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Energy dissipation capacities of CAD-CAM restorative materials: A comparative evaluation of resilience and toughness

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ABSTRACT

Statement of problem. Well-balanced physical properties of computer-aided design and computer-aided manufacturing (CAD-CAM) materials are important to ensure the clinical success and longevity of restorations. Therefore, the capacity of a material to dissipate destructive fracture energy by means of elastic and plastic material deformation is of interest. However, little information is available on how to quantify the resilience and toughness of CAD-CAM materials.

Purpose. The purpose of this in vitro study was to investigate and compare the resilience and toughness of CAD-CAM restorative materials and assess their capability to dissipate destructive fracture energy in comparison with a high–gold-content alloy.

Material and methods. Restorative materials for 3-unit fixed partial dentures (Alphador No. 1, IPS e.max CAD, Lava Plus, PEEK Optima), crowns and onlays (CERASMART, CEREC Blocs, Lava Ultimate, VITA ENAMIC), and interim prostheses (M-PM Disc, Telio CAD) were investigated. The strain energy density was determined with a 3-point bend test to calculate the modulus of toughness, the modulus of resilience, and the elastic recovery and thus characterize the material properties of resilience and toughness. Data were statistically analyzed with a generalized linear mixed model by using the Huber-White sandwich estimator (α=.05).

Results. Significant differences were found among the materials concerning the modulus of toughness, the modulus of resilience, the elastic recovery, and the difference between the elastic recovery and the modulus of resilience (P<.001). Alphador produced the highest mean regarding the modulus of toughness followed by Telio CAD, Lava Plus, M-PM Disc, CERASMART, and Lava Ultimate; all showed significantly higher capacities to dissipate energy by elastic and plastic deformation when compared with the ceramic materials (IPS e.max CAD, VITA ENAMIC, CEREC Blocs). For the modulus of resilience and elastic recovery, Lava Plus and Alphador showed the highest mean values and therefore better able to only elastically absorb destructive fracture energy; the least able materials were VITA ENAMIC and CEREC Blocs. As PEEK Optima, M-PM Disc, and Lava Ultimate showed higher mean values for the modulus of resilience than IPS e.max CAD, they were better able to elastically dissipate energy.

Conclusions. Alphador had the highest values for the modulus of toughness, the elastic recovery, and the difference between the elastic recovery and the modulus of resilience; this was equivalent to pronounced energy dissipation capacities. In comparison, Lava Plus showed the highest modulus of resilience but significantly lower results for all other parameters and therefore fewer energy-consuming capabilities. The new polymer-based CAD-CAM restorative materials in general had a higher modulus of toughness and elastic recovery than ceramics and thereby partially resemble Lava Plus, all with similar capacities to dissipate destructive energy. (J Prosthet Dent 2019;121:101-9)

The replacement of natural composite materials such as bone and teeth requires the use of biomimetic restorative materials with physical properties that match the existing biological structures as closely as possible.[1,2] A carefully optimized balance of elasticity and plasticity is an essential mechanical factor for ensuring the long-term stability of natural composite materials.[3-5] This special characteristic balance is important in effectively dissipating destructive fracture energy and preserving integrity.[6-8] Unfortunately, little information is available regarding how to quantify these properties simultaneously for dental restorative materials. A reliable characterization of resilience and toughness of new computer-aided design and computer-aided manufacturing (CAD-CAM) restorative materials and their ability to dissipate destructive fracture energy is needed.

A conventional 3-point bend test in combination with

Juvora Ltd provided PEEK Optima; and Schuetz Dental GmbH provided commercial Alphador No 1 alloy with the desired specimen geometry.
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Clinical Implications

CAD-CAM restorative materials do not yet provide the same resilience and toughness of high–gold-content alloys and therefore are less able to dissipate destructive fracture energy. Nevertheless, new polymer-based materials seem clinically promising to preserve material integrity as only they provide adequate resilience and toughness when compared with ceramic materials. They have not yet, however, achieved the performance of zirconia in all aspects.

the concept of strain energy density to assess the relationships between forces and material deformation appears to be a promising method.[9,10] The area under a typical stress-strain curve (strain energy density) describes the energy absorbed per unit of volume at any elongation. The section up to the elastic limit represents the pure elastic material properties (Fig. 1). Defined as the modulus of resilience, this characteristic specifies the capacity of a specimen to elastically absorb energy without displaying permanent plastic deformation.[9,11]

Defining the elastic limit where the stress-strain curve deviates from linearity and enters the plastic region is nearly impossible; hence, this point is typically approximated by the yield strength at a specific predefined plastic deformation.[12,13] If the elastic limit is surpassed, a permanent plastic deformation of the specimen will be detected when bending forces cease. Consequently, the recoverable amount of energy from elastic deformation at this higher strain level is different from the modulus of resilience and is defined as the elastic recovery in cases of specimen rupture (Fig. 1).[10] It is represented by the area of a triangle, where the hypotenuse has the same slope as the triangle for the modulus of resilience.

