Clin Oral Invest (2012) 16:139–146
DOI 10.1007/s00784-010-0482-y

ORIGINAL ARTICLE

Micromechanical properties of veneer luting resins after curing through ceramics

Elif Öztürk · Reinhard Hickel · Şükran Bolay · Nicoleta Ilie

Received: 9 April 2010 / Accepted: 17 October 2010 / Published online: 6 November 2010

Abstract The aim of this study was to assess the performance of light-cured luting resin after curing under the ceramic restoration in comparison to dual-cured luting resin, by evaluating the micromechanical properties. Two hundred seventy thin luting composite films of ca. 170 μm in thickness were prepared by using two light-cured luting resins (Variolink Veneer, Ivoclar Vivadent; RelyX Veneer, 3M ESPE) and a dual-cured luting resin (Variolink II, Ivoclar Vivadent). The composites were cured by using a LED-unit (Bluephase®, Ivoclar Vivadent) with three different curing times (10, 20, and 30 s) under two ceramics (IPS e.max Press, Ivoclar Vivadent; IPS Empress® CAD, Ivoclar Vivadent) of different thicknesses (0, 0.75, and 2 mm). Forty-five groups were included, each containing six thin films. The samples were stored after curing for 24 h at 37°C by maintaining moisture conditions with distilled water. Micromechanical properties of the composites were measured with an automatic microhardness indenter (Fisherscope H100C, Germany). For each sample, ten indentations were made, thus totalizing 60 measurements per group. Micromechanical properties of the luting resins were statistically analyzed (SPSS 17.0). Significant differences were observed between the micromechanical properties of the luting resins ($p<0.05$). Variolink II showed the highest values in modulus of elasticity (E=11±0.5)* and Vickers hardness (HV=48.2±3.2)* and the lowest values in creep (Cr=4.3±0.1)* and elastic–plastic deformation (We/Wtot=38.6±0.7)* followed by RelyX Veneer (E=6.9±0.3, HV=33±2.5, Cr=4.6±0.2, We/Wtot=41.8±1.0)* and Variolink Veneer (E=4.4±0.4, HV=20.1±2.6, Cr=5±0.2, We/Wtot=43.7±1.3)*. Dual-cured luting resin expressed higher values in the micromechanical properties compared to the light-cured luting resins. The effect of luting resin type on the micromechanical properties of the luting resins was higher than the effect of curing time, ceramic type and ceramic thickness respectively (*The values of reference without ceramics for 30 s curing time).

Keywords Luting resins · Veneers · Micromechanical properties

E. Öztürk (✉) · Ş. Bolay
Faculty of Dentistry, Department of Conservative Dentistry,
Hacettepe University,
Sihhiye,
06100 Ankara, Turkey
e-mail: elifoz@hacettepe.edu.tr

Ş. Bolay
e-mail: sbolay@hacettepe.edu.tr

R. Hickel · N. Ilie
School of Dentistry, Department of Restorative Dentistry,
Ludwig-Maximilians-University,
Goethestrasse 70,
80336 Munich, Germany

R. Hickel
e-mail: hickel@dent.med.uni-muenchen.de

N. Ilie
e-mail: nilie@dent.med.uni-muenchen.de

Introduction

In the last few decades, patient demand for aesthetic restorations forced the manufacturers to develop new adhesive technologies and more resistant aesthetic materials [1]. Porcelain laminate veneer restorations are one of the most popular aesthetic treatment alternatives for anterior teeth [2]. A conservative preparation with a minimum of tooth reduction, a potential for excellent aesthetics, and maintenance of healthy tissues are the major advantages of porcelain laminate veneers [3]. The excellent aesthetic outcome of these restorations is a result of the fact that ceramics have a translucency similar to that of tooth structure [4]. However, there are some problems associated with porcelain laminate veneer restorations such as inadequate bonding and unpredictable final shade [5].

Improvements in dental ceramic systems have made porcelain laminate veneers a valuable clinical option. In recent years, new, high-strength ceramics, such as glass-infiltrated [6] and CAD/CAM-fabricated densely sintered high-purity alumina [7] ceramics and zircon ceramics, have become more common in restorative dentistry. On the other hand, silica-based ceramics, such as leucite-reinforced and lithium-disilicate glass ceramics, are frequently used for porcelain laminate veneers, inlays/onlays, and all-ceramic restorations because of their excellent aesthetic properties [8]. The use of ceramic materials has continuously increased due to their natural appearance, fluorescence, biocompatibility, durability, chemical stability, high compressive resistance as well as their thermal expansion being similar to tooth structure [9].

For the longevity of porcelain laminate veneer restorations a vital importance is attributed to the luting materials [10]. Generally, resin based adhesive composites are used for luting ceramic restorations [11]. These materials are classified according to their activation modes, which are chemical, photo or dual activation [12].

