown the resultant translucency of MZ to be dependent on various factors, including differences in material composition [18,22–32], material thickness [18,25,26,28–34], surface finishing [28–31] and sintering protocols [24,25,27,35–37]. In recent years, several manufacturers have brought "chairside" zirconias to market, allowing for the delivery of an MZ crown in a single visit. Conventional laboratory processing of MZ includes long sintering times that exceed a reasonable amount of time for a patient to wait for the restoration to be fabricated. To overcome this, sintering furnaces have been developed with "speed" sintering options, drastically reducing the time needed to process an MZ restoration. The purpose of this investigation was to compare the translucency of several chairside-oriented MZs, both glazed and polished at recommended manufacturer minimum thicknesses, sintered in various sintering ovens. The null hypothesis was that differences in finishing method, material thickness, and sintering oven used would have no effect on the translucency of the zirconia specimens.

2. Materials and methods

The zirconias, manufacturer-recommended minimal thicknesses, sintering furnaces used, and sintering times were listed in Table 1. The needed minimum sample size of seven per group was determined via an a priori power analysis of a previous study [18] using a computer program (G*Power v. 3.1.9.6; Heinrich Heine Universität, Düsseldorf, Germany). For calculating the effect size, the perceived threshold for a ΔTP > 1.33 [16] was considered to be a minimal detectable difference. A sample size of ten per group was chosen to accommodate for any possible complications during specimen processing and evaluation.

2.1. Preparation of zirconia discs

For each MZ, shade A2 chairside CAD/CAM blocks were first milled into 14 mm diameter cylinders (PrograMill PM7; Ivoclar, Schaan, Lichtenstein). Cylinders were then sliced into 1.6 mm thick discs using an Isomet 1000 (Buehler, Lake Bluff, Illinois). Discs were polished with 800-grit sandpaper and assigned to one of the four furnace groups, ten per group, using block randomization and an online calculator (https://www.randomizer.org/).

For each MZ group and furnace tested, manufacturer-provided sintering programs from the included instructions for use were used. Following sintering, specimens were polished with water cooling with 320-, 400-, 600- and 1,2000-grit sandpaper down to manufacturer-recommended minimal thicknesses, verified to an accuracy of 0.02 mm by five digital caliper (Mitutoyo-500-171-30; Mitutoyo, Sakado, Japan) measurements at different places on each disc. One side of each disc was glazed with the same glaze paste (Ivocolor; Ivoclar) and fired following manufacturer instructions for use.

2.2. Translucency parameter and contrast ratio measurement

Specimens were measured using a calibrated, dual-beam spectrophotometer (UltraScan VIS; HunterLab, Reston, Virginia) with a spectral range of 360 mm–780 nm and a wavelength resolution of < 2 nm. Measurements were made in reflectance mode against white and black backgrounds, all in the same physical location, under identical conditions with respect to ambient temperature, relative humidity, ambient lighting, and air pressure. Specimens were measured with three flashes per measurement and five measurements per specimen to calculate an

Table 1
Materials, Ovens and sintering times.

Zirconia	Manufacturer	Composition[a]	Oven[b]	Sintering Times[c]	Minimal thickness[d]
ZirCAD LT (ZLT)	Ivoclar	3 mol % yttria	S2	09:50:00	0.6
		100 % tetragonal	CS4	00:28:00	0.6
			CS6	00:23:00	0.6
			SF	00:28:30	0.6
CEREC Zirconia+ (CZ+)	Dentsply Sirona	Unknown	S2	01:41:00	0.7
			CS4	01:08:00	0.7
			CS6	01:05:30	0.7
			SF	00:21:58	0.7
3M Chairside (3M)	3M	4 mol % yttria	S2	05:19:00	0.8
		75 % tetragonal	CS4	00:38:00	0.8
			CS6	00:39:30	0.8
			SF	00:14:13	0.8
KATANA Zirconia Block (KT)	Kuraray Noritake	4.8 mol % yttria	S2	07:15:00	1.0
		30-40 % tetragonal	CS4	01:36:00	1.0
			CS6	00:42:30	1.0
			SF	00:18:39	1.0

[a] mol % yttria content / % tetragonal phase content by wt.
[b] CEREC SpeedFire (SF), Ivoclar CS4 (CS4), Ivoclar CS6 (CS6), Ivoclar S2 (S2).
[c] Hours:Minutes:Seconds.
[d] millimeters.

average value for each specimen.

