ARCHIVES OF ORAL BIOLOGY 56 (2011) 846–854

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Analysis of thermal-induced dentinal fluid flow and its implications in dental thermal pain

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ARTICLE INFO

Article history:
Accepted 11 February 2011

Keywords:
Dentinal fluid flow
Dentinal tubule
Thermomechanics
Deformation
Thermal pain mechanism
Neural discharge pattern

ABSTRACT

Objectives: The initiation of the pain sensation experienced following the thermal stimulation of dentine has been correlated with fluid flow in the dentinal tubules. There may be other mechanisms.

Methods: This study examines this possibility using a mathematical model to simulate the temperature and thermal stress distribution in a tooth undergoing thermal stimulation. The results obtained were then used to predict the fluid flow in a single dentinal tubule by considering the deformation of the dentinal tubules and dentinal fluid.

Results: Deformation of the pulp chamber was observed before a noticeable temperature change was recorded at the dentine–enamel junction. Tubule deformation leads to changes in fluid flow more rapidly than fluid expansion or contraction. This finding agreed with previously reported experimental observations. An initially high rate of outward fluid flow under cooling was found to correspond to short latency neural responses whilst heating was associated with long latency neural responses.

Conclusion: Rapid fluid flow caused by thermal deformation of dentinal tubules may account for the short latency (<1 s) activation of mechano-sensitive receptors after of cooling. Long latency (>10 s) neural responses could be associated with the activation of thermo-sensitive receptors.

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1. Introduction

Amongst the various theories that have been proposed thus far to explain the excitation of pulpal nociceptors under thermal stimulation,[1] the ''hydrodynamic theory'' has been widely accepted. The ''hydrodynamic theory'' states that dentinal fluid flow induced by thermal expansion/contraction of dentinal fluid within dentinal tubules (Fig. 1a and b) activate pulpal nociceptors, resulting in pain.[2–5] This theory was supported by the co-occurrence of fluid flow through dentinal tubules and the intradental neural discharge.[6,7] Dentinal fluid flow may cause sufficiently high shear stress on intradental nerve terminals, activating the mechano-sensitive ion channels (e.g., ASIC3, TREK1, TREK2)[8–10] and hence leading to dental pain sensation.[8,11,12]

Another phenomenon which may be explained by dentinal fluid flow is the difference between heat and cold pain: rapid transient pain sensation under cold stimulation versus dull lasting pain under hot stimulation.[13–16] Although the

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0003–9969/$ – see front matter. Published by Elsevier Ltd.
doi:10.1016/j.archoralbio.2011.02.011