A number of medium-to-long term clinical studies have reported the clinical performance of porcelain laminate veneer restorations, as their aesthetic was excellent, patient satisfaction was high and no adverse effect on periodontal health was noted [13].

The majority of the clinical studies reported a low failure rate (0% to 7%) [14–16]. However, there were also few clinical studies reporting higher failure rates (14% to 33%) [17–20]. Peumans et al. observed in their clinical study a dramatic increase in the number of failures on the porcelain laminate veneers from 5 years (4%) to 10 years (34%) [21]. They claimed that shrinkage of the luting resin, as well as thermal and mechanical loading can cause failures in the porcelain veneer restorations. In addition, it has been reported that porcelain veneer failures may occur due to use of inappropriate luting agents [13].

The success of a ceramic veneer restoration is mainly based on a high bond strength between ceramic and luting resin and between luting resin and dental hard tissues [22]. In order to obtain high bond strength, an optimal curing of the luting agent is required [23]. Moreover, the degree of a polymerization of the luting resin affects the mechanical properties of the adhesive luting resins and thus the survival of the restoration [24]. To maintain an adequate polymerization of the material an adequate quantity of light is required [25]. Several in vitro studies quantified a considerable light attenuation promoted by ceramics [26–28]. Furthermore, the crystalline structure, the thickness, the opacity and the shade of the ceramics may play a role on the light attenuation to the luting resin under a ceramic restoration [29].

For cementation of porcelain veneers a light-curing luting resin is preferred by dentists due to their color stability when compared with dual-cured luting resins [30]. Nevertheless, it is important that there is enough light transmittance throughout the porcelain veneer to polymerize the light-cured luting resin. Therefore, the aim of this study was to evaluate whether light-cured luting resins perform as good as dual-cured luting resins, when polymerized through ceramics by measuring the micromechanical properties and by assessing the influence of parameters like composite type, curing time, ceramic type, and ceramic thickness.

Materials and methods

This study analyzed the influence of the following parameters on the curing quality of the luting resins.

- Curing time: 10, 20, and 30 s
- Ceramic type: lithium disilicate glass-ceramic and leucite reinforced glass-ceramic
- Ceramic thickness: none (control group), 0.75 and 2 mm
- Luting resin type: a dual and two different light curing luting resins

Two different ceramics were selected for this study: a lithium disilicate glass-ceramic (IPS e.max Press; Ivoclar Vivadent, Schaan, Liechtenstein) and a leucite reinforced glass-ceramic (IPS Empress®CAD; Ivoclar Vivadent, Schaan, Liechtenstein). Vita shade A1 of low translucency was selected for both of the ceramics. For the IPS e.max Press ceramic wax patterns of 0.75 mm and 2 mm in thickness and 10 mm in diameter were prepared, invested in Starvest®-SOFT-3 investment (Weber Dental, Stuttgart, Germany) and burnout in a furnace (Type CL-V2; Heraus Kulzer, Hanau, Germany) at the temperatures of 800°C for 60 min, 600°C for 30 min and 850°C for 60 min respectively. The investment and an ingot of IPS e.max Press were then transferred to the furnace (EP 500; IPS Empress, Ivoclar Vivadent, Schaan, Liechtenstein) and automatically pressed with program 16 (930°C, 60 min). Similar discs were prepared from the IPS Empress®CAD ceramic bloc by cutting with a low speed saw (Isomet® Low Speed Saw, Buehler®, IL, USA). All ceramic discs were then grinded with silicon carbide paper of grit 600 (Leco® VP 100, Leco Instrumente GmbH, Germany).

Two light-cured luting resins [Variolink Veneer (Ivoclar Vivadent, Schaan, Liechtenstein), RelyX Veneer (3M

ESPE, Seefeld, Germany)] and a dual-cured luting resin [Variolink II (Ivoclar Vivadent, Schaan, Liechtenstein)] of shade A1 were selected for this study. Descriptions of the luting resins and ceramics included in this study are summarized in Table 1.

The manufacturer suggests a curing time of 10–30 s in each section for Variolink Veneer luting resin and of 30 s for RelyX Veneer luting resin. Therefore, luting resin films were cured by using a LED-unit (Bluephase®, Ivoclar Vivadent, Schaan, Liechtenstein, 1200 mW/cm^2) with three different curing times of 10, 20, and 30 s. The combination of all parameters gives a total of 45 groups, each containing six thin luting-resin films of ca. 170 μm in thickness, thus totalizing 270 films. In order to avoid oxygen-inhibition during polymerization, mylar strips were positioned over the luting resins before curing procedure. The curing unit was directly centered on the sample surface to maintain the maximum energy of light onto the surface of measurement. The samples were stored after curing for 24 h at 37°C by maintaining moisture conditions with distilled water.

