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Microtensile Bond Strength and Impact Energy of Fracture of CAD-Veneered Zirconia Restorations

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Keywords
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Abstract

Purpose: With state-of-the-art CAD/CAM technology, the fabrication of large and complex zirconia frameworks is just a click away. On the other hand, veneering of the frameworks is still operator-dependent. The aim of this work was to evaluate CAD veneering of zirconia restorations in terms of zirconia veneer bond strength and impact energy of fracture in a step towards complete automation of the fabrication process.
Materials and Methods: A new CAD/CAM system was used to fabricate a resin replica of the esthetic ceramic required to veneer a zirconia framework. The replica was seated on the zirconia framework and further processed using press-on technology. The bond strength between zirconia and the CAD veneer was evaluated using microtensile bond strength test. The impact energy of fracture of the specimens was also investigated. Manually layered zirconia specimens served as a control ($\alpha = 0.05$).
Results: There was no significant difference in the microtensile bond strength between zirconia and either of the used veneers (39 MPa). Even though the impact energy of fracture of the CAD-veneered and manually layered specimens was almost identical (0.13 J), the former demonstrated a cohesive fracture of the veneer, while the latter failed by delamination of the veneer ceramic.
Conclusion: CAD veneering is a reliable method for veneering zirconia restorations.

The introduction of yttrium partially stabilized tetragonal zirconia polycrystal (Y-TZP) to the dental field opened the design and application limits of all-ceramic restorations with greater confidence and success rates. With its superior mechanical properties, three or four-unit fixed partial dentures (FPDs) are no longer the safe limit for the construction of core veneered all-ceramic restorations.[1]

Combined with CAD/CAM technology, the design and fabrication of zirconia frameworks have became relatively simple procedures. Advanced scanning devices allow direct construction of 3D digital images of not only the prepared model, but also of the opposing dentition; thus the design of the zirconia framework can be optimized to provide a better support for the overlaying veneer ceramic. Additionally, in the CAD phase, computer simulations can be carried out to optimize the connector dimensions and location, provide adequate thickness of the framework, and to improve the marginal design.[2]

As zirconia is relatively opaque and monochromatic in color, a layer of veneering ceramic is built on to provide the restoration with the required esthetics. While manual layering of the veneer ceramic gives the dental ceramist full control over the expected color and shape, it is still in principle a lengthy and a time-consuming process. Even with maximum care and attention, structural defects, such as air bubbles, voids, and micro-gaps at the core–veneer interface remain unavoidable. These structural defects act as stress concentration sites where crack initiation and propagation are highly expected, leaving the veneered restoration susceptible to delamination or chipping.[3]

A new category of veneering ceramics makes use of the lost-wax technique where the required shape and form of the veneer ceramic is built using wax modulation over the zirconia framework and processed by pressing the heated ceramic veneer in a low viscosity state over the zirconia framework. With this technique, the complex anatomical forms of dental restorations, which are difficult to control using manual layering technique, are easily achieved. In addition, the zirconia framework is subjected only to one controlled firing cycle, reducing the possibility of thermal fatigue. Furthermore, the press-on technique uses prefabricated ceramic pellets and is performed under controlled temperature, pressure, and vacuum, all of which result in less incorporation of structural defects in the veneer ceramic.[4]

As a press-on veneer has a monochromatic color, this technique was basically designed for posterior restorations. To overcome this limitation, the double veneering technique could be used. The enamel representing the layer of the press-on veneer is taken into account in the wax design or ground back after pressing and rebuilt using manually layered enamel ceramic with the required shade and color; thus, both advantages of manual layering and press-on techniques could be combined in one restoration.[5] Nevertheless, the manual construction of the wax modulation of the veneer ceramic requires a longer time and much more effort than the computerized production of zirconia frameworks. Furthermore, the wax design still remains operator-dependent, and the factor of human error remains. A point worth considering is that building a veneer ceramic with the required anatomical form that is also in occlusal and gnathologic harmony with the neighboring and opposing dentition and with the jaw movements of the patient is not an easy task, especially when using ceramic slurries.

CAD/CAM technology might offer an option to fabricate a CAD resin replica of the required veneer ceramic that is in anatomical and functional relationship with the surrounding dentition. The resin replica could then be seated on the zirconia framework and processed according to the instructions of the press-on technique. The aim of this work was to evaluate CAD veneering of zirconia frameworks in terms of zirconia veneer bond strength and impact energy of fracture.

