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RESEARCH AND EDUCATION

Effect of tooth substrate and porcelain thickness on porcelain veneer failure loads in vitro

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ABSTRACT

Statement of problem. Bonded porcelain veneers are widely used esthetic restorations. High success and survival rates have been reported, but failures do occur. Fractures are the commonest failure mode. Minimally invasive or thin veneers have gained popularity. Increased enamel and porcelain thickness improve the strength of veneers bonded to enamel, but less is known about dentin or mixed substrates.

Purpose. The purpose of this in vitro study was to measure the influences of tooth substrate type (all-enamel, all-dentin, or half-dentin-half-enamel) and veneer thickness on the loads needed to cause initial and catastrophic porcelain veneer failure.

Material and methods. Model discoid porcelain veneer specimens of varying thicknesses were bonded to the flattened facial surfaces of incisors with different enamel and dentin tooth substrates, artificially aged, and loaded to failure with a small sphere. Initial and catastrophic fracture events were identified and analyzed statistically and fractographically.

Results. Fracture events included initial Hertzian cracks, intermediate radial cracks, and catastrophic gross failure. All specimens retained some porcelain after catastrophic failure. Cement failure occurred at the cement–porcelain interface not at the cement–tooth interface. Porcelain veneers bonded to enamel were substantially stronger and more damage-tolerant than those bonded to dentin or mixed substrates. Increased porcelain thickness substantially raised the loads to catastrophic failure on enamel substrates but only moderately raised the loads to catastrophic failure on dentin or mixed substrates. The veneers bonded to half-dentin-half-enamel behaved remarkably like those bonded wholly to dentin.

Conclusions. Porcelain veneers bonded to enamel were substantially stronger and more damage-tolerant than those bonded to dentin or half-enamel-half dentin. (J Prosthet Dent 2017;■:■-■)

Bonded porcelain veneers have been long and widely used to address esthetic dental problems.[1-4] Compared with complete crowns, preparation for veneers preserves precious tooth structure, notably enamel and the dentinoenamel junction.[5-7] The clinical success of porcelain veneers has been attributed to a durable bond between 2 materials of similar elastic moduli, that is, porcelain and enamel.[8-12]

Veneer preparation protocols have varied from nonreduction to the extensive.[2,13-29] Enamel, not dentin, has generally been recognized as the optimal substrate.[10] However, preparations partly involving dentin are extremely common.[23,25,30] Mean enamel thicknesses in the cervical third of incisors range between 0.3 and 0.4 mm, tapering to zero at the cementoenamel junction.[31] Some authorities have advocated deep preparations or preparations of at least 0.5 mm to accommodate porcelain thickness.[4-17,19-33]

Cervical exposure of dentin may be inevitable with anything other than minimal preparation depth. Furthermore, dentists tend to be inconsistent in the amount of tooth reduction achieved.[34,35] Even when

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Clinical Implications

For a bonded feldspathic porcelain veneer model system, the importance of maximizing the enamel area after preparation is paramount. Increased veneer thickness improves strength but to a much lesser extent. Dentists are strongly advised to maintain as much enamel surface area as possible during tooth preparation; much closer to 100% than 50% should remain.

conservative preparation is desired, excessive preparation and substantial exposure of dentin may occur.[34,35]

Expert opinions have attributed failure to exposed dentin.[31,36-38] Clinical reports often show photographs of failed veneers on more extensive tooth preparations involving dentin.[39-41] Exposed dentin is considered undesirable because bonding to dentin is less predictable than to enamel,[4,10,25,31,36,42] because enamel better matches the elastic modulus of feldspathic porcelain[4,9,36] and because porcelain bonded to enamel has a higher load-to-failure than when bonded to dentin.[4,43] Likewise, failures have been attributed to the cementation of veneers to underlying composite resin restorations.[9,25,39,44] Marginal staining is a common complication of porcelain veneers, often appearing some years after placement in cervical areas,[25,37,40,45] where dentin is most likely to have been exposed during preparation.[23,39]

