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Numerical fatigue analysis of premolars restored by CAD/CAM ceramic crowns

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ABSTRACT

Objectives. The purpose of this study was to estimate the fatigue life of premolars restored with two dental ceramics, lithium disilicate (LD) and polymer infiltrated ceramic (PIC) using the numerical method and compare it with the published *in vitro* data.
Methods. A premolar restored with full-coverage crown was digitized. The volumetric shape of tooth tissues and crowns were created in Mimics®. They were transferred to IA-FEMesh for mesh generation and the model was analyzed with Abaqus. By combining the stress distribution results with fatigue stress–life (S–N) approach, the lifetime of restored premolars was predicted.
Results. The predicted lifetime was 1,231,318 cycles for LD with fatigue load of 1400 N, while the one for PIC was 475,063 cycles with the load of 870 N. The peak value of maximum principal stress occurred at the contact area (LD: 172 MPa and PIC: 96 MPa) and central fossa (LD: 100 MPa and PIC: 64 MPa) for both ceramics which were the most seen failure areas in the experiment. In the adhesive layer, the maximum shear stress was observed at the shoulder area (LD: 53.6 MPa and PIC: 29 MPa).
Significance. The fatigue life and failure modes of all-ceramic crown determined by the numerical method seem to correlate well with the previous experimental study.

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1. Introduction

Porcelain-fused-to-metal crowns have been the standard treatment for restoring heavily broken down teeth over the decades [1]. However, owing to the increasing aesthetic demand and higher cost of precious metals, all-ceramic restorations have become a preferred restorative option [2–4]. In general, all-ceramic restorations are considered to be brittle with high clinical failure rates, particularly when they are placed on posterior teeth [5,6]. In order to tackle the problem, CAD/CAM ceramics have been developed which is structurally more homogenous and mechanically much stronger than the conventional feldspathic ceramics [7,8]. Moreover, using CAD/CAM ceramics, the design and fabrication process is less time consuming, less technique sensitive and does not require multiple steps when compared with the conventional method [3,9]. Furthermore, various enhanced bonding protocols for CAD/CAM ceramics including zirconia are now available for improving the retention and longevity of the restorations [10,11].

Lithium disilicate-based glass ceramics (LD), commercially available as *e.g.* IPS e.max® CAD which is partially crystallized, is one of the widely used modern CAD/CAM all-ceramic material [12]. Despite the superior aesthetic properties and colour stability, LD might not be strong enough for posterior teeth [13]. To compensate this weakness, a polymer infiltrated ceramic (PIC), which is more ductile, has been recently developed. This hybrid material, commercially available as VITA enamic®, contains 86 wt% ceramic with 14 wt% polymer [14] and it has been claimed to be less susceptible to fracture than pure ceramics [15]. Indeed it possibly demonstrated a result of Dugdale cracking model, i.e. the increase of observable crack resistance with the crack length does not toughen the material, but only lowered the scattering of the strength and thus increase the apparent Weibull modulus [16]. Various studies [9,14,16] have shown the PIC has a higher Weibull modulus of fracture strength test data than LD under bending conditions. Like LD, PIC is also etchable by hydrofluoric acid which creates certain roughness for durable bonding to tooth tissues [16].

To evaluate a new restorative material, on the one hand, conducting prospective clinical studies is often considered to be the preferred approach. However, with the addition of many stringent measures, obtaining ethics approval for clinical trials is getting notoriously difficult nowadays. Moreover, many parameters could not be controlled in the clinical setting which could become confounding variables of the trial. Furthermore, clinical studies usually takes a long period of time [17,18] and it has been recommended that clinical trials for indirect restorations should require at least 5 years of observation [19]. On the other hand, laboratory studies [20–22] could be another approach which attempts to simulate the oral conditions and predict the resistance of restorations against occlusal loading. However, the setup of experiment is expensive and indeed the experiments do not invariably result in the same fracture pattern [23]. Moreover, they only reveal the strength and modes of fracture [6]. Nevertheless, numerical methods seem to be a powerful alternative for assessing the stress distribution in the restored tooth as a whole and that could help to envisage the mechanical problems which might arise [24]. As such, finite element method (FEM) is the most accepted technique [25]. It can determine the stress concentration areas, especially in the area of physical properties mismatch between different materials, such as ceramic–adhesive interface. The first step for any finite element analyses (FEA) entails the development of a digital model and computed tomography (CT) is one of the most accurate and commonly used methods for obtaining detailed geometric data in medicine and dentistry [26].

Although the most common mechanical failure of a restored tooth clinically is usually due to fatigue, many FEA studies focused on static analysis only. There are only a few studies which have evaluated the fatigue resistance of restored teeth using FEM [23,25,27,28]. In addition, most of the FEA studies used a model where only a point force was applied for simulating occlusal loading, however, it might probably not be the case in the oral environment [27,29,30]. In this study, a hemispherical indenter was used instead and the stress distributions from the static FEA were post-processed with fatigue stress–life (S–N) behaviors. The aim of this study was to numerically estimate the fatigue life of a tooth restored with two different ceramic crowns, and verified with the previous *in-vitro* study [31].

2. Materials and methods

Fig. 1 demonstrates a sequential set of equipment and software which were used for the FEA of a restored first maxillary premolar with LD and PIC ceramic crowns. The restored tooth was first digitized with a micro X-ray computed tomography (micro-CT) scanner (SkyScan 1172, Kontich, Belgium) with a 1.3 megapixel camera. The beam accelerating voltage and beam current were adjusted to 80 kV and 100 μA, respectively with Al + Cu filter. The frames were taken for 180° of the sample with the rotation step of 0.4° and the exposure time of 4.477 s for each frame. Images with 9.98 μm pixel size in 16 bit Tag Image File Format (TIFF) were obtained with a software (SkyScan 1172, Version 1.5) operated in a workstation (Dell Precision T7500 Intel® Xeon 4 Gb CPU, 3.07 GHz).

The images were reconstructed using the NRecon® software (SkyScan, Belgium). Smoothing, beam-hardening corrections, alignment optimization, and ring artifact reduction were applied during the reconstruction. The output

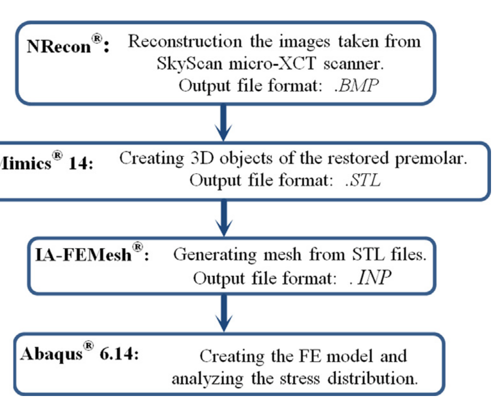

Fig. 1 – Sequential workflow for performing the finite element analysis.

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