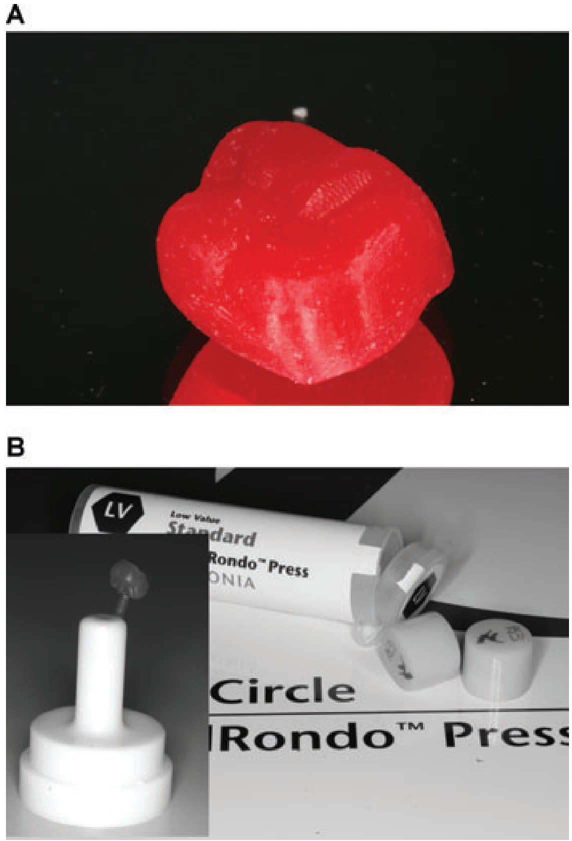

Figure 1 (A) Milled carving block demonstrating the outer surfaces of the CAD veneer replica. Notice presence of milling trace lines on the surface. Final surface finish and small corrections are possible before pressing. (B) After burning off the wax pattern, the ceramic pellets with the selected shade are pre-heated and inserted in the casting ring. After reaching the required temperature, the molten ceramic is pressed to fill the space previously occupied by the resin replica.

Materials and methods

Preparation of the zirconia frameworks

Maxillary and mandibular teaching models were selected, and a mandibular lower right molar was prepared to receive a full coverage all-ceramic restoration. The preparation accounted for 1.5-mm occlusal clearance, 1-mm axial reduction, and a 0.5-mm round chamfer finish line. Both arches were then laser-scanned, and a 3D digital model was constructed, after which a 0.5-mm thick zirconia coping was designed based on the data inserted in the computer system (CYRTINA® system, Oratio B.V., Zwaag, The Netherlands).[6] Computer simulations accounted for determination of the ideal insertion path and optimal occlusal relationship with the antagonist teeth. CAD/CAM zirconia milling blocks were then ground to the required dimension (BioZyram, Shade Z3, Lot no. 300098, Oratio B.V.) and sintered according to manufacturer recommendations (HT 04/16, Nabertherm GmbH, Lilienthal, Germany). Thirty-six zirconia copings were produced.

Design and processing of the veneer ceramic

A sintered zirconia coping was placed on the prepared model, which was scanned again. The required form of the veneer ceramic, taking into account the occlusal and proximal contacts and the emergence profile of the cervical region, was digitally constructed. The occlusal contacts were designed according to digital articulation simulations performed by the software and following the occlusal criteria given by the operator.[2] On average, four to five centric occlusal contact points were reproduced. The data obtained were used to mill a block of carving resin with a melting point of 116°C (Matt Carving Resin CA2763; Du-Matt Corp., Guttenberg, NJ) to the required form (Fig 1A). The CAD veneer was milled with 2 and 1 mm hard metal burs, which resulted in a relatively smooth surface after which the resin veneer was placed over the zirconia coping and processed following the instructions of the press-on technique (NobelRondo Press Zirconia, A3.5, Nobel Biocare, Goteborg, Sweden).[4] Each resin replica was seated on its respective zirconia coping, and the margins were sealed with a hot instrument. A 2 mm wax sprue was attached to the buccal cusps of every veneer replica, and five specimens were attached to the casting plastic ring. A freshly prepared vacuum-mixed investment material was cast to completely fill the casting ring. After completion of the burning time, two pre-heated ceramic pellets were inserted in the casting ring (Fig 1B), followed by an alumina plunger, and the ring was transferred to the press furnace (EP500, Ivoclar Vivadent, Schaan, Liechtenstein), which automatically controls the heating rate, vacuum, and the applied pressure. Eighteen CAD-veneered zirconia restorations were produced.