Several veneer preparation studies have indicated that much dentin is exposed during routine preparation. One standardized technique using 0.5-mm-deep grooves resulted in dentin being exposed on 50% of the preparation area.[46] Another study showed wide variance, with the area of dentin exposure varying from 0% to 83% among different preparation designs.[34] Dentin exposure is more common in cervical areas.[35] Friedman[38] has suggested that the best long-term retention for porcelain veneers occurs when 50% or more of the supporting substrate is enamel. Criteria for inclusion in some research reports included veneer situations where more than 50% of enamel remained for bonding and where more than 50% of total tooth structure remained.[36,44,47]

A review of the literature on porcelain veneer outcomes has reported reasonable evidence that veneer preparation into dentin adversely affects survival.[48] Many authors have also attributed failure to exposed dentin.[9,25,30,36,39,40,44,49] One analysis indicated that porcelain veneers with margins in dentin or with dentin exposure were more than 10-fold more likely to fail than those completely bonded to enamel.[30] Another analysis of veneer failures indicated that veneers cemented to dentin substrates underwent different timelines and modes than those cemented to enamel substrates.[36]

Clinical fracture modes for bonded porcelain veneers include longitudinal or radial cracking; chipping or fracturing in incisal areas; areas of occlusal contact; and areas close to the veneer margins, with chipping or semicircular, half-moon-shaped fractures,[16,17,21,25,32,36,39-41,50] Fractures have been ascribed to the application of flexural tensile stresses to porcelain veneers by functional loading.[25,36,37,39]

A recent in vitro study of model porcelain veneers cemented to enamel determined that increased enamel thickness and/or increased porcelain thickness profoundly raised the failure loads necessary to cause catastrophic fracture.[12] Another study of model porcelain plate crowns bonded to dentin found that porcelain thickness influenced fracture resistance.[51]

Hence, the effects of both tooth substrate and porcelain thickness on the fracture resistance of veneers warrant investigation.[31] The purpose of this study was to measure the influence of tooth substrate type (all-enamel, all-dentin, or half-dentin-half-enamel) and veneer thickness on the loads needed to cause initial and catastrophic porcelain veneer failure. The null hypotheses were that substrate type and veneer thickness would not influence the loads needed to produce catastrophic failure.

MATERIAL AND METHODS

Disk-shaped feldspathic porcelain veneer specimens were fabricated for maxillary incisors and measured as previously described.[12] Veneers of different thickness were assigned to teeth by using a random numbers table. After being used as all-enamel substrates, teeth were refinished to provide half-enamel-half-dentin substrates and subsequently to provide all-dentin substrates. Porcelain veneers were etched with 9.5% buffered hydrofluoric acid gel (Porcelain Etchant; Bisco) for 90 seconds, rinsed with water, and thoroughly air dried. Two coats of a 2-part silane coupling agent (Bis-Silane; Bisco) were applied and dried 30 seconds later. The teeth were cleaned with a pumice slurry, rinsed, and dried. The enamel was etched with 32% phosphoric acid with benzalkonium chloride (UNI-Etch; Bisco) for 15 seconds, rinsed thoroughly, and dried lightly, leaving the enamel visibly moist. Two coats of a 2-part dual-polymerized bonding agent (All-Bond3; Bisco) were applied for the all-enamel group; 3 coats were applied for the half-enamel-half dentin group and the all-dentin group. The specimens were air dried for 12 seconds to evaporate solvents and light polymerized for 10 seconds. Thin layers of a bonding resin

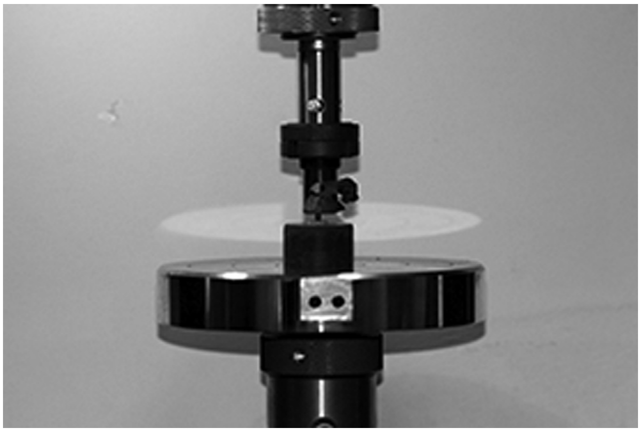

Figure 1. Experimental arrangement.

