An investigation of dentinal fluid flow in dental pulp during food mastication : simulation of fluid–structure interaction

Chang, Chih-Han; Su, Kuo-Chih; Chuang, Shu-Fen; Ng, Eddie Yin-Kwee

2013

Su, K.-C., Chuang, S.-F., Ng, E. Y.-K., & Chang, C.-H. (2013). An investigation of dentinal fluid flow in dental pulp during food mastication : simulation of fluid–structure interaction. *Biomechanics and modeling in mechanobiology*, 13(3), 527-535.

<https://hdl.handle.net/10356/98700>

<https://doi.org/10.1007/s10237-013-0514-z>

© 2013 Springer-Verlag Berlin Heidelberg. This is the author created version of a work that has been peer reviewed and accepted for publication by *Biomechanics and Modeling in Mechanobiology*, Springer-Verlag Berlin Heidelberg. It incorporates referee's comments but changes resulting from the publishing process, such as copyediting, structural formatting, may not be reflected in this document. The published version is available at: [Article DOI: <http://dx.doi.org/10.1007/s10237-013-0514-z>].

Downloaded on 26 Apr 2023 20:00:35 SGT

Title	An investigation of dentinal fluid flow in dental pulp during food mastication : simulation of fluid–structure interaction(Main article)
Author(s)	Su, Kuo-Chih; Chuang, Shu-Fen; Ng, Eddie Yin-Kwee; Chang, Chih-Han
Citation	Su, K.-C., Chuang, S.-F., Ng, E. Y.-K., & Chang, C.-H. (2014). An investigation of dentinal fluid flow in dental pulp during food mastication: simulation of fluid–structure interaction. Biomechanics and modeling in mechanobiology, 13(3), 527-535.
Date	2013
URL	http://hdl.handle.net/10220/24163
Rights	© 2013 Springer-Verlag Berlin Heidelberg. This is the author created version of a work that has been peer reviewed and accepted for publication by Biomechanics and Modeling in Mechanobiology, Springer-Verlag Berlin Heidelberg. It incorporates referee's comments but changes resulting from the publishing process, such as copyediting, structural formatting, may not be reflected in this document. The published version is available at: [Article DOI: http://dx.doi.org/10.1007/s10237-013-0514-z].

An investigation of dentinal fluid flow in dental pulp during food mastication—simulation of fluid-structure interaction

Kuo-Chih Su, Shu-Fen Chuang, Eddie Yin-Kwee Ng, Chih-Han Chang*

Kuo-Chih Su

Department of Biomedical Engineering, College of Engineering, National Cheng Kung University, 1 University Road, Tainan City 701, Taiwan

Shu-Fen Chuang

Institute of Oral Medicine and Department of Stomatology, College of Medicine and Hospital, National Cheng Kung University, 1 University Road, Tainan City 701, Taiwan

Eddie Yin-Kwee Ng

School of Mechanical and Aerospace Engineering, College of Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

Chih-Han Chang

Department of Biomedical Engineering, College of Engineering, National Cheng Kung University, 1 University Road, Tainan City 701, Taiwan

***Corresponding author:**

Chih-Han Chang, Professor

Department of Biomedical Engineering, College of Engineering, National Cheng Kung University, Tainan, Taiwan

1 University Road, Tainan 701, Taiwan.

Tel.: +886-6-2757575 ext. 63427

Fax.: +886-6-2343270

E-mail address: cchang@mail.bme.ncku.edu.tw

cchcaesar@gmail.com

Abstract

This study uses fluid-structure interaction (FSI) simulation to investigate the relationship between the dentinal fluid flow in the dental pulp of a tooth and the elastic modulus of masticated food particles, and to investigate the effects of chewing rate on fluid flow in the dental pulp. Three-dimensional simulation models of a premolar tooth (enamel, dentine, pulp, periodontal ligament, cortical bone, and cancellous bone) and food particle were created. Food particle with elastic modulus of 2000 and 10000 MPa were used **respectively**. The external displacement loading (5 μm) was gradually directed to the food particle surface for 1 s and 0.1 s, respectively, to simulate the chewing of food particles. The displacement and stress on tooth structure and fluid flow in the dental pulp were selected as evaluation indices. The results show that masticating food with a high elastic modulus results in high stress and deformation in the tooth structure, causing faster dentinal fluid flow in the pulp **in comparison with** that obtained with soft food. In addition, fast chewing of hard food particles can induce faster fluid flow in the pulp, which may result in dental pain. FSI analysis is shown to be a useful tool for investigating dental biomechanics during food mastication. FSI simulation can be used to predict intrapulpal fluid flow in dental pulp; this information may provide the clinician with important **concept** in dental biomechanics during food mastication.

Keywords: Dental biomechanics, Fluid-structure interaction, Dentinal fluid flow, Mastication, Chewing rates

1. Introduction

During food mastication, the mean chewing frequency is 1.57 Hz (Po et al. 2001). Thus, in this rapid frequency, the dental pain may be induced by inadvertent **collision** between relatively hard food particles and tooth. A previous study investigated the relationship between dental structure failure and the elastic modulus of masticated food (Dejak et al. 2003). The results showed that masticating food with a high elastic modulus leads to considerable stress concentration in the occlusal enamel of a tooth, which may damage tooth structure.

