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Fatigue behavior and crack initiation of CAD/CAM resin composite molar crowns

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ABSTRACT

Objective. The aim of this study was to evaluate long-term fatigue behavior using an *in vitro* step-stress accelerated life test (SSALT), and to determine the crack initiation point using *in silico* finite element analysis for computer-aided designed and manufactured (CAD/CAM) molar crowns fabricated from three commercial CAD/CAM resin composite blocks: Cerasmart (CS; GC, Tokyo, Japan), Katana Avencia Block (KA; Kuraray Noritake Dental, Niigata, Japan), and Shofu Block HC (HC; Shofu, Kyoto, Japan).

Methods. Fifty-one mandibular first molar crowns luted on a resin core die were embedded in acrylic resin and covered with a polyvinyl chloride tube. Single compressive tests were performed for five crowns. SSALT was conducted for 36 crowns using three profiles and reliabilities at 120,000 cycles, and a Weibull analysis was conducted. The maximum principal strain of each CAD/CAM resin composite crown model was analyzed by three-dimensional finite element analysis.

Results. Fracture loads of CS and KA (3784 ± 144 N and 3915 ± 313 N) were significantly greater than that of HC (2767 ± 227 N) ($p < 0.05$). Fracture probabilities at 120,000 cycles were 24.6% (CS), 13.7% (KA), and 14.0% (HC). Maximum principal strain was observed around the mesiolingual cusps of CS and KA and the distobuccal cusp of HC.

Significance. CAD/CAM resin composite molar crowns containing nano-fillers with a higher fraction of resin matrix exhibited higher fracture loads and greater longevity, suggesting that these crowns could be used as an alternative to ceramic crowns in terms of fatigue behavior.

Abbreviations: CAD/CAM, computer-aided design/computer-aided manufacturing; SSALT, step-stress accelerated life test; FEA, finite element analysis; MPS, maximum principal strain; RCB, resin composite block; PVC, polyvinyl chloride; XRD, X-ray diffraction; SEM, scanning electron microscopy; ANOVA, analysis of variance; HSD, honest significant difference.

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1. Introduction

Computer-aided design/computer-aided manufacturing (CAD/CAM) resin composite blocks (RCBs) containing a high density of nano-filler particles are available for use in posterior restorations [1]. Because of the preliminary polymerized resin matrix, the nano-filler particles are homogeneously dispersed in the resin matrix, providing stable and excellent mechanical properties such as flexural strength and fracture toughness when compared with those of conventional resin composites used in fillings [2,3]. As an alternative material to metals or ceramics, CAD/CAM RCBs are attracting much attention because their esthetics are more favorable than metals and their cost is lower than ceramics [4]. CAD/CAM RCBs have excellent fatigue resistance with no catastrophic failures when compared with ceramics [5]. The resin matrix of CAD/CAM RCBs prevents crack propagation during cyclic loading and leads to greater flexural strength and a lower flexural modulus [6].

The long-term fatigue behavior of bar-shaped CAD/CAM RCB specimens after fatigue treatment has been measured using a three-point bending test, and was found to be comparable to lithium disilicate glass-ceramic [7]. However, the fatigue behavior of crown-shaped specimens is still unknown. A frequency of 15 Hz with a load of 10–40 N for 1.2×10^6 cycles (∼22 h) is required to prepare each specimen for the three-point bending test.

A step-stress accelerated life test (SSALT) that mimics the sliding contact movement in the mouth has been used to investigate the longevity of dental implants [8] and all-ceramic crowns [9,10]. Fracture patterns of bar-shaped specimens after fatigue tests with or without step-stress profiles were similar; that is, SSALT has been validated and could be more time-efficient than fatigue testing with a constant load [11]. The fatigue behavior of CAD/CAM resin composite crowns has been evaluated and was found to be comparable to leucite reinforced glass-ceramic crowns, with no catastrophic failures occurring in the CAD/CAM resin composite crowns [5]. The fracture pattern of crown-shaped specimens after catastrophic failure is important to ascertain the crack initiation point and to improve the composition and physical properties of CAD/CAM resin composite. Fractographic analysis has been used to evaluate the fractured surface after SSALT for dental implants [12,13], ceramics [14], and polymer infiltrated ceramic network materials [15]. However, it is difficult to determine the specific crack initiation point because the fracture has already occurred.