Vickers hardness (HV), modulus of elasticity (*E*), creep (Cr) and elastic–plastic deformation (We/Wtot) were evaluated by using an automatic micro hardness indenter (Fischerscope H100C, Fischer, Sindelfingen, Germany) according to DIN 50359-1:1997-10. For each sample ten indentation points were selected and 60 measurements were made per group. The test procedure was carried out force controlled. The test load increased and decreased with constant speed between 0.4 and 30 mN. The load and the penetration depth of the indenter were continuously measured during the load-unload-hysteresis.

The Universal hardness was defined as the test force divided by the apparent area of the indentation under the applied test force. From a multiplicity of measurements stored in a database supplied by the manufacturer, a conversion factor between Universal hardness and Vickers hardness was calculated and implemented into the software so that the measurement results were indicated in the more familiar Vickers hardness units (HV). The indentation modulus was calculated from the slope of the tangent of indentation depth-curve at maximum force and is comparable with the modulus of elasticity of the material (*E*). By measuring the change in indentation depth for 5 s with a constant test force of 30 mN, a relative change in the

Table 1 Materials used in this study

Brand name	Manufacturer	Composition	Filler loading	LOT number
Variolink II	Ivoclar Vivadent, Schaan, Liechtenstein	Dimethacrylates Inorganic fillers	73.4% weight[1] 46.7% volume[1]	K04678[1]
		Catalysts and stabilizers Pigments	77.2% weight[2] 52.0% volume[2]	K35373[2]
RelyX™ Veneer	3M ESPE, Seefeld, Germany	BisGMA TEGDMA		9ER
		Zirconia/silica and fumed silica	66% weight	
		Pigments	47% volume	
		Photoinitiator		
Variolink Veneer	Ivoclar Vivadent, Schaan, Liechtenstein	Dimethacrylates Inorganic filler	 60.1% weight	M13040
		Ytterbium Trifluoride		
		Catalysts and stabilizers	40% volume	
		Pigments		
IPS e.max Press	Ivoclar Vivadent, Schaan, Liechtenstein	SiO_2, Li_2O K_2O, P_2O_5		M13076
		ZrO_2, ZnO		
		Other oxides		
		Color oxides		
IPS Empress®CAD	Ivoclar Vivadent, Schaan, Liechtenstein	SiO_2 Al_2O_3		M02654
		K_2O, Na_2O		
		Other oxides		
		Pigments		

According to manufacturers' information

[1] Base

[2] Catalyst with high viscosity

indentation depth was calculated. This was a value for the creep of the materials (Cr). The total mechanical work (Wtot) was measured during the indentation procedure according to the formula $W = \int F dh$ (F = load; h = indentation depth). The plastic deformation work (Wp) and the work of the elastic reverse deformation (We), which are the two components of the mechanical work, were also measured. The elastic–plastic deformation (We/Wtot) was calculated as the percentage of Wtot represented by We.

Results were statistically analyzed using one-way ANOVA and Tukey HSD post hoc-test (SPSS 17.0) (α= 0.05) as well as a multivariate analysis (general linear model) to test the influence of luting resin type, filler loading (percent volume and percent weight), curing time, ceramic type and ceramic thickness.

Results

As a function of the tested parameters, which are luting resin type, ceramic thickness, and curing time, micro-mechanical properties of the luting resins polymerized through the IPS e.max Press and the IPS Empress®CAD ceramics are shown in Tables 2 and 3. Table 4 presents the level of the effect of different ceramic types, ceramic thicknesses and curing times on the micromechanical properties of three different luting resins by showing the eta-squared values derived from ANOVA analysis.

The statistical analysis revealed significant differences in the micromechanical properties between the tested three luting resins (Tables 2 and 3). For all the given parameters as curing time, ceramic type and ceramic thickness,

Table 2 Luting composite, ceramic thickness, curing time, modulus of elasticity, Vickers hardness, creep, and elastic–plastic deformation for the ceramic type of IPS e.max Press