Previous studies have indicated that physical stimuli (force, temperature) on a tooth may cause dental pain (Orchardson and Gillam 2006). The most widely accepted theory of dental pain is the hydrodynamic theory (Brännström et al. 1967; Mehta et al. 2009). Linsuwanont et al. (2008) stated that external stimuli applied to teeth cause dental pulp wall deformation, which may induce intrapulpal fluid flow that triggers a nerve impulse and thus tooth pain. Moreover, some studies have indicated that fluid flow of the contents in dentinal tubules could induce nerve impulse, which could cause tooth pain (Andrew and Matthews 2000; Vongsavan and Matthews 2007). Charoenlarp et al. (2007) investigated the relationship between pain intensity and the rate of fluid flow through dentine in different osmotic pressure stimuli. The results showed that the pain threshold during the negative pressure stimuli was -125 mmHg

and the positive pressure stimuli was 200 mmHg, which caused dentinal fluid flow rates of $3.29 \text{ (nL/s} \cdot \text{mm}^2)$ and $5.75 \text{ (nL/s} \cdot \text{mm}^2)$ in exposed dentine, respectively. In addition, some previous studies have investigated the effects of chewing rate on mandibular kinematics. The EMG burst duration of masseter muscle became shortened with the increment of chewing frequency (Plesh et al. 1987). Besides, the distance of mandibular **movement** would be shortened and the velocity of mandible would be also increased under the circumstance of high chewing frequency (Throckmorton et al. 2001). However, none have investigated the relationship between the chewing rate and fluid flow in the dental pulp of a tooth. Thus, the **influence** of dentinal fluid flow in the pulp chamber during chewing at various rates is still unclear.

Some previous studies have investigated hydrodynamic theory and have set up devices to measure intrapulpal fluid flow or pressure in the dental intrapulpal chamber in vitro (Elgalaid et al. 2004; Wylie and Wilson 1994). 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 external stimuli (force, thermal stimulation or clinical dental treatments). Paphangkorakit and Osborn (2000) investigated the teeth suffered from bite force with loading force from 20 to 120 N.

The fluid moved away from the dental pulp immediately after the tooth was loaded.

The outward-moving volume of the fluid flow ranged from 3.5 to 22.2 nL. Some studies investigated the temperature distribution of tooth, the deformation of tooth structure and the movement of dentinal fluid after thermal stimuli on tooth. The expansion or contraction of the tooth may induce intrapulpal fluid flow when subjected to thermal stimulation (Linsuwanont et al. 2007; Linsuwanont et al. 2008).

Lin et al. (2011a) used a tooth mathematical model to simulate the temperature change and thermal stress distribution when the tooth was suffered from thermal stimulation. Besides, some studies investigated the dentinal fluid flow and cuspal displacement during the period of dental restoration after the filling of composite resin.

The shrinkage of resin and the heat produced by dental handpieces and light-curing resin caused mechanical and thermal stresses, which resulted in cuspal displacement and tooth deformation and then induced intrapulpal fluid flow (Ratih et al. 2006;

Ratih et al. 2007; Kim et al. 2010). Although the dental fluid flow can be measured in dentinal tubules of coronal dentine, 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 such experiments, the tooth is altered so much that one may pervert the physiology of the pulp. Therefore, combining finite element method (FEM)

and computational fluid dynamics (CFD) is a good choice for analyzing dental

biomechanics.

In dental research, tooth structure simulations are frequently investigated **by** using the FEM (Huang et al. 2009; Hsu et al. 2011). Conventional FEM models are usually used to analyze the food mastication (Daas et al. 2008; Ichim et al. 2007; Macho and Spears 1999) and solid tooth structure without the pulp chamber being filled with dentinal fluid (Er et al. 2007; Fenner et al. 1998). Therefore, the 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 (Souli and Benson 2010). FSI analysis has been proven to be a useful tool for investigating vascular biomechanics (Küttler et al. 2010; Khalafvand et al. 2011; Siau et al. 2000). The FSI method can be used to determine solid deformation or movement due to external forces, and thus fluid flow **can be also induced from that solid structural change**. This method can be used to model a solid structure interacting with a fluid flow, such as tooth deformation inducing dental pulp fluid flow in an intact tooth during food mastication.

Previous studies have demonstrated that during food mastication, the external force applied to the tooth structure may result in tooth failure (Ichim et al. 2007). However, most in vitro analyses of dental biomechanics did not analyze the fluid mechanics in the dental pulp chamber. The dentinal fluid flow in the dental intrapulpal

chamber during food mastication is thus unclear. The present study uses FSI simulation to investigate the relationship between the fluid flow in the dental pulp of a tooth and the elastic modulus of masticated food particles, and to investigate the **impact** of chewing rate on fluid flow in the dental pulp.

