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Insight into Mechanical and Clinical Perspectives of Zirconia -A Systematic Review

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Abstract:
Back ground: *All ceramic restorations are the current trend in prosthodontics. Zirconia as an esthetic restoration is upcoming. But confusions exist regarding the bonding and clinical use of zirconia .Hence the current literature reviews articles related to zirconia dated from 1989 to 2015 in an attempt to have a clear understanding. A research was conducted using PubMed and Medline correlated with hand search for any relevant papers using key words like zirconia, machining, structure, chemical and mechanical bonding.*
Aim: *This study helps to give a complete understanding of material science of zirconia and its clinical implications including different bonding mechanisms.*
Review results: *A total of 37 publications were identified for analysis. Articles that are relevant for our review dealing with the mechanical properties and clinical implications of zirconia were included. Numerous studies were identified regarding zirconia and its properties but the results were different and difficult to interpret.*
Conclusions: *Zirconia restorative material is suited to satisfy both in aesthetic and functional aspect. Further research is indispensable to resolve the conflicting results and to arrive at a common solution which is essential for the prognosis of these restorations.*
Keywords: *systematic review, bonding, machining, surface finish*

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I. Introduction

Progression in ceramic materials for dental use led to the development of high strength materials i.e. zirconia based ceramics. Although zirconia has superior mechanical properties, there are some clinical problems associated with it in terms of bonding.A detailed introspection of material science of zirconia is a pre-requisite before we discuss the clinical aspects.

Evolution of zirconia

Burgeoning of newer aesthetic materials to give a natural appearance had to be accompanied with superior mechanical properties .This was possible by the addition of more crystals that can withstand greater forces. These were glass- infiltrated ceramics e.g. alumina and glass ceramics with added crystals. But this had its own disadvantages for it can be used only up to three unit bridges in the premolar region .[1]To overcome this, new polycrystalline ceramics such as aluminium oxide and zirconia oxide ceramics were introduced.

Structure of zirconia

Zirconia (or) zirconium dioxide (ZrO_2) was obtained by heating zircon (gem). This was elicited by a German chemist Martin Heinrich Klaproth in 1789 .It is also called as ceramic steel as proposed by Garvie in 1975.Zirconia is polymorphic in nature i.e. different crystal structure exists at different temperatures. It has different crystalline forms like monoclinic at low temperatures, tetragonal above 1170° C and cubic above 2370° C [2] during cooling. This change in the crystal structure from tetragonal to monoclinic form induces large stresses with 3-4 % volume increase. The zirconia tetragonal to monoclinic phase transformation is called as martensitic transformation.[3]Due to the volume increase there can be cracks in the ceramic if no stabilising oxides are added like Ceria (CeO_2), Yttria ($Y_2 O_3$), Alumina ($Al_2 O_3$), Magnesium (MgO) and Calcia (CaO) etc.[2]Under normal cooling conditions, the cubic and tetragonal phases are retained and hence there is no crack formation due to phase transformation. The addition of 2-3 mol % of Y_2O_3 to ZrO_2in $Y_2 O_3$-ZrO_2 system creates a metastable matrix of tetragonal crystals called as tetragonal zirconia polycrystal (TZP). Consequently, zirconia used for dental purposes exists as metastable tetragonal PSZ at room temperature with the trapped energy ready to drive it back to the monoclinic phase.Zirconia grains thus undergo transformation in the vicinity of the crack tip with a 4% volume increase.[4]This seals the crack and thereby increases the surface toughness .This is known as transformation toughening.

Different types of zirconia ceramics:

a) Yttrium Tetragonal zirconia poly crystals(Y-TZP):

3mol % yttria is added acting as a stabiliser. It has superior mechanical properties.[5]It has a flexural Strength of 900-1200 Mpa and fracture strength of about 9-10 Mpa (m) $^{1/2.}$ Most manufactures of 3Y-TZP blanks for dental applications do not advocate grinding or sandblasting. This is to avoid surface flaws that could be harmful to the long-term performance.

b) Glass- infiltrated zirconia-toughened alumina (ZTA):

