Continuing Education

Course Number: 161

The Enigma of the Bilayered Zirconia Restoration

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Upon successful completion of this CE activity 2 CE credit hours may be awarded.
LEARNING OBJECTIVES

After participating in this CE activity, the individual will learn:

1. Certain factors contributing to the controversy regarding zirconia laminated restorations.
2. Requirements for successful zirconia laminated restorations.

ABOUT THE AUTHORS

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Disclosure: Dr. Kay reports no disclosures.

INTRODUCTION

For years, the dental profession has been searching for an aesthetic, strong, and predictable alternative for the PFM restoration. Because of their biocompatibility and aesthetic nature, several different ceramic materials have been tried; however, their brittle nature and minimal flexural strength have limited their use. In the late 1990s, the introduction of partially stabilized zirconia, in combination with CAD/CAM technology, opened a new opportunity for the use of all-ceramic restorations throughout the entire mouth. The partially stabilized zirconia—yttrium-tetragonal zirconia polycrystals (YTZP)—possesses the flexural strength and superior fracture toughness required to allow it to replace the traditional metal core, and when veneered with a compatible ceramic, the requisite aesthetic results are also achievable.

This combination of extremely fracture resistant core and aesthetic porcelain veneer seemed to hold the promise as
the alternative the profession had been seeking; however, clinical studies of medium-term use of these restorations yield conflicting results. 1-5 Although incidences of zirconia core fracture were very rare, incidences of chipping and spalling of the veneered porcelain were reported in some studies at an unacceptable rate, while other studies reported few or no instances of chipping or fracture.

In this article, several controversies and potential causes for inconsistencies in clinical results with zirconia will be discussed. However, a current contention that zirconia material is responsible for these failures could not be supported by the literature.

MATERIAL PROCESSING
Partially stabilized zirconia can exist at room temperature as a multiphase material, with the most important tetragonal phase poised to convert to the more stable monoclinic phase when subjected to stress, either through processing or stress under function. This tetragonal to monoclinic phase change results in a 3% to 5% volume increase in grain size at the tip of an advancing crack, acting to pinch off and retard crack propagation. It is this property (transformational toughening) that gives the material its very high fracture toughness and strength.

However, the fraction of tetragonal phase obtained at room temperature is highly dependent upon the final composition of the material as well as the quality of manufacturer processing. A yttrium content of 3 mol% and a final grain size of 0.8 µm or less are required to promote the metastability of this tetragonal to monoclinic transformation. 6

In addition to the microstructure of the zirconia powder, the physical and mechanical properties of each presintered block are also highly dependent upon the manufacturing process of that block. 7,8 Currently, the vast majority of zirconia cores are shaped from blocks that have not been fully sintered (hardened) and are then placed back into a furnace to complete the sintering process. Variations in the densities of the pressed powders within a given block, defects, and porosity induced during manufacturing, as well as differences in the sintering times and temperatures, fixed partial dentures (FPD) frame support, and even staining procedures used by dental laboratories working with presintered blocks can all affect the properties of each core or frame produced from that block. These variations could prove to have a meaningful effect on the veneered porcelain as well. In addition, the fit of each core is dependent upon the porosity of its block.

The calculated shrinkage expected for cores milled from a given block is based on an average density for the entire block, in spite of areas of differing densities within that block. This discrepancy in shrinkage from cores milled from the same block may result in restorations with varying degrees of accuracy of fit, 9 possibly leading to the instances of cement debonding that have been reported in some clinical studies. Because of the inherent inaccuracies of the presintered process, nonlinear and longer-span FPDs made in this fashion cannot be made to fit accurately, 10 and this is why presinter milled zirconia restorations are not recommended for use in FPDs beyond 4 units in length.

In an effort to avoid the discrepancies and problems associated with postsintering the anisotropic, milled presintered zirconia, some researchers 5 have milled the fully sintered, hot isostatic pressed (HIP’d) isotropic zirconia blocks. These blocks have been subjected to an additional sintering cycle at 1,400°C to 1,500°C in an inert gas atmosphere at 15,000 psi. The resulting material is composed of 100% tetragonal zirconia, has a grain size of 0.5 µm with a total density of 99.99%, and is structurally the same in all 3 dimensions. There is no variation of physical properties among all blocks. No shrinkage is involved during the production of cores from this material, and it has been shown to be more structurally reliable, 11 with a higher fracture resistance than the presintered material. 12 The hard nature of the HIP’d material makes it more difficult and time consuming to machine, however. Consequently, most manufacturers choose to work with and market the less predictable presintered material.

CORE DESIGN AND CERAMIC VENEER
A second source of discrepancy in results among the various clinical studies is the design of the zirconia core. Early CAD software did not provide for incorporation of porcelain veneer supporting features in the underlying core, and it is not surprising that many of the earlier clinical studies reported much higher instances of porcelain spalling (chipping) and debonding than later studies. Subsequent in
vitro studies\textsuperscript{13} substantiated the hypotheses of those clinical researchers who incorporated supportive design features into the core in an attempt to improve the clinical behavior of those restorations.\textsuperscript{5,14,15} Building upon an early finite element analysis study,\textsuperscript{16} one research group has clinically demonstrated that a specific ring structure built into core design (Figures 1 and 2) not only supports the veneering porcelain from shearing forces, but also protects the core from damaging tensile stresses (Figures 3a and 3b) that act to stress the veneer layer.\textsuperscript{5} As a result, all currently used software design programs have incorporated some of these features, as support and stress reduction of the porcelain are recognized as a requirement for a successful all-ceramic bilayered restoration.

Bilayer dental ceramics still exhibit a significant amount of postfired residual stresses; some may be detrimental, while others are beneficial. Aboushelib et al\textsuperscript{17} and Taskonak et al\textsuperscript{18} have demonstrated that residual stresses in a bilayer ceramic composite can strengthen those systems. Some of these stresses are the result of a mismatch of the coefficient of thermal expansion (CTE) between the zirconia and its veneering ceramic. This mismatch should be as small as possible, preferably approximately $1 \times 10^{-6}/^\circ C$ or less, and it is also desirable to have the CTE of the porcelain less than that of the zirconia. This relationship generates strengthening compressive forces on the porcelain at the zirconia surface. Swain\textsuperscript{19} has demonstrated that these compressive forces may extend from this surface to as much as 65\% into the internal surface of a one-mm thick layer of porcelain. Although researchers have studied the role of the CTE mismatch, and studies have been conducted to evaluate the mechanical properties of some of these materials,\textsuperscript{20,21} there are no studies that relate chipping and spalling rates directly to particular brands of porcelain. It has clearly been demonstrated that the failure of porcelain in these restorations is cohesive failure within the porcelain layer itself, not a failure of the porcelain to bond to zirconia.\textsuperscript{22} This is an important consideration in light of the fact that the study by Sailer et al,\textsuperscript{1} often quoted to stress the high incidence of chipping with bilayer restorations, clearly states that the veneering porcelain used in that study was placed on a thimble shaped core and was “prototype” porcelain, recently developed for zirconia.

**PORCELAIN APPLICATION AND COOLING PROTOCOL**

The unacceptable incidence of chipping experienced by some investigators has also led to research into other thermal interactions between the veneering porcelain and zirconia during porcelain application. Internal residual stresses developed during restoration production as a result of thermal gradients produced during cooling have been demonstrated, and some have implicated them in the chipping problem of some porcelain.\textsuperscript{19,23,24} Since zirconia is reputed to have a lower coefficient of thermal diffusivity than dental porcelains,\textsuperscript{24} a slower heating and cooling regimen has been proposed to minimize the effects of this difference and the proposed harmful results from these residual stresses.\textsuperscript{23,24} Although studies have demonstrated
these stresses, and there is anecdotal evidence that slow cooling may lead to better clinical results for some materials\textsuperscript{,25} there is no corroboration that these procedures are applicable for all porcelains or the different zirconia.

