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Endodontic access cavity simulation in ceramic dental crowns

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ABSTRACT

Objectives. It is proposed that a non-uniform rational B-spline (NURBS) based solid geometric model of a ceramic crown would be a flexible and quick approach to virtually simulate root canal access cavities. The computation of strain components orthogonal to surface flaws generated during the drilling would be an appropriate way of comparing different access cavity configurations.
Methods. A μCT scan is used to develop a full 3D NURBS geometric solid model of a ceramic crown. Three different access cavity configurations are created virtually in the geometric model and there are then imported into proprietary finite element software. A linear analysis of the each crown is carried out under appropriate in vivo loading and the results are post-processed to carry out a quantitative comparison of the three configurations
Results. The geometric model is shown to be a flexible and quick way of simulation access cavities. Preliminary indications are that post processed strain results from the finite element analysis are good comparators of competing access cavity configurations.
Significance. The generation of geometric solid models of dental crowns from μCT scans is a flexible and efficient methodology to simulate a number of access cavity configurations. Furthermore, advanced post-processing of the primary finite element analysis results is worthwhile as preliminary results indicate that improved quantitative comparisons between different access cavity configurations are possible.

1. Introduction

Classical structural mechanics fails to produce an adequate elucidation of the stresses and strains developed in a system as geometrically complex as a grinding tooth. Naturally, the boundary of such a surface cannot be described by a singular component such as a beam or a plate, and therefore a computer simulation must be carried out. All physical phenomena are modeled mathematically as partial differential equations. It is rare that the solutions for these partial differential equations are trivial [1], but since the development of the computer, numerical solutions are now mainstream. For boundary value field problems, including structural mechanics, the finite element method (FEM) is the standard numerical approach. The ability of the FEM to accurately compute stress

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and strain fields has particular advantages in the field of restorative dentistry where an understanding of the deformation responses due to in vivo loading is of critical importance.

A very common procedure performed by dentists is root canal treatment (RCT). RCT is performed when the pulp becomes infected or damaged, causing pain to proliferate through the tooth. Indeed, this is such a common complaint that 'root canal' is a something of a vernacular synonym for serious discomfort and distress. Clinically, root canal pain is tackled by endodontic therapy, which involves any number of procedures that take place inside the tooth, the general principles of which have been traced as far back as 1826 [2]. Studies have shown that the side-effects of crown fabrication and installation can cause irreversible pulp necrosis (tissue death), which may consequently necessitate RCT. In fact, a 3–25% pulpal necrosis rate has been recorded in teeth with full coverage fixed restorations over an 18–25 month period [3]. It is further estimated [4] that between 20% and 50% of all RCT is performed through complete coverage crowns [5,6].

1.1. Motivation

It has been known for quite some time [7–9] that endodontic access itself can cause varying levels of distress to the crown due to subsequent in vivo loading. Flaws generated by the action of the drilling burs are hypothesized to ultimately develop into cracks and propagate causing failure in crowns. Recent studies have shown that the failure load of restorations post-access is independent of drilling implement or technique [10,11]. Therefore, whether or not one selects a high efficiency diamond rotary cutting instrument or a tungsten carbide fissure burr has no appreciable effect, as some micro cracks will form, regardless of the instrument. The clinician has control over the following: geometry, location, number of access cavities and the filling material. Research into these parameters has not been very active and provides the motivation for this work. If recommendations of optimal access cavity configurations, alongside a choice of filling material, could be formulated, they would be clinically useful. Currently there is no conclusive body of research that has determined the correct restoration method and material; judgments based on 3D modeling could effect change as it offers a wide scope relative to biomedical research, a field in which it may be either prohibitively expensive to or ethically questionable to test on in vivo or even in vitro samples [12].

1.2. Purpose

This paper aims to demonstrate that a non-uniform rational B-spline (NURBS) based solid geometric model of ceramic crowns is a flexible and quick approach to virtually simulate root canal access cavities. Furthermore, it is proposed that tensor strain components orthogonal to surface flaws, rather that scalar strain quantities, are an appropriate way of comparing different access cavity configurations.

1.3. Paper summary

Section 2 will describe the development of the geometric model from a μCT scan of a representative dental ceramic crown and the virtual modeling of three different access cavity configurations. The geometric model is then imported into proprietary FE software and an in vivo loading scenario is applied and the results of the FE analyses are presented in Section 3. Section 4 discusses the effectiveness of the geometric modeling approach presented and presents some preliminary results of a strain based post-processing methodology that better predicts the long term effect of low intensity cyclic loading on the crown. The conclusions are detailed in Section 5.

2. Materials and methods

In any finite element analysis (FEA), there are four key factors that the analyst must consider in order to develop a sound model; geometry, material properties, loading and boundary conditions. To that end the modeling methodology used in this work will be illustrated under those headings.

2.1. Geometry

2.1.1. Acquisition

For the purposes of this work, a representative sample ceramic crown was created using the lost-wax technique in a dental laboratory in Cork University Dental School & Hospital. This crown is approximately 9.35 mm at its widest and 8.16 mm at its highest, and depicts the crown of a mandibular first molar, purposively selected as it is the most common tooth to undergo endodontic treatment [4,13,14]. This tooth was scanned by a *Scanco*® *CT40*μCT device and the outputted data was saved in the scanner's native format.

2.1.2. Data processing

A simple *MATLAB*® procedure converted the original data to the more commonly used DICOM format. Each μCT slice is a greyscale image, 1024 × 1024 pixels in size, and has a 16-bit color depth. In total, 450 slices at a thickness of 0.02 mm were recorded amounting to approximately 950 MB of data. Therefore to facilitate visualization, a workstation with 16 GB of RAM operating on 64-bit Windows was used. It may be noticed that the data recovered from a μCT scan is raw and requires some basic image processing before 3D reconstruction is possible. In this work, all image processing and reconstruction work is undertaken in *3D Slicer*, an open source medical visualization software package [15–17].

The main point of a 3D reconstruction from μCT imaging is to identify the structures of interest from each slice and assemble these into a 3D model. This process is commonly referred to as segmentation and it refers to the conglomeration of all points on the μCT slice that are of interest into one cogent structure known as a label map, which is simply a binary image superimposed over the original slice. In essence, one is designating particular areas of the μCT image that they want to include in the resulting model as the label map(s) that are used to create the 3D visualization. Note that there is the possibility of isolating several structures: one could simply create several label maps, based on areas of the slice of different radiodensity (the quality, which is analogous to corporeal, physical density). Commonly, dentists use μCT imagery to segment and create models encompassing all major structures