In contrast to the modulus of resilience, elastic recovery results describe the amount of elastic energy dissipation during permanent plastic deformation. For brittle materials such as ceramics, the elastic recovery usually shows results of the same magnitude as the modulus of resilience but markedly higher values for materials which may undergo plastic deformation, such as polymers or composite resins. Hence, the difference between elastic recovery and modulus of resilience represents a further characteristic for assessing energy dissipation in restorative materials. The higher this difference in ductile materials, the higher the gain of additional elastic energy dissipation before material rupture occurs. However, materials with low values that converge towards zero may be unequivocally characterized as brittle.

Finally, the total area up to material rupture represents the modulus of toughness (Fig. 2), which is related to material ductility and characterizes both the elastic and plastic properties.[9] So far, the modulus of toughness and the related stress-strain curves have been readily used to describe the capacity of biological materials[14,15] and synthetic composite resins[11,16,17] to absorb fracture energy. Whether this approach is suitable for assessing the fracture risk of different restorative materials is unclear.

To date, studies of new CAD-CAM restorative materials have analyzed mechanical,[18-29] optical,[30-33] wear,[34-38] and bond strength[39,40] properties as well as machinability[41,42] but have not included an examination of resilience and toughness. Only 3 studies tangentially discussed the modulus of resilience, but the equation used for its calculation did not provide a reliable value,[25,43,44] which was clearly based on deceptive assumptions.[45,46] Hence, the modulus of resilience values reported in the dental literature to date—where flexural strength values were used for the calculation instead of the yield strength—reflect elastic recovery values and therefore higher values than the correctly calculated modulus of resilience.[25,43,44]

The purpose of this in vitro study was to assess the energy dissipation capacities of CAD-CAM restorative materials and compare their resilience and toughness properties by calculating the modulus of toughness, modulus of resilience, and elastic recovery from the strain energy density results of a 3-point bend test. The null hypotheses were that the modulus of toughness, the modulus of resilience, the elastic recovery, and the difference between the elastic recovery and modulus of resilience of CAD-CAM restorative materials are independent of the CAD-CAM material used.

MATERIAL AND METHODS

Ten representative restorative materials for 3 different clinical indications were investigated (Table 1). Because of limited milling block dimensions and for reasons of material comparison, bar-shaped specimens (4.0×1.5×17.0 mm, n=10) were prepared for all CAD-CAM materials in accordance with ISO 6872[47] by using a water-cooled precision saw (IsoMet 1000; Buehler Co). Final specimen sizes were adjusted by grinding on wet silicon carbide abrasive paper (800 grit; Leco Corp), and specimens of IPS e.max CAD and Lava Plus were subsequently sintered, both according to the recommended sintering programs. Gold alloy specimens with the same dimensions were cast by the manufacturer and used without any further treatment.

After storage in distilled water for 24 hours at 37.0 ±1.0°C, the specimens were loaded until rupture in a 3-point bend test in a newly calibrated universal testing machine (1454; Zwick/Roell) and a 0.5-kN load cell.[48] The span width was 15.0 mm, and the crosshead speed was 1 mm/min.[47] If specimen deflection surpassed 2.5

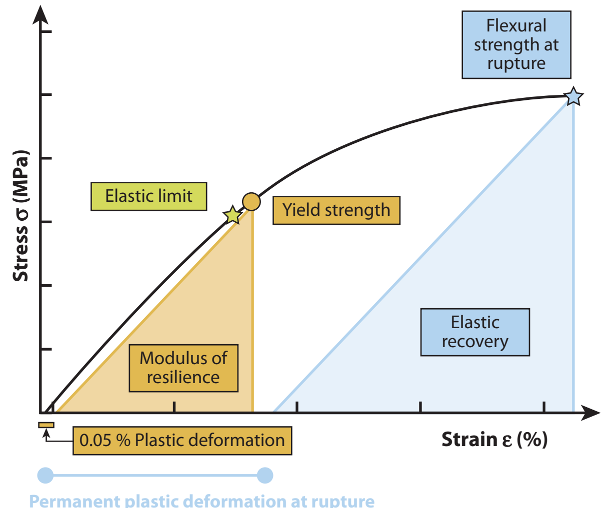

Figure 1. Stress-strain curve exemplifies elastic energy absorption during specimen bending. Areas of triangles represent strain energy density for elastic energy dissipation without or with permanent plastic deformation.

