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| REVIEW

Evaluation of mechanical properties of CAD/CAM ceramic systems: literature review

Avaliação das propriedades mecânicas dos sistemas cerâmicos CAD/CAM: revisão de literatura

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ABSTRACT

Computer aided design / computer aided manufacturing (CAD/CAM) systems are among the most technological advanced techniques in oral rehab today. Compared with conventional techniques, they can optimize the resistance and the adaptation of dental ceramics. Thus, their indications of use have been widened, making the technique more and more well-known and widespread. Therefore, the aim of this study is to present a literature review on comparative studies of the mechanical properties of ceramic systems produced by CAD / CAM. A search for scientific articles published between 2009 and 2019, in English, Spanish or Portuguese, was performed through the databases SCIELO, BIREME and PUBMED, using the descriptors "Ceramics", "Computer Aided Design" and " Partial Fixed Prosthesis ". Currently, all ceramic systems appear to have adequate strength for simple rehabilitations, but ceramic restorations produced by CAD/CAM systems present greater reliability than other manufacturing methods, presenting a wider array of indications due to their higher mechanical resistance. These systems, besides their versatility, also present an excellent aesthetic result, guaranteeing appropriate optical properties such as translucency and fluorescence, similar to natural teeth. Although the cost is a limiting factor, CAD/CAM technology is in full development and with high success rates that qualifies it as the state of art in oral rehabilitation.

Indexing terms: Ceramics. Computer-aided design. Fixed partial denture.

RESUMO

O sistema CAD-CAM (computer aided design/computer aided manufacturing), que significa desenho auxiliado por computação e manufatura auxiliada por computação, é um dos recursos mais tecnológicos e modernos na reabilitação oral atualmente. É uma alternativa que otimizou a resistência e a adaptação das cerâmicas odontológicas. Dessa maneira, suas indicações de uso têm-se ampliadas, tornando-o cada vez mais conhecido e difundido. O objetivo deste estudo é apresentar uma revisão da literatura sobre estudos comparativos das propriedades mecânicas dos sistemas cerâmicos produzidos por CAD/CAM. Foi realizada a busca de artigos científicos publicados entre 2009 e 2019, em inglês, espanhol ou português, nas bases de dados SCIELO, BIREME e PUBMED, utilizando os descritores: "Ceramics", "Computer Aided Design" e "Prótese Parcial Fixa". Atualmente todos os sistemas cerâmicos parecem ter uma adequada resistência para reabilitações simples, mas as restaurações cerâmicas produzidas por sistemas CAD/CAM apresentam

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maior confiabilidade do que outros métodos de fabricação; apresentando maiores possibilidades de indicações devido aos seus maiores valores de resistência mecânica. Esta tecnologia embora apresente o custo como um fator limitante, está em pleno desenvolvimento e já apresenta propriedades mecânicas suficientes e com índices de sucesso que a qualificam como o estado da arte em reabilitação oral.

Termos de indexação: *Cerâmica. Desenho assistido por computador. Prótese parcial fixa.*

INTRODUCTION

In recent decades, the increased cost of precious metals and number of patients with high aesthetic expectations have led to a growing demand for natural and fabricated restorations, thus boosting technological development and the emergence of new ceramic materials [1].

Working with these concepts once required a large amount of time, but with the modernization of the laboratory process associated with more accurate clinical techniques, rehabilitations started to be developed in a standardized way, increasing the performance with more quality [2]. Within this context, computer aided design/ computer aided manufacturing (CAD/CAM) technology emerged; an advanced system that allows the preparation of prostheses based on a three-dimensional design [3].

CAD/CAM is a technology introduced in dentistry in the late 1970s by Bruce Altschuler in the USA, François Duret in France, and Werner Mormann and Marco Brandestini in Switzerland [4]. The implementation of CAD/CAM technology within various systems has affected not only "mass production" but also the improvement of the surgical procedure and restorations in general. These technologies promote dynamic interactions within the workflow, as well as generate a more reliable communication between clinical activity and laboratory activity, by exchanging data between CAD/CAM subsystems [3].