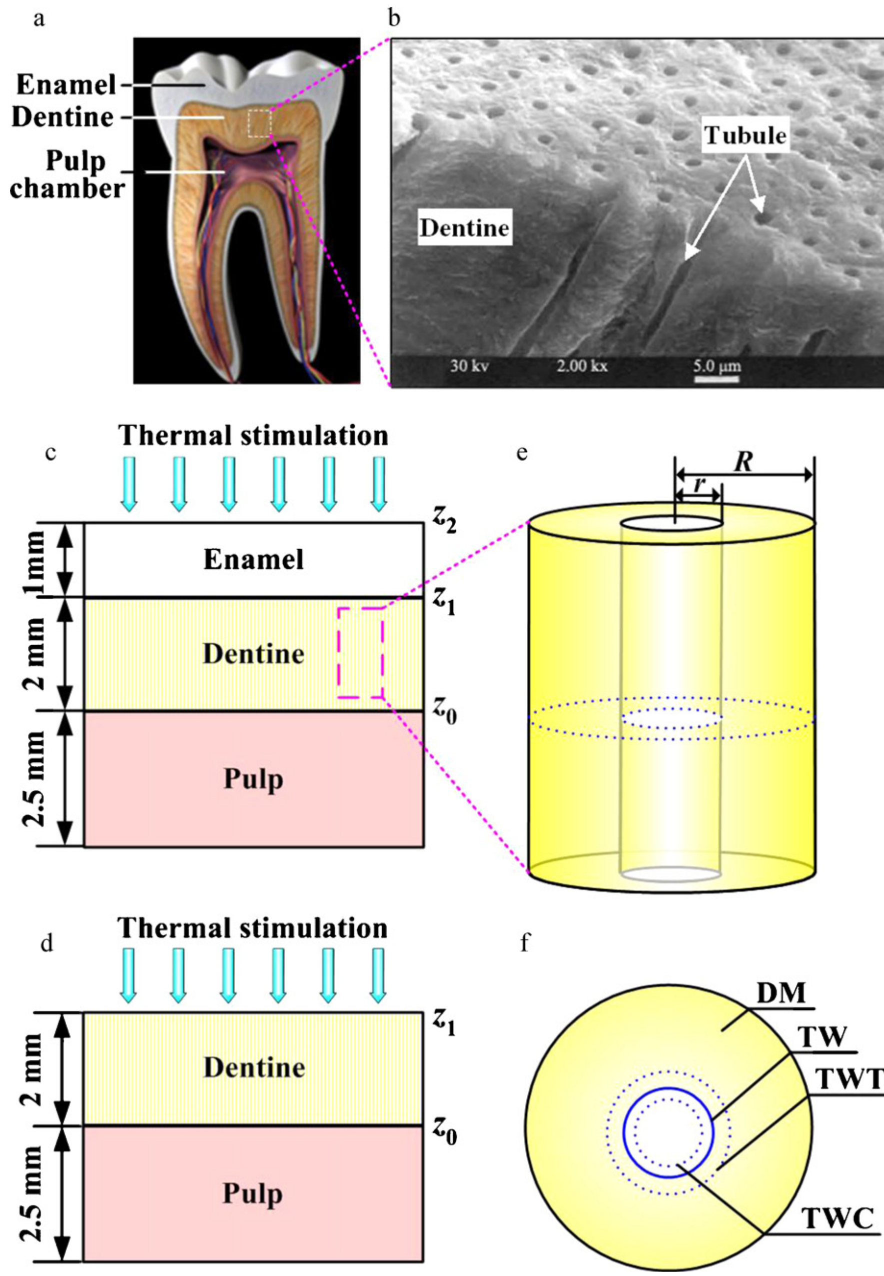

Fig. 1 – Physiological relevant structures: (a) cut-away image of human tooth illustrating composite layers (www.3dscience.com); (b) SEM image of dentine showing solid dentine material and micro tubules running perpendicularly from pulpal wall towards dentine–enamel junction.[24] Illustration of idealized physical models: (c) one-dimensional three-layer tooth model (modelling thermal stimulation on intact teeth); (d) one-dimensional two-layer model (modelling thermal stimulation on exposed dentine surface); (e) single dentine micro tubule; (f) representative area sectioned from (e) depicting thermal deformation of tubule wall. DM: dentine matrix; TW: tubule wall before deformation; TWC: deformed tubule wall caused by compressive thermal stress; TWT: deformed tubule wall caused by tensile thermal stress.

transduction mechanism is yet clear, the direction of fluid flow through dentinal tubules has been identified as outward flow (away from the pulp) under cold stimulation and inward flow (into the pulp) under hot stimulation,[6,7,17] with the intradental neural discharge rate increasing with increasing fluid flow rate.[6,7] Hence, a better understanding of dentinal fluid flow characteristics under thermal stimulation may provide insights into the mechanisms underlying the intradental neural responses.[9] Mathematical model that provides mechanistic insights into the difference between hot and cold dental pain sensations has been recently proposed by Min et al.[10]