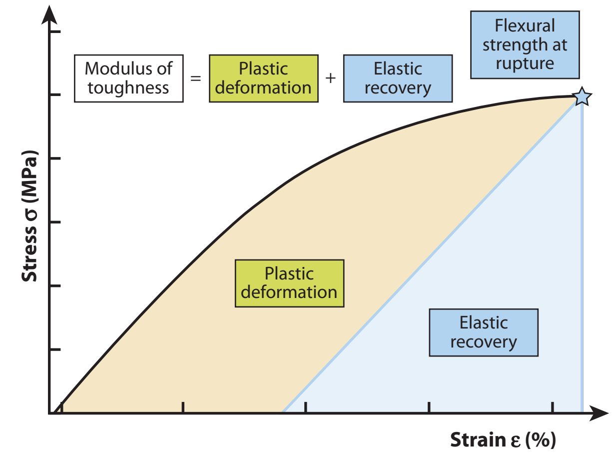

Figure 2. Stress-strain curve exemplifies combination of elastic with plastic energy absorption during specimen bending. Area up to rupture represents total strain energy density for energy dissipation (modulus of toughness).

mm without fracture, loading was ceased, and the results were noted as "not available." Flexural strength,[49,50] modulus of elasticity,[49,50] and modulus of toughness[51] (Fig. 2) were calculated by using the following equations:

$$FS=\frac{3F_{max}L}{2wh^2},\ ME=\frac{F_{lin}L^3}{4d_{lin}wh^3},\ MT=\frac{9A}{whL},$$

where F_{max} (N) is the maximum load, L (mm) is the span width between the 2 support bars, and w (mm) and h (mm) are the width and height of the specimen. F_{lin} (N) is the force in the linear part of the stress-strain curve, and d_{lin} (mm) is the corresponding deflection at F_{lin}. A (J) is the total area under the load-deformation curve (work performed by the applied load to deflect and fracture the specimen) obtained with the software used for the testing machine (TestXpert V 10.11; Zwick/Roell). The equation to calculate the modulus of resilience was[9,11]:

$$MR=\frac{YS^2}{2ME},$$

where YS is the yield strength (MPa) at 0.05% plastic deformation (Fig. 1),[12] and ME (MPa) is the respective modulus of elasticity. The same equation was used to calculate the elastic recovery at rupture by replacing yield strength with flexural strength (Fig. 1).[25,43-46]

The data were analyzed by using statistical software (IBM SPSS Statistics for Windows, v24; IBM Corp). To consider potential correlations among the 4 tested variables (modulus of toughness, modulus of resilience, elastic recovery, and difference between elastic recovery and modulus of resilience), a multivariate model was tested by using a generalized linear mixed model implemented by SPSS GENLINMIXED, with a robust estimation method for standard errors (Huber-White sandwich estimator) to account for heterogeneity of variances. For multiple testing among the 4 variables and among the 10 materials, *P* values were adjusted by using the Holm Sequential Bonferroni Procedure.[52]

Table 1. Tested restorative materials

Clinical Indication	Restorative Material	Manufacturer	Lot No.	Classification
3-unit FPD	Alphador No. 1	Schuetz Dental	16L0086HR	Gold alloy[a]
	Lava Plus	3M ESPE	616299 (d)	Zirconia (Y-TZP)
	IPS e.max CAD LT A3	Ivoclar Vivadent AG	U22012 (b)	Lithium disilicate glass-ceramic
	PEEK Optima	Juvora Ltd	J000025 (d)	PEEK polymer
Crown/onlay	CEREC Blocs S3 PC	Dentsply Sirona	39090 (b)	Feldspathic ceramic
	Lava Ultimate A2 HT	3M ESPE	N472545 (b)	Particle-filled resin-based composite
	VITA ENAMIC 2M2HT	VITA Zahnfabrik	38910 (b)	Polymer infiltrated ceramic network
	CERASMART A2 HT	GC Dental Products	1412041 (b)	Particle-filled resin-based composite
Interim prosthesis	M-PM Disc A2	Merz Dental	31213 (d)	PMMA polymer
	Telio CAD LT A3	Ivoclar Vivadent AG	VW9680 (b)	PMMA polymer

b, block; d, disk; FPD, fixed partial denture; PEEK, poly(etheretherketone); PMMA, poly(methylmethacrylate); Y-TZP, yttria-stabilized tetragonal zirconia polycrystal.
[a]Au: 85.9 wt%, Pt: 11.7 wt%, Zn: 1.5 wt%.

