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Impact of machining on the flexural fatigue strength of glass and polycrystalline CAD/CAM ceramics

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ABSTRACT

Objectives. To assess the effect of machining on the flexural fatigue strength and on the surface roughness of different computer-aided design, computer-aided manufacturing (CAD/CAM) ceramics by comparing machined and polished after machining specimens.

Methods. Disc-shaped specimens of yttria-stabilized polycrystalline tetragonal zirconia (Y-TZP), leucite-, and lithium disilicate-based glass ceramics were prepared by CAD/CAM machining, and divided into two groups: machining (M) and machining followed by polishing (MP). The surface roughness was measured and the flexural fatigue strength was evaluated by the step-test method (n = 20). The initial load and the load increment for each ceramic material were based on a monotonic test (n = 5). A maximum of 10,000 cycles was applied in each load step, at 1.4 Hz. Weibull probability statistics was used for the analysis of the flexural fatigue strength, and Mann-Whitney test ($\alpha = 5\%$) to compare roughness between the M and MP conditions.

Results. Machining resulted in lower values of characteristic flexural fatigue strength than machining followed by polishing. The greatest reduction in flexural fatigue strength from MP to M was observed for Y-TZP (40%; M = 536.48 MPa; MP = 894.50 MPa), followed by lithium disilicate (33%; M = 187.71 MPa; MP = 278.93 MPa) and leucite (29%; M = 72.61 MPa; MP = 102.55 MPa). Significantly higher values of roughness (Ra) were observed for M compared to MP (leucite: M = 1.59 μm and MP = 0.08 μm; lithium disilicate: M = 1.84 μm and MP = 0.13 μm; Y-TZP: M = 1.79 μm and MP = 0.18 μm).

Abbreviations: CAD/CAM, computer-aided design computer-aided manufacturing; FDPs, fixed dental prostheses; SCG, slow crack growth; Y-TZP, yttria-stabilized polycrystalline tetragonal zirconia; Ra, average surface roughness (μm); Rz, arithmetic mean peak-to-valley height (μm); λc, cut-off value.

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Significance. Machining negatively affected the flexural fatigue strength of CAD/CAM ceramics, indicating that machining of partially or fully sintered ceramics is deleterious to fatigue strength.

1. Introduction

Recent improvements in the mechanical properties of dental ceramic systems and the implementation of computer-aided design, computer-aided manufacturing (CAD/CAM) technology in restorative dentistry have widely contributed to the increase in the use of all-ceramic restorations as an alternative for satisfying the high esthetic demand of patients [1].

A great variety of ceramic materials are available for CAD/CAM, with each differing in microstructure, mechanical behavior, and also machining mode [2,3]. Feldspar-, leucite-, and lithium disilicate-based ceramics are commonly available in a full sintered stage for hard machining [4]. These materials contain high volumes of glassy phases and, consequently, have a lower fracture toughness compared to that of polycrystalline ceramics [5,6]. In lithium disilicate glass ceramics, the presence of lithium disilicate crystals promotes crack deflection, which improves its fracture strength [7]. Therefore, this material is recommended not only for the manufacture of veneers, inlays, onlays, and anterior and posterior crowns, as with leucite glass ceramics [8], but also for implant superstructures of single-tooth restorations [9].

Yttria-stabilized polycrystalline tetragonal zirconia (Y-TZP) can be milled either from pre-sintered blocks (soft machining) followed by sintering at high temperature, or from fully-sintered blocks (hard machining) [10]. Soft machining is the most used process to manufacture Y-TZP restorations, since hard machining is more time consuming and requires tougher cutting devices [10,11]. Y-TZP ceramics exhibit a transformation toughening mechanism that acts to resist crack propagation. It involves the transformation of metastable tetragonal crystallites to the monoclinic phase at the crack tip, which, accompanied by a volumetric expansion, induces compressive stresses, hindering further crack propagation [12]. It may be used as infrastructure for crowns and fixed dental prostheses (FDPs) covered by glass-ceramic [3] or as monolithic full-contour restorations [13,14], besides being indicated for implant abutments [3].

Despite the promising clinical success rates, framework fracture of all-ceramic restorations is still a technical problem [15–17], which may warrant additional costs to the patient and to the dentist for the replacement of the restoration. In a recent systematic review, with the inclusion of 67 clinical studies, 5-year framework fracture rates of up to 18.4%, 5.5%, and 1.7% were reported for single crowns made of feldspathic ceramic, reinforced glass ceramic (including both leucite- and lithium disilicate-based glass ceramics), and densely sintered zirconia, respectively [16]. When multiple-unit fixed dental prostheses were considered, these rates increased up to 15.3% for reinforced glass ceramic and up to 3.2% for densely sintered zirconia [17]. There seem to be a remarkable difference between leucite- and lithium disilicate-reinforced ceramics in terms of mechanical behavior, which is reflected in the survival rates of the restorations. For a mean period of 4.5 years, the fracture rate of leucite-based single crowns was estimated in 3.8%, with molars showing the highest fracture rate (6.7%) [18]; while the fracture rate of lithium disilicate single crowns was 1.22%, over a period of 3.5 years [15].

Due to the brittle nature of ceramics, their fracture strength is strongly influenced by the presence of defects, which can be considered particularly critical when located at the zones of tensile stress concentration [19,20]. Fractographic analysis of clinically failed all-ceramic restorations [19,21,22] and finite element analysis [23,24] showed that the cementation surface of all-ceramic crowns concentrates tensile stress, and that defects on this surface may be the origin of fracture in failed restorations [19,21,22]. Besides, the cervical margins of all-ceramic restorations seem to have an important role in the fracture initiation, as indicated by fractographic studies [25,26]. Therefore, procedures that affect the intaglio surface and the cervical margins of all-ceramic restorations must be investigated regarding their impact on the ceramic strength.

Despite reducing processing defects, once the CAD/CAM blocks are produced in a standard process, machining induces a complex network of events in the ceramic, resulting in radial and lateral cracks, chipping, subsurface damage, and residual stresses [27–30]. Hard machining resulted in damage to the ceramic surface, and reduced the biaxial flexural strength of a leucite glass ceramic by approximately 27% [31]. Soft machining also resulted in surface damage and significantly reduced the strength of zirconia, which may result in unexpected failures at stresses much lower than the ideal strength of the material [32]. Kelly et al. [33] reported that the defects introduced by the CEREC® (Sirona Dental Systems Gmbh, Germany) CAD/CAM system appeared to be the origin of the failure in ceramics subjected to a uniaxial bending test.

It is important to consider that in the oral environment, all-ceramic restorations are subject to many challenges, such as cyclic loads, humidity, pH, and temperature variations. Consequently, failure tends to occur due to fatigue [34]. Ceramics are susceptible to a slow and stable crack growth (SCG) when subjected to stresses below the critical value, especially in the presence of water. This phenomenon can eventually lead to strength degradation over time, decreasing the lifetime of dental prostheses and appears to be most related to the ceramic microstructure [35].

Therefore, considering the increasing use of CAD/CAM technology in restorative dentistry, in which the machining process introduces new features in the cementation surface of ceramic restorations, and the susceptibility of ceramic materials to fatigue, this study aimed to assess the effect of CAD/CAM machining on the biaxial flexural fatigue strength and on