Although thermal-induced dentinal fluid flow has been experimentally studied for long,[6,17–21] the understanding of the underlying mechanism remains unclear. According to ''hydrodynamic theory'', dentinal fluid flow is assumed to be purely caused by thermal expansion/contraction of dentinal fluid,[5] or in other words, fluid flow occurs only after heat is transferred to the dentine layer housing the dentinal fluid. However, a recent study showed that dentinal fluid flow occurred before temperature change at DEJ could be observed.[17] Instead of fluid thermal expansion/contraction, a rapid structural deformation of the pulpal wall was observed when thermal stimulation was applied on the enamel surface.[22] The response latency of the structural deformation was also comparable with that of the fluid flow.[22] These observations indicate that the rapid fluid flow response may be attributed to the thermal-induced structural deformation. However, no theoretical study on this has been applied.

In this study, we hypothesize that: (i) thermal-induced dentinal tubule deformation results in the rapid response of fluid flow; (ii) dentinal fluid flow rather than temperature change (at the position of pulpal nociceptors) accounts for the short latency in intradental neural discharge under cooling. To check our hypotheses, we developed a thermomechanical model to analyse the temperature and thermal stress distribution in tooth under either hot or cold stimulation. Dentinal fluid flow caused by dentinal tubules thermal deformation and that by thermal expansion/contraction of dentinal fluid were modelled separately to investigate the mechanism underlying initiation of fluid flow. The model was then employed to investigate the differences in intradental neural discharge patterns evoked by hot and cold stimulations.

2. Mathematical modelling

2.1. *Modelling of heat transfer and thermal stress in tooth*

For quantitative analysis of dental pain sensation, please refer to the study by Min et al.[10] In this study, focusing on the qualitative analysis of teeth thermomechanical behaviour and dental thermal pain, we assume that a tooth is a one-dimensional (1D) multi-layer structure (e.g., enamel, dentine and pulp layers) as shown schematically in Fig. 1c and d. Such assumption should not significantly affect the fundamental characteristics of heat transfer and thermal deformation behaviours of teeth.[22]

To study the transfer of heat in the layered tooth model, 1D Fourier heat transfer equation was employed:

$$\rho_i c_i \frac{\partial T(z,t)}{\partial t} = k_i \frac{\partial^2 T(z,t)}{\partial x^2} \tag{1}$$

where i is the index of sub-layers ($i = 1, 2, 3$ represent enamel, dentine and pulp layers, respectively); T (K) is the temperature which depends on time t (s) and location z (m); k_i (W m^{-1} K^{-1}), c_i (J kg^{-1} K^{-1}) and ρ_i (kg m^{-3}) are the thermal conductivity, specific heat capacity and mass density in sub-layer i, respectively. The physical properties of each layer used in the present study are listed in Table 1.

Thermal stresses develop whenever thermal expansion/contraction is restrained from the mismatch of thermal properties or/and temperature gradient within a construct.[9] Since pulp layer is a liquid layer, it only serves as a heat transfer medium without restraining the thermal deformation of enamel and dentine from the thermomechanical point of view. Hence, thermal stresses do not exist in pulp layer in the 1D layered model.

To model the application of thermal stimulation on exposed dentine surface where enamel is worn-out, a two-layer model (Fig. 1d) was employed. The in-plane thermal stresses parallel to the dentine layer can be obtained as[23]:

$$\sigma(z,t) = -\bar{E}\bar{\lambda}(T(z,t) - T_0) + \frac{\bar{E}\bar{\lambda}}{z_1 - z_0}\int_{-(z_1-z_0)/2}^{(z_1-z_0)/2}(T(z,t) - T_0)\,dz + \bar{E}\bar{\lambda}\frac{12z}{(z_1-z_0)^3}\int_{-(z_1-z_0)/2}^{(z_1-z_0)/2}(T(z,t) - T_0)z\,dz \tag{2}$$

where $\bar{E} = E/(1-\nu^2)$, $\bar{\lambda} = (1-\nu)\lambda$. E (Pa), ν and λ (K^{-1}) are the Young's modulus, Poisson ratio and coefficient of thermal expansion of dentine, respectively.