Composite	Ceramic thickness (mm)	Curing time (s)	*E*		HV		Cr		We/Wtot	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
Variolink II	Reference without ceramic	10	10.68^{pqr}	0.4	42.98^{o}	3.0	4.63^{klmno}	0.1	37.20^{a}	1.0
		20	11.22st	0.5	48.86^{qrstu}	3.8	4.28^{cdef}	0.1	38.91^{bcd}	1.1
		30	11.07^{rst}	0.5	48.21^{qrst}	3.2	4.34^{cdefgh}	0.1	38.60^{abc}	0.7
	0.75	10	10.60^{pq}	0.5	46.16^{pq}	5.3	4.46^{fghijk}	0.2	39.43^{bcdef}	2.2
		20	11.12^{rst}	0.4	51.92^{vw}	5.7	4.31^{cdefg}	0.2	40.78^{fgh}	2.3
		30	11.37st	0.4	51.71^{uvw}	6.4	4.33^{cdefg}	0.2	39.88^{cdefg}	2.3
	2	10	9.58^{o}	0.7	38.57^{lm}	4.0	4.89^{rstu}	0.2	37.03^{a}	1.8
		20	10.30^{p}	0.4	42.80^{no}	6.0	4.59^{ijklm}	0.3	38.20^{ab}	3.3
		30	10.31^{p}	0.6	47.90^{qrs}	6.0	4.40^{defghi}	0.3	40.67^{efgh}	2.8
Variolink Veneer	Reference without ceramic	10	3.53^{cd}	0.3	16.52^{de}	1.9	4.77^{mnopqrs}	0.2	45.43^{nop}	1.9
		20	3.74^{de}	0.6	17.60^{ef}	3.1	4.92^{stu}	0.2	45.55^{op}	3.9
		30	4.47^{gh}	0.4	20.18^{fgh}	2.6	5.00^{u}	0.2	43.77^{lmn}	1.3
	0.75	10	3.09^{b}	0.3	14.20^{cd}	2.8	4.87^{rstu}	0.2	44.14^{mno}	1.4
		20	4.20^{fg}	0.4	20.18^{fgh}	4.4	4.84^{qrstu}	0.3	45.18^{nop}	2.4
		30	4.74^{hi}	0.2	22.82^{h}	1.9	4.88^{rstu}	0.3	45.29^{nop}	1.8
	2	10	2.05^{a}	0.2	9.17^{a}	1.7	4.66^{lmnopq}	0.3	44.14^{mno}	1.9
		20	3.24^{bc}	0.3	15.24^{cde}	2.0	4.90^{rstu}	0.3	45.08^{nop}	2.1
		30	4.62^{gh}	0.5	22.36^{h}	4.7	4.90^{rstu}	0.3	45.19^{nop}	2.1
RelyX Veneer	Reference without ceramic	10	6.30^{j}	0.3	28.11^{I}	3.3	4.53^{hijkl}	0.2	40.56^{defgh}	2.4
		20	7.06^{kl}	0.4	33.97^{k}	3.1	4.59^{jklmn}	0.1	41.76^{hijk}	1.1
		30	6.96^{k}	0.3	33.41^{jk}	2.5	4.67^{lmnopq}	0.2	41.87^{hijk}	1.0
	0.75	10	6.39^{j}	0.4	28.49^{i}	2.9	4.40^{defghi}	0.2	40.80^{fghi}	1.7
		20	7.37^{kl}	0.2	35.80^{kl}	2.9	4.24^{bcd}	0.2	43.01^{klm}	1.3
		30	8.00^{n}	0.3	43.68^{op}	3.3	4.02^{a}	0.2	45.89^{p}	1.3
	2	10	4.25^{fg}	0.3	17.96^{efg}	2.4	4.95^{tu}	0.1	39.20^{bcdef}	1.1
		20	6.39^{j}	0.2	29.95^{i}	2.6	4.43^{efghij}	0.2	42.09^{hijk}	1.2
		30	7.27^{kl}	0.3	34.61^{k}	2.5	4.37^{cdefgh}	0.2	42.46^{ijkl}	1.3

Superscript letters show statistically homogeneous subgroups (Tukey HSD test, α=0.05)

E elasticity, *HV* Vickers hardness, *Cr* creep, *We/Wtot* elastic–plastic deformation

Table 3 Luting composite, ceramic thickness, curing time, modulus of elasticity, Vickers hardness, creep, and elastic–plastic deformation for the ceramic type of IPS Empress®CAD