2. Materials and Methods

2.1 Simulation geometry model

A three-dimensional simulation model of premolar tooth (enamel, dentine, pulp, periodontal ligament (PDL), cortical bone, and cancellous bone) was created. The tooth model was 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 view, and a 1024×1024 pixel image resolution. The images were converted into three-dimensional models using the medical imaging software Mimics (Materialise NV, Leuven, Belgium). The gray-scale values of the images represent the density of the material. The contours of the models were segmented from CT data. By setting threshold values, it was possible to separate the enamel, dentine, and pulp. Above the enamel surface, a hemispherical shape (diameter = 1 mm) was created using SolidWorks to model a food particle (Fig. 1A). These models were imported into ANSYS Workbench 13.0 (ANSYS Inc., Canonburg, PA) for simulation.

2.2. Material properties of the model

Soft and hard food particles were used. (The value of Young's modulus of common food is lower such as Cheeses (2.26 MPa) and Brazil nut (33.8MPa)

(Agrawal et al. 1998). However, sometimes carelessly have a bite on hard objects or particles like bone (13700MPa) and prawn shell (2050MPa) (Hepburn et al. 1975), which are foods simulated in this study.) Table 1 shows the material properties (density, Young's modulus, and Poisson's ratio) were used to simulate the solid structure (Er et al. 2007; Chang and Lin 2010). The total volumes were meshed using 41945 elements and 71551 nodes for the structural part (Fig. 2). For the fluid part (pulp), the values of the material properties of water (density = 0.997 g/cm^3 and viscosity = $8.899 \times 10^{-4} \text{ kg/m}\cdot\text{s}$) were obtained from previous studies (De Vree et al. 1983; Su et al. 2012b). The total volumes were meshed using 662743 elements and 221986 nodes for the fluid part. The reliability of the FSI model was checked by convergence tests. The intrapulpal fluid turbulence option was set to laminar flow (Reynolds number < 2100 , see Appendix A), and the fluid pressure of the pulp chamber was set to 15 cmH₂O to simulate pulpal pressure, which is the hydrostatic pressure in the pulp chamber, as given in previous studies (Pashley 1996).

2.3. Process of fluid-structure interaction in ANSYS Workbench

In this study, ANSYS Workbench was used to set up and solve the FSI problem. The ANSYS transient structural module was used to conduct a structural analysis of the solids (finite element analysis (FEA)), and the ANSYS CFX module was used to

conduct an analysis of fluid flow (computational fluid dynamics (CFD)). ANSYS Workbench was used to model two-way interaction on the fluid-solid interface in the FSI simulation. The FSI interface was defined before analysis. During the analysis of the transient mechanical simulation, the working time was divided into many sub-steps. In every sub-step, the results of the solid FEA (deformation) were transferred to the CFX module to constitute a new boundary (velocity) for the CFD calculation. The disturbed liquid exerted a pressure on the FSI interface, resulting in stress on the solid.

2.4. Loading conditions and boundary conditions

The mesial and distal sides of the dental cortical and cancellous bone were fixed in all degrees of freedom as the boundary constraints (Fig. 1B). The intact tooth was subjected to external displacement forces as it received vertical loads transmitted by food (Here, on this food-bitten simulation model, the degrees of displacement are the same whatever the hard or soft ingredients are encompassed within the bolus. Hence, displacement control was used as loading conditions, which made the simulation closer to its real-life situations.). The external displacement was gradually directed to the food particle surface with magnitudes of 0 to 5 μm . In the case of biting, gradual external displacement rates of 5 $\mu\text{m/s}$ and 50 $\mu\text{m/s}$ were applied for 1 s and 0.1 s,

respectively (number of sub-steps = 40) (Fig. 1B). The initial velocity of the fluid domain in the X, Y, and Z axes was set to zero at $t = 0$ s. This setting assumes that when the teeth are not chewing food (not subject to external forces), fluid in the pulp chamber is stationary. For the FSI simulation process, tooth structure simulations were analyzed **by** using the FE method. The results of pulpal wall deformation were used as the intrapulp fluid loading condition (pulp wall movement velocity) on the FSI interface. In addition, the interface condition between the food particle and tooth was set to no-separation contact, which is defined in ANSYS Workbench as two surfaces with a contact condition that prohibits separation in their normal direction, but allows small sliding relative to each other (Lee 2010). This option is used to simulate food contact with teeth. Food is allowed to transfer a pressure on the surface of the teeth and some sliding of the food on the surface of the teeth is allowed. Besides, the more the displacement of food is, the greater contact area with teeth is.

In this study, the von Mises stress at the enamel, the displacements at the enamel and pulp wall, the fluid flow velocity in the dental pulp, and the average and maximum fluid flow velocities from the radicular pulp and the fluid flow velocity in the coronal pulp (Fig. 1C) were selected as the evaluation indices.