To model the application of thermal stimulation on enamel surface (in intact tooth), a three-layer model (Fig. 1c) was employed. In-plane thermal stresses in enamel and dentine layers can be calculated as[23]:

$$\{\sigma(z,t)\}_e = \bar{E}_e(1+\nu_e)\left\{\begin{array}{l} -\bar{\lambda}_e\,\Delta T + \left[(a'_{11}+a'_{12})\left(\int_{z_0}^{z_1}\bar{E}_e\bar{\lambda}_e\,\Delta T\,dz + \int_{z_1}^{z_2}\bar{E}_d\bar{\lambda}_d\,\Delta T\,dz\right) + (b'_{11}+b'_{12})\left(\int_{z_0}^{z_1}\bar{E}_e\bar{\lambda}_e\,\Delta T\,z\,dz + \int_{z_1}^{z_2}\bar{E}_d\bar{\lambda}_d\,\Delta T\,dz\right)\right] \\ +z\left[(b'_{11}+b'_{12})\left(\int_{z_0}^{z_1}\bar{E}_e\bar{\lambda}_e\,\Delta T\,dz + \int_{z_1}^{z_2}\bar{E}_d\bar{\lambda}_d\,\Delta T\,dz\right) + (d'_{11}+d'_{12})\left(\int_{z_0}^{z_1}\bar{E}_e\bar{\lambda}_e\,\Delta T\,z\,dz + \int_{z_1}^{z_2}\bar{E}_d\bar{\lambda}_d\,\Delta T\,dz\right)\right] \end{array}\right\} \tag{3}$$

$z_2 \le z < z_1$ enamel layer

$$\{\sigma(z,t)\}_d = \bar{E}_d(1+\nu_d)\left\{\begin{array}{l} -\bar{\lambda}_d\,\Delta T + \left[(a'_{11}+a'_{12})\left(\int_{z_0}^{z_1}\bar{E}_e\bar{\lambda}_e\,\Delta T\,dz + \int_{z_1}^{z_2}\bar{E}_d\bar{\lambda}_d\,\Delta T\,dz\right) + (b'_{11}+b'_{12})\left(\int_{z_0}^{z_1}\bar{E}_e\bar{\lambda}_e\,\Delta T\,z\,dz + \int_{z_1}^{z_2}\bar{E}_d\bar{\lambda}_d\,\Delta T\,dz\right)\right] \\ +z\left[(b'_{11}+b'_{12})\left(\int_{z_0}^{z_1}\bar{E}_e\bar{\lambda}_e\,\Delta T\,dz + \int_{z_1}^{z_2}\bar{E}_d\bar{\lambda}_d\,\Delta T\,dz\right) + (d'_{11}+d'_{12})\left(\int_{z_0}^{z_1}\bar{E}_e\bar{\lambda}_e\,\Delta Tz\,dz + \int_{z_1}^{z_2}\bar{E}_d\bar{\lambda}_d\,\Delta T\,dz\right)\right] \end{array}\right\} \tag{4}$$

$z_1 \le z < z_0$ dentine layer

where $\Delta T = T(z, t) - T_0$. The in-plane extensional, coupling and bending stiffness of the overall laminate of tooth structure are governed by, respectively:

$$\left.\begin{array}{l} A_{ij} = \sum_{k=1}^{2}(\bar{Q}_{ij})_k(z_k - z_{k-1}) \\ B_{ij} = \frac{1}{2}\sum_{k=1}^{2}(\bar{Q}_{ij})_k(z_k^2 - z_{k-1}^2) \\ D_{ij} = \frac{1}{3}\sum_{k=1}^{2}(\bar{Q}_{ij})_k(z_k^2 - z_{k-1}^2) \end{array}\right\} \quad (i, j = 1, 2, 6) \tag{5}$$

Table 1 – Physical properties of teeth.