Composite	Ceramic thickness (mm)	Curing time (s)	*E*		HV		Cr		We/Wtot	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
Variolink II	Reference without ceramic	10	10.68^{pqr}	0.4	42.98^{o}	3.0	4.63^{klmno}	0.1	37.20^{a}	1.0
		20	11.22st	0.5	48.86^{qrstu}	3.8	4.28^{cdef}	0.1	38.91^{bcd}	1.1
		30	11.07^{rst}	0.5	48.21^{qrst}	3.2	4.34^{cdefgh}	0.1	38.60^{abc}	0.7
	0.75	10	10.95^{qrs}	0.6	47.05^{qr}	6.1	4.27^{bcde}	0.2	39.19^{bcdef}	2.0
		20	11.29st	0.4	50.86^{tuv}	4.5	4.19^{abc}	0.2	40.03^{cdefg}	1.6
		30	11.40^{t}	0.6	54.14^{w}	3.0	4.10^{ab}	0.2	41.26^{ghij}	1.1
	2	10	9.51^{o}	0.6	37.65^{lm}	3.8	4.74^{mnopqrs}	0.1	37.19^{a}	1.4
		20	11.22st	0.4	50.07^{stuv}	4.6	4.21^{bc}	0.2	39.70^{bcdefg}	1.7
		30	11.33st	0.3	49.30^{rstuv}	2.6	4.28^{bcdef}	0.1	39.00^{bcde}	0.7
Variolink Veneer	Reference without ceramic	10	3.53^{cd}	0.3	16.52^{de}	1.9	4.77^{mnopqrs}	0.2	45.43^{nop}	1.9
		20	3.74^{de}	0.6	17.60^{ef}	3.1	4.92^{stu}	0.2	45.55^{op}	3.9
		30	4.47^{gh}	0.4	20.18^{fgh}	2.6	5.00^{u}	0.2	43.77^{lmn}	1.3
	0.75	10	2.85^{b}	0.4	12.52^{bc}	2.3	4.72^{mnopqr}	0.2	43.14^{klm}	1.1
		20	4.25^{fg}	0.5	20.53^{gh}	3.7	4.91^{stu}	0.2	45.25^{nop}	1.8
		30	4.43^{fgh}	0.5	22.02^{h}	4.3	4.85^{qrstu}	0.2	45.08^{p}	2.1
	2	10	2.14^{a}	0.3	9.77^{ab}	2.1	4.80^{opqrst}	0.2	43.82^{lmn}	1.6
		20	3.61^{cde}	0.5	17.74^{efg}	3.8	4.78^{nopqrst}	0.2	45.76^{op}	3.0
		30	4.36^{fgh}	0.4	21.81^{h}	3.4	4.90^{rstu}	0.2	45.76^{op}	1.9
RelyX Veneer	Reference without ceramic	10	6.30^{j}	0.3	28.11^{I}	3.3	4.53^{hijkl}	0.2	40.56^{defgh}	2.4
		20	7.06^{kl}	0.4	33.97^{k}	3.1	4.59^{jklmn}	0.1	41.76^{hijk}	1.1
		30	6.96^{k}	0.3	33.41^{jk}	2.5	4.67^{lmnopq}	0.2	41.87^{hijk}	1.0
	0.75	10	6.50^{j}	0.4	28.92^{i}	2.4	4.68^{lmnopq}	0.1	40.03^{cdefg}	0.9
		20	7.50^{lm}	0.2	35.84^{kl}	2.5	4.59^{ijklm}	0.2	41.88^{hijk}	1.6
		30	7.87^{mn}	0.4	39.92^{mn}	3.9	4.49^{ghijkl}	0.1	42.64^{jklm}	1.4
	2	10	5.09^{i}	0.7	22.09^{h}	3.8	4.82^{pqrstu}	0.2	39.42^{bcdef}	2.8
		20	4.01^{ef}	1.1	30.70^{ij}	3.7	4.64^{klmnop}	0.3	52.35^{r}	4.4
		30	6.40^{j}	2.4	35.65^{kl}	3.8	4.11^{ab}	0.5	48.18^{q}	2.9

Superscript letters show statistically homogeneous subgroups (Tukey HSD test, α=0.05)

E elasticity, *HV* Vickers hardness, *Cr* creep, *We/Wtot* elastic–plastic deformation

Variolink II exhibited the highest HV, *E* values and the lowest Cr and We/Wtot values followed by RelyX Veneer and then Variolink Veneer ($p<0.05$).

Luting resin type, curing time and ceramic thickness showed a significant effect on the microhardness of the luting resins (Table 4). The effect of luting resin type on the HV values of the luting resins was the highest followed by curing time and ceramic thickness (Table 4).

Ceramic type expressed the lowest effect on the HV values of the luting resins (Table 4). The two light-cured luting resins polymerized through IPS e.max Press and IPS Empress®CAD ceramics of 2 mm in thickness for 20 and 30 s showed no significant differences in HV values ($p>0.05$), which were significantly higher than HV values of the light-cured luting resins cured for 10 s under ceramics. The dual-cured luting resin polymerized through IPS e.max Press and IPS Empress®CAD ceramics of 0.75 mm in thickness for 20 and 30 s showed comparable HV values ($p>0.05$).

Luting resin type showed the highest effect on *E* and Cr values of the luting resins followed by curing time and ceramic thickness (Table 4). Ceramic type showed no significant effect on *E* and Cr values of the luting resins ($p>0.05$).

The effect of filler loading (%vol and %wt) of the luting resins on the micromechanical properties is presented in Table 4. Filler loading of the luting resins showed the highest effect on *E* values followed by HV, We/Wtot, and Cr values.

Ceramic thickness showed no significant effect on We/Wtot values of the luting resins ($p>0.05$). Composite type showed the highest effect on We/Wtot values of the luting resins followed by curing time and ceramic type (Table 4).