3. Results

The total deformation on the enamel at $t = 1$ s and $t = 0.1$ s obtained from the FSI simulation is shown in Fig. 3A. During the mastication of hard food particles, the total deformation (maximum total deformation = 2×10^{-4} mm) is much greater than that during the mastication of soft food particles (maximum total deformation = 6×10^{-5} mm). The deformation distribution patterns on the enamel at $t = 1$ s and $t = 0.1$ s are almost the same. Fig. 3B shows the von Mises stress on the enamel at $t = 1$ s and $t = 0.1$ s. During mastication, hard food particles induce greater stress (9.6MPa) on the enamel where contact is made. The stress distribution patterns are almost the same at $t = 1$ s and $t = 0.1$ s. Fig. 3C and 3D respectively show the distribution of total deformation on the pulpal wall and the vector of total dentine deformation on the pulpal wall at $t = 1$ s and $t = 0.1$ s. Hard food particles induce greater deformation (maximum total deformation = 8.3×10^{-5} mm) on the dental pulp wall during mastication. The deformation distribution patterns on the dental pulp wall are almost the same at $t = 1$ s and $t = 0.1$ s. Fig. 4 and 5 respectively show the cross-section distribution and streamline of the fluid flow velocity in the dental pulp and the flow direction and vector of fluid flow velocity from the radicular pulp at $t = 1$ s and $t = 0.1$ s. Mastication causes the fluid flow to be directed out of the pulp chamber via the apical foramen at the tip of the radicular pulp. For hard food particles, the fluid flow

velocity in the dental pulp is faster than that for soft food. Fig. 6A and 6E show the values of force reaction on the bone during the mastication of soft and hard food at $t = 1$ s and $t = 0.1$ s, respectively. The mastication of hard food causes a higher reaction force on the bone (10.74 N for hard food, 3.06 N for soft food). Fig. 6B and 6F show the values of the maximum fluid flow velocity outflows from the radicular pulp at $t = 1$ s and $t = 0.1$ s, respectively. The magnitudes of maximum fluid flow velocity in the radicular pulp are in the order of hard food at $t = 0.1$ s > soft food at $t = 0.1$ s > hard food at $t = 1$ s > soft food at $t = 1$ s. Fig. 6C and 6G show the values of the average fluid flow velocity outflows from the radicular pulp at $t = 1$ s and $t = 0.1$ s, respectively. The magnitudes of average fluid flow velocity in the radicular pulp are in the order of hard food at $t = 0.1$ s > soft food at $t = 0.1$ s > hard food at $t = 1$ s > soft food at $t = 1$ s. Fig. 6D and 6H show the values of the fluid flow velocity in the coronal pulp at $t = 1$ s and $t = 0.1$ s, respectively. The magnitudes of average fluid flow velocity in the coronal pulp are in the order of hard food at $t = 0.1$ s > soft food at $t = 0.1$ s > hard food at $t = 1$ s > soft food at $t = 1$ s.

4. Discussion

In this study, FSI analysis was demonstrated to be a useful tool for investigating problems with coupled solid and fluid structures. The FSI method can be used to determine the relationship between dentin deformation and the situation in the pulp chamber with external stimuli applied to the tooth. It can also be used to observe the physical quantities (velocity, pressure, flow, streamline, etc.) of the liquid in the pulp chamber at any location. Thus, FSI analysis is a valuable method for investigating dental biomechanics.

During the mastication of hard food particles (high elastic modulus), the total deformation and von Mises stress on the tooth were greater than those produced during the mastication of soft food at $t = 1$ s and $t = 0.1$ s. In previous studies that applied the FEA to dentistry, masticating food with high elastic moduli was found to cause considerable stress concentration on the occlusal enamel of the tooth (Dejak et al. 2003). This result is consistent with the findings of the present study. The mastication of hard food (high elastic modulus) induced a higher reaction force on the bone (Fig. 6A and 6E). When the food was subjected to a given displacement loading, food with a high elastic modulus induced a higher external force transmitted to the tooth (Hooke's law $F=k\Delta x$). Thus, biting hard food may damage the tooth structure. In addition, the deformation distribution patterns and stresses at $t = 1$ s and $t = 0.1$ s

are almost the same. The main reason is that the teeth are subjected to the same external force (known from reaction force) when food is force down on the teeth at $t = 1\text{ s}$ and $t = 0.1\text{ s}$.

With regard to the effect of food mastication on fluid flow within the pulp, the mastication of food causes the fluid flow to be directed outward from the pulp chamber to the radicular pulp because the vertical downward force induces deformation at the top of the pulpal wall from the top to the bottom. At a given external displacement rate on food particles (working time = 1 s or 0.1 s), a higher total deformation rate on the pulp wall of the tooth may induce faster fluid flow in the dental pulp. **Besides**, during the mastication of hard food (e.g., bone), the fluid flow velocity from the radicular pulp or in the coronal pulp is higher than that obtained for soft food at the same chewing frequency. In addition, as shown in Fig. 6B, 6C, 6D, 6F, 6G and 6H, because of the difference of food particle in contact with the dental crown area, the velocity curve moves up and down with time.