Property	Tooth component	Values	References
Thermal conductivity, k [W m^{-1} K^{-1}]	Enamel	0.81	28
	Dentine	0.48	28
	Pulp[a]	0.63	29
Specific heat, c_p [$\times 10^{-3}$ J kg^{-1} K^{-1}]	Enamel	0.71	30
	Dentine	1.59	30
	Pulp[a]	4.2	29
Density, ρ [$\times 10^{-3}$ kg m^{-3}]	Enamel	2.80	30
	Dentine	1.96	30
	Pulp[a]	1.00	29
Young's modulus, E [GPa]	Enamel	94	31
	Dentine	20	31
Poisson ratio, ν	Enamel	0.30	32
	Dentine	0.25	31
Coefficient of thermal expansion, λ [$\times 10^{-5}$ K^{-1}]	Enamel	1.696	33
	Dentine	1.059	33

[a] Values taken from water following de Vree et al.[29]

where k is the index of sub-layers, with $k = 1$ and 2 representing enamel and dentine layer, respectively. A_{ij}, B_{ij} and C_{ij} are separately assembled into the elements of stiffness matrices [A], [B] and [D], and the elements a'_{11}, a'_{12}, b'_{11}, b'_{12}, d'_{11}, d'_{12} can be determined by:

$$\begin{aligned} a'_{11} &= [A^{-1}B(D-BA^{-1}B)^{-1}BA^{-1}]_{11}, \quad a'_{12} \\ &= [A^{-1}B(D-BA^{-1}B)^{-1}BA^{-1}]_{12}, \quad b'_{11} \\ &= [-(A^{-1}B)(D-BA^{-1}B)^{-1}]_{11}, \quad b'_{12} \\ &= [-(A^{-1}B)(D-BA^{-1}B)^{-1}]_{12}, \quad d'_{11} \\ &= [(D-BA^{-1}B)^{-1}]_{11}, \quad d'_{12} = [(D-BA^{-1}B)^{-1}]_{12} \end{aligned} \tag{6}$$

Finally, the stiffness matrix of the layered structure, $[\bar{Q}]_k$, is defined by:

$$[\bar{Q}]_k = \begin{bmatrix} \frac{E_k}{1-\upsilon_k^2} & \frac{\nu_k E_k}{1-\upsilon_k^2} & 0 \\ \frac{\nu_k E_k}{1-\upsilon_k^2} & \frac{E_k}{1-\upsilon_k^2} & 0 \\ 0 & 0 & \frac{E_k}{2(1-\nu_k)} \end{bmatrix} \tag{7}$$

2.2. *Modelling of fluid flow in dentinal tubule*

The dentinal tubule is modelled as a hollow cylinder with inner and outer radii of r and R (Fig. 1e). The fact that the dentinal tubule generally runs perpendicularly from pulpal wall to dentine–enamel junction[24] suggesting that the in-plane thermal stress distribution (in dentine layer in the layered model) is perpendicular to the longitudinal direction of the tubule. Hence, we assume that the outer surface of the cylinder is subjected to thermal stressing throughout the dentine layer in its radial direction. Given that in general $R > 3r$,[24] the displacement of the tubule wall (Fig. 1f) can be approximately expressed as[25]:

$$u_\rho \approx \frac{2}{E}(1+\upsilon)(1-\upsilon)r\sigma(z,t) \tag{8}$$

The volume change of dentinal tubule is then:

$$V(t) = \int_{z_0}^{z_1} [\pi(u_\rho(z,t)+r)^2 - \pi r^2]\,dz \tag{9}$$

and, correspondingly, the fluid flow velocity at the pulpal end of dentinal tubule due to tubule deformation, u_1, is:

$$u_1(t) = \frac{V'(t)}{\pi r^2} \tag{10}$$

The volume change of dentinal fluid caused by thermal expansion/contraction is governed by:

$$\delta V(t) = -\int_{z_0}^{z_1} 3(T(z,t)-T_0)\alpha\pi r^2\,dz \tag{11}$$

This leads to the fluid flow velocity at the pulpal end of dentinal tubule due to thermal expansion/contraction of dentinal fluid, u_2, as:

$$u_2(t) = \frac{\delta V'(t)}{\pi r^2} \tag{12}$$

Finally, when the contributions by deformation in both dentinal tubule and dentinal fluid are considered, the fluid flow velocity is:

$$u(t) = \frac{V' + \delta V'(t)}{\pi r^2} \tag{13}$$

Upon thermomechanics analysis in the layered tooth model, the distributions of temperature $T(z, t)$ and thermal stress $\sigma(z, t)$ in the dentine layer were obtained. Subsequently, Eqs. (10), (12) and (13) were solved for different fluid flows *vs.* time curves as contributed by dentinal tubule deformation, dentinal fluid expansion/contraction and deformation in both dentinal tubule and dentinal fluid, respectively. The results are presented below.

3. Results and discussion

3.1. *Tooth thermomechanics*

Simulated temperature and thermal stress distributions within tooth (three-layer model) during and after cold stimulation are shown respectively in Fig. 2a and b. At the initial stage of cooling, the temperature change has yet reached the inner layer (Fig. 2a). Cold stimulation causes tensile stresses (positive in values) at the enamel surface and compressive stresses (negative in values) at the DEJ (Fig. 2b).