RESULTS

The mean and standard deviation values of the data obtained from the universal testing machine software are summarized in Table 2. All deduced and calculated results are displayed in Figures 3 to 6. The statistical analysis showed that the material factor had a significant

Table 2. Mean ±standard deviation of data obtained from 3-point bend test

Clinical Indication	Restorative Material	Flexural Strength (MPa)	Flexural Strength[a] (MPa)	Modulus of Elasticity (MPa)	Modulus of Elasticity[a] (MPa)	Yield Strength (MPa)	A (J)
3-unit FPD	Alphador No.1	984.5 ±35.8	NA	69490.0 ±2857.5	95000	595.5 ±14.5	0.58265 ±0.05108
	Lava Plus	931.9 ±99.6	>1100.0[b]	137592.8 ±6812.8	210000	931.9 ±99.6	0.03222 ±0.00767
	IPS e.max CAD	363.2 ±19.9	360.0[b] ±60.0	79977.9 ±5890.7	95000.0 ±5000.0	363.2 ±19.9	0.00835 ±0.00084
	PEEK Optima	202.1 ±3.1	170.0	4145.5 ±109.2	4200.0	130.5 ±3.7	NA
Crown/onlay	CEREC Blocs	114.9 ±7.5	113.0 ±10.0	56131.9 ±1949.1	45000.0 ±500.0	87.0 ±6.4	0.00102 ±0.00014
	Lava Ultimate	197.7 ±10.9	204.0 ±19.0	12074.2 ±451.3	12770.0 ±990.0	156.7 ±9.1	0.02019 ±0.00253
	VITA ENAMIC	142.4 ±6.3	150.0 -160.0	28067.3 ±1857.3	30000.0	124.1 ±5.6	0.00340 ±0.00017
	CERASMART	174.1 ±6.6	231.0	8771.7 ±355.4	NA	117.3 ±9.6	0.02293 ±0.00206
Interim prosthesis	M-PM Disc	113.8 ±5.6	96.6	2828.9 ±130.1	2773.0	83.4 ±5.7	0.03195 ±0.00469
	Telio CAD	115.6 ±8.2	130.0 ±10.0	2870.7 ±162.3	3200.0 ±300.0	60.6 ±7.4	0.05366 ±0.01946

A, total area under load-deformation curve; FPD, fixed partial denture; NA, not applicable. [a]Data from manufacturer specification. [b]Biaxial flexure test.

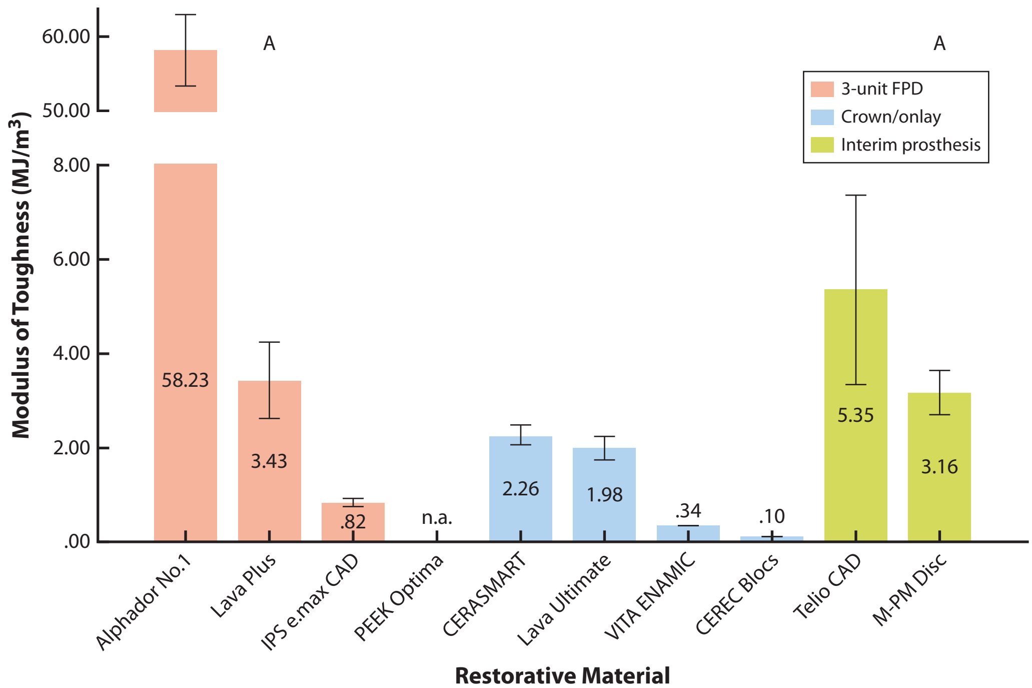

Figure 3. Mean modulus of toughness (MJ/m^3) with error bars representing standard deviation. Identical uppercase letters denote no significant differences among groups (*P*>.05) n.a., not available.