2.3. Outcome variables

TP measurements were calculated using the CIE $L^*a^*b^*$ values (for easier comparison with previous studies) with the following equation:

$$TP_{ab} = \left[(L*B - L*W)^2 + (a*B - as*W)^2 + (b*B - b*W)^2\right]^{1/2}$$

The contrast Ratio (CR) was also calculated using the equation:

$$CR = Y^b / Y^w$$

S2 oven samples were then progressively polished on the polished side to a uniform thickness of 0.5 mm, re-verified by digital caliper measurements, and remeasured for TP and CR on both glazed and polished surfaces.

The TP and CR values were input in an MS Excel sheet grouped by MZ materials, ovens, and thickness groups (IFU and 0.5 mm). Besides highlighting the significant difference, whether the two groups' absolute difference was over the perceptibility threshold was labeled in MS Excel. According to previous studies, the $\Delta TP > 1.33$ [16] and $\Delta CR > 0.04$ [17] were chosen for the threshold. The individual specimens deviated from their respective group averages more than the thresholds were counted for each group.

2.4. Statistics

All statistical analyses were performed in SPSS (version 28, IBM Corp. U.S.). The effect of glaze on the TP and CR values was evaluated by a linear mixed model. The linear mixed model assumes the normality of the Pearson residual created by the model, which was checked by visual inspection of the residual Q-Q plot. Furthermore, the Kolmogorov-Smirnov test indicated no deviation (p=0.200) from the normality of the residuals in either 0.5 mm or manufacturer recommended thickness (IFU) data sets. The homogeneity and homoscedasticity of the residuals were checked by plotting them against the predicted values and predictors.

In the 0.5 mm thick experiment, the material, surface treatment, and their interaction were the main fixed factors. For the manufacturer recommended thickness groups, the material, oven, surface treatment, and their interaction were the main fixed factors. Due to the significant interaction, pairwise comparisons between polished and glazed surfaces were made for each material and oven separately.

The difference between polished and glazed surfaces was uniform regardless of the oven, thickness, and materials. Therefore, further analyses of the manufacturer's recommended thickness groups were simplified by evaluating only the polished surfaces. A linear mixed model was used to compare TP and CR between materials within an oven and between ovens within a material. The effect of thickness and firing time on the TP and CR were evaluated by multiple linear regression. The time was converted to a logarithm scale.

Finally, the precision (reproducibility) of the oven was estimated by the mean absolute deviation (MAD). The MAD was calculated by deducing the actual TP or CR value from their respective group mean. The MAD of ovens was compared statistically by the Kruskall-Wallis test. The percentage of outliers (cases higher than $\Delta TP > 1.33$ values within a group) in ovens was statistically compared by the Chi-square test.

3. Results

3.1. Effect of surface treatment on TP and CR with standard 0.5mm thickness in the S2 oven

The glazed surface had significantly higher TP ($p < 0.001$) and lower CR ($p < 0.001$) than the polished one in all materials (Table 2). For each material, the differences in TP and CR were perceptible to the human eye.

3.2. Effect of surface treatment on TP and CR with manufacturer recommended minimal thickness in various ovens

The glazed surface had significantly higher TP ($p < 0.001$) and lower CR ($p < 0.001$) than the polished surface in all materials (Table 3). All TP differences were perceptible for each material. However, some CR differences were not visible.

3.3. Difference between polished materials (0.5 mm thickness) in S2 oven

The transparency (in terms of TP and CR) of KT was significantly higher than ZLT ($p < 0.001$), 3M ($p < 0.001$), and CZ+ ($p < 0.001$). All differences were higher than the perceptibility threshold. There were no significant differences between ZLT, 3M, and CZ+.

3.4. Difference between polished materials at manufacturer recommended thickness

The TPs of ZLT and CZ+ were the highest and not significantly different in SF, CS6, and S2 ovens, except in CS4, where the CZ+ was significantly higher than ZLT (Table 4 and Fig. 1A.). The 3M and the KT had significantly lower TP than the ZLT and CZ+. The TP of 3M was significantly higher than KT in SF and CS4 but not in CS6 and S2.