(Porcelain Bonding Resin Hema-free unfilled resin; Bisco) were applied to the veneers, which were lined with a light-polymerized veneer cement (Veneer cement, Choice 2; Bisco). The veneers were gently seated and static vertical loads of 2.83 N were applied to standardize seating load and cement layer thickness.[52] Seated veneers were light polymerized (Optilux 500; Kerr Corp) for 4 seconds to tack them in place before excess cement was removed. The veneers were then polymerized circumferentially from their peripheries for 40 seconds before being polymerized from their facial aspects for a further 40 seconds. Bonded specimens were stored and thermocycled as previously described.[12]

Moist specimens were placed onto the platen of a universal testing machine (5966; Instron Corp) with the porcelain uppermost. A tungsten carbide sphere, 1.59 mm in radius, was placed on the center of each model veneer (Fig. 1). The radius of the sphere was somewhat larger than the radius of an incisal edge but smaller than that of a large cusp. This method has been found to produce Hertzian cracking, radial cracking, and catastrophic failure.[12,53,54] The specimens were loaded at a crosshead speed of 0.01 mm/min, and load-time data were recorded until catastrophic failure occurred. Individual fracture events were identified by post hoc analysis of the universal testing machine load-time data files by using a spreadsheet (Excel; Microsoft Corp). A total of 88 specimens were prepared from 30 teeth and tested. Qualitative fractographic analysis was performed using light microscopy.[12] Fracture load was plotted against porcelain thickness. Regression analysis was used to identify the simple linear equations relating fracture load to thickness, and correlation coefficients, R^2, were calculated.

Pairwise comparisons of regression plots were made by using formal tests of hypotheses concerning the slope