Table 4 The effect of included parameters on the micromechanical properties with eta-squared values

Parameters	Micromechanical properties	Eta-squared values
Composite type	HV	0.894
	E	0.956
	Cr	0.345
	We/Wtot	0.511
Vol%	HV	0.841
	E	0.862
	Cr	0.510
	We/Wtot	0.546
Wt%	HV	0.874
	E	0.937
	Cr	0.463
	We/Wtot	0.602
Curing time	HV	0.467
	E	0.429
	Cr	0.052
	We/Wtot	0.157
Ceramic type	HV	0.006
	E [a]	–
	Cr [a]	–
	We/Wtot	0.017
Ceramic thickness	HV	0.248
	E	0.354
	Cr	0.045
	We/Wtot [a]	–

The higher the eta-squared value, the stronger the effect of the independent parameters on the measured micromechanical properties

[a] Statistically no significant effect ($p>0.05$)

Discussion

The present study analyzed the micromechanical properties of two light-cured and one dual-cured composite luting resins to evaluate whether light-cured luting resins perform similar to dual-cured luting resins when polymerized under ceramics by considering the effect of luting resin type, curing time, ceramic type and ceramic thickness. All these effects were expressed in terms of *E*, HV, Cr, and We/Wtot measured on thin luting resins.

The mechanical properties of a material can be a factor when the material is in clinical service [31]. Surface hardness is a parameter frequently used to evaluate material surface resistance to plastic deformation by penetration [32]. The Vickers hardness (HV) value in this study is the result of the described measurement procedure by applying a load of 0.4 to 30 mN and measuring simultaneously the indentation depth. The indentation modulus was calculated from the slope of the tangent of indentation depth-curve at maximum force. The mechanical work (Wtot) indicated during the indentation procedure is only partly consumed as plastic deformation work (Wplast). During the removal of the test force the remaining part was set free as work of the elastic reverse deformation (We). According to the definition of the mechanical work as $W = \int F dh$ (F = load; h = indentation depth) and with consideration of the force variation during load and discharge, the total mechanical work and its components are calculated. The elastic–plastic deformation was expressed in our study in percentage as We/Wtot. Furthermore, when a material subjected to a constant load (in this study 30 mN for 5 s), it generally expresses a time-dependent increase in strain. This phenomenon is known as creep (Cr), a term which is used to describe the tendency of a solid material to slowly deform permanently to relieve stresses. Therefore, optimal resin cements should exhibit increases in HV and *E* values as well as decreases in Cr values. In this study, compared to the light-cured luting resins, the dual-cured luting resin showed higher *E* and HV values and lower Cr and We/Wtot values for all the given parameters by a direct application of the curing unit on the specimen surface.

The chemical composition of a luting resin may clinically influence the aesthetic outcomes, especially when the luting resin is used with thin translucent veneer ceramics [33]. The base paste of Variolink II contains both aliphatic amine and aromatic tertiary amine and the catalyst paste contains benzoyl peroxide. The color changes of dual-cured luting resin are mainly caused by the oxidization of the amine, which is a necessary component of the polymerization initiation system maintaining by the catalyst paste [34].

Therefore, in the anterior region of the dental arch, where aesthetics is the most important factor, dentists prefer light-cured resins when luting the ceramic restorations. In this study, hardness and modulus of elasticity of dual-cured luting resin were significantly higher than light-cured luting resins for all the groups. However, it is still undetermined whether the mechanical properties of the luting resin correlate with their clinical performance [35]. Moreover, in addition to use of an inappropriate luting resin, there are some other factors implicated reducing the long term success of a restoration such as unfavorable occlusion and articulation, excessive loss of dental tissue, unprepared teeth and partial adhesion to large exposed dentin surfaces [21]. Aykor & Ozel reported that 300 porcelain laminate veneers, which were luted with a light-cured luting resin, exhibited successful performance after 5 years of clinical service [36].

In this study, Variolink II showed the highest *E* and HV values and the lowest Cr and We/Wtot values followed by RelyX Veneer and Variolink Veneer. According to the results of this study, significant correlation was found between the filler loading (%vol and %wt) and the micromechanical properties of the luting resin. The higher the filler loading of the luting resin, the higher the *E* and HV values and the lower the We/Wtot and Cr values (Tables 2, 3, and 4). Therefore, the mechanical properties of the light-cured luting resin can be improved by increasing the filler loading of the material. On the other hand, the viscosity will increase as well, thus limiting the thickness of the luting resin.

The results of this study showed that curing time had a significant effect on HV, *E*, Cr, and We/Wtot values. The curing unit selected in this study was a LED unit with a high irradiance (1,200 mW/cm^2). With this high irradiance, mechanical properties of the material were increased for all the groups, when curing time was increased from 10 to 20 s. No significant difference was found between 20 and 30 s for the mechanical properties of dual-cured luting resin. These results showed that in addition to chemical catalyst-base reaction, the effect of light activated polymerization reaction on mechanical properties is limited in dual-cured luting resins. Ilie and Hickel [22] found that the role of light activation in the dual-cured composite Variolink II cannot be neglected; however an unrestricted increase in irradiation will not be able to accelerate the polymerization process.