Dental pain is induced by fluid flow in dentinal tubules according to hydrodynamic theory (Brännström 1963). External mechanical stimuli applied to a tooth may cause deformation of dentine, which induces inward-directed dentinal fluid flow that causes shear stress on the surface of mechanoreceptors nerve endings, **resulting in the openings of sodium channels and triggering nerve**

impulses (Linsuwanont et al. 2008). An in-vitro study on fluid flow from the dental pulp found that the fluid flow velocity of tooth pain threshold for dentinal tubules was 3.29×10^{-6} m/s, as observed fluid flow through the dentinal tubules to the capillary **by** using a microscope and noting when the hydrostatic pressure stimuli caused tooth pain (Charoenlarp et al. 2007). Thus, the tooth pain threshold can be used to compare the relationship between the fluid flow velocity on the top of the pulp chamber and tooth pain (Lin et al. 2011b).

In the present FSI study, during the mastication of hard or soft food particles in a 1 s interval (the external displacement rate on food particles was 5 $\mu\text{m/s}$), the magnitudes of the maximum fluid flow velocity in the radicular pulp and the fluid flow velocity in the coronal pulp were below the fluid flow velocity of the tooth pain threshold. Thus, pain may not be triggered during the biting of hard or soft food particles for the 1 s interval cases. The external displacement rate of 5 $\mu\text{m/s}$ on food particles does not trigger dental pain. If the chewing rate of food particle is faster (e.g., 10 times, 0.1 s interval case, with corresponding external displacement rate of 50 $\mu\text{m/s}$), the fluid flow velocity in the radicular pulp or coronal pulp will near the value of the tooth pain threshold, resulting in dental pain, when biting hard food particles. Therefore, slow chewing should be used to avoid dental pain when biting hard food particles.

Kim connected the pulp chamber to a sub-nanoliter fluid flow measuring device and found that the minimum measurable fluid flow volume of water movement from the pulp chamber is 0.196 nL (Kim et al. 2010). Therefore, minor fluid flow changes from the pulp can be measured accurately. Although the experiment could measure the fluid flow volume from the dental chamber accurately, it could not observe the situation of fluid flow in the pulp chamber. An advantage of FSI simulation is that it allows the numerical calculation of the fluid flow volume from the pulp chamber (the outflow fluid flow volume was calculated as the fluid displacement from the radicular pulp ($\text{displacement} = \int v dt$) multiplied by the cross-section area of the radicular pulp). Thus, FSI can be used to investigate the relationship between the various external stimuli (e.g., mastication, dental clinical treatment, and thermal stimulation) and fluid flow in the pulp chamber. In addition, the flow velocity values in the pulp obtained using FSI simulation may differ from the measured values because experiments can only measure the fluid outflow from the pulp on the outside of the tooth. Although the fluid flow in the pulp chamber cannot be easily observed in experiments, it can be modeled by using the FSI method which was able to investigate each of the fluid flow situations in pulp chamber with the CT image to create an intact tooth model for analysis. In this way, one can thus avoid damaging the tooth for the actual measurement (Kato and Ohno 2009).

In this FSI simulation study, the FSI model did not consider dentinal tubules, resulting in difficulty describing the relationship between dentinal fluid flow and tooth pain. However, the fluid flow velocity on coronal pulp could be observed. Because the fluid flow disturbance on coronal pulp maybe can induce nerve fiber triggers in dentinal tubules (the intratubular nerve fibers located in the inner one third of the dentin, which is near coronal pulp) (Pashley 1986). In addition, the FSI model is based on previous FEA studies (Mehta et al. 2008), which have indicated that external stimuli applied to a tooth causes pulpal wall deformation, which in turn induces intrapulpal fluid flow that triggers a nerve impulse. This FSI study assumed that the tooth enamel structure is complete and that dentine has not been exposed. In addition, dentinal tubules are very thin (the dentinal tubule diameter is approximately 3 μm) (Pashley 1996), thus, enclosed dentinal tubules (non-exposed dentine) do not flow easily.

There were some limitations to FSI simulation. A premolar was selected as simulation model mainly because premolars are single-root teeth and molars are double-root or triple-root teeth. Therefore, it is very complicated and hard to observe the condition of fluid flow in the dental pulp of molars. Thus, for simplifying the evaluation of fluid flow in the dental pulp, it is relatively easier and wiser to choose single-root as a research object than double-root or triple-root teeth. As a result,

we selected the premolar as our simulation model. The FSI models used in this study created the complete structure of a tooth, with the material properties considered to be homogeneous, isotropic, and linearly elastic, as done in most previous FEA studies (Hsu et al. 2006; Su et al. 2012a; Hsu et al. 2009). In addition, PDL model is a thin layer structure in the outside of the tooth. Although the boundary constraints were fixed at the mesial and distal side of cortical and cancellous bone, the lower elastic modulus for PDL material property may still cause a larger deformation on dentine when tooth subjected to external force, which was may **result in the over-prediction** of the fluid flow velocity in pulp chamber. The dental pulp is a soft tissue component of the pulpodentin complex (Hargreaves and Goodis 2002). However, in this FSI study, the intrapulpal material properties values for water were used (De Vree et al. 1983; Su et al. 2012b) as done in previous in vitro studies. These simplifications may induce some differences with the real situation.