The statistical differences between materials for CR were identical to TP in SF (Table 4 and Fig. 1B). However, in the other ovens, there were slight differences.

Table 2
The contrast ratio (CR) and translucency parameter (TP) of four 0.5mm thick material specimens with two surface treatments after sintering in an Ivoclar S2 oven.

		Surface treatment								
		Polished			Glaze			difference		
	Material	N	Mean	SD	N	Mean	SD	in mean	p values	PD
TP	ZLT	10	22.4	0.95	10	24.6	0.51	2.19	0.001	&
	3M	10	21.7	1.81	10	24.9	0.84	3.25	0.001	&
	CZ+	10	22.1	1.56	10	24.9	0.59	2.75	0.001	&
	KT	10	25.3	0.84	10	28.7	0.50	3.45	0.001	&
CR	ZLT	10	0.54	0.017	10	0.50	0.010	-0.04	0.001	#
	3M	10	0.55	0.034	10	0.48	0.017	-0.06	0.001	#
	CZ+	10	0.54	0.030	10	0.49	0.013	-0.05	0.001	#
	KT	10	0.48	0.019	10	0.41	0.019	-0.06	0.001	#

SD, standard deviation.
PD, the perceived difference between glaze and polished, & > 1.33 TP, # > 0.04 CR.
ZLT: IPS e.max ZirCAD LT; 3M: 3M Chairside; CZ+: CEREC Zirconia+; KT: KATANA Zirconia.

Table 3
Descriptive statistics of TP and CR of four materials sintered in four ovens and the effect of surface treatment.

Surface treatment:			polished			glaze			difference in		
	Material	Oven	N	Mean	SD	N	Mean	SD	glaze-polished	p-value	PD
TP	ZLT	SF	10	18.4	2.25	10	20.0	2.67	1.6	0.000	&
		CS4	10	20.0	0.95	10	22.5	0.90	2.5	0.000	&
		CS6	10	22.1	0.77	10	23.7	0.83	1.6	0.000	&
		S2	9	22.2	0.94	10	24.8	0.52	2.6	0.000	&
	3M	SF	10	16.2	1.05	10	17.9	0.68	1.8	0.000	&
		CS4	10	18.3	0.74	10	20.4	0.66	2.1	0.000	&
		CS6	10	15.3	0.80	10	16.9	0.69	1.6	0.000	&
		S2	10	16.9	0.39	10	18.8	0.29	1.9	0.000	&
	CZ+	SF	10	17.7	1.21	10	20.5	0.91	2.8	0.000	&
		CS4	10	21.9	0.43	10	24.2	0.71	2.3	0.000	&
		CS6	10	21.7	1.28	10	23.7	1.23	2.0	0.000	&
		S2	10	22.8	0.68	10	26.0	1.07	3.2	0.000	&
	KT	SF	10	13.2	1.28	10	16.5	1.11	3.3	0.000	&
		CS4	10	16.1	0.92	10	18.6	0.69	2.4	0.000	&
		CS6	10	17.2	1.02	10	19.0	0.51	1.8	0.000	&
		S2	10	17.7	0.67	10	20.6	0.50	2.9	0.000	&
CR	ZLT	SF	10	0.65	0.049	10	0.62	0.055	-0.033	0.000	
		CS4	10	0.62	0.019	10	0.57	0.021	-0.048	0.000	#
		CS6	10	0.55	0.016	10	0.52	0.014	-0.028	0.001	
		S2	9	0.55	0.022	10	0.50	0.012	-0.050	0.000	#
	3M	SF	10	0.69	0.019	10	0.65	0.012	-0.040	0.000	#
		CS4	10	0.63	0.016	10	0.59	0.015	-0.043	0.000	#
		CS6	10	0.71	0.017	10	0.67	0.015	-0.038	0.000	
		S2	10	0.66	0.008	10	0.61	0.005	-0.045	0.000	#
	CZ+	SF	10	0.64	0.026	10	0.58	0.022	-0.055	0.000	#
		CS4	10	0.59	0.011	10	0.54	0.014	-0.049	0.000	#
		CS6	10	0.58	0.013	10	0.54	0.013	-0.048	0.000	#
		S2	10	0.57	0.010	10	0.52	0.007	-0.051	0.000	#
	KT	SF	10	0.73	0.024	10	0.67	0.027	-0.067	0.000	#
		CS4	10	0.68	0.025	10	0.64	0.022	-0.047	0.000	#
		CS6	10	0.66	0.032	10	0.62	0.017	-0.045	0.000	#
		S2	10	0.63	0.021	10	0.57	0.016	-0.061	0.000	#