Firing of porcelain onto a final restoration starts with a dome-shaped zirconia core covered by a highly insulating material, the dental porcelain. That entity is then subjected to radiant energy from the coils in the furnace while in a vacuum atmosphere. The porcelain layer rises in temperature as a result of the radiant energy transferred from the furnace coil, and the core receives its heat by means of heat conduction through the contacting porcelain layer. As a result of the vacuum atmosphere, the inner surface of the core only receives heat by transfer from the outer surface through the thickness of the core walls. The heat flux across the zirconia sample is dependent upon the conductivity and diffusivity of that particular zirconia, and it is also very dependent upon the thickness of the material and the time of exposure to the heat. Given the thickness of the walls of a typical core (approximately 0.5 to 0.7 mm), it is likely that the core not only reaches the same temperature as the veneering porcelain during a normal firing cycle, but cools in the same time frame as well. The geometry of a typical crown makes accurate thermal testing very difficult; however, a mathematical analysis was performed where the multidimensional temperature profile of the firing process of a porcelain/zirconia crown followed a transient conduction situation through radiant heating. Such a system is difficult to study because the boundary conditions change with time, although under known heating and cooling conditions, the situation can initially be approximated by reducing it to one dimension. An exact solution can then be computed for temperature dependence based on both location and time. This solution requires a known heating protocol as well as the values for the particular porcelain furnace size, British thermal unit (BTU) output, heat flux, and vacuum. Additionally, the coefficients of conductivity and the coefficients of thermal diffusivity for both porcelain and zirconia must be known. Using the authors’ furnace, with its known values and reported thermal coefficients for porcelain and zirconia, this
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Crown temperature profiling was accomplished. (The values for porcelain will vary among different brands, and the values for zirconia will vary depending on the porosity of the sample.)

Porcelain Furnace: Size—5” diameter x 6” tall
Furnace BTU: 12 Watt/hr
Furnace Heat Flux: (1 x 10^4) Watt/m^2
Vacuum: 50 m Torr

Zirconia:
- Conductivity (k) 3-YTZP zirconia @ 600°C = 2.6 W/mK
- Diffusivity (α) 3-YTZP zirconia @ 600°C = 7.6 x 10^(-7) m^2/s

Porcelain:
- Conductivity (k) porcelain @ 630°C = 1.55 W/mK
- Diffusivity (α) porcelain = 7.38 x 10^(-7) m^2/s

The model considered 2 layers, porcelain and HIP’d zirconia, in nonresistive contact, at a uniform temperature of 20°C, which is suddenly exposed to radiation at 600°C on one surface (outer porcelain layer), such that the net heat flux is maintained at a constant value of 5 x 10^4 W/m^2. The high temperature of the cycle was set at 910°C. Approximating the layers as semi-infinite media, the appropriate analytical expression is given by Equation 1, which can be applied to any point in the porcelain layer. The zirconia layer profile will be continuous at the layer interface, but will be described by Equation 2. The expressions hold for constant heat flux; however, because the heat flux varies with time, T_i will vary accordingly but can be numerically simulated for a sufficiently small discrete time window, e.g., T_i = T_i(x, t_i + Δt).

Equation 1: Constant Surface Heat Flux
\[ T(x, t) - T_i = \frac{2k}{\alpha} \left( \frac{c_p}{\alpha} \right)^2 \exp \left( \frac{-x^2}{4\alpha t} \right) \frac{\dot{q}_s}{k} x \text{erfc} \left( \frac{x}{2\sqrt{\alpha t}} \right) \]

Equation 2: Constant Surface Temperature
\[ \frac{T(x, t) - T_i}{T_f - T_i} = \text{erf} \left( \frac{x}{2\sqrt{\alpha t}} \right) \]

And at x = 0
\[ \dot{q}_s(t) = k \frac{T_f - T_i}{\sqrt{\alpha t}} \]

Where, T is temperature, \( \dot{q}_s \) is surface heat flux, \( \dot{q}_\alpha \) is a constant surface heat flux, t is time, x is distance, \( \alpha \) is thermal diffusivity, and k is thermal conductivity.

Considering a hypothetical case with a ramp-up heat flux for 6 minutes and a one-minute high temperature hold time, the temperature profile in the porcelain and zirconia was calculated. A 1.0-mm layer of porcelain was calculated to reach a temperature of approximately 907°C. A contacting 0.5 mm thick layer of zirconia was calculated to reach a temperature of approximately 906°C. From these calculations it is possible to see that the differences in thermal properties are not sufficient to cause any temperature differences in the 2 materials under the normal porcelain firing cycle, within these dimensions. The system in effect acts as a 1.5 mm thick monolithic layer, and there is little evidence to suggest the theory that the zirconia heats up or cools down more slowly than the porcelain. On the other hand, Tholey et al. conducted a study where thermocouples were placed onto the interior core wall as well as on the porcelain surface of a test crown, but a 10-minute heat soak was added beyond the final firing temperature to assure that zirconia cores of varying thickness and porcelain did reach the same temperature. However, in their study, the wall thicknesses of the cores varied considerably from 0.7 to 0.3 mm. It was also noted that the thicker zirconia cores did not prevent the porcelain from reaching its final firing temperature. On consideration, this would be expected, as the specific heat capacity (c_p) of porcelain is 0.739 J/(g*K) while that of zirconia is only 0.456 J/(g*K). Specific heat capacity is the measurable physical quantity that characterizes the amount of heat required to change a substance's temperature by a given amount.

