ARCHIVES OF ORAL BIOLOGY 58 (2013) 575–582

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The effect of dentinal fluid flow during loading in various directions—Simulation of fluid–structure interaction

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ARTICLE INFO

Article history:
Accepted 1 October 2012

Keywords:
Dentinal fluid flow
Hydrodynamic theory
Pulpal nerve stimulation
Dental biomechanics
Fluid–structure interaction

ABSTRACT

Objectives: This study uses a fluid–structure interaction (FSI) simulation to evaluate the fluid flow in a dental intrapulpal chamber induced by the deformation of the tooth structure during loading in various directions.

Methods: The FSI is used for the biomechanics simulation of dental intrapulpal responses with the force loading gradually increasing from 0 to 100 N at 0°, 30°, 45°, 60°, and 90° on the tooth surface in 1 s, respectively. The effect of stress or deformation on tooth and fluid flow changes in the pulp chamber are evaluated.

Results: A horizontal loading force on a tooth may induce tooth structure deformation, which increases fluid flow velocity in the coronal pulp. Thus, horizontal loading on a tooth may easily induce tooth pain.

Conclusion: This study suggests that experiments to investigate the relationship between loading in various directions and dental pain should avoid measuring the bulk pulpal fluid flow from radicular pulp, but rather should measure the dentinal fluid flow in the dentinal tubules or coronal pulp. The FSI analysis used here could provide a powerful tool for investigating problems with coupled solid and fluid structures in dental biomechanics.

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1. Introduction

Force loading on a tooth may induce tooth structural deformation[1] during daily activities (mastication, bruxism, external traumatic force, etc.) or may cause postoperative sensitivity.[2,3] In addition, according to hydrodynamic theory, physical stimuli on a tooth can cause dental pain,[4] which is induced by the movement of the contents of the dentinal tubules.[5] Linsuwanont et al.[6] determined that external stimuli applied to a tooth causes pulpal wall deformation and induces intrapulpal fluid flow that triggers a nerve impulse.

Dental research often requires a lot of teeth in laboratory studies. Therefore, computational numerical analysis is useful for investigating dental biomechanics, as it does not require actual teeth. The finite element method (FEM) is usually used to analyse the stress and deformation of a tooth structure.[7,8] Takahashi et al.[9] used FEM to investigate the behaviour of a tooth under various loading conditions, with results showing that horizontal loading has a much greater influence on tooth structural deformation than does vertical loading. It is known that dental pain may be induced by a fluid disturbance in the dental intrapulpal chamber.[6] Thus, some studies have used hydrodynamic theory and have set up devices to measure

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http://dx.doi.org/10.1016/j.archoralbio.2012.10.004

intrapulpal fluid flow or pressure in the dental intrapulpal chamber in vitro.[5,10,11] In these studies, a tooth was connected to a glass capillary and a manometer via a short tube filled with saline, and the distal movement and pressure on the root of the tooth were recorded. Thus, the dentinal fluid flow situation could be measured during force stimuli,[12] thermal stimuli[13,14] and during clinical dental treatments.[15–17] Although the dental fluid flow can be measured in the dentinal tubules of coronal dentin, the intact teeth used in such experiments must have the roots resected, and a capillary tube must be inserted to allow observation from the outside. In order to reduce the amount of the tooth consumed in the experiment and to avoid the complicated procedures for measuring dentinal tubules experimentally, the analysis of dental biomechanics using combined FEM and a computational fluid dynamics (CFD) approach is a good choice.

Conventional FEM models are usually used to analyse the solid tooth structure without the pulp chamber being filled with dentinal fluid.[8,18] Therefore, FEM cannot explain the fluid situation in the pulp chamber. The fluid–structure interaction (FSI) method has been used in computational engineering to solve many problems with coupled solid and fluid structures.[19,20] FSI analysis has been proven to be a powerful tool for investigating vascular biomechanics.[21,22] Thus, this method can be an effective tool in the analysis of the fluid flow within dental pulp and for investigating intact tooth biomechanics.

Currently, in view of the lack of previous FSI studies, numerical methods have been applied to investigate problems with coupled solid and fluid interactions in dentistry. Thus, the purpose of this study is using an FSI simulation to evaluate the fluid flow in the dental intrapulpal chamber as induced by the tooth structural deformation during loading in various directions.

2. Materials and methods

2.1. Build a simulation geometry model

For the FSI computation, a three-dimensional (3D) model of the enamel, dentine, pulp, periodonatal ligament (PDL), cortical bone, and cancellous bone was built. The models (enamel, dentine, and pulp chamber) were based on micro-computed tomography (micro-CT) data (Skyscan 1076, Skyscan, Belgium) obtained from a premolar with the following parameters: a 0.172-mm slice interval, a 34.4-mm field of scan, and a 1024×1024-pixel image resolution. Cortical bone and cancellous bone model images were based on dental computed tomography (dental-CT) data (ProMax 3Ds, PLANMECA, Finland) obtained from humans. The images were converted into 3D models using Mimics medical imaging software (Materialise NV, Leuven, Belgium). The grey-scale values of the images represented the density of the material. Contours of the models were segmented from micro-CT and dental-CT images. By setting threshold values, it was possible to separate enamel, dentine, pulp, cortical bone, and cancellous bone. These models were imported into ANSYS Workbench 13.0 (ANSYS Inc., Canonburg, PA) for simulation (Fig. 1a).

2.2. Material properties of 3D model

In the present study, the 3D simulation model was divided into solid parts (enamel, dentine, PDL, cortical bone, and cancellous bone) and a liquid part (pulp). For the solid parts, the material properties used in the analysis namely the density, Young's modulus, and the Poisson's ratios are given in Table 1. All of the material properties were assumed to be homogeneous and isotropic. For the pulp, the values of the material

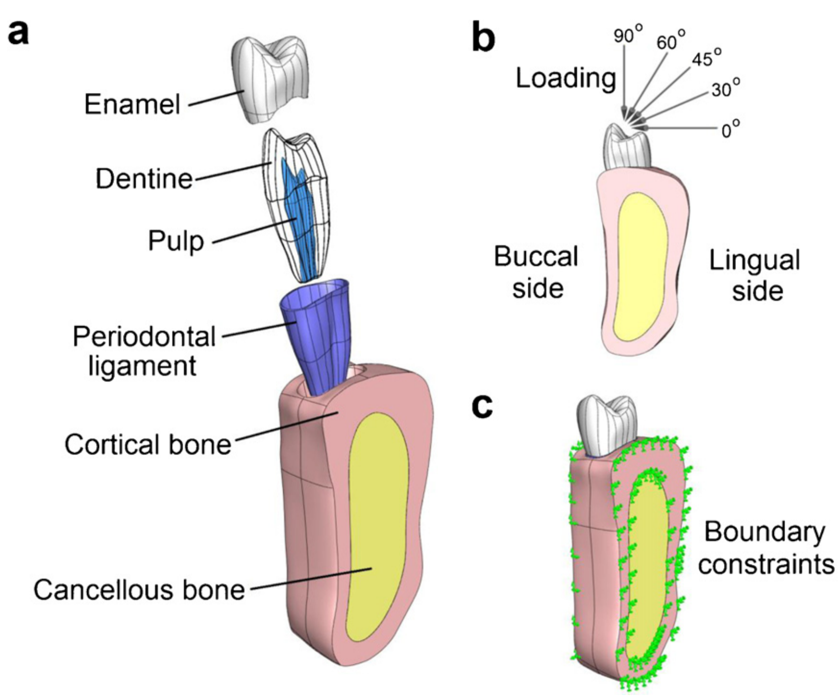

Fig. 1 – (a) FSI simulation model of intact tooth structure, (b) five force loading directions, and (c) boundary conditions.

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