Zirconia can combined with alumina to form zirconia-toughened alumina. In Ceram Zirconia was developed by adding 33 vol% of 12 mol % zirconia to In Ceram Alumina.[6] It can be processed by soft machining or slip casting.One Advantage of Ce-TZP ceramics is that it has better thermal stability.

c) Zirconia containing lithium silicate ceramics (Zls):

10 wt. % of Zirconia oxide added to lithium silicate gave a dual microstructure consisting of lithium metasilicate (Li_2SiO_3) and lithium disilicate ($Li_2SiO_2O_5$) crystals in a glassy matrix of ZrO_2 in solution.[7]These were better than zirconia ceramics .

d) Magnesia partially stabilised zirconia (Mg-PSZ):

This material was not successful due to the presence of porosity, low mechanical properties, low stability and increased wear of the opposing structure.

e) ***Resin nano-ceramic materials***:

Lava Ultimate* CAD/CAM restoration is a cross-linked polymeric matrix containing three types of fillers. They are zirconia and silica nano particles agglomerated into clusters, individually bonded silica nano particles, and individually bonded zirconia nano particles. These can be used in heavy stress areas like second molar region.[8]

Machining of zirconia:

CAD/CAM zirconia restorations can be made by two different machining techniques. They are soft machining of pre-sintered blanks or hard machining of fully sintered blanks.

Soft Machining: In this technique the powder has crystals of about 40 nm in diameter and the blanks are manufactured by cold isostatic pressing. A pre-sintering heat treatment is done to eliminate the binder in the blanks.The heat treatment should be slow otherwise it might cause cracks due to the elimination of the binder and the burn out products. If the temperature is more, it can also cause surface roughness. It is then sintered using programmed furnaces. Final sintering temperature ranges between 1350 °C and 1550 °C. Restorations can be fabricated after machining by immersing these in solution of various metal salts like cerium, bismuth etc.[9]The color will develop after final sintering. Disadvantage of this technique is that it causes shrinkage (20%). This can be partly compensated at the designing stage.Systems using soft machining of 3Y-TZP blanks are Procera, Lava TM, YZ cubes for Cerec InLab.

Hard Machining**:** Initially, pre-sintering of the powder is done below 1500°C to reach at least 95% dense. Then these blocks are hot isostatically pressed at temperatures between 1400-1500°C under high pressure in an inert gas atmosphere.[10] The blocks are then machined using a specially designed milling system .Coarse diamond burs were effective for finishing than fine burs since it caused ductile type of damage.[11]Disadvantage of this technique is wearing of the grinding tools and flaws produced as a result of machining that decreases the mechanical properties of these restorations.[12] Systems like Denzir and DCZirkon are available for hard machining of zirconia restorations.

CAD-CAM processes in common has three main steps:Acquisition of digital data, followed by processing and designing. Since there were difficulties in digitizing the intra-oral abutment using a digital scanner, conventional stone models were poured for the fabrication ofcrowns. Some of the currently used CAD-CAM systems are Everest and Arctica, Lava, Procera, Cercon smart ceramics, CEREC AC, Hint- ELs system, Aadva system, C-Pro system, Katana and Zeno Tec system. The application of CAD/CAM is currently limited to laboratory processing and the final finishing is done by the lab technician.

Advantages of CAD /CAM were use of durable materials, increase in the efficiency of laboratory processing, better esthetics,and earlier function of restoration, better quality, better fit, increased mechanical durability and predictability. A new fabrication system using digital veneering is also available.[13]

Esthetics in zirconia:

Though all-ceramic systems are better in aesthetics the transparency of zirconia based crowns is less than that of lithium disilicate ceramics.[14] In Ceram zirconia, an aluminium oxide - based ceramic with 35% zirconium dioxide, has a relatively low transparency equal to that of metal ceramic crowns .This can be an hindrance to achieve good acceptable aesthetics.Since zirconia based ceramics (like Y-TZP) are polycrystalline, most of the light passing through these restorationsget scattered and diffusely reflected leading to an opaque appearance. Jiang et al found Y-TZP can have 17-18% of light transmittance if sintering is done between 1145°C -1500°C.[15] Transmission of light through Y-TZP depends on thecomposition and thickness of the zirconia framework along with thephysical properties and degree of glazing of the porcelain.Future studies should be conducted about the new generation full contour zirconia.[16] Monolithic zirconia has a monochromic colour structure and an opaque appearance and thus it is unable to imitate the optical property of the tooth.

Veneering ceramics in zirconia:

Zirconia based restorations has a zirconia infrastructure that is veneered with porcelain to form the anatomic contour of teeth. There are two main ways of veneering zirconia infrastructure. They are the traditional layering and the hot press method.[17]Chipping of the veneering porcelain is the most common complication of zirconia restorations.

Factors responsible for chipping of the veneering porcelain were

- Improper framework supporting the veneering porcelain
- Improper handling in the laboratory
- Improper application technique of the veneering porcelain[18]
- Mismatch in mechanical and thermal properties such as fracture toughness, flexural strength, COTE and elastic modulus.[19]

There are two ways that may avoid chipping of veneering porcelain. One is hybrid –structured FPD'S with CAD-CAM fabricated zirconia framework veneered with CAD-CAM fabricated veneering porcelain. Advantage is high precision as the manual work was replaced by digital procedures.

Surface finish of zirconia restorations:

Mirror polishing of zirconia restorations should be done to avoid wearing of the opposite enamel .The different grinding rotary instruments for zirconia restorations includes abrasives containing diamond, corundum, titanium oxide(rutile or anatase), and zinc oxide. Polishing paste for surface finishing of zirconia restorations contains mixture of diamond, anatase, pumice, zinc oxide, corundum, silicon carbide in varying proportions.

As the microstructure of zirconia is homogeneous, a smooth surface of zirconia can be obtained with polishing. Also highly polished zirconia causes least wear of the opposing enamel .[20]

Bonding mechanisms of zirconia based ceramics:

Zirconia is a non-silica based ceramic and so it cannot be etched using traditional methods. Retention of zirconia based ceramic restorations depends on different surface treatments. The surface treatment includes micromechanical bonding techniques and chemical bonding techniques.

Micromechanical bonding techniques:

Air borne particle abrasion is used for roughening zirconia's surface thatincreases the mechanical inter-locking. It also increases the total surface contact area. [21]Surface roughness produced by smaller alumina grains (25 or 50 µ) or larger alumina grains (110µ) did not have any marked differences even though it resulted in different surface roughness.[22]APA has two side effects .It causes micro cracks on the surface and phase transformation from t→ m form at the surface and subsurface reducing the mechanical properties of the material. Hence manufacturers suggest heating to be done after APA to reverse the conversion[23] or to do APA after sintering.[24]

Grinding with disks and diamond Rotary instruments is yet another method to create surface roughness. But disadvantage of grinding methods is the possible creation of micro cracks in the surface.

SIE (Selective infiltration etching technique) is a latest surface roughening technique.[25]It pre-stresses the grain boundaries with molten glass by a heat induced process. Later it is etched with hydrofluoric acid .This forms a 3D network of inter-granular porosity which causes micromechanical retention to the resin cement .Advantage is that it has control over the area to be etched. Aboushelib et al showed that SIE increased the micro-tensile bond strength (49.8 ± 2.7 Mpa) when compared to particle abrasion (33.4 ±2.1 Mpa).

Other techniques like use of fused glass micro pearls applied to the surface of ZrO_2also increased the bond strength of resin cements to ZrO_2.[26]

Chemical treatments includes use of 40% HF for 210 sec that showed improved shear bond strength.[27] Application of HCl and F_2Cl_3 solution for 30 minutes also enhanced the bond strength better than APA.[28] Sulphuric acid in solution with H_2O_2 (Piranha solution) also increased the bonding of zirconia with resin cements.[29]

ND: YAG (Neodymium-doped yttrium aluminium garnet) laser increased surface roughness and bond strength.[30]CO_2 laser is suitable for ceramics as its wavelength (2.3 to 10.6 µm) is absorbed by ceramics. Further CO_2 laser improved both roughness and the zirconia-porcelain bond.[31]Er: YAG laser (Erbium doped yttrium aluminium garnet) at 150 mJ, 1W low power for 20 seconds seemed to improve bond strength.High speed pulse lasers also called as femtosecond lasers was also used for creating surface roughness.[32]

Chemical Bonding Techniques:

Silicatisation systems like ROCATEC and COJET are used to create a silica layer through high speed impact of the silica modified alumina particleson the ceramic surface.[33]This tribochemical effect allowed micromechanical bond to the resin and also promoted the formation of a chemical bond between the silica coated ceramic surface with the resin through a silane coupling agent.