SD, standard deviation.
PD, the perceived difference between glaze and polished, & > 1.33 TP, # > 0.04 CR.
ZLT: IPS e.max ZirCAD LT; 3M: 3M Chairside; CZ+: CEREC Zirconia+; KT: KATANA Zirconia.
SF: CEREC SpeedFire, CS4: Ivoclar CS4, CS6: Ivoclar CS6, S2: Ivoclar S2.

Table 4
Differences between polished materials (IFU thickness) in TP and CR.

		TP			CR		
		estimated difference	p-value	PD	estimated difference	p-value	PD
SF	3M - CZ+	-1.57	0.000	&	0.050	0.000	#
	3M - KT	2.97	0.000	&	-0.045	0.000	#
	3M - ZLT	-2.23	0.000	&	0.037	0.001	
	CZ+ - KT	4.54	0.000	&	-0.095	0.000	#
	CZ+ - ZLT	-0.67	0.202		-0.013	0.209	
	KT - ZLT	-5.20	0.000	&	0.082	0.000	#
CS4	3M - CZ+	-3.58	0.000	&	0.044	0.000	#
	3M - KT	2.20	0.000	&	-0.054	0.000	#
	3M - ZLT	-1.71	0.001	&	0.011	0.260	
	CZ+ - KT	5.78	0.000	&	-0.098	0.000	#
	CZ+ - ZLT	1.87	0.001	&	-0.033	0.004	
	KT - ZLT	-3.91	0.000	&	0.065	0.000	#
CS6	3M - CZ+	-6.43	0.000	&	0.125	0.000	#
	3M - KT	-1.88	0.000	&	0.045	0.000	#
	3M - ZLT	-6.79	0.000	&	0.157	0.000	
	CZ+ - KT	4.55	0.000	&	-0.080	0.000	#
	CZ+ - ZLT	-0.36	0.486		0.032	0.003	
	KT - ZLT	-4.91	0.000	&	0.112	0.000	#
S2	3M - CZ+	-5.90	0.000	&	0.081	0.000	#
	3M - KT	-0.79	0.054		0.026	0.008	
	3M - ZLT	-5.31	0.000	&	0.107	0.000	#
	CZ+ - KT	5.11	0.000	&	-0.056	0.000	#
	CZ+ - ZLT	0.59	0.273		0.026	0.018	
	KT - ZLT	-4.52	0.000	&	0.081	0.000	#

SD, standard deviation.
PD, the perceived difference between glaze and polished, & > 1.33 TP, # > 0.04 CR.
SF: CEREC SpeedFire, CS4: Ivoclar CS4, CS6: Ivoclar CS6, S2: Ivoclar S2.
ZLT: IPS e.max ZirCAD LT; 3M: 3M Chairside; CZ+: CEREC Zirconia+; KT: KATANA Zirconia.