The main goal of CAD / CAM in restorative dentistry is the automation and mechanization of the ceramic making process. The conventional process of making demands time, skill of the laboratory technician and a larger percentage of defects. For example, the layering technique or craft technique presents a manual confection, where the production of a restoration is by mixing the porcelain powder with the modeling liquid on a glass plate until a paste is applied. with a brush over, for example, a refractory die. Given this processing, for example, it is clear which fragile and dependent is this conventional technique. Therefore one of the advantages of using the CAD-CAM system in this case is the fact that the infrastructure obtained from the partially sintered block ("dry press") has better quality (less defects). However, CAD / CAM has disadvantages, including the fact that restoration can not be done in layers with different colors and degrees of opacity, translucency, as occurs in the layer sintering method.

Two essential concepts based on high clinical performance can justify the use of CAD/CAM systems: the emphasis of the concept "minimally invasive dentistry", consisting of minimal and selective dental wear; and "zero fitting in prosthesis", implying minimal adjustments of the ceramic restorations performed clinically, thus allowing an efficient communication protocol with the prosthesis technician [2].

The production of a prosthesis by CAD/CAM follows the principles of mimicking the natural dentition; proper mastery over its functions and characteristics are necessary for the identification and evaluation of the clinical performance of prostheses under CAD/CAM. Thus, it is of fundamental importance to understand the mechanical behavior of the tooth when submitted to masticatory loads. In addition, the mechanical properties of dentin can be influenced by the area investigated, the orientation of the tubules, the tubular density and the age. The collagen matrix, for example, contributes to 25 to 30% of the tensile strength in human root dentin and 11 to 12% in human coronary dentin [5].

In a 3-point flexion test (coronary region, dentin and root), when the natural tooth is loaded, a flexural strength of 194.26 MPa was found in dentin and 152.86 MPa in the coronary region. In comparison, the flexural strength of the root was found to be 224.86 MPa. The fact that the flexural strength of the human root dentin is significantly greater than the resistance of the coronary dentin is probably due to the approximately parallel alignment of the tubules in the root dentine and the relative consistency of their diameter in the long axis, thus providing a greater homogeneity in the distribution of the perineal and intertubular dentin [5].

The mechanical strength of ceramic systems varies according to their chemical and physical characteristics.

CAD/CAM systems have substantially increased the strength of metal-free restorations, which has led to increased longevity of the restorations. A study of the mechanical properties of the ceramic systems is fundamental to strengthen its credibility and safety for various indications [6]. The aim of this study is to perform a review of the literature on the mechanical properties of CAD/CAM systems.

Characteristics of CAD/CAM systems

Several CAD/CAM systems are currently available on the market (chart 1), developed based on an initial reading system, planning software (CAD) and a milling system (CAM). Within the national and international market there are several types of CAD/CAM systems (chart 1); however, according to Amaroso et al. [7] the three most used systems in Brazilian dentistry are Procera, Lava and CEREC.

The systems consist of a high-precision scanner, which acquires a digital image of a dental cast or from the patient's own dental arch. This 3D virtual scan is processed by a trained professional who builds a digital model of the structure that is to be manufactured (e.g. a crown) using a dedicated software program. Subsequently the "part" is sent to the printer, which is a milling unit, to form pre-synthesized ceramic blocks. Then, the piece is polished and applied in the mouth [8].

Therefore, the aim of this study is to present a literature review on comparative studies of the mechanical properties of ceramic systems produced by CAD / CAM.

Chart 1. Non-exhaustive overview of commercially available CAD/CAM systems.

Systems	Companies
CEREC 3D® CEREC InLab®	Sirona Dental Systems GmbH, Germany
Procera®	Nobelbiocare AB, Sweden
Everest®	KaVo Dental GmbH, Germany
Lava®	3MESPE, Germany
DigiDent®	Hint-Els GmbH, Germany
Cercon®	Degudent GmbH, Germany
Evolution 4D®	D4D Technologie, USA
Etkon®	Etkon, Germany
Precident DCS®	DCS, Switzerland
Pro 50®	Cynovad, Canada
Wol-Ceram	Wol-Dent, Germany

In addition, this review shows some results of studies on the mechanical properties of CAD/CAM ceramic systems, comparing them with the conventional technique of making dental ceramics.