In the present study statistically significant differences were found between *E* and HV values of the two light-cured luting resins polymerized under lithium disilicate ceramics of 0.75 and 2 mm in thicknesses at all exposure times. When curing time was increased, *E* and HV values of the materials also increased. However, this increase in *E* and HV values between the exposure times from 20 to 30 s was relatively minor, when comparing to the differences from 10 to 20 s. There were no significant differences between Cr and We/Wtot values of the light-cured luting resins polymerized under lithium disilicate ceramics at the exposure times of 20 and 30 s (Table 2). This means that at least 20 s of curing time is necessary to maintain an adequate polymerization of these light-cured luting resins when curing with units of similar output to the curing light used in this study.

There were no significant differences between the mechanical properties of the two light-cured luting resins polymerized under the leucite-reinforced glass ceramic of 0.75 mm in thickness at the exposure times of 20 and 30 s (Table 3). However, significant differences were found between the mechanical properties of the two light-cured luting resins polymerized under the leucite-reinforced glass ceramic of 2 mm in thickness at all exposure times. These differences among the curing times are also related to ceramic type and ceramic thickness for the light curing luting resins.

In this study, ceramic type and ceramic thickness exhibited a significant effect on HV and We/Wtot. However, when ceramic thickness showed significant effect on *E* and Cr values, ceramic type did not reveal any significant effect on *E* and Cr values. Furthermore, the effect of ceramic type on HV and We/Wtot values was extremely low (Table 4). Borges et al. evaluated the effect of different kind of ceramic types at 1.2 mm in thickness on surface hardness and found significant differences between leucite-reinforced glass ceramic and lithium glass ceramic [9]. On the other side, Pazin et al. found no significant differences between dual- and light-cured luting resin specimens under leucite-reinforced glass ceramic of 0.7 mm in thickness [11]. This means that ceramic type may be a factor that influences the properties of underlying luting resins at the certainly limited thicknesses.

The present study is limited to use just two ceramics, three luting resins and just three exposure times of 10, 20, and 30 s according to the manufacturer's instructions. Furthermore, no long term measurement was performed by assessing the behavior of the tested materials after aging. Therefore, further researches should be conducted considering the above mentioned limitations.

Conclusions

Within the limitation of this study, following conclusions may be addressed:

1. Luting resin type has a significant effect on the micromechanical properties of the luting resins.
2. The dual-cured luting resin, Variolink II, expresses better performance compared to the light-cured luting resins, RelyX Veneer and Variolink Veneer.
3. Curing time has a significant effect on the mechanical properties of the luting resins. At least 20 s of curing

time is necessary for the luting resins used in this study.

4. Ceramic thickness affects the mechanical properties of the luting resin. However, this effect is not as efficient as the effect of luting resin type and curing time.
5. Ceramic type has an influence only on HV and We/Wtot in this study. However this effect is very small when comparing with the effects of luting resin type, curing time and ceramic thickness.

Acknowledgements This investigation was conducted in Dental School of the Ludwig-Maximilians-University, which is a collaborating research laboratory located in Continental European Division of the International Association for Dental Research area, by winning of the IADR.CED Visiting Scholar Stipend.