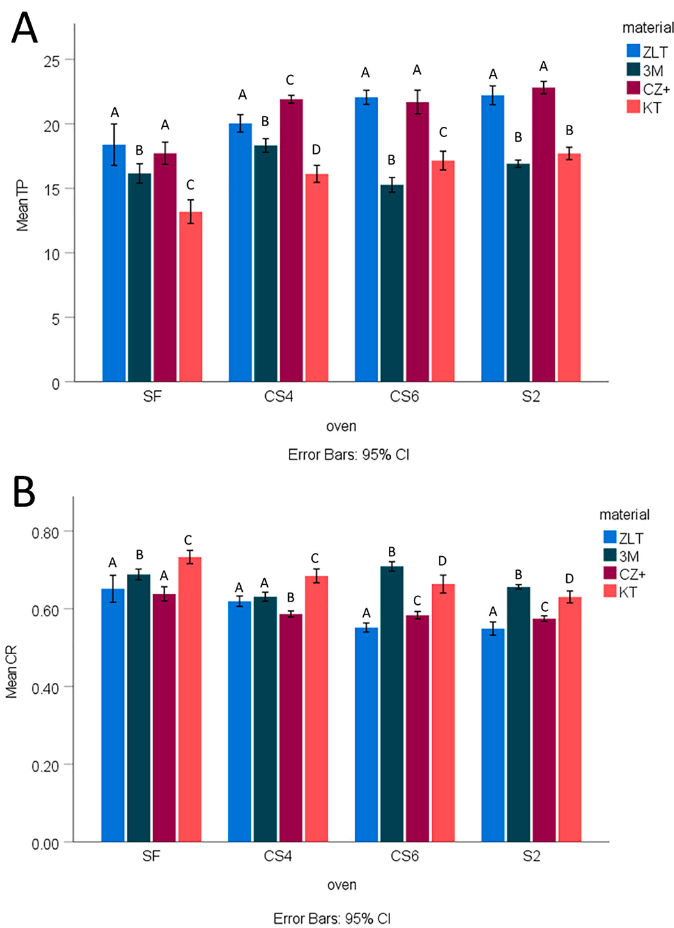

Fig. 1. The comparison of the translucency parameter (A, TP) and contrast ratio (B, CR) between materials (IFU thickness) grouped by oven. The different capital letters indicate a significant difference between materials in an oven. ZLT: IPS e.max ZirCAD LT; CZ+: CEREC Zirconia+; 3M: 3M Chairside; KT: KATANA Zirconia. SF: CEREC SpeedFire; CS4: Ivoclar CS4; CS6: Ivoclar CS6; S2: Ivoclar S2.

The mean TP and CR differences reached the perceptibility threshold in two-thirds of the pairwise comparisons (Table 4).

3.5. *Effect of the oven on the TP and CR for polished materials*

The significant interaction ($p < 0.001$) between the material and oven indicated that the TP and CR differences between ovens varied depending on the material (Table 5, Fig 2).

The ascending order of TP for ZLT and KT was SF<CS4<CS6=S2 (Fig. 2A). For CZ+, the order was SF<CS4=CS6<S2. For 3M, the rank was somewhat different: CS6<SF<S2<CS4. The CR order (but descending) was statistically identical for ZLT and 3M (Fig. 2B) and slightly varied for CZ+ and KT. The significant differences between ovens were visible, except for two comparisons for 3M and one for KT.

3.6. *Effect of sintering time and material thickness on the TP and CR values*

Multiple regression analysis revealed a significant moderate positive correlation (partial r = 0.41, $p < 0.001$) between log(time) and TP and a significantly strong negative correlation (partial r = -0.73, $p < 0.001$) between thickness and TP. Based on the r-squared values, the thickness is responsible for 53 % and time for 17 % of the resultant TP.

3.7. *Oven precision (MAD of TP)*

The ascending order (representing the precision) of MAD was S2 (0.47, 0.16-78), CS4 (0.49, 0.33-0.82), CS6 (0.60, 0.32-0.90), SF (0.67, 0.44-1.74) (Fig. 3.). The MAD of SF was significantly higher than the S2 ($p < 0.01$) and CS4 ($p < 0.05$). When considering the perceptibility threshold of Δ TP 1.33, the number of outliers was significantly higher ($p < 0.05$) in SF (35 %) than in S2 (5.1 %), CS4 (7.5 %), and CS6 (15 %).

Table 5
Effect of ovens on TP and CR of zirconia with IFU thickness.