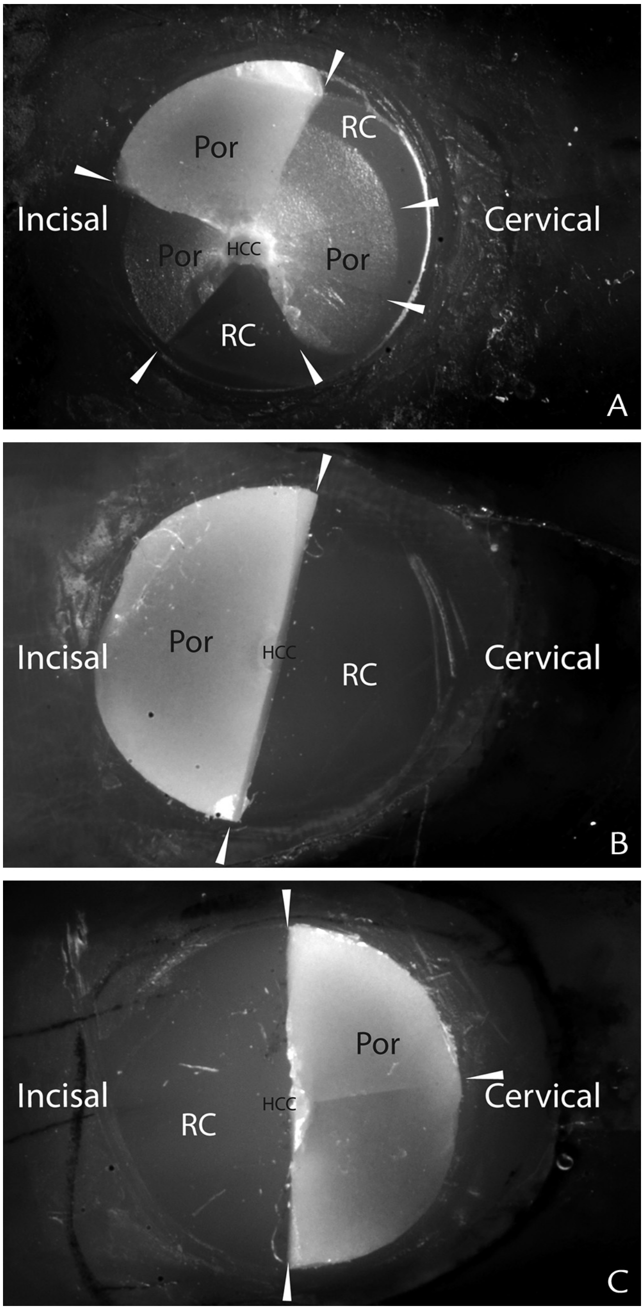

Figure 2. Facial view of porcelain veneer (original magnification ×1; approximate diameter, 5.45 mm). A, All-enamel substrate with initial central Hertzian cone crack (HCC) and intermediate radial cracks (white arrows) after catastrophic failure. Much porcelain (Por) remained bonded to enamel; some resin cement (RC) is visible. B, Half-enamel-half-dentin substrate with initial central HCC and intermediate radial cracks (white arrows) after catastrophic failure. Half of Por remained bonded to enamel; some RC overlaid dentin. C, All-dentin substrate with initial central HCC and intermediate radial cracks (white arrows) after catastrophic failure. Half of Por remained bonded to dentin; some RC overlaid dentin.

and intercept of each regression (Chow test) to determine whether the true coefficients in 2 linear regressions on different data sets were equal. The separate regression results were replicated by estimating the augmented models described below. Denoting each regression by using the notation

$$Y\_i=\beta_1 + \beta_2 X\_i + u\_i, \quad (1)$$

the original regressions were augmented by adding the data from a second plot, along with 2 new parameters. The first, β_3, served as the coefficient on an indicator variable that equals 0 for observations from the original plot and 1 for observations from the added plot. That is, β_3 shifts the intercept from its original location for data from the second plot. In a similar manner, the added parameter, β_4, shifts the slope. Estimates of β_1 and β_2 replicate the original results, because they correspond to the case Di=0; estimates of β_3 and β_4 indicate the change in those estimates needed to reproduce results using only data from the added plot

$$Y\_i=\beta_1 + \beta_2 X\_i + \beta_3 D\_i + \beta_4 D\_i\, X\_i + u\_i. \quad (2)$$

Thus, the joint hypothesis that β_3 and β_4 are zero is equivalent to the hypothesis that the data correspond to a single, common regression line. Such hypotheses were tested using an F test; rejection of a hypothesis means that the plot lines differed.

RESULTS

Porcelain fracture did not occur during cementation, thermal cycling, or storage. However, 1 all-dentin specimen debonded during thermocycling. The bonding failure occurred at the cement−veneer interface; this specimen was excluded from further testing and regression analysis.

For the all-enamel specimens, the initial fracture event was the formation of a Hertzian cone crack in the porcelain veneers of all thicknesses (Fig. 2A). In 15 of 30 all-enamel specimens, complete cone cracks continued through the cement and extended into enamel; in another 3 specimens, partial cone cracks extended into enamel. The enamel extensions of the cone cracks varied in depth, but all that reached the dentinoenamel junction were arrested and did not cross into dentin. Intermediate fracture events involved the formation of radial cracks in the veneer before final catastrophic failure (Fig 2A). Radial cracks appeared to originate from sites on the internal intaglio surface involved in the Hertzian cracks, rather than from natural flaws directly under the blunt loading point. Radial cracks extended from porcelain into enamel, or vice versa, but none crossed the dentinoenamel junction into dentin. A single intermediate event was capable of producing multiple radial cracks. In all specimens, some porcelain remained bonded to enamel even after catastrophic failure.

The half-enamel-half-dentin specimens displayed similar courses, initial surface Hertzian cone cracking followed by intermediate radial cracking from the internal intaglio surface and final catastrophic failure (Fig. 2B). These Hertzian cone cracks rarely penetrated enamel. For 27 of 29 half-enamel-half-dentin specimens, approximately half of the porcelain veneer remained bonded to the substrate after catastrophic failure. The bulk of each remaining fragment remained bonded to enamel, not dentin. Specimens in this group typically suffered a single diametral crack approximately overlying the border between enamel and dentin substrates.