Silicoating based on the pyrolytic deposition of silicon to form a SiO_x -C with a thickness of 0.1µ also producedstronger bonds with resin cements after silanation.

Pyrosilpen uses flame treatment oxidises the surface of polymeric materials to form polar reactive groups like hydroxyl and carboxyl groups which improves surface free energy and wettability to aid in bonding.

Plasma spraying involves plasma spraying hexamethyldisiloxane to form a thin siloxane coating less than 1µ.

In vapour deposition, zirconia specimens are exposed to chlorosilicide gas ($SiCl_4$) in the presence of water vapour for 15 minutes to produce an activated siliconized surface to ensure bonding.

Coupling agent promotes chemical bond to zirconia based ceramic by the use of a ceramic primer. Ceramic primers containing an acidic adhesive monomer such as MDP can be used for the priming of zirconia based ceramics.Kern and Wegner found that luting agents containing a phosphate monomer i.e. 10-methacryloxyloxydecyl dihydrogen phosphate (MDP)effectively increased the bonding to zirconia.

Biocompatibility of zirconia ceramics:

Zirconia has proved to be biocompatible .It is osseoconductive. Physical and chemical treatment of zirconia can affect the soft tissue interaction with fibroblasts. Studies have also shown that zirconia and its derivatives like ZrN has the ability to reduce plaque on implant and surrounding tissues.[34]Thus zirconia with standardized topography or chemistry can be manufactured to be used in the field of implantology.

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Clinical perspectives of zirconia:

Zirconia restorations have number of applications. In contrast to the other all ceramic systems that is used mostly in anterior teethzirconia ceramic FDP'scan also be used on molars.

Tooth preparation for zirconia restorations has to have a chamfer or rounded shoulder margin. External line angle of preparation must be linear to allow scanning. Anterior teeth reduction should have a4° 6° taper with 1.5mm incisal reduction and 1.0mm of axial reduction in aesthetic areas that can be extended up to 1.5mm. Posterior teeth should be prepared with 1.5mm of occlusal reduction and with 1.0 mm of axial reduction on marginal region with a 4° 6° taper [35]. Edelhoff advocated inlays and onlays with zirconia core. In order to fabricate these restorations, an occlusal reduction of almost 2mm is necessary, and the axial reduction must be 1.5mm with a cavosurface angle of 100 -120°.

Connecting surface area of the FPD's must be at least 6.25mm.[36] Because of this ceramic FPD's can be used only when the distance between the inter-proximal papilla and the marginal ridge is close to 4.0mm. 5 unit FPD's are reported to be as maximal as possible though some manufacturers claim for full arch restorations.

After die scanning, restorations are fabricated either by soft or hard machining. It was found that zirconia sintered after milling had better mechanical properties than densely sintered zirconia. After fabrication, veneering can be done with glass ceramics. Controlling zirconia core thickness can also reduce the fracture.

Since zirconia restorations are opaque it can also be used for a dischromic tooth or to conceal a metal post. After veneering the zirconia core and finishing, luting of the restoration can be performed. The need for internal surface treatment requires further experimental evaluation. Tribochemical treatment gave promising results with the combined use of an MDP monomer as primer or MDP containing resin cement.

Zirconia can also be used to fabricate implant abutments .Precision at the implant interface between the abutment and the fixture was evaluated by comparing the rotational freedom of titanium, alumina and zirconia abutments with hexagonal external connections .The rotational freedom between the zirconia abutment and the fixture was found to be less than 3°. Also zirconia abutment combined with a machined titanium base showed a rotational freedom less than 3°.[37]

II. Conclusion

The rapid surge of materials and processing techniques has made the use of zirconia based FDP's promising. With the collaboration of the dentist and the technician it is possible to eliminate the errors and obtain a successful restoration. Long-time clinical evaluations is an essential pre-requisite to prove the usefulness of zirconia FDP's with newer options.

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