A search for scientific articles published between 2009 and 2019, in English, Spanish or Portuguese, was performed through the databases SCIELO, BIREME and PUBMED, using the descriptors "Ceramics", "Computer Aided Design" and " Partial Fixed Prosthesis ". The search yielded 64 articles about in vitro studies CAD/CAM ceramics, from which 37 were selected after reading titles and abstracts and excluding those that did not involve some method of evaluation of the mechanical properties of these systems.

Type of test performed

An important factor in any dental prosthesis planning is resistance, a mechanical property attributed to any material that ensures that the prosthetic part meets physiological functions, safely and with longevity. Resistance refers to the material's ability to resist induced stresses, without any fracture or permanent deformation, in other words, this material must have a certain elastic tension to withstand these stresses. The mechanical properties can be quantified through some tests; they are: tensile stress (the material is subjected to a force that tends to stretch or lengthen the body), compression stress (the material is subjected to a compressive force on an axis of the body), shear stress (the material tends to resist the sliding of a portion of a body over another) and flexural strength (the material tends to resist the bending stress).

In a recent (2015) systematic review, including 67 clinical cases using CAD/CAM, clinical fracture rates after 5 years of up to 18.4%, 5.5% and 1.7% (chart 2) were reported for crowns made of feldspathic ceramics, reinforced glass ceramics and densely sintered zirconia, respectively [9]. Pjetursson [10] evaluated the 5-year clinical fracture rates for multiple fixed dental prostheses, which were 15.3% for enhanced glass ceramics and up to 3.2% for densely sintered zirconia (chart 2).

When evaluating fatigue strength degradation in ceramic materials made by conventional laboratory processing using a protocol of 20,000 cycles at a frequency of 0.5 Hz, Belli et al. [11] showed a value of 440 MPa for Y-TZP (polystyrene tetragonal zirconia stabilized with yttria), 121 MPa for lithium disilicate used for CAD/CAM, and 38 MPa for feldspathic used for CAD/CAM: 38 MPa (chart 2).

Due to the characteristics of resistance, translucency and color diversity, vitreous ceramics based on lithium disilicate can be used for the manufacturing of monolithic restorations or infrastructures for subsequent coating. Clinical results of monolithic CAD/CAM restorations made with vitreous ceramics enhanced by lithium disilicate showed a survival rate of 97% after 7 years [1].

In a study by Belli et al. [11], within a 3.5-year period, 1.4% (7 of 491) all-ceramic restorations fractured. Regarding the types of ceramics produced by CAD/CAM, for the observed period, lithium disilicate presented a slightly higher failure rate (presence of cracks or fracture in the prosthetic part) for the unit crowns (1.23% failure) compared with the onlays (0.71% failure) and inlays (0.36% failure). Regarding fixed partial prostheses, the survival of lithium disilicate-coated zirconia was lower (3.93% failure) than that of porcelain-covered zirconia (0.82% failure) and monolithic zirconia (no failure); a summary of these findings is shown in chart 2.

In a literature review, the flexural strength of feldspar ceramics presented the lowest values of strength in relation to the other types of ceramics mentioned. Lithium disilicate (LD) for injection (e.max® Press) had the lowest reduction in resistance after undergoing flexion test with 29.6%, whereas lithium disilicate for milling (e.max® CAD) showed a reduction of 53.4% [12].

André et al. (2006) e Ferruzzi et al. (2018) [12,13] investigated monolithic blocks of lithium disilicate-reinforced ceramics after milling and crystallization at 840 °C, showing that lithium disilicate crystals grow in a controlled manner to 70% of the material volume, after which the color remains unchanged and the strength is about 360 MPa, according of flexural resistance (chart 4). This result is reaffirmed by Padua et al. [14], who found that these high-strength or lithium disilicate-reinforced vitreous ceramics can have from 260 to 540 MPa of flexural strength (chart 3).

Using FESEM (Field-emission Scanning Electron Microscopy), Fraga et al. [15] showed defects on CAD/CAM machining surfaces, as well as increased surface roughness and significantly reduced flexural strength in all the investigated ceramics, compared with a post-machining polished ceramic. However, after polishing, the surface was smoothened and the experimental hypothesis of increasing the resistance of CAD/CAM-produced

Chart 2. Clinical failure rate in crowns made by CAD/CAM.

Authors/year	Type of ceramics	Study	Relevant information	Results
Sailer et al. [9]	Feldspatic Reinforced glass ceramics Zirconia	Fracture rate of 5 years (presence of cracks or fracture in the prosthetic part)	67 clinical studies	18.4% 5.5% 1.7%
Pjetursson et al. [10]	Reinforced glass-ceramic Densely sintered zirconia	Fracture rate of 5 years (presence of cracks or fracture in the prosthetic part)	Multiple fixed dental prostheses	15.3% 3.2%
Belli et al. [11]	Single crowns Onlays Inlays	Clinical observational study - 3.5 years (Presence of cracks or fracture in the prosthetic part)	Fixed single or partial crowns made with lithium disilicate	1.23% 0.71% 0.36%
Belli et al. [11]	Zirconia coated with lithium disilicate Zirconia covered by porcelain Monolithic zirconia	Clinical observational study - 3.5 years (Presence of cracks or fracture in the prosthetic part)	Fixed partial prostheses	3.93% 0.82% no failure

Chart 3. Values of flexural strength of crowns made by CAD/CAM after machining versus machining and polishing.

Authors/year	Type of ceramics	Measured index	Relevant information	Results
Fraga et al. [15]	Glass-ceramics enhanced by leucite	Biaxial flexural strength	Hard cutting Machining followed by polishing	128.20 Mpa 177.2 MPa
Pádua et al. [14]	High strength vitreous ceramics or reinforced by lithium disilicate	Flexural resistance	Values found after milling	260 to 540 MPa

ceramics was accepted. The same study showed that hard-cut machining resulted in a 27% lower biaxial flexural strength (128.2 MPa) of a leucite-reinforced glass-ceramic compared with machining followed by polishing (177.2 MPa). Using scanning electron microscopy (SEM) of the cross-section of the disks, it was observed that machining introduced defects in the ceramic surface, which were removed by polishing. The average roughness of the machined group was 1.37 μm, while that of the machined and polished group was 0.04 μm (chart 3).

DISCUSSION

CAD/CAM x Conventional Laboratory Processing

Chart 4. Comparative values of the flexural strength of the dentin-enamel complex, fracture strength of the metallic infrastructures and flexural strength of the ceramic crowns made by conventional laboratory processing and CAD/CAM crowns.

It can be noticed in chart 4 that crowns made with zirconia showed a flexural resistance well above the value found in the three dental portions (dentine, coronary portion and root portion), indicating that this type of material can be suitable for posterior teeth, where they receive the highest masticatory load. Chart 4 shows flexural strength values of 768 MPa for CAD/CAM-processed zirconia crowns and 440 MPa for zirconia crowns made by conventional laboratory processing.

Regarding feldspathic ceramics, it can be seen in chart 4 that both CAD/CAM and conventional laboratory processing result in low flexural strength (66 Mpa and 121 Mpa, respectively). Therefore, these ceramics are suitable for coating cosmetic cores or ceramic laminates, for example.

When comparing the values of flexural strength of ceramics produced by CAD/CAM and metal infrastructures, it can be seen that strength obtained by CAD/CAM are closer to those of the dentin-enamel complex. Thus, the practicality of CAD/CAM together with its accuracy in terms of mechanical properties and adaptation, have been major factor in its increasing popularity.

Types of comparison

Ceramics are materials that bear almost no elastic deformation; consequently, they fracture suddenly and irreversibly. Defects present in this material can act as points of concentration of stresses, initiating the propagation of a crack when the stored elastic energy exceeds a threshold [13].

According to Ferruzzi et al. [13], a high value of flexural strength was exhibited by lithium disilicate ceramics (e.max® Press, 360 MPa) and zirconia ceramics (768 Mpa). Clinically, these two types of ceramics fit into various clinical applications (Chart 4), it is therefore apparent that crowns milled from a CAD/CAM system can have a great mechanical advantage compared with crowns made by injection or pressing, for example (Chart 4).

Belli et al. [11], found that the flexural strength of lithium disilicate ceramics made by conventional laboratory processing was 121 MPa, reaffirming the result found by Ferruzzi et al. [13] that CAD/CAM significantly increases the flexural strength of the ceramic material. He also observed the failure of crowns in an observational study of 3.5 years, finding a low fracture index for these ceramics, with zirconia covered by lithium disilicate showing the highest failure rate (3.93% of 491 prostheses) (chart 4).

Fraga et al. [15] indicated that only CAD/CAM milling is not enough to consolidate and guarantee the mechanical properties of dental ceramics. Although CAD/

Chart 4. Comparative values of the flexural strength of the dentin-enamel complex, fracture strength of the metallic infrastructures and flexural strength of the ceramic crowns made by conventional laboratory processing and CAD/CAM crowns.

Dentin-enamel complex	Metal infrastructures - Molten metal core	Crowns for conventional laboratory processing	CAD/CAM crowns
Schlichting et al. [16] - Dentine: 194.26 MPa - Coronary portion: 152.86 MPa - Root portion: 224.86 MPa	Porto et al. [17] Conventional laboratory processing: 939.61 MPa	Belli et al. [11] - Lithium Dissilicate: 121 MPa - Feldspathic: 38 MPa - Yttrium stabilized polycrystalline tetragonal zirconia: 440 MPa	Ferruzzi et al. [13] - Feldspaths: 66 MPa - Leucite Strengthened Feldspaths: 85 MPa - Lithium Dissilicate (e.max® Press): 360 Mpa - Zirconia: 768 MPa

CAM showed a lower degree of surface defects, the presence of defects may cause propagation of a possible failure. They also stated that hard-cut machining reduced the biaxial flexural strength of a leucite-enhanced vitreous ceramic by about 27% when compared to machining followed by polishing (Chart 3).

Pádua et al. [14] reaffirmed the results found in almost all studies: an increase of flexural strength by CAD/CAM systems compared with traditional manufacturing (Chart 3).

The strength of ceramics depends on the size, number and distribution of defects in the area with the highest tensile stress concentration, as well as the ability of the material to withstand the rapid propagation of the crack (fracture toughness). Some examples of defects that can be found in ceramics are: pores, cracks, inclusions, as well as surface defects due to wear and machining [4,5,13].

Composition and failure about CAD/CAM ceramics

In view of the constant stress that restorative materials are subjected to in the buccal environment, in the presence of salivary moisture, fillers and masticatory forces and changes in temperature and pH, restorations tend to fail due to a phenomenon called fatigue, i.e. the failure of a material subjected to stresses or deformations over a period of time [15]. The composition and the conformation of each ceramic confers to its mechanical properties, which can favor or hinder the development of factures by fatigue [18] (chart 5).

Regarding the study of mechanical properties of ceramic materials, cyclic fatigue tests can reproduce a condition that is close to what occurs clinically. Thus, it is possible to acquire and develop a clinical view of possible variables that the ceramic prosthesis can suffer from in the buccal environment [12,13].

Cracks tend to propagate at points of greatest tensile stress. Although a ceramic restoration can fracture abruptly from a single intense overload, the failure is more likely to occur cumulatively after a prolonged period of seemingly innocuous but lower-load events. Such fractures are manifested in the clinical literature as ‘lifetime’ or ‘survival rate’ [15-17].

When a monolithic ceramic is manufactured, to make it resistant to cracking without interfering with the aesthetic properties, the goal is to avoid weak veneer/core interfaces, minimizing the risk of delamination. Some examples of ceramics in this condition are: lithium disilicate glass-ceramic (IPS e.max Press or CAD by Ivoclar-Vivadent), fine-grained zirconia (e.g. Lava Plus from 3M ESPE, Bruxzir from Glidewell, Allzir from New Image) and surface-infiltrated glass (chart 6) [15,18,19].

Chart 5. Mechanical properties of dental ceramics [12,13].

	Modulus of elasticity (GPa)	Flexural strength (MPa)	Fracture toughness (Mpa.m^{-2})
Feldspathic Ceramics	45-70	66	0.7-1,1
Reinforced by leucite - addition of leucite at a ratio of 35 to 45%	65-86	85	1.3
Reinforced by Lithium Dissilicate	95-96	360	2.75 (Press) 2.25 (CAD)
Zirconia	210	768	5.5-7

Chart 6. Composition and indications of ceramics enhanced by lithium disilicate.

	% (Weight) glassy phase	Crystalline structure	Composition	Indication
e.max CAD	30%	Lithium disilicate crystals (0.5 to 4 µm)	57-80% $SiO_{2,}$ 11-19% $LiO_{2,}$ 0-13% K_2O, P_2O_5, $ZrO_{2,}$ ZnO, AL_2O_3, MgO and coloured oxides.	Inlays Onlays Facets Total crowns anterior and posterior Fixed prosthesis anterior and posterior, up to the first molar
IPS e.max Zircad	≅1%	Yttria stabilized polycrystalline tetragonal zirconia	95% ZrO_2,5% HfO_2+Al_2O_3+Y_2O_3+ others, Rh_2O_3 + Al_2O_3+Y_2O_3	Crown infrastructure Partial dentures in all regions

André et al. [12] e Ferruzzi et al. [13] showed that, currently, lithium disilicate-reinforced ceramics are also available in the form of partially crystallized blocks for CAD/CAM manufacturing (e.max®CAD, Ivoclar Vivadent®). The blocks are available in a size compatible with unitary restorations. Partial crystallization allows fast and easy milling. In this phase lithium metasilicate crystals are formed, showing more favorable processing properties, although the ceramic already presents high resistance (from 130 to 150 MPa) and is able to guarantee intact margins. In this context, the increase in flexural strength between dentures made by CAD/CAM and natural teeth is also of importance.

Fractures occur when the stresses imposed on a given material are greater than the cohesive forces existing between the atoms that compose it, that is, when it is submitted to tensions superior to its fracture resistance limit. Values of fracture strength of dental ceramics indicated for the posterior region are between 160 and 1300 MPa. Considering the contact areas in posterior teeth, even under an extreme load of e.g. 3,500N, the contact pressures during usual maximum intercuspation reach around 55 MPa in women and 67 MPa in men (chart 5) [15,20-22].

It is necessary to understand that the resistance to fracture of a material can be diminished by the presence of defects or cracks, often imperceptible, that act as factors of concentration of tensions. Failures in ceramics are often associated with existing defects [15,16].

When stress values approach the flexural strength value, so-called cracks are observed in monolithic structures. When viewed from the top, they have a starry appearance. Radial cracks can propagate throughout the thickness of the material, reach the side walls or penetrate the substrate on which the ceramic material is cemented. They are identified as the probable responsible for catastrophic failures (complete fracture) in monolithic crowns [15,23-25].

Recently, due to the development of ceramic materials with improved mechanical properties and the practicality introduced by CAD/CAM systems, it is possible to obtain aesthetics and strength. Reinforced single-layer materials can be characterized with extrinsic paint and exhibit satisfactory aesthetic performance. In addition to dispensing ceramic coating, such restorations have been shown to have increased toughness to masticatory efforts [14,15,26-30].

CAD/CAM technology provides powerful restoration and conservative preparation; however, for best performance the materials should be chosen during the treatment planning.The digital system allows preparations that are less complex and also less invasive; in addition, it provides the same strength of other treatment options. Studies have shown unexpected behavior like the higher fatigue resistance of polymer-based materials when compared with that of ceramics. The flexural modulus of polymer-based materials is very similar to that of dentin, which creates a single body in regarding mechanical behavior, and consequently polymer-based materials can be widely used [31-38].

CONCLUSION

It can be stated that prefabricated monolithic blocks for CAD/CAM show a lower concentration of defects, which can still be introduced during manipulation due to adjustments with rotary instruments or due to masticatory activity. In this context, the increase in flexural strength between dentures made by CAD/CAM compared with natural teeth, except for feldspathic ceramics, is also relevant. The mechanical strength of these systems indicates their reliability for clinical indications; however, more randomized controlled clinical trials with longitudinal analyzes including different biological variables are necessary to consolidate the clinical success of these materials.

Collaborators

AEC LIMA, preparation and design of the study; development and writing of the manuscript; data analysis and interpretation and revision of the manuscript. HBL FALCÃO FILHO, preparation and design of the study; data analysis and interpretation and revision of the manuscript. HFO PARANHOS, data analysis and interpretation and revision of the manuscript.

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