FSI can be used to investigate intrapulpal fluid biomechanics of a tooth when masticating food. However, suitable material properties need to be used and a model of dentinal tubules needs to be established. In order to simulate more realistic dental biomechanics, future work should consider a more complete FSI structural model and more suitable material properties. FSI technology can be applied to investigate dentinal fluid flow under conditions such as external traumatic force, thermal

stimulation, and clinical dental treatments.

5. Conclusions

This study applied the FSI method to evaluate the effect of food particle hardness on dentinal fluid flow in the dental pulp. Masticating food with a high elastic modulus results in high stress and deformation in the tooth structure and a high reaction force on the bone, causing faster dentinal fluid flow in the pulp than that produced for food with a low elastic modulus. In addition, the fast chewing of hard food particles can make the fluid flow velocity in pulp may reach the value of the tooth pain threshold, triggering dental pain. **Therefore, this study raised some hypothetical suggestions**

by the results of FSI simulation (like slowing chewing may avoid toothache when carelessly biting hard food particles). Perhaps, concepts from the current study could be applied for clinical researches in the future.

Acknowledgment

The authors would like to thank Dr. Jui-Ting Hsu (School of Dentistry, China Medical University) for the assistant in building the numerical analysis models.

Conflict of interest statement

The authors indicate no potential conflicts of interest in this manuscript.

Appendix A.

The Reynolds number (Re) is used to characterize flow regimes, such as laminar flow or turbulent flow. Laminar flow takes place at low Reynolds numbers ($Re < 2100$). Turbulent flow takes place at high Reynolds numbers ($Re > 4000$). Re is generally defined as:

$$Re = \rho v D / \mu \quad (A1)$$

where ρ is the density of the fluid, v is the mean velocity of the object relative to the fluid, D is the hydraulic diameter of end of the root ($D = 4 \times (\text{cross-sectional area}) / (\text{perimeter})$), and μ is the dynamic viscosity of the fluid. In this FSI simulation, the material properties of the liquid were set to: $\rho = 0.997 \text{ g/cm}^3$, $\mu = 8.899 \times 10^{-4} \text{ kg/m}\cdot\text{s}$, and $D = 6.59 \times 10^{-4} \text{ m}$. If the pulp chamber fluid flow regime is laminar, Re must be less than 2100. Therefore, the fluid flow velocity of the pulp chamber must be less than 2.84 m/s. Previous studies have shown that the fluid flow velocity of the pulp chamber is far lower than 2.84 m/s (Su et al. 2012b). Thus, in this FSI study, the turbulence option of CFD (ANSYS Workbench CFX) was set to laminar liquid.

References

Agrawal K, Lucas P, Bruce I, Prinz J (1998) Food properties that influence neuromuscular activity during human mastication. *J Dent Res* 77:1931-1938

Andrew D, Matthews B (2000) Displacement of the contents of dentinal tubules and sensory transduction in intradental nerves of the cat. *J Physiol* 529:791-802

Brännström M (1963) Dentin sensitivity and aspiration of odontoblasts. *J Am Dent Assoc* 66:366-370

Brännström M, Linden LA, Aström A (1967) The hydrodynamics of the dental tubule and of pulp fluid. A discussion of its significance in relation to dentinal sensitivity. *Caries Res* 1:310-317

Chang WJ, Lin CL (2010) Estimation of the retainer height biomechanical contribution in posterior resin-bonded fixed partial dentures: a structural-thermal coupled finite element analysis. *Med Biol Eng Comput* 48:1115-1122

Charoenlarp P, Wanachantararak S, Vongsavan N, Matthews B (2007) Pain and the rate of dentinal fluid flow produced by hydrostatic pressure stimulation of exposed dentine in man. *Arch Oral Biol* 52:625-631

Daas M, Dubois G, Bonnet AS, Lipinski P, Rignon-Bret C (2008) A complete finite element model of a mandibular implant-retained overdenture with two implants: comparison between rigid and resilient attachment configurations. *Med Eng Phys* 30:218-225

Dejak B, Mlotkowski A, Romanowicz M (2003) Finite element analysis of stresses in molars during clenching and mastication. *J Prosthet Dent* 90:591-597

De Vree J, Spierings TAM, Plasschaert A (1983) Materials Science A Simulation Model for Transient Thermal Analysis of Restored Teeth. *J Dent Res* 62:756-759

Elgalaid T, Youngson C, McHugh S, Hall A, Creanor S, Foye R (2004) In vitro dentine permeability: the relative effect of a dentine bonding agent on crown preparations. *J Dent* 32:413-421

Er O, Yaman SD, Hasan M (2007) Finite element analysis of the effects of thermal obturation in maxillary canine teeth. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 104:277-286

Fenner DN, Robinson PB, Cheung PM (1998) Three-dimensional finite element analysis of thermal shock in a premolar with a composite resin MOD restoration. *Med Eng Phys* 20:269-275

Hargreaves KM, Goodis HE (2002) *Seltzer and Bender's dental pulp*. Quintessence Pub. Co., Chicago

Hepburn H, Joffe I, Green N, Nelson K (1975) Mechanical properties of a crab shell. *Comp Biochem Physiol* 50:551-554.

