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Influence of veneering porcelain thickness and cooling rate on residual stresses in zirconia molar crowns

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ABSTRACT

Objective. The aim of this study was to investigate the influence of increasing veneering porcelain thickness in clinically representative zirconia molar crowns on the residual stresses under fast and slow cooling protocols.

Methods. Six veneered zirconia copings (Procera, Nobel Biocare AB, Gothenburg, Sweden) based on a mandibular molar form, were divided into 3 groups with flattened cusp heights that were 1 mm, 2 mm, or 3 mm. Half the samples were fast cooled during final glazing; the other half were slow cooled. Vickers indentation technique was used to determine surface residual stresses. Normality distribution within each sample was done using Kolmogorov–Smirnov & Shapiro–Wilk tests, and one-way ANOVA tests used to test for significance between various cusp heights within each group. Independent *t*-tests used to evaluate significance between each cusp height group with regards to cooling.

Results. Compressive stresses were recorded with fast cooling, while tensile stresses with slow cooling. The highest residual compressive stresses were recorded on the fast cooled 1 mm cusps which was significantly higher than the 2 and 3 mm fast cooled crowns ($P < 0.05$). There was a significant linear trend for residual stress to decrease as veneering porcelain thickness increased in the fast cooled group ($P < 0.05$). No significant differences were found between the various cusp heights during slow cooling ($P \geq 0.05$).

Significance. Cooling rate and geometric influences in a crown anatomy have substantially different effects on residual stress profiles with increasing veneering porcelain thickness compared to the basic flat plate model.

1. Introduction

Despite the success in developing high strength ceramic cores for bilayered all-ceramic restorations in the posterior of the mouth [1,2], chipping of the veneering porcelain in zirconia-based restorations has been reported to be higher than that for metal-ceramics and other all-ceramic restorations [3]. Molin and Karlsson found the incidence of chipping fractures to be 35% in zirconia-based fixed partial dentures (FPDs) over 5 years [4], while Larsson et al. reported an incidence of 54% in 1 year [5]. Reuter and Brose reported a chipping rate of 2.5% for metal-ceramic FPDs after 5 years [6], whereas no veneering

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Table 1 – Thermal conductivity of common dental materials from highest to lowest (modified from Swain [15]).

Material	Thermal conductivity ($W m^{-1} K^{-1}$)
Gold alloys	200
Base metals	40
Alumina	30
In-Ceram alumina	14
Zirconia	2
Feldspathic porcelains	2

porcelain chipping was observed for glass infiltrated ceramic-based frameworks after 5 years in two other studies [7,8]. The chipping of veneering porcelain has been identified as a major setback for zirconia-based restorations, instigating a plethora of studies investigating the causes and its prevention.

The literature has indicated a number of reasons why zirconia-based all-ceramic restorations have a higher incidence of chipping fractures, being due to cohesive failures within the veneering porcelain rather than adhesive failure between the zirconia core and veneer. These include mismatch of the coefficient of thermal expansion between the zirconia core and veneering porcelain [9], mechanically defective microstructural regions in the porcelain, areas of porosities [10], surface defects or improper support by the framework [11,12], overloading and fatigue [13], and low fracture toughness of the veneering ceramic [14]. Nevertheless the most accepted explanation so far is the development of high residual tensile stresses within the veneering porcelain caused by fast cooling zirconia restorations [15]. Indeed, since the introduction of zirconia restorations in dentistry, manufacturers have introduced slow cooling firing programs in order to reduce the risk of chipping fractures.

Zirconia is a very poor thermal conductor compared to metal alloys and even other all-ceramic core materials (Table 1). It is important to note that the rate at which the inner veneering porcelain in a bilayered restoration cools below its glass transition temperature (T_g) during the end of a firing cycle will depend on the neighboring core material and its thermal conductivity properties. For instance, when a metal-ceramic restoration is fast cooled by air-bench cooling, the veneering porcelain cools rapidly both from the outside and inside of the restoration because of the high thermal conductivity of the metal core. On the other hand, when a zirconia-based restoration is fast cooled, the center of the veneering porcelain close to the zirconia core remains at temperatures above T_g for longer. A large thermal gradient forms between the outer surface of the veneering porcelain and the inner regions, influencing the type and magnitude of residual stresses in the veneering porcelain [16–18]. It was known as early as 1979 that thermal conductivity of the core material was a contributing factor in the development of thermal stresses in metal-ceramic restorations [19]. However, this factor was not previously investigated since all metal alloys are relatively good thermal conductors and it is unlikely that differences amongst them had any clinical significance.

Just as commercial tempering is used to strengthen glass for windscreens and glass doors/windows [20], tempering of metal-ceramic restorations by removing them from the furnace at high temperatures and allowing them to bench-cool in air at ambient temperatures, has been established as common practice by dental laboratories to strengthen the veneering porcelain [21,22]. This process in effect toughens the veneering porcelain by the development of compressive stresses on the outer surface of the veneer. As a result, applied tensile loads that may fracture non-strengthened glass initially have to exceed the surface compressive stresses before surface cracks begin to be placed in tension, and therefore the strength of the tempered material will be approximately increased by the extent of the reinforcing surface compressive stresses. It is important to note however, that although the overall "effective" fracture toughness of tempered glass increases, once a crack begins to grow through the thin compressed superficial layer, the glass can spontaneously shatter, as internal tensile stresses rapidly accelerate and cracks bifurcate [23,24].

In terms of the classic literature pertaining to metal-ceramics, transient and residual stresses in dental porcelain cooled at various rates investigated using porcelain disks [22,25–28], and metal-porcelain disks [21,29], report analogous results. Regardless of the exact values reported in each study, surface residual compressive stresses are observed with faster cooling rates, while slow cooled samples exhibit residual tensile stresses. Consequently, the aforementioned studies concluded that fast cooling metal-ceramic restorations is preferable in order to strengthen the veneering porcelain, thereby its clinical life, and indeed has been the established procedure for decades.

Taskonak et al. determined residual stresses in zirconia-based bilayered disks under both fast and slow cooling rates using fracture mechanics (biaxial flexural strength test) [30]. They also found that fast cooling generated surface residual compressive stresses with an upper compressive limit of −21 MPa, and slow cooling generated surface residual tensile stresses with an upper tensile limit of +19 MPa. The authors concluded that residual stresses can be altered using different heat treatments, and that these changes are a direct result of the viscoelastic behavior of the glass veneer during various cooling rates. The authors nevertheless did not make any technical recommendations regarding cooling rates for zirconia-based restorations. These results may suggest that bilayered zirconia restorations behave similarly to metal-ceramics during fast cooling, however stress profiles in bilayered zirconia and metal disk samples have been found to be different [31], and to also exhibit opposite trends when the veneering porcelain thickness was varied [32]. In the mean time, the practice of fast cooling has been recognized as being the offending factor when considering the cause of zirconia-based restorations chipping [15,33]. *In vitro* studies using mathematical modeling and finite element analysis (FEA) [17,18], optical polarimetery [16], fracture load resistance testing [34], shear bond strength in veneer/zirconia disks [35], and Vickers indentation of sectioned FPD samples [36] confirm the relationship between residual tensile stresses in the veneering porcelain and fast cooling zirconia restorations. Using zirconia spheres and 5 zirconia compatible veneering porcelains, Guazzato et al. found that the incidence of cracking of veneering porcelains increased when using a faster cooling rate, demonstrating that the superficial compressive strength generated with fast cooling may be less of an advantage than the hazardous tensile stresses developed within the veneers