The other half of the zirconia frameworks were manually layered using a newly released ceramic veneer system without the application of a liner material (NobelRondo Zirconia, A3.5). The frameworks were first coated with a thin wash layer of ceramic slurry and sintered according to the manufacturer's instructions (Austromat 3001, Dekema Dental-Keramiköfen GmbH & Co, Frielassing, Germany). The frameworks were then individually placed in a silicone mold, which helped build up the dentine ceramic layer with the same thickness and external dimensions resembling the CAD-veneered specimens.

Impact energy of fracture of the zirconia veneered restorations[7]

The veneered zirconia crowns were cemented on composite resin tooth replicas (Filtek Z250, shade A1, 3M ESPE, St. Paul, MN) using a light-polymerized adhesive resin (Panavia F 2.0, Kuraray Co, Tokyo, Japan). The cemented restorations were attached to a modified, calibrated impact machine, which delivered impact energy to a stainless steel ball (4-mm diameter) located at the center of the occlusal surface of the restorations. The impact energy was calculated using the relevant formulas. Data were corrected for the energy lost in vibration and friction. Failure was classified as either cohesive chipping of the veneer, interfacial failure resulting in delamination of the veneer ceramic from intact zirconia framework, or fracture of both the veneer ceramic and the underlying framework.

Evaluation of the zirconia veneer bond strength and interface quality

Sixteen zirconia discs (19.4-mm diameter, 3-mm thick) were prepared by cutting and sintering zirconia milling blocks (Cercon Base, Degudent, GmbH, Hanau-Wolfgang, Germany). Half the discs were veneered with discs made of the same carving resin and were processed as previously described for the production of the CAD-veneered zirconia restorations. The other half was manually layered using a special mold. The same press-on and manually layered veneer ceramics were used as for the contruction of the crown specimens.

The bi-layered specimens were cut into microbars (6 mm × 1 mm × 1 mm) using a precision cutting instrument (Isomet 1000, Buehler, Lake Bluff, IL) and a diamond-coated cutting disc (Diamond Wafering Blade, No 11-4276, Buehler). The locations of the cuts were controlled using a traveling stage and a horizontally placed digital micrometer (ID-C1508; Mitutoyo Corporation, Utsunomiya, Japan).

Each microbar was bonded to a stainless steel attachment unit using a light-polymerized adhesive resin (Clearfil SE, Kuraray Co.) taking care to center the zirconia–veneer interface at the free space between the two plates of the attachment unit. The zirconia veneer microtensile bond strength (MPa) was measured by applying axial load (N) over the bonded area (1 mm^2) using a calibrated universal testing machine (Instron 6022, Instron Limited, High Wycombe, UK). The computer-controlled crosshead speed (1 mm/min) was monitored using a digital micrometer (Millitron, Feinpruf Perthen GmbH, Gottingen, Germany). Eighteen microbars were tested for the two groups.

Additionally, zirconia veneer sections were obtained by slicing the zirconia–veneered specimens and polishing the sections with silicon carbide paper (Microcut, Buehler) using 400, 600, 800, and 1200 grits on a rotating metallographic polishing device (Ecomet, Buehler) under water cooling and fixed load (250 g). The polished sections were cleaned, dried, gold sputter coated (S150B sputter coater, Edwards, Crawly, UK), and examined under a scanning electron microscope (XL 20, Philips, Eindhoven, The Netherlands).

Statistics

Independent samples *t*-test was used to analyze the data. Power analysis indicated that based on the sample size (N = 18), the chosen level of significance ($\alpha = 0.05$), and a large effect size ($F = 0.4$), the selected test of choice had relatively adequate power ($1 - \beta = 0.7$) to detect statistical differences that could be interpreted in terms of clinical performance.[8]

Results

There was no statistically significant difference ($t = 0.51$, $p < 0.6$) in the microtensile bond strength test or in the impact energy of fracture between CAD-veneered (38.6 ± 6 MPa and 0.131 ± 0.011 J, respectively) and manually layered zirconia restorations (39 ± 8 MPa and 0.131 ± 0.01 J, respectively).

Cross-section SEM examination revealed good adaptation and contact between the CAD veneer and zirconia in contrast to the layered veneer specimens, which sometimes demonstrated the presence of air bubbles (10-μm diameter) and micro-gaps at the zirconia–veneer interface. SEM examination of the fractured crown specimens revealed different fracture mechanics between CAD and layered veneer ceramics. CAD-veneered zirconia specimens fractured by chipping of a small part of the veneer ceramic under the impact area, while the restoration remained structurally intact (Fig 2). Layered zirconia specimens demonstrated delamination of the veneer ceramic, exposing the surface of the underlying zirconia framework (Fig 3). Additionally, occlusally originated cracks were occasionally observed to deflect and to propagate at the zirconia–veneer

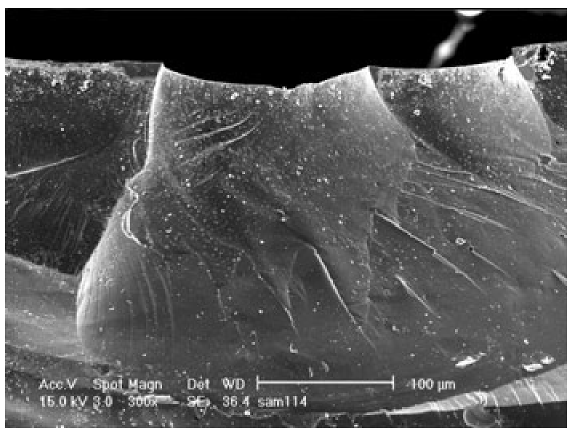

Figure 2 SEM image, 300×, chipped CAD veneer ceramic under impact area demonstrating classical features of brittle fracture.

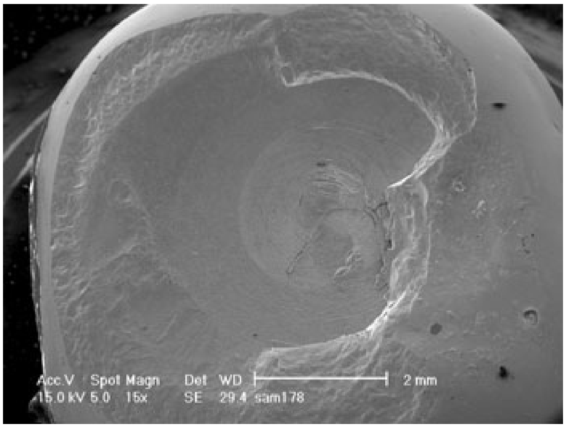

Figure 3 SEM image, 15×, demonstrating delamination of layered veneer ceramic from intact zirconia framework after impact testing.

interface where structural defects as air bubbles and gaps were observed (Fig 4A). On the other hand, good wetting between zirconia and the press veneer was observed (Fig 4B). The zirconia framework of two manually layered specimens was fractured, and the fracture origin was located at the zirconia–veneer interface (Fig 5). The previous data are summarized in Table 1.

Discussion

In this study, two important parameters were selected as an indication of the expected performance of zirconia-veneered crown restorations. The impact energy of fracture of the specimens was selected in place of the traditional fracture strength test, because it produces fracture patterns resembling those obtained from clinical failures, while in most cases fracture strength tests produce cone cracks due to crushing of the veneer ceramic under the loading indenter. In a previous study, it was observed that fast loading of core-veneered all-ceramic crown restorations decreased the percentage of formation of cone cracks and produced other failure patterns pertinent to clinical failure, such as radial cracks and core–veneer interface fractures.[7] While the observed impact energy of fracture of the tested specimens could not be directly compared to the nature of stresses generated during a masticatory cycle, it shed some light on the expected performance of zirconia-veneered restorations, especially when subjected to fast loading. Additionally, it could predict possible failure mechanisms, considering the brittle nature of both zirconia and, in particular, its veneering ceramics.

The second important parameter is the zirconia veneer bond strength. For the layered restoration to gain the full benefit of the underlying core material, the bond between the weaker ceramic and the stronger framework must be of a certain minimum value and toughness to allow proper transfer of loading stresses between the two materials. During mastication, the restoration receives functional stresses, which induce a sort of temporary deformation of the restoration and result in the generation of