		TP			CR		
		estimated difference	p-value	PD	estimated difference	p-value	PD
ZLT	CS4 - S2	-2.18	0.003	&	0.07	0.000	#
	CS4 - CS6	-2.02	0.004	&	0.07	0.000	#
	CS4 - SF	1.65	0.017	&	-0.03	0.035	
	S2 - CS6	0.16	0.800		0.00	0.836	
	S2 - SF	3.84	0.000	&	-0.10	0.000	#
	CS6 - SF	3.67	0.000	&	-0.10	0.000	#
3M	CS4 - S2	1.41	0.000	&	-0.03	0.001	
	CS4 - CS6	3.05	0.000	&	-0.08	0.000	#
	CS4 - SF	2.17	0.000	&	-0.06	0.000	#
	S2 - CS6	1.64	0.000	&	-0.05	0.000	#
	S2 - SF	0.76	0.030		-0.03	0.000	
	CS6 - SF	-0.88	0.024		0.02	0.003	
CZ+	CS4 - S2	-0.91	0.096		0.01	0.353	
	CS4 - CS6	0.21	0.647		0.00	0.680	
	CS4 - SF	4.19	0.000	&	-0.05	0.000	#
	S2 - CS6	1.12	0.046		-0.01	0.496	
	S2 - SF	5.09	0.000	&	-0.06	0.000	#
	CS6 - SF	3.98	0.000	&	-0.05	0.000	#
KT	CS4 - S2	-1.58	0.001	&	0.05	0.000	#
	CS4 - CS6	-1.03	0.035		0.02	0.066	#
	CS4 - SF	2.94	0.000	&	-0.05	0.000	#
	S2 - CS6	0.55	0.198		-0.03	0.007	
	S2 - SF	4.52	0.000	&	-0.10	0.000	#
	CS6 - SF	3.97	0.000	&	-0.07	0.000	#

SD, standard deviation.
PD, the perceived difference between glaze and polished, & > 1.33 TP, # > 0.04 CR.
SF: CEREC SpeedFire, CS4: Ivoclar CS4, CS6: Ivoclar CS6, S2: Ivoclar S2.
ZLT: IPS e.max ZirCAD LT; 3M: 3M Chairside; CZ+: CEREC Zirconia+; KT: KATANA Zirconia.

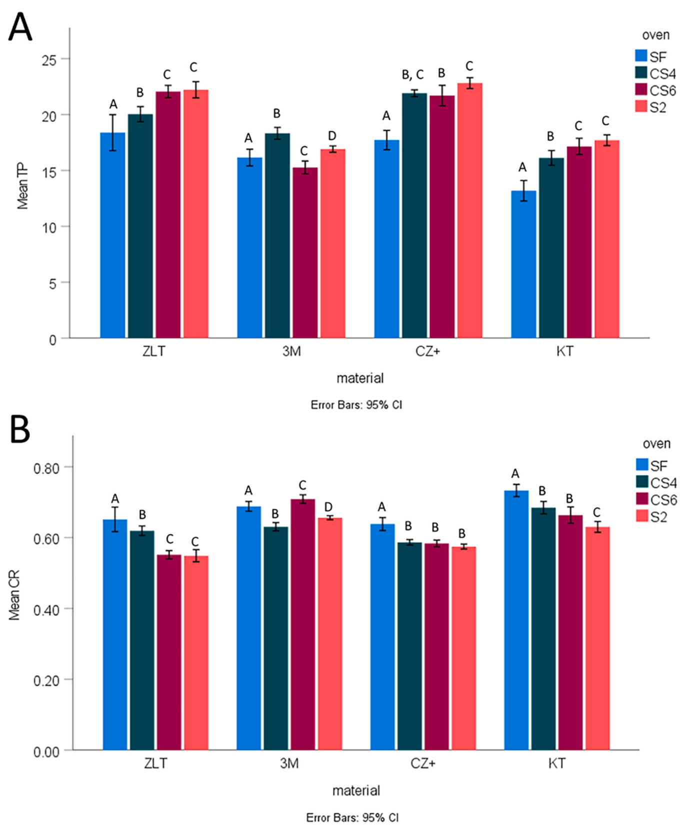

Fig. 2. The comparison of the translucency parameter (A, TP) and contrast ratio (B, CR) between ovens grouped by materials (IFU thickness). The different capital letters indicate a significant difference between ovens within the particular material group. ZLT: IPS e.max ZirCAD LT; CZ+: CEREC Zirconia+; 3M: 3M Chairside; KT: KATANA Zirconia. SF: CEREC SpeedFire; CS4: Ivoclar CS4; CS6: Ivoclar CS6; S2: Ivoclar S2.

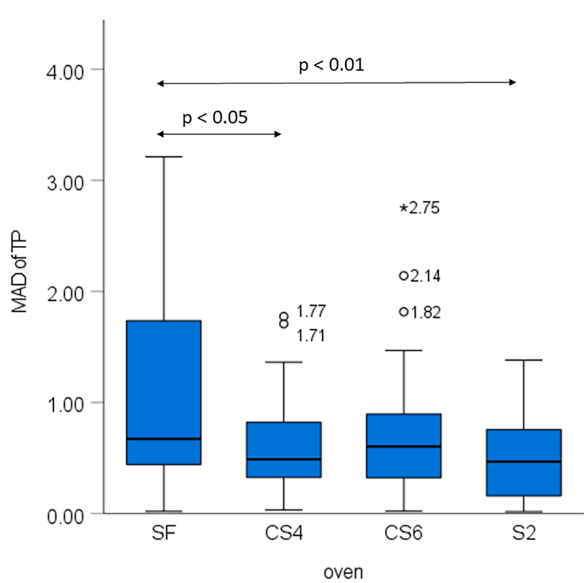

Fig. 3. The box and whiskers plot of the mean absolute deviation (MAD) of the transparency parameter (TP) of the zirconia pucks sintered in SpeedFire (SF), CS4, CS6, or S2 ovens. The MAD of SF was significantly higher than the S2 ($p < 0.01$) and CS4 ($p < 0.05$). The circles and asterisk with actual TP values indicate outliers.

4. Discussion

The null hypothesis was rejected, as specimen translucency was significantly affected by each of the variables of finishing method, material thickness, and sintering oven used.

Glazed specimens were significantly more translucent than polished specimens for all zirconias, regardless of specimen thickness or oven used. According to perceptibility thresholds established for ΔTP, many of these differences are visible to the human eye (ΔTP >1.3). This could be clinically problematic, given a recent study showing a perceptible change in MZ with five years of simulated tooth brushing [38]. A visible loss of translucency for MZ restorations could be reminiscent of older porcelain-fused-to-metal restorations, becoming opaque with time as surface characterization wears off. This potential for esthetic degradation via glaze layer wear does not appear to affect monolithic glass ceramic restorations in the same way [38]. It is quite possible that the glaze layer's effect on restoration translucency and how resistant it is to wear is dependent on the glaze and MZ composition. To this point, the results of this study are in opposition to those of two others that used a different brand of glaze. One of those studies found the glaze layer to not affect TP of the MZ tested [28], while another found glazing to decrease translucency [29]. Meanwhile, another investigation showed that the effects of the same glaze on TP vary depending on the brand and thickness of zirconia specimens [30].

At an equal thickness of 0.5 mm, KT was significantly more translucent than the other groups. This is to be expected, given KT's yttria content and amount of cuboidal phase make it close to being a 5Y-PSZ [39], while the rest are 3Y-TZP and 4Y-PSZ. There was no significant difference in TP or CR between CZ+, ZLT, and 3M at 0.5 mm. Yet at varying thicknesses based on manufacturer recommended minimums, significant differences between all groups were found, with KT and 3M having the lowest TP values. ZLT and CZ+ had the highest translucency values regardless of the sintering oven used. This indicates that material thickness plays a larger role in determining the translucency of an MZ restoration than the material composition. A multiple regression analysis of the data showed a strong negative correlation between thickness and translucency. Several other investigations have found zirconia thickness to significantly affect translucency [18,25,26,28–34]. This factor is important for clinicians to note when patient circumstances allow for minimal crown preparation. Further reduction of tooth structure to facilitate the use of a "more esthetic" MZ does not actually provide an improvement in restoration translucency and might result in a restoration that is less translucent.

Sintering time was also moderately correlated with outcome. The SF oven had the fastest sintering times, lowest TP values, and highest CR values for each material. For ZLT, CZ+, and KT, the S2 oven had the longest sintering times and the highest TP values. Several other investigations have documented similar trends, with longer sintering times resulting in more translucent outcomes [24,25,27,37]. However, several MZ/furnace combinations in this study broke this trend. Speed sintering in the CS6 furnace produced specimens equal to the S2 controls in terms of TP for ZLT and KT. Meanwhile, for 3M, the highest TP values were produced by speed sintering in the CS4 oven, exceeding the S2 control group. In contrast, other studies have found speed sintering to increase translucency [35,36]. The heterogeneity presented by the current study along with other available literature, reflects the inherent difficulties for clinicians when choosing a particular brand of furnace and MZ. Differences in furnace technology, sintering times, and MZ brand and composition can all have a significant influence on translucency outcomes.