Finite element analysis (FEA) is a powerful tool for calculating stress and strain distribution in dental implants [16,17] and CAD/CAM RCBs [18]. FEA can be used to predict the crack initiation point by using maximum principal strain as an effective failure criteria [19].

The aim of this study was to evaluate long-term fatigue behavior using *in vitro* SSALT, and to determine the crack initiation point using *in silico* FEA for CAD/CAM resin composite molar crowns fabricated from three commercial CAD/CAM RCBs: Cerasmart (CS; GC, Tokyo, Japan), Katana Avencia Block (KA; Kuraray Noritake Dental, Niigata, Japan), and Shofu Block HC (HC; Shofu, Kyoto, Japan).

2. Materials and methods

2.1. CAD/CAM RCBs

Three types of commercially available CAD/CAM RCBs were used: Cerasmart (CS; GC, Tokyo, Japan), Katana Avencia Block (KA; Kuraray Noritake Dental, Niigata, Japan), and Shofu Block HC (HC; Shofu, Kyoto, Japan). Details of the composition of each block is shown in Table 1.

2.2. Specimen preparation

An impression was taken of a mandibular first molar abutment tooth model (A55A-461, Nissin, Kyoto, Japan) using silicone impression material. A total of 51 abutment teeth were fabricated by incremental build-up and photopolymerization of core resin (Clearfil DC Core Automix, Kuraray Noritake Dental) in the impression cavity. The mandibular right first molar model (A5A-500, Nissin) and the abutment tooth were scanned (SC-5, Kuraray Noritake Dental) and designed (DentalDesigner, Kuraray Noritake Dental). Both models were fabricated using a milling machine (DWX-50, Kuraray Noritake Dental). To strengthen the adhesion of the crowns [20], the inner surface of the crowns were sand blasted with an air pressure of 0.2 MPa using Al_2O_3 particles 30–50 μm in diameter. After ultrasonic cleaning for 2 min and air-drying, the inner surface of the crowns was etched with phosphoric acid gel (K-etchant gel, Kuraray Noritake Dental). After 5 s, ceramic primer (Clearfil Ceramic Primer, Kuraray Noritake Dental) was applied after rinsing with water and air-drying. The crowns were cemented on the abutment tooth and exposed to light for 5 s, followed by removal of excess cement.

2.3. Single compressive testing

All specimens were vertically embedded in a 25-mm diameter polyvinyl chloride (PVC) tube of acrylic resin (Unifast Lab type F, GC, Tokyo, Japan) with the buccal margin of the crown positioned 2 mm higher than the top surface of the acrylic resin. After storage in distilled water at 37 °C for 24 h, a single compressive test (AGS-500D, Shimadzu, Kyoto, Japan) was performed at a crosshead speed of 0.5 mm/min (n = 5), and mean fracture load and standard deviation were calculated.

2.4. Step-stress accelerating life testing

Based on the mean load of the static compression test, three fatigue loading profiles were designed for the 12 specimens for SSALT [8]. The designed profiles were designated as mild (n = 6), moderate (n = 4), and aggressive (n = 2), following the ratio of 3:2:1 (Fig. 1). The crowns were immersed in distilled water (Fig. 2) during SSALT. SSALT was performed at a frequency of 5 Hz. Weibull analysis and a reliability assessment were conducted. Fractured specimens were observed with stereomicroscopy (SMZ-745T, Nikon, Tokyo, Japan) using high dynamic range software (NIS-Elements Ver.4.0, Nikon) and scanning electron microscopy (SEM; JSM-6390BU, JEOL, Tokyo, Japan) with 20× magnification at 5 kV.

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