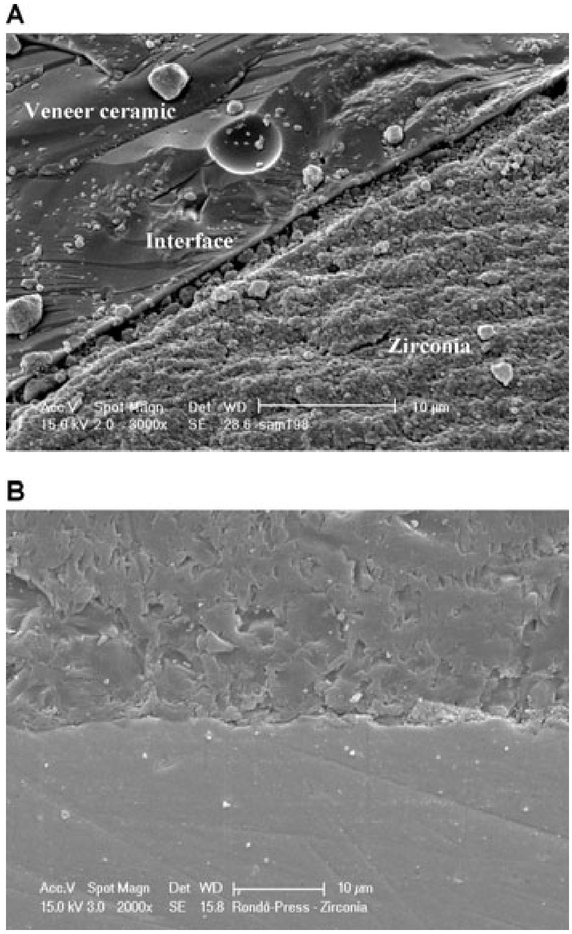

Figure 4 (A) SEM image, 3000×, demonstrating deflection of an occlusally originated crack at zirconia-layered veneer interface. Notice the presence of air bubble in this region. (B) SEM image, 2000×, demonstrating good wetting between the pressed ceramic and zirconia. As pressing was conducted under pressure and vacuum, no air bubbles or voids were observed at the interface or in the bulk of the ceramic.

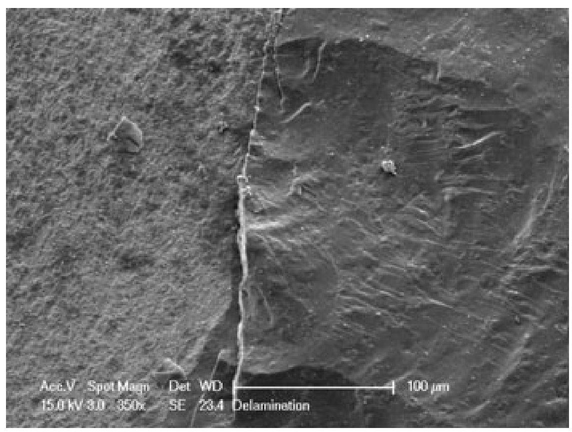

Figure 5 SEM image, 350×, demonstrating zirconia-layered veneer interface as the fracture initiation site.

Table 1 Microtensile bond strength values, impact energy of fracture, and associated fracture type of CAD-veneered and layered zirconia specimens

	MTBS (MPa)	Impact strength (J)
CAD-veneered zirconia	38.8 ± 6 100% cohesive	0.131 ± 0.01 100% cohesive
Layered veneer zirconia	39 ± 8 50% interfacial	0.131 ± 0.1 78% interfacial

For impact energy of fracture, chipping of the veneer ceramic was considered as cohesive failure, and delamination was classified as interfacial failure.

strain energy, which becomes stored in the system. During unloading, the restoration elastically recovers to its original shape, and the stored energy is released. With cyclic loading, the interface between zirconia and the veneer ceramic must resist these changes, and this is where the bond between the two materials comes into function.[3]

Several test approaches, such as shear bond strength and 3- or 4-point flexure, were previously selected for measuring core veneer bond strength. A common disadvantage of these approaches is that they require a relatively large specimen size, and in the case of ceramic materials, this would result in higher incorporation of structural flaws, which lead to premature failure of the specimens before the bond strength level is reached. Additionally, the inhomogeneous stress distribution in these tests results in cohesive failure of the veneer ceramic, giving a misleading feeling of a superior core veneer bond strength.[9–11] Direct advantages of the microtensile bond strength test are that it requires much smaller specimen dimensions where the loading stresses are perpendicular to the interface; thus failure becomes directly a function of the tested bond strength. On the contrary, this method subjects the zirconia–veneer interface to direct tension, a state that rarely occurs during functional loading, where the interface is subjected to different forces that change in magnitude and in direction. Nevertheless, a weak zirconia veneer microtensile bond strength would suggest a higher probability of delamination failure, especially under the influence of fatigue and in the presence of water.