Hsu JT, Fuh LJ, Lin DJ, Shen YW, Huang HL (2009) Bone strain and interfacial sliding analyses of platform switching and implant diameter on an immediately loaded implant: experimental and three-dimensional finite element analyses. *J periodont* 80:1125-1132

Hsu JT, Lai KA, Chen Q, Zobitz ME, Huang HL, An KN, Chang CH (2006) The relation between micromotion and screw fixation in acetabular cup. *Comput Meth Programs Biomed* 84:34-41

Hsu JT, Huang HL, Tsai MT, Fuh LJ, Tu MG (2011) Effect of screw fixation on temporomandibular joint condylar prosthesis. *J Oral Maxillofac Surg* 69:1320-1328

Huang HL, Fuh LJ, Ko CC, Hsu JT, Chen CC (2009) Biomechanical effects of a maxillary implant in the augmented sinus: a three-dimensional finite element analysis. *Int J Oral Maxillofac Implants* 24:455-462

Ichim I, Li Q, Li W, Swain MV, Kieser J (2007) Modelling of fracture behaviour in biomaterials. *Biomaterials* 28:1317-1326

Kato A, Ohno N (2009) Construction of three-dimensional tooth model by micro-computed tomography and application for data sharing. *Clin Oral Investig* 13:43-46

Khalafvand SS, Ng EYK, Zhong L (2011) CFD simulation of flow through heart: a

perspective review. *Comput Methods Biomech Biomed Engin* 14:113-132

Kim SY, Ferracane J, Kim HY, Lee IB (2010) Real-time measurement of dentinal fluid flow during amalgam and composite restoration. *J Dent* 38:343-351

Küttler U, Gee M, Förster C, Comerford A, Wall W (2010) Coupling strategies for biomedical fluid–structure interaction problems. *Int J Numer Meth Biomed* 26:305-321

Lee HH (2010) *Finite Element Simulations with ANSYS Workbench 12*. Schroff Development Corporation, USA

Lin M, Liu S, Niu L, Xu F, Lu TJ (2011a) Analysis of thermal-induced dentinal fluid flow and its implications in dental thermal pain. *Arch Oral Biol* 56:846-854

Lin M, Luo ZY, Bai BF, Xu F, Lu TJ (2011b) Fluid mechanics in dentinal microtubules provides mechanistic insights into the difference between hot and cold dental pain. *PLoS One* 6:e18068

Linsuwanont P, Palamara JE, Messer HH (2007) An investigation of thermal stimulation in intact teeth. *Arch Oral Biol* 52:218-227

Linsuwanont P, Versluis A, Palamara JE, Messer HH (2008) Thermal stimulation causes tooth deformation: a possible alternative to the hydrodynamic theory? *Arch Oral Biol* 53:261-272

Macho GA, Spears IR (1999) Effects of loading on the biochemical behavior of molars of Homo, Pan, and Pongo. *Am J Phys Anthropol* 109:211-227

Mehta N, Maloney GE, Bana DS, Scrivani SJ (2009) *Head, face, and neck pain: science, evaluation, and management: an interdisciplinary approach*. Wiley-Blackwell, London

Orchardson R, Gillam DG (2006) Managing dentin hypersensitivity. *J Am Dent Assoc* 137:990-998

Paphangkorakit J, Osborn JW (2000) The effect of normal occlusal forces on fluid movement through human dentine in vitro. *Arch Oral Biol* 45:1033-1041

Plesh O, Bishop B, McCall W (1987) Mandibular movements and jaw muscles' activity while voluntarily chewing at different rates. *Exp Neurol* 98:285-300

Pashley DH (1986) Dentin permeability, dentin sensitivity, and treatment through tubule occlusion. *J Endod* 12:465-474

Pashley DH (1996) Dynamics of the pulpo-dentin complex. *Crit Rev Oral Biol Med* 7:104-133

Po JM, Kieser JA, Gallo LM, Tesenyi AJ, Herbison P, Farella M (2011) Time-frequency analysis of chewing activity in the natural environment. *J Dent Res* 90:1206-1210

Ratih DN, Palamara JEA, Messer HH (2006) Minimizing dentinal fluid flow associated with gap formation. *J Dent Res* 85:1027-1031

Ratih DN, Palamara JEA, Messer HH (2007) Dentinal fluid flow and cuspal displacement in response to resin composite restorative procedures. *Dent Mater* 23:1405-1411

Siauw WL, Ng EYK, Mazumdar J (2000) Unsteady stenosis flow prediction: a comparative study of non-Newtonian models with operator splitting scheme. *Med Eng Phys* 22:265-277

Souli M, Benson DJ (2010) Arbitrary Lagrangian-Eulerian and Fluid-structure Interaction: Numerical Simulation. ISTE, London

Su KC, Chang CH, Chuang SF, Ng EYK (2012a) Biomechanical evaluation of endodontic post-restored tooth - finite element analysis. *J Mech Med Biol*. doi: 10.1142/S0219519413500127