There is further evidence that zirconia conductivity is not the major problem of porcelain integrity and that fast cooling may actually help resolve the chipping problem. In a study on the effect of cooling rate and spontaneous crack development in 5 bilayered samples with 2 different thicknesses of veneering porcelain, Guazzato et al. demonstrated that 2 of the 5 did not exhibit cracking with either the manufacturers’ recommended cooling or a fast cool protocol. They also found that for a third material, the fast cool protocol resulted in surface cracking in the sample with the thicker veneer only. Other researchers have pointed out the significance of veneer layer thickness, as well as the CTE mismatch as the 2 most significant parameters in the reduction of residual stress in the
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Figure 4a. Pre-op photo of a reconstruction candidate with significant occlusal parafunctional habits.

Figure 4b. Cores with “buttress ring” design for single-unit zirconia porcelain laminated restorations.

Figure 4c. One year post-op photo of reconstructed patient.

Bilayered system. It is also known that the most effective method of strengthening glasses is to produce compressive forces in their surfaces, and faster cooling has been shown to increase dental porcelain surface compression, strength, and fracture toughness through tempering. The combination of compressive forces being placed on the porcelain adjacent to the surface of the core as a result of a CTE mismatch, as well as external surface compressive forces as a result of “tempering” from faster cooling may, in fact, act in concert to significantly strengthen the veneer layer and minimize the problem of chipping.

On the other hand, there is evidence that slow cooling may be beneficial for some porcelain. Leucite is the main crystalline phase of most dental ceramics, and its content governs the major properties of that ceramic: expansion and strength. Cesar et al have shown that the fracture toughness of dental porcelains is directly related to their leucite content. This toughening results from crack deflection around the leucite particles. Deflection occurs as a result of stress fields around those particles, which are produced by a mismatch of the CTE between them and the feldspathic glass matrix. However, there is a critical particle size required to prevent excessive microcracking in dental porcelains and these microcracks are of consequence, as they can reduce the strength of the porcelain. Consequently, it appears that there may be an optimum leucite content and particle size for the best possible strength. In spite of this, low- and nonleucite-containing porcelains have been introduced, and these low firing porcelains rely on the addition of alkali-oxide to raise their CTEs. Unfortunately, their mechanical properties are lower than those of conventional porcelains because of the low leucite and high alkali contents. Yet Mackert and Evans have shown that additional leucite may be generated through a slow cooling of low-leucite-containing porcelain. These changes would obviously have implications for the strength of that porcelain, as well as its CTE. These studies offer a reasonable explanation why slow cooling of some porcelain seems to improve clinical performance, while for others it makes no difference.

SUMMARY

Like the transition from acrylic on gold to PFM restorations in the 1960s, the current transition to zirconia laminated restorations is not without problems, but the contention that the zirconia material is responsible for porcelain spalling is not supported by the evidence. As a better understanding of the materials and their relationships evolve, restoration success rates for all clinicians will continue to improve, and they will find use in even the most difficult restorative situations (Figures 4a to 4c). The areas in need of further research are the influence of core design, the different compositions of the veneering porcelains, and their interactions with zirconia samples of differing densities while subjected to different firing cycles. These are complex issues that will take time to elucidate. Yet all throughout this period, monolithic materials have been aggressively sold as an alternative to the bilayered restoration, even to the point of constructing studies with an outcome designed to favor those products. Now, others actively promote monolithic zirconia as the new alternative.

Unfortunately, wear of the opposing occlusion and low temperature degradation (LTD) of the material, with the resultant occlusal surface breakdown, are potential future
problems with these restorations. Zirconia is also actively promoted as an aesthetic material for custom abutments for dental implants. LTD will prove to be a concern with these restorations as well, and fret wear caused by these abutments in an implant is another unknown that is being assessed.39

As with the zirconia bilayered restoration, adequate long-term research is often missing as new products are introduced, leaving clinicians and patients with the unfortunate task of determining long-term results through clinical experience.

CONCLUSIONS
Issues that the reader should recognize after reading this article are:

1. All zirconia material is not the same.
2. HIP’d zirconia has the highest structural integrity and provides the best fitting restorations due to its lack of change during the restoration fabrication process.
3. Core design is a fundamental element of the successful bilayered restoration.
4. The “slow cool” protocol cannot be substantiated by thermodynamic calculations.
5. It is plausible that porcelain spalling is related more to porcelain composition than zirconia thermal conductivity.
6. Aesthetically veneered HIP’d zirconia restorations may be applied in all sites as single units or multiple unit fixed restorations.

REFERENCES


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POST EXAMINATION QUESTIONS

1. The $t$ to $m$ transformation in zirconia is:
   a. Not important.
   b. Responsible for the high fracture toughness of zirconia.
   c. Dependent upon the porosity of the material.
   d. Uniformly present in all zirconia.

2. The content of yttria in a zirconia sample:
   a. Is important for a predictable $t$ to $m$ transformation.
   b. Should be 3 mol %.
   c. Both of the above.
   d. None of the above.

3. The calculated shrinkage during final sintering of cores milled from presintered blocks is:
   a. Extremely accurate.
   b. Constant for every core milled from the same block.
   c. Based on an average density of that block.
   d. The same for all manufacturers.

4. Hot isostatic pressed (HIP’d) zirconia:
   a. Is structurally the same in all 3 dimensions.
   b. Is easy to machine.
   c. Is commonly used to make cores for bilayered restorations.
   d. Requires extra processing.

5. Cores made from HIP’d zirconia:
   a. Have only 0.01% porosity.
   b. Are not subject to change during the production process.
   c. Are more structurally reliable than cores made through the presintered process.
   d. All of the above.

6. The zirconia core must:
   a. Be supportive of the veneering porcelain.
   b. Be designed to reduce tensile stresses in the porcelain.
   c. Both a and b.
   d. Be at least one mm thick.

7. The coefficient of thermal expansion (CTE) of porcelain and zirconia:
   a. Contribute to postfired residual stresses in the restoration.
   b. Should be closely matched.
   c. May create stresses that extend well into the porcelain layer.
   d. All of the above.
8. Slow cooling after porcelain firing is:
   a. Necessary for all restorations.
   b. Done to increase residual stress in the final restoration.
   c. Scientifically validated.
   d. None of the above.

9. When fired in the furnace, the zirconia core receives its heat:
   a. By convective heat transfer.
   b. By conduction through the contacting porcelain.
   c. Both a and b.
   d. As a result of the vacuum atmosphere.

10. The coefficient of conductivity of zirconia:
    a. Is greater than that of most porcelains.
    b. Is less than that of most porcelains.
    c. Is the same as all porcelains.
    d. Is not a factor in the firing process.

11. In a mathematical calculation of a normal firing cycle:
    a. Zirconia is shown not to reach the same approximate temperature as porcelain.
    b. Zirconia is shown to heat up much more slowly than porcelain.
    c. Zirconia requires more heat to reach the same temperature as porcelain.
    d. None of the above.

12. Fast cooling after porcelain firing:
    a. Increases porcelain surface compression.
    b. Reduces porcelain fracture toughness.
    c. Results in surface cracking in all porcelains.
    d. Has no effect on the final restoration.

13. Residual stresses in final restorations:
    a. May be reduced by the design of the core.
    b. May be reduced by matching the CTE of porcelain to the zirconia core.
    c. Both a and b.
    d. Are fully known and understood.

14. Zirconia compatible porcelains:
    a. Have been thoroughly researched.
    b. Demonstrate chipping as a cohesive failure.
    c. Require no support from the core.
    d. Preferably have a CTE greater than that of zirconia.

15. Leucite content in dental porcelains:
    a. Is approximately the same for all porcelains.
    b. Is responsible for the fracture toughness of the porcelain.
    c. May be increased by a slow cooling process.
    d. Both b and c.

16. Variation in success rates of bilayer restoration studies:
    a. Is a result of having zirconia as the core.
    b. Is not a matter of concern.
    c. Is the result of several poorly understood interactions.
    d. Suggests that these restorations should no longer be used.
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