The all-dentin specimens also displayed courses similar to the all-enamel and half-enamel-half-dentin groups (Fig. 2C). Of the 29 all-dentin specimens tested, 20 failed, with approximately one-third to half of the porcelain veneer remaining bonded to the substrate after catastrophic failure; 9 specimens completely debonded; and 1 catastrophically fractured specimen remained bonded. In all cases, a single intermediate event produced multiple radial cracks, and bond failure occurred at the cement veneer interface with cement remaining on the exposed dentin.

Tooth substrate had a distinct effect on initial porcelain veneer fracture events. The linear equations produced by regression analysis for the influence of enamel thickness on the initial cone crack were y=−131 × +402 (R^2=.04) for all-enamel; y=69 × +140 (R^2=.1) for half-enamel-half-dentin; and y=258 × −72 (R^2=.9) for all-dentin specimens. Several trends are clear. First, the intercept on the y axis, the load needed to initiate fracture is highest for all-enamel, intermediate for half-enamel-half-dentin, and lowest for all-dentin substrates. Second, the slope of the initial fracture plot changed sign, once dentin became a partial or complete substrate, a reflection of increased substrate flexure. For all-enamel substrates, increased porcelain thickness resulted in decreased loads needed to cause initial fracture; whereas once dentin was introduced as a partial or complete substrate, increased porcelain thickness resulted in increased loads needed to cause initial fracture (Fig. 3). Pairwise testing by type of tooth substrate type indicated that all regression plots for fracture initiation differed from one another (Table 1).

Tooth substrate had a marked effect on catastrophic porcelain veneer fracture events (Fig. 3). The linear equations produced by regression analysis for the influence of enamel thickness on catastrophic fracture were y=723 × +517 (R^2=.5) for all-enamel; y=295 × +162 (R^2=.3) for half-enamel-half-dentin; and y=251 × +189 (R^2=.1) for all-dentin specimens. Several trends are clear. The all-enamel substrate produced much larger y-axis intercepts than did the half-dentin-half-enamel and for all-dentin substrates. The all-enamel veneers were approximately 3 times better able to resist catastrophic failure than the half-enamel-half-dentin and all dentin veneers. The loads needed to cause the catastrophic failure of veneers placed on the all-enamel substrate