Su KC, Chang CH, Chuang SF, Ng EYK (2012b) The effect of dentinal fluid flow during loading in various directions—Simulation of fluid–structure interaction. *Arch Oral Biol*. doi: 10.1016/j.archoralbio.2012.10.004

Throckmorton G, Buschang B, Hayasaki H, Phelan T (2001) The effects of chewing rates on mandibular kinematics. *J Oral Rehabil* 28:328-334

Vongsavan N, Matthews B (2007) The relationship between the discharge of intradental nerves and the rate of fluid flow through dentine in the cat. Arch Oral Biol 52:640-647

Wylie SG, Wilson PR (1994) An investigation into the pressure transmitted to the pulp chamber on crown cementation: a laboratory study. J Dent Res 73:1684-1689

Table Caption

Table 1 Material properties of solid parts. (Er et al. 2007; Chang and Lin 2010)

Figure Captions

Fig. 1 (A) FSI model of intact tooth structure during the mastication of food particle. (B) Displacement condition on a food particle in contact with the tooth crown surface and boundary conditions on the bone. (C) The FSI interface is at the pulp wall and the opening of the radicular pulp; the velocities from the radicular pulp and in the coronal pulp were selected as the evaluation indices.

Fig. 2 FSI mesh model of solid part and fluid part.

Fig. 3 (A) Distribution of total deformation on enamel at $t = 1$ s and $t = 0.1$ s. (B) Distribution of von Mises stress on enamel at $t = 1$ s and $t = 0.1$ s. (C) Distribution of total deformation on the pulpal wall at $t = 1$ s and $t = 0.1$ s. (D) Vector of total dentine deformation on the pulpal wall at $t = 1$ s and $t = 0.1$ s.

Fig. 4 Cross-section distribution and streamline of fluid flow velocity in dental pulp at $t = 1$ s and $t = 0.1$ s.

Fig. 5 Flow direction and vector of fluid flow velocity from radicular pulp at $t = 1$ s and $t = 0.1$ s.

Fig. 6 (A) Values of reaction force on the bone during the mastication of food at $t = 1$ s. (B) Maximum fluid flow velocity outflows from radicular pulp at $t = 1$ s. (C) Average fluid flow velocity outflows from radicular pulp at $t = 1$ s. (D) Fluid flow velocity in the coronal pulp at $t = 1$ s. (E) Values of reaction force on the bone during the mastication of food at $t = 0.1$ s. (F) Maximum fluid flow velocity outflows from radicular pulp at $t = 0.1$ s. (G) Average fluid flow velocity outflows from radicular pulp at $t = 0.1$ s. (H) Fluid flow velocity in the coronal pulp at $t = 0.1$ s.

Table 1 Material properties of solid parts. (Er et al. 2007; Chang and Lin 2010)

Material	Density (g/cm ³)	Young's modulus (MPa)	Poisson's ratio	Number of nodes	Number of elements
Enamel	2.9	84100	0.33	12149	7131
Dentine	4	18600	0.31	19622	12547
Periodontal ligament	1	69	0.45	11149	5513
Cortical bone	1.3	13700	0.3	8562	4733
Cancellous bone	1.3	1370	0.3	9607	5762
Soft food	1	2000	0.4	10462	6259
Hard food	1	10000	0.28	10462	6259

Fig. 1 (A) FSI model of intact tooth structure during the mastication of food particle. (B) Displacement condition on a food particle in contact with the tooth crown surface and boundary conditions on the bone. (C) The FSI interface is at the pulp wall and the opening of the radicular pulp; the velocities from the radicular pulp and in the coronal pulp were selected as the evaluation indices.

Structural part

Fluid part

Fig. 2 FSI mesh model of solid part and fluid part.

Fig. 3 (A) Distribution of total deformation on enamel at $t = 1$ s and $t = 0.1$ s. (B) Distribution of von Mises stress on enamel at $t = 1$ s and $t = 0.1$ s. (C) Distribution of total deformation on the pulpal wall at $t = 1$ s and $t = 0.1$ s. (D) Vector of total dentine deformation on the pulpal wall at $t = 1$ s and $t = 0.1$ s.

Fig. 4 Cross-section distribution and streamline of fluid flow velocity in dental pulp at $t = 1\text{ s}$ and $t = 0.1\text{ s}$.

Fig. 5 Flow direction and vector of fluid flow velocity from radicular pulp at $t = 1 \text{ s}$ and $t = 0.1 \text{ s}$.

Fig. 6 (A) Values of reaction force on the bone during the mastication of food at $t = 1$ s. (B) Maximum fluid flow velocity outflows from radicular pulp at $t = 1$ s. (C) Average fluid flow velocity outflows from radicular pulp at $t = 1$ s. (D) Fluid flow velocity in the coronal pulp at $t = 1$ s. (E) Values of reaction force on the bone during the mastication of food at $t = 0.1$ s. (F) Maximum fluid flow velocity outflows from radicular pulp at $t = 0.1$ s. (G) Average fluid flow velocity outflows from radicular pulp at $t = 0.1$ s. (H) Fluid flow velocity in the coronal pulp at $t = 0.1$ s.