effect on the modulus of toughness [F(8,333)=725, *P*<.001], modulus of resilience [F(9,333)=1785, *P*<.001], elastic recovery [F(8,333)=1586, *P*<.001], and difference between elastic recovery and modulus of resilience [F(8,333)=577, *P*<.001]. Determined flexural strength and modulus of elasticity values closely resembled the respective manufacturer specifications (Table 2) or published results,[19,22] which shows the suitability of the test procedure. For the properties of PEEK Optima, no results for the modulus of toughness and elastic recovery were obtained, as the specimens demonstrated no rupture. However, flexural strength, modulus of elasticity, and yield strength values could be easily determined as described previously.[53] All the other materials demonstrated specimen rupture at maximum load. For Lava Plus and IPS e.max CAD, the modulus of resilience was calculated by replacing yield strength with flexural strength in the respective equation, as the stiff and rigid material behavior impeded the achievement of 0.05% plastic deformation.

For the modulus of toughness, the Alphador mean exhibited the highest value determined in this investigation (*P*<.001), showing better capacity to dissipate energy simultaneously by elastic and plastic deformation (Fig. 3). The similar mean modulus of toughness values of Lava Plus and M-PM Disc (*P*=.333) together with the results of Telio CAD, CERASMART, and Lava Ultimate were significantly higher than the mean values of IPS e.max CAD, VITA ENAMIC, and CEREC Blocs (*P*<.001).

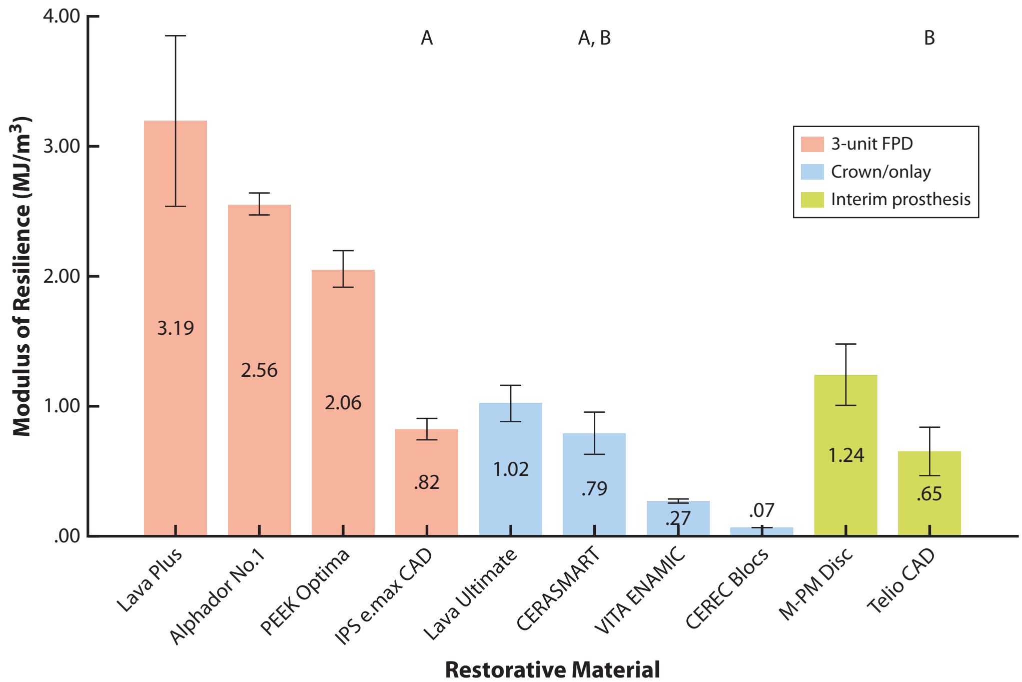

Figure 4. Mean modulus of resilience (MJ/m^3) with error bars representing standard deviation. Identical uppercase letters denote no significant differences among groups (*P*>.05).

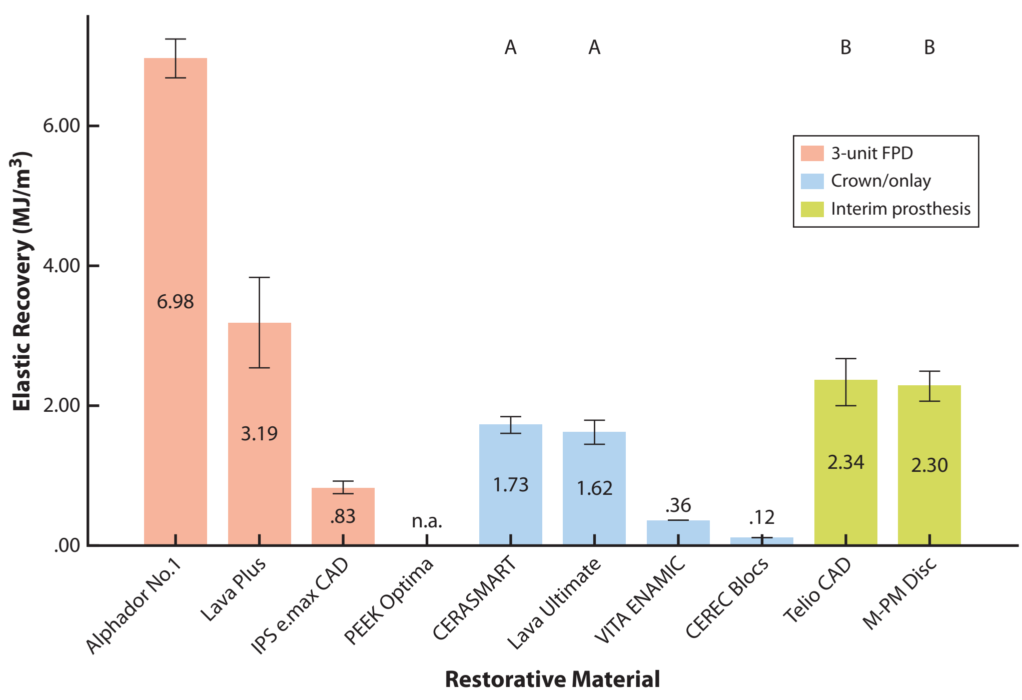

Figure 5. Mean elastic recovery (MJ/m^3) with error bars representing standard deviation. Identical uppercase letters denote no significant differences among groups (*P*>.05) n.a., not available.

The mean modulus of resilience values of the Lava Plus and Alphador specimens represented the highest results determined in this study (Fig. 4) (*P*<.001). Consequently, both materials showed the highest capacity to only elastically dissipate destructive energy. While the modulus of resilience mean values of PEEK Optima, M-PM Disc, and Lava Ultimate were higher than those of IPS e.max CAD, CERASMART, and Telio

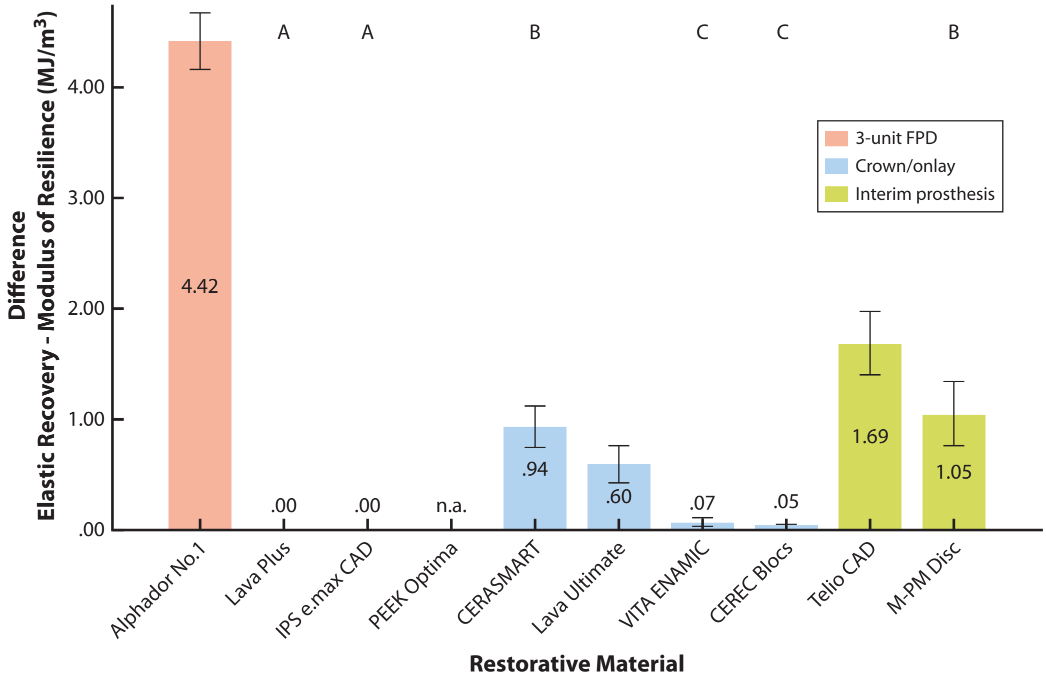

Figure 6. Mean difference between elastic recovery and modulus of resilience (MJ/m^3) with error bars representing standard deviation. Identical uppercase letters denote no significant differences among groups (P>.05) n.a., not available.

CAD (P<.010), the lowest means for VITA ENAMIC and CEREC Blocs were detected (P<.001) (Fig. 4). Furthermore, the results of the statistical analysis revealed that for the elastic recovery (Fig. 5) and the difference between elastic recovery and modulus of resilience (Fig. 6), the Alphador mean was significantly higher than that of all CAD-CAM materials investigated (P<.001), which implied a distinct gain of elastic energy dissipation capacity before material rupture. The corresponding mean values of the polymer-based CAD-CAM materials (Telio CAD, M-PM Disc, CERASMART, Lava Ultimate) were significantly higher than those determined for the ceramics (IPS e.mac CAD, VITA ENAMIC, CEREC Blocs), which showed the lowest results (P<.001). While for Lava Plus the elastic recovery mean value was significantly higher than those of the other CAD-CAM materials (P<.001), the lowest mean was recorded for the difference between elastic recovery and modulus of resilience.

DISCUSSION

The null hypotheses were rejected as all investigated material parameters were dependent on the CAD-CAM restorative material. As anticipated, the high–gold-content alloy (Alphador), as a reference material, demonstrated the greatest capacity among the tested materials to dissipate destructive energy. It showed the highest mean values for the modulus of toughness (Fig. 3), elastic recovery (Fig. 5), and the difference between elastic recovery and modulus of resilience (Fig. 6), which describe the energy-consuming processes that contribute considerably to the prevention of early material rupture and therefore provide material robustness. Finally, the received results, which demonstrate a perfect balance of resilience and toughness, were consistent with the observation that gold restorations generally show better clinical performance.[54]

On analyzing the data obtained for the CAD-CAM restorative materials, the mean modulus of toughness values were significantly lower for Lava Plus than Alphador, reflecting the inability of zirconia to be plastically deformed (Fig. 3); therefore, this restorative material has comparatively brittle characteristics, which is further verified by its lower elastic recovery (Fig. 5). As a result, Lava Plus reveals a poorer balance of resilience and toughness to withstand destructive fracture energy when compared with Alphador.

When the material behavior of IPS e.max CAD to be used for 3-unit FPDs is estimated considering only the flexural strength and modulus of elasticity results (Table 2), all the other CAD-CAM materials except Lava Plus show lower values and appear to perform worse than IPS e.max CAD. However, the resilience and toughness properties reveal different results referring to material stability and robustness as the mean modulus of toughness (Fig. 3), elastic recovery (Fig. 5), and the difference between elastic recovery and modulus of resilience (Fig. 6) values of CERASMART, Lava Ultimate, M-MP Disc, and

Telio CAD show significantly higher results than those of IPS e.max CAD, and therefore, these materials are better able to dissipate destructive fracture energy before material rupture occurs. This effect is caused by a high number of plastic energy-consuming properties, similarly demonstrated by Alphador, and results from the polymer content of these CAD-CAM materials. A similar resilience and toughness could be expected for PEEK Optima when its modulus of resilience (Fig. 4) and the respective stress-strain curves are considered. As a result, the higher energy-consuming capacities of Telio CAD, M-PM Disc, and PEEK Optima compared with those of IPS e.max CAD explain their performance during load-bearing capacity tests of fixed dental prostheses,[26,27] the successful clinical application of PMMA-based polymers as long-term fixed dental prostheses,[55] and the use of PEEK as a framework material.[56] However, to estimate the long-term survival of these polymer-based materials reliably, further parameters such as abrasion resistance must be considered.[38] In addition, for IPS e.max CAD, the limitation of the material as stated by the manufacturer for 3-unit FPDs "up to the second premolar as the terminal abutment" may be supported in light of the results of the present investigation.[57] IPS e.max CAD showed the lowest values for all material parameters among the tested materials for 3-unit FPDs, indicating an inferior capacity to elastically and plastically dissipate energy. Therefore, 3-unit FPDs of IPS e.max CAD may not withstand destructive fracture forces in the posterior region, especially when compared with Alphador or Lava Plus.

The present study revealed a comparatively high value for the modulus of resilience mean of PEEK Optima that almost approached that for Alphador and that consequently indicates a similar high capacity to dissipate destructive energy elastically (Fig. 4). Furthermore, for PEEK Optima, a high capacity to dissipate energy plastically could be assumed, based on the appearance of the obtained stress-strain curves, which showed markedly increased strain values. Hence, the question arises whether PEEK Optima could be used for FPDs with more than 1 pontic, despite the lack of evidence for this clinical indication; to date, the manufacturer only approves 3-unit FPDs.

The comparison of CAD-CAM crowns and onlay materials showed significantly higher mean values for all investigated properties of Lava Ultimate and CERASMART than those of VITA ENAMIC and CEREC Blocs. This outcome has been reported previously, although the parameters were inadvertently described as the modulus of resilience rather than elastic recovery.[25,43] However, all studies conclude that VITA ENAMIC has a considerably lower capacity to dissipate fracture energy elastically than Lava Ultimate and CERASMART, which may similarly explain the better performance of polymer-based over ceramic restorations previously reported.[24,28,29] In addition, Lava Ultimate, which had significantly higher material property values than IPS e.max CAD, might be suitable for 3-unit FPDs. However, the manufacturer recently stated that this material is not suitable for crowns,[58] probably for reasons other than its physical properties and related to restoration loosening[39,40] resulting from flexure of the axial walls. The findings of the present study on its elastic and plastic material behavior support consideration of this milling block for application in 3-unit FPDs if appropriate luting systems are used, at least for the same indication as IPS e.max CAD.

The modulus of toughness values of the materials used for interim prostheses revealed a high capacity to dissipate destructive energy similar to that of Lava Plus (Fig. 3), readily explaining their applicability as long-term restorative materials for interim prostheses. However, in contrast with Lava Plus, both materials showed considerably more energy being transferred to plastic deformation; conversely, only a minor part of the bending energy is quenched elastically, as shown by the modulus of resilience mean values (Fig. 4). This ability to absorb fracture energy by plastic deformation has previously been reported and was used to explain the unexpected performance of restorative materials for interim prostheses in implant-supported posterior crowns.[22] Nevertheless, this high deformability, which was similarly observed for PEEK Optima in the present investigation, might cause problems in clinical applications over the long term, leading to, for example, restoration misfits. This question remains unanswered as meaningful clinical data are not yet available.

From a theoretical point of view, pure elastic energy dissipation that does not change the integrity of the material seems more advantageous than plastic energy dissipation; this is because on the macroscale, material distortion belonging to the modulus of resilience is reversible and therefore impedes restoration misfit. Conversely, plastic energy dissipation mechanisms at the microscale and molecular level, such as sacrificial bonds and hidden lengths,[7] are important for natural composites to provide robustness and long-term survival.[5] Therefore, efforts to develop new biomimetic CAD-CAM restorative materials should take this principle into account, as nature has evolved this effective concept for composite survival over millions of years. However, to reliably estimate long-term behavior of new CAD-CAM materials, further parameters such as abrasion resistance should be considered, and meaningful and comparative clinical studies will be essential.

CONCLUSIONS

Based on the results of the present in vitro study, the following conclusions were drawn:

1. All investigated properties were affected by the type of CAD-CAM restorative material.

2. Alphador had the highest mean values for the modulus of toughness, elastic recovery, and the difference between elastic recovery and modulus of resilience and therefore the highest capacity to dissipate destructive fracture energy.
3. Lower mean values of the modulus of toughness and elastic recovery account for the inferior energy dissipation capacities of Lava Plus as compared with Alphador.
4. All modulus of toughness values of the polymer-based CAD-CAM materials and Lava Plus were significantly higher than those of IPS e.max CAD, VITA ENAMIC, and CEREC Blocs, implying a higher capacity to consume destructive energy before material rupture occurs.
5. From an energy dissipation capacity point of view, polymer-based CAD-CAM restorative materials seem to be clinically promising, with considerable robustness and the potential for improvement for additional indications.

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