The mean absolute deviation of TP of the SF furnace was significantly more than the S2 and CS4 ovens. When considering outliers at the perceptibility threshold of ΔTP >1.3, it produced significantly more outliers than the S2, CS4, and CS6. This indicates that the precision of SF was significantly lower than that of the other furnaces. TP values for ZLT in the SF furnace had a high enough standard deviation to indicate a perceptible difference between specimens was possible. Furthermore, the mean ΔTP and ΔCR values between SF and the CS6 and S2 ovens for ZLT indicate that differences would be detectable to the human eye as well. Findings were similar for CZ+ and KT, except that SF was also visibly less translucent than the CS4. Results for 3M were different from the rest, with no detectable differences for SF in TP compared to other furnaces, except that it was visibly less translucent when compared to the CS4. These noticeable differences in translucency could have a significant impact on a clinician's ability to predictably match a patient's surrounding dentition. Given the already relatively opaque nature of MZ and the difficulties in producing an esthetically pleasing restoration, furnaces producing noticeably less translucent restorations would only increase these difficulties.

Previous studies have established a strong inverse correlation between TP and CR [13,14]. The current investigation also found this to be the case, though there were exceptions. With regards to material outcomes, there were no differences between TP and CR outcomes in oven rankings for ZLT and 3M. For CZ+ and KT, there were differences, but the SF was still significantly worse than the other furnaces. When grouped by oven, TP vs. CR outcomes by material generally correlated with slight differences except for SF, which had the same ranking for both TP and CR. The threshold of perceptibility established by TP and CR also produced generally congruent outcomes, with exceptions. Perceptible differences identified by a ΔTP >1.3 or ΔCR > 0.04 are generally correlated, with minor differences depending on the material, surface treatment, and oven. As previously mentioned, factors affecting human eye perception are numerous, including many factors separate from restoration translucency. Thus, while ΔTP and ΔCR values might indicate possible perceptible differences between specimens/groups, it is impossible to say with absolute certainty how impactful these differences are on clinical outcomes.

In addition to the uncertainty of correlating ΔTP and/or ΔCR values with clinical relevance, there are several other limitations to this *in vitro* study. While specimen size was estimated to approximate that of a single unit crown restoration and set to manufacturer recommended minimal thickness, the shape, size, and geometry of actual crown restorations might have a significant effect on perceived or actual restoration translucency. As noted above, only one particular glaze was used in the study, which means results might not apply to different stain/glaze systems. Along these lines, the results are also only applicable to the MZ and furnaces tested and might not reflect results obtainable with other systems. It is impossible for one laboratory study to replicate all of the possible armamentarium-related factors that can affect restoration esthetics clinically, such as stump shade, cement, and surface texture, not to mention the numerous environment-related and observer-related factors, such as the influence of the surrounding dentition, ambient lighting intensity and color, and the perceptive capabilities of the observer. Thus, caution must be exercised in setting clinical expectations based on the results of this one *in vitro* study. Given the large number of MZ brands and furnaces available today, with new additions and technologies being added all the time, further research is indicated to evaluate how these systems function and interact with all of these different variables in order to set appropriate expectations for clinicians with respect to restoration esthetics.

5. Conclusions

Within the limitations of this study, MZ thickness was the strongest determinant of resultant translucency. The furnace and sintering cycle used, and the surface finish also had a significant effect on translucency. The combination of these variables could result in perceptible differences in translucency. For minimal thickness crown preparations, further reduction of tooth structure to use more translucent zirconia does not lead to an improvement in translucency. Several chairside-oriented MZ/furnace combinations had translucency outcomes equal to the laboratory furnace control.

CRediT authorship contribution statement

Clinton D. Stevens: Conceptualization, Investigation, Methodology, Validation, Writing – review & editing, Writing – original draft. **Walter G. Renné:** Conceptualization, Investigation, Supervision, Writing – review & editing. **János Vág:** Data curation, Formal analysis, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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