It was previously reported that press-on veneer ceramics had higher zirconia-veneer bond strength than many available layering ceramics. This superior bond could be attributed to many of the attractive properties of the press-on technology, which is performed under controlled conditions, resulting in less incorporation of structural defects, improved wetting of zirconia surface by the molten pressed ceramic, and less incorporation of air bubbles, which are known to dramatically affect the strength of the veneer ceramic and its bond strength to the underlying framework material.[4,12,13] On the other hand, preparing a workable ceramic slurry for manual layering technique is operator-dependent, and variations in the powder:liquid ratio and mixing technique are known to affect the density, the strength, the percentage of structural defects, and the number and size of air bubbles in the fired veneer.[14] Another important factor to consider is that press-on veneers have a thermal expansion coefficient that exactly matches that of zirconia (10.5 μm/°C), while layering ceramics have a slightly lower value (9.3 μm/°C), which could be responsible for the generation of tensile pre-stresses resulting in weakening the zirconia veneer bond strength.[15]

The results of the present study initially indicated identical performance between the CAD-veneered specimens and those that were manually layered. The impact energy of fracture of the test specimens and the zirconia bond strength to both used veneer ceramics were almost identical. On the contrary, SEM of the fractured specimens demonstrated the relationship between the fracture mechanics and the zirconia veneer bond strength and interface quality. During impact testing, the veneer ceramic absorbs the delivered energy and transmits it to the supporting framework. If the total amount of the delivered energy, excluding the energy lost in vibration and friction, exceeds the impact strength of the restoration, fracture results. For CAD-veneered zirconia specimens, the initiated occlusal crack resulted in minor chipping of the veneer ceramic leaving behind an intact restoration (Fig 2). When delivering an equal amount of energy to a manually layered zirconia restoration, the initiated crack was able to cross the full thickness of the veneer ceramic and to deflect and propagate at the zirconia–veneer interface, resulting in delamination failure. All other variables being equal, the presence of structural defects located at the zirconia–veneer interface could greatly increase the chances of delamination failure during function.[16] Naturally enough, the extent of the fracture would have clinical implications regarding the repair method of choice, as small chipping failures could be more easily handled.[17]

As chewing is a dynamic process, the restoration is subjected to dynamic loading forces during every masticatory cycle and could receive impact forces during sudden biting on an unexpected hard object. Comparing the impact energy of fracture of the tested specimens (Table 1) with the dynamic energy delivered during mastication, it seems possible that damage could be introduced to the weaker veneer ceramic.[18] Thus for a single or a short-span FPD restoration, choosing a framework material that establishes a strong bond with the veneer ceramic could be more important than the flexural strength of the framework material itself, for example, a lithium disilicate-reinforced all-ceramic framework. Selection of a polycrystalline framework material, such as zirconia or alumina, would remain indispensable for the construction of restorations subjected to higher flexural stresses.[7]

During impact testing, the framework of only two layered zirconia crowns was fractured. For these two specimens, the crack initiation site was not located on the occlusal surface, but at the zirconia–veneer interface where the crack propagated in occlusal and radial directions (Fig 5). In previous studies that fractographically assessed failure mechanisms of all-ceramic restorations, the core–veneer interface was sometimes reported to be the crack initiation site.[19–21] Such findings shed light on the complex relationship between the design of the restoration, material properties, and the resultant stress distribution in dental restorations. Keep in mind that different laboratory fracture strength tests offer a controlled environment for preparing and testing the mechanical properties of the restorations. Nevertheless, only long-term clinical studies are considered the final judge of the performance of these restorations where fatigue is the most dominant factor contributing to failure.

Aside from mechanical properties, the anatomical quality of all-ceramic restorations remains a considerable factor in the selection of the veneering system of preference. Manual reconstruction of the occlusal relationship, proximal contacts, and the emergence profile of all-ceramic restorations depends basically on the skills of the ceramist.[22] These parameters have a critical role on the clinical performance of the inserted restoration and on the health of the surrounding tissue.[23] With CAD-veneering technology, human error is no longer an influential factor.[6] On the other hand, CAD veneering requires investing a lot of effort to update the CAD/CAM milling software and the milling procedure to enable high quality production of the veneer resin replicas. Additionally, it mandates careful seating of the replicas over the underlying frameworks and adequate sealing of the margins to prevent penetration of the investment material between the framework and the replicas during the pressing procedure.

New techniques emerge every day that promise superior performance, and a common factor between all these techniques is the tendency to shift to CAD/CAM technology with promised higher reliability, accuracy, and precision and reduced cost.[24] The accuracy of the technique, the cost in terms of time and manual labor, the superiority of design in terms of occlusion and proximal relationships, and handling simplicity all remain factors that should be considered during selection of the veneering technique.

Conclusion

Under the conditions of this study, CAD veneering has been shown to be a reliable method for veneering zirconia restorations.

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