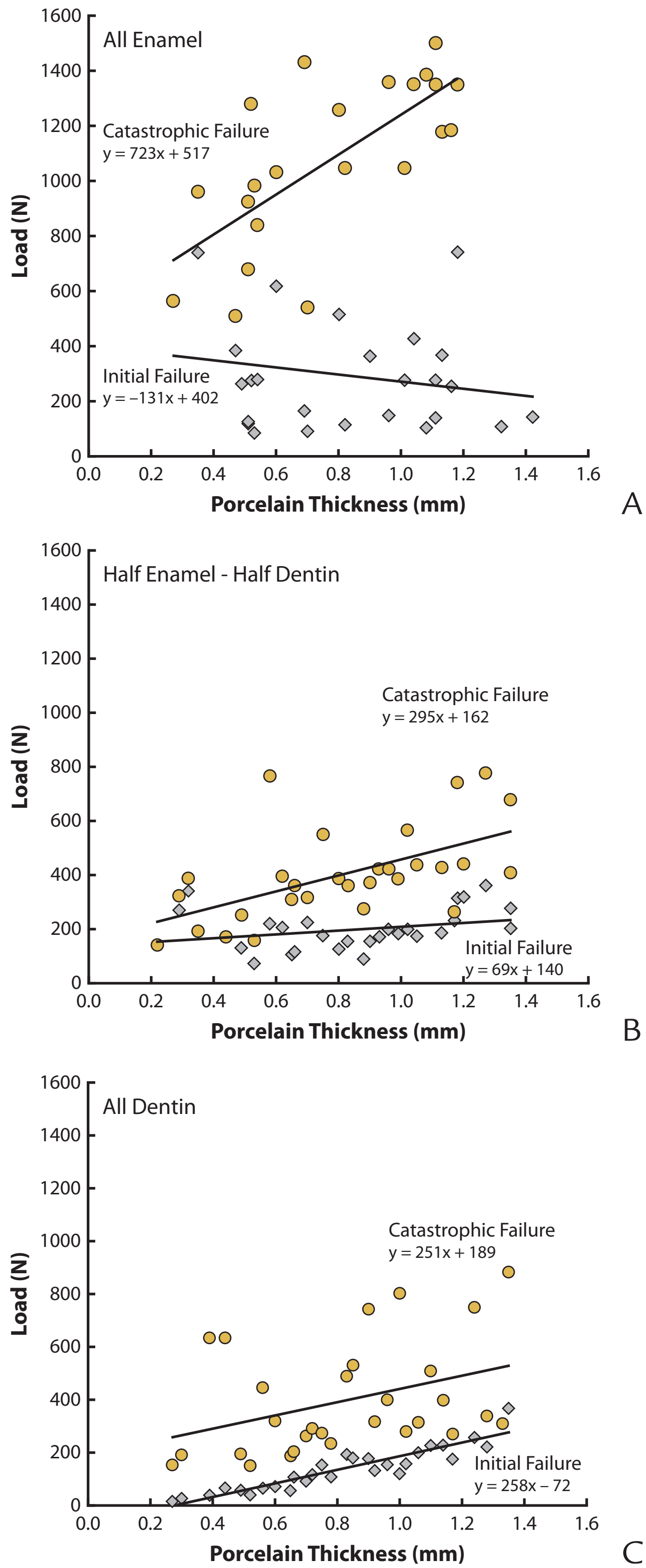

Figure 3. Plot of fracture load against porcelain veneer thickness. Initial Hertzian surface cracks are plotted as light blue diamonds, intermediate radial cracks as small black dot, and final catastrophic failures as large blue circles. Regression lines for initial Hertzian surface cracks and final catastrophic failures plotted. A, All-enamel substrate. B, Half-enamel-half-dentin substrate. C, All-dentin substrate.

Table 1. Pairwise comparisons of regression plot lines

Fracture Initiation of Porcelain Veneers	*P* Value
All-enamel to half-dentin-half-enamel	.01
All-enamel to all-dentin	<.001
Half-dentin-half-enamel to all-dentin	<.001
Catastrophic Failure of Porcelain Veneers	
All-enamel to half-dentin-half-enamel	<.001
All-enamel to all-dentin	<.001
Half-dentin-half-enamel to all-dentin	.8

were much more sensitive to thickness than for partial or complete dentin substrates. The equations describing catastrophic failure for the half-enamel-half-dentin and all-dentin groups were remarkably alike (see above and Fig. 3B, C). Pairwise testing by tooth substrate type for catastrophic failure indicated that the regression plot for all-enamel differed from those for half-enamel-half-dentin and from all-dentin; however, the plots for half-enamel-half-dentin did not differ from that of all-dentin (Table 1).

Increasing porcelain thickness tended to slightly decrease the loads needed to form initial cone cracks for all-enamel, whereas, it tended to slightly increase the loads needed to form initial cone cracks for half-enamel-half-dentin and all-dentin substrates (Fig. 3). Increasing porcelain thickness tended to substantially increase the loads needed to produce catastrophic failure for all-enamel substrates, whereas, it tended to increase only moderately the loads needed to produce catastrophic failure for both half-dentin-half-enamel and all dentin substrates (Fig. 3). Increased porcelain thickness did not compensate for lack of enamel area.

DISCUSSION

The null hypotheses were rejected: both substrate type and porcelain thickness influenced the loads needed to produce catastrophic failure of model porcelain veneers. Overall, the results of this study suggest that retaining the maximal amount of enamel surface area after tooth preparation is paramount and that thicker veneers will also better resist catastrophic failure.