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Yoshida K, Tsuo Y, Meng X, Atsuda M (2007) Mechanical properties of dual-cured resin luting agents for ceramic restoration. J Prosthodont 16:370–376
2. Gurel G (2007) Porcelain laminate veneers: minimal tooth preparation by design. Dent Clin Nort Am 51:419–431
3. Zhang F, Guido H, Razzoog M (2000) Double-layer porcelain veneers: effect of layering on resulting veneer color. J Prosthet Dent 84:425–431
4. Horn HR (1983) Porcelain laminate veneers bonded to etched enamel. Dent Clin Nort Am 27:671–684
5. Sheets CG, Taniguchi T (1990) Advantages and limitations in the use of porcelain veneer restorations. J Prosthet Dent 64:406–411
6. Pröbster L (1996) Four year clinical study of glass-infiltrated, sintered alumina crowns. J Oral Rehabil 23:147–151
7. Oden A, Anderson M, Krystek-Ondracek I, Magnusson D (1998) Five-year clinical evaluation of Procera AllCeram crowns. J Prosthet Dent 80:450–456
8. Blatz MB, Sadan A, Kern M (2003) Resin-ceramic bonding: a review of the literature. J Prosthet Dent 89:268–274
9. Borges GA, Agarwal P, Miranzi BAS, Platt JA, Valentino TA, Santos PH (2008) Influence of different ceramics on resin cement Knoop hardness number. Oper Dent 33(6):622–628
10. Blatz MB, Sadan A, Martin J, Lang B (2004) In vitro evaluation of shear bond strengths of resin to densely-sintered high-purity zirconium-oxide ceramic after long-term storage and thermal cycling. J Prosthet Dent 91(4):356–362
11. Pazin MC, Moraes RR, Goncalves LS, Borges GA, Sinhoretti MA, Correr-Sobrinho L (2008) Effects of ceramic thickness and curing unit on light transmission through leucite-reinforced material and polymerization of dual-cured luting agent. J Oral Sci 50(2):131–136
12. Rosenstiel SF, Land MF, Crispin BJ (1998) Dental luting agents: a review of the current literature. J Prosthet Dent 80:280–301
13. Peumans M, Van Meerbeek B, Lambrechts P, Vanherle G (2000) Porcelain veneers: a review of the literature. J Dent 28:163–177
14. Aristidis GA, Dimitra B (2002) Five-year clinical performance of porcelain laminate veneers. Quintessence Int 33:185–189
15. Fradeani M (1998) Six-year follow-up with Empress veneers. Int J Periodontics Restor Dent 18:216–225
16. Magne P, Perroud R, Hodges JS, Belser UC (2000) Clinical performance of novel-design porcelain veneers for the recovery of coronal volume and length. Int J Periodontics Restor Dent 20:117–124
17. Dunne SM, Millar JA (1993) A longitudinal study of the clinical performance of porcelain veneers. Br Dent J 175:317–321
18. Shaini FU, Shortall ACC, Marquis PM (1997) Clinical performance of porcelain laminate veneers. A retrospective evaluation over a period of 6.5 years. J Oral Rehabil 24:553–559
19. Sieweke M, Salomon-Sieweke U, Zöfel P, Stachniss V (2000) Longevity of oroincisal ceramic veneers on canines—a retrospective study. J Adhes Dent 2:229–234
20. Walls AWG (1995) The use of adhesively retained all-porcelain veneers during the management of fractured and worn anterior teeth. Part II: clinical results after 5-year follow-up. Br Dent J 178:337–339
21. Peumans M, Munck JD, Fieuws S, Lambrechts P, Vanherle G, Meerbeek BV (2004) A prospective ten-year clinical trial of porcelain veneers. J Adhes Dent 6:65–76
22. Ilie N, Hickel R (2008) Correlation between ceramics translucency and polymerization efficiency through ceramics. Dent Mater 24:908–914
23. Moraes RR, Correr-Sobrinho L, Sinhoretti MA, Puppin-Rontani RM, Ogliari FA, Piva E (2008) Light activation of resin cement through ceramic: relationship between irradiance intensity and bond strength to dentin. J Biomed Mater Res B Appl Biomater 85B:160–165
24. Rasetto FH, Driscoll CF, von Fraunhofer JA (2001) Effect of light source and time on the polymerization of resin cement through ceramic veneers. J Prosthodont 10(3):133–139
25. Tarle Z, Knezevic A, Demoli N, Meninga A, Sutalon J, Unterbrink G, Ristic M, Pichler G (2006) Comparison of composite curing parameters: effects of light source and curing mode on conversion, temperature rise and polymerization shrinkage. Oper Dent 31(2):219–226
26. Jung H, Friedl KH, Furch H, Bernhart S, Schmalz G (2006) Polymerization efficiency of different photocuring units through ceramic discs. Oper Dent 31:68–77
27. Rasetto FH, Driscoll CF, Prestipino V, Masri R, von Fraunhofer JA (2004) Light transmission through all-ceramic dental materials: a pilot study. J Prosthet Dent 91:441–446
28. Koch A, Kroeger M, Hartung M, Manetsberger I, Hiller KA, Schmalz G, Friedl KH (2007) Influence of ceramic translucency on curing efficacy of different light-curing units. J Adhes Dent 9:449–462
29. Soares CJ, da Silva NR, Fonseca RB (2006) Influence of the feldspathic ceramic thickness and shade on the microhardness of dual resin cement. Oper Dent 31:382–389
30. Albers HF (1989) Bonded tooth colored restoratives: indirect bonded restorations. Alto Books, Santa Rosa, pp 1–42, Supplement
31. Wang L, D'alpino PHP, Lopes LG, Pereira JC (2003) Mechanical properties of dental restorative materials: relative contribution of laboratory tests. J Appl Oral Sci 11(3):162–167
32. Cattani-Lorente MA (1999) Comparative study of the physical properties of a polyacid-modified composite resin and a resin-modified glass ionomer cement. Dent Mater 15:21–32
33. Nathanson D, Banasr F (2002) Color stability of resin cements. An in vitro study. Pract Proced Aesthet Dent 14:449–455
34. Lu H, Powers JM (2004) Color stability of resin cements after accelerated aging. Am J Dent 17:354–358
35. Magni E, Ferrari M, Hickel R, Ilie N (2009) Evaluation of the mechanical properties of dental adhesives and glass-ionomer cements. Clin Oral Investig 14:79–87
36. Aykor A, Ozel E (2009) Five-year clinical evaluation of 300 teeth restored with porcelain laminate veneers using total-etch and a modified self-etch adhesive system. Oper Dent 34(5):516–523