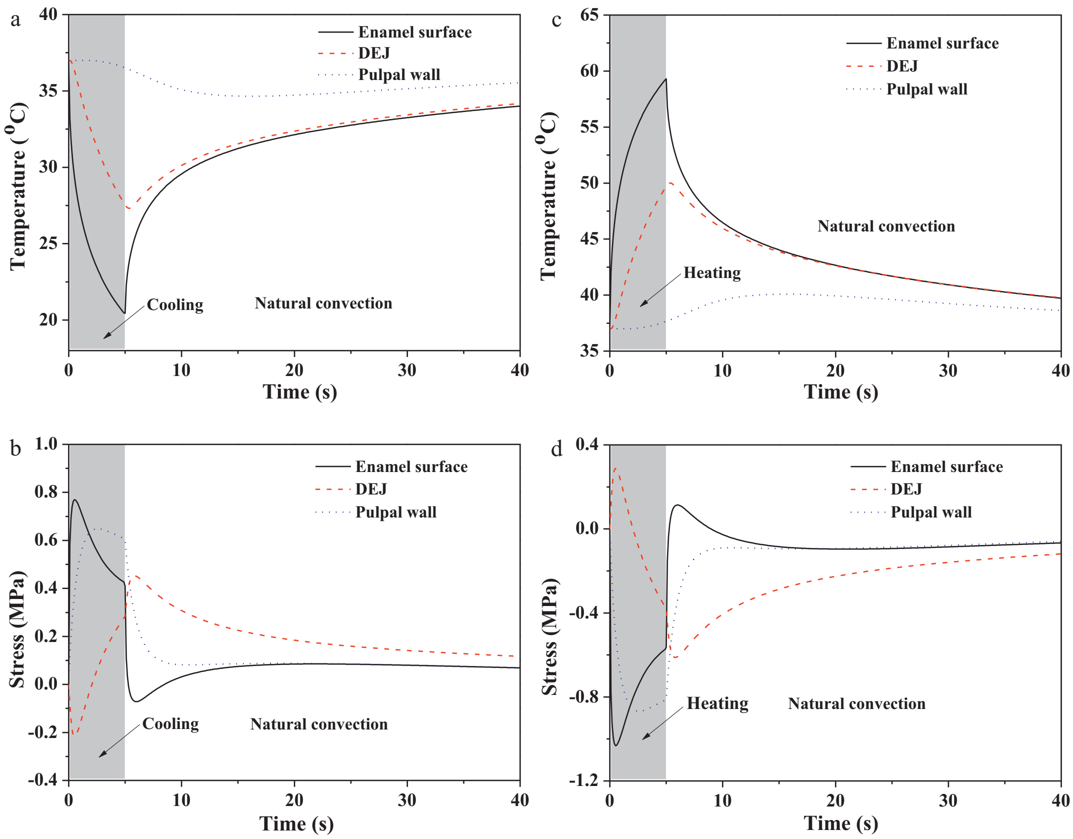

Fig. 2 – Simulated temperature and thermal stress change as a function of time at enamel surface, dentine–enamel junction (DEJ) and pulpal wall during and after application of 5 °C cold water (a, b) and 80 °C hot water (c, d) on enamel surface. After thermal stimulation (5 s duration) was removed, the enamel was exposed to natural convection, namely, cooling with ambient temperature 25 °C with heat transfer coefficient ~10 W/(m^2 K). Initial body temperature was 37 °C. Temperature at bottom of pulp layer was assumed to remain unchanged (37 °C) during and after thermal stimulation.

Both the tensile and the compress stresses reach maximum at $t \approx 1$ s, which coincide with the finite elements analysis in the literature.[26] The contraction of the outer layer induced by cold stimulation results in flexure of the layered tooth structure, which stretches the pulpal wall leading to rapid development of tensile stresses at the pulpal wall (Fig. 2b). The tensile stresses at the pulpal wall decrease when the temperature change reaches deeper into the inner layer, causing thermal contraction of the structure, counteracting the initial flexure. These deformation characteristics are consistent with the experimental observations by Linsuwanont et al.[22]

Under hot stimulation, the present model predictions exhibit a reverse trend in the change of temperature and stresses as opposed to that under cold stimulation; see Fig. 2c and d.

3.2. *Mechanism of fluid flow initiation*

Simulated fluid flow caused by thermal stimulation of exposed dentine (tow-layer model) is shown in Fig. 3a. We observed that the simulated fluid flow velocity considering dentine tubule thermal deformation only (dashed line, Fig. 3a) is significantly different from that considering thermal expansion/contraction of dentinal fluid only (dotted line, Fig. 3a). The former shows an initially rapid response of inward flow under heating and outward flow under cooling, whilst the latter shows a slow response of fluid flow at the initial stage of heating or cooling. Besides, the change of fluid flow as induced by dentinal tubule deformation at the interval of heating and cooling is opposite to that induced by expansion/contraction of dentinal fluid. The simulated dentinal fluid flow when considering both dentinal tubule deformation and dentinal fluid expansion/contraction (solid line, Fig. 3a) agree qualitatively with existing experimental observations.[6]

The results of Fig. 3a and b imply that both dentinal tubule deformation and dentinal fluid expansion/contraction are responsible for the initiation of fluid flow, and dentinal tubule deformation accounts for the initially rapid response of fluid flow during and after thermal stimulation. Although the magnitude of fluid flow velocity may vary, we observed similar behaviour in fluid flow change when thermal stimulation was applied on the enamel surface with the three-layer tooth