The results of this study demonstrated that veneer preparations on half-enamel-half-dentin behaved essentially like those placed on all-dentin substrates with respect to catastrophic failure loads (Fig. 3). These data dispel the notion that having 50% enamel remain after preparation is in any way comparable to an all-enamel preparation; instead, it was directly comparable to an all-dentin preparation. Dentists are strongly advised to maintain as much enamel surface area as possible during tooth preparation, much closer to 100% than 50%.

With respect to initial failure, the half-enamel-half-dentin substrate was intermediate between the all-enamel and all-dentin substrates (Fig. 3). Initial failure is of less consequence than catastrophic failure to patients. The spread between initial failure and catastrophic failure was large for the all-enamel substrate, whereas it was small for the half-enamel-half-dentin and all-dentin substrates. Hence, veneers cemented to enamel were several times more damage-tolerant (the difference between the plots lines for initial and catastrophic failure) than those cemented to half-enamel-half-dentin or all-dentin substrates.

The beneficial effect of increased veneer thickness on catastrophic failure was much more pronounced when an all-enamel substrate was used but was still present, to a much lesser extent, for half-enamel-half-dentin and all dentin groups (see regression line slopes) (Fig. 3).

Loads needed to produce initial failure of thinner veneers bonded to dentin were low (Fig. 3C). Should veneers be cemented to dentin, porcelain thickness should be maximized. However, 1.4-mm-thick veneers bonded to the half-enamel-half-dentin and all-dentin substrates were weaker than 0.2-mm veneers bonded to an all-enamel substrate (Fig. 3).

These data reflected the performance of feldspathic porcelain, which was chosen because it has been widely used, requires only ordinary porcelain ovens, and allows internal layering and characterization. However, stronger, tougher, and stiffer glass–ceramic materials are also used to make veneers, but these monolithic materials do not facilitate internal characterization.

Initial reports on porcelain veneers in the 1980s advised a nonreduction technique, preserving the entire enamel thickness wherever it had not previously been damaged by caries or prior restoration.[1-3,18] The nonreduction technique largely fell out of favor as nonreduction veneers were generally considered excessively contoured and unsightly, especially in their gingival emergence profiles. Furthermore, a clear finish line can guide the technician during fabrication and the dentist during cementation. The results of this study and of a prior study of the effects of enamel and porcelain thickness strongly support the concept of nonreduction veneers from the perspective of resistance to catastrophic failure.[12] Minimal reduction may be a more reasonable approach. Ultraconservative cervical reduction between 0.1 and 0.2 mm should be considered; this would typically preserve between 0.1 and 0.3 mm of cervical enamel thickness. However, this is a demanding clinical technique, challenging the technician with respect to opacity management, shade management, and the practicality of finishing such a thin delicate restoration. A thicker veneer could be cemented and then thinned by the dentist and carefully polished, but this is difficult and adds to the risk of traumatizing the gingiva. Another possibility is to terminate the veneer margin short of the cementoenamel junction, but this may be unsightly. Still, the failure of a porcelain veneer is of much lesser consequence than the failure of a complete crown. There are no easy answers, but the preservation of enamel area and thickness are paramount (Fig. 3).[12]

Caution must be exercised when extrapolating in vitro data from this study to the more complex clinical situation, even though the resultant failure modes were comparable to those found in vivo.[12] Key limitations include the substitution of storage and thermocycling for years of clinical use, the simple discoid geometry of the model veneers, and the mode of delivering a quasi-static load to the model veneers. Nothing can substitute for meticulous long-term, controlled clinical investigation of multiple predictive variables, but the authors are unaware of such studies. Until such data are available, expert opinion and in vitro data may assist in the understanding and avoidance of potential hazards.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. Porcelain veneers bonded to enamel were substantially stronger and more damage-tolerant than those bonded to dentin or mixed substrates.
2. Veneers on half-enamel-half-dentin substrates were no more resistant to catastrophic failure than those placed completely on dentin.
3. Increased porcelain thickness substantially raised the loads to catastrophic failure on all-enamel substrates.
4. Increased porcelain thickness only moderately raised the loads to catastrophic failure on all-dentin or half-enamel-half-dentin substrates.

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