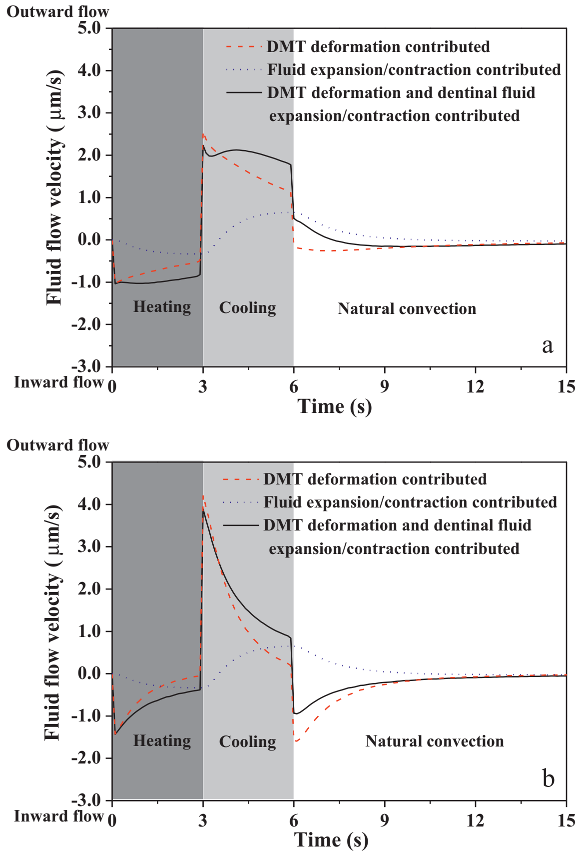

Fig. 3 – Mechanism for initiation of dentinal fluid flow induced by thermal stimulation on (a) exposed dentine surface and (b) intact teeth surface (enamel surface). Thermal boundary was identical to experimental condition,[6] namely, heated by 55 °C hot water for 3 s, followed by 5 °C cold water for 3 s, and thereafter natural convection on exposed dentine surface (ambient temperature 25 °C).

model of Fig. 3b. This similarity indicates that the mechanism for dentinal fluid flow remains the same whether the thermal stimulation is applied on the enamel surface or the dentine surface. It should be noted that the fluid flow velocity at the initial stage of thermal stimulation on enamel surface is higher than that on exposed dentine surface. This difference means that at the initial stage of thermal stimulation, the presence of outer enamel layer will cause more significant deformation in dentine layer (especially the pulpal wall) which coincides with the finite element analysis by Linsuwanont et al.[22] The calculated initial fluid flow velocity evoked by cold is higher in intact teeth than in teeth with exposed dentine. This may not suitable for directly usage in explaining clinical observations that teeth with exposed dentine are more sensitive. Because that the current model does not consider the fluid expansion/contraction in pulpal chamber. For exposed dentine, heat is easily transferred into pulp chamber (housing most of the dentinal fluid) causing fluid expansion/contraction and thus contributing significantly to fluid flow velocity. In other words, in *in vivo* situation, cold may evoke higher fluid flow velocity in teeth with exposed dentine than in intact teeth. Teeth morphology may also moderate the fluid flow velocity, but the basic mechanism underlying thermal-induced dentinal fluid flow remains the same.

We also observed that the simulated fluid flow velocity has a magnitude (several micrometres per second) considerably smaller than that measured experimentally (hundreds of micrometres per second) as reported by Andrew and Matthews.[6] This discrepancy may be attributed to the difference between the simulation and the experimental conditions. In the study of Andrew and Matthews,[6] the fluid flow velocity was recorded from the sectioned tooth root with thermal stimulation applied on exposed dentine. In other words, the measured fluid flow was induced by both pulpal chamber deformation and fluid expansion/contraction in pulpal chamber, leading to a higher fluid flow velocity than that occurring only in dentinal tubule (*i.e.*, in our simulation). Despite the difference, our simulation is capable of capturing the main features of the responses of dentinal fluid under thermal stimulation.

3.3. *Implications of fluid flow in dental thermal pain*

3.3.1. *Fluid flow in response to cold stimulation*

In vivo studies have shown that intradental nerve terminals respond with an initially high-frequency discharge after a short latency (<1 s) of cold stimulation (0–5 °C).[6,14,15] The discharge rate then decreased[14,15] and eventually ceased within 4 s[15] though the stimulation was persistent (Fig. 4a and b). The mechanism underlying this dynamic neural response remains unclear. It is unlikely that the neural discharge characteristics originated from thermo-sensitive receptors, because: (i) the first impulse was recorded within 1 s after cold stimulation, and the intrapulpal temperature had not decreased to the level to activate the cold receptors[15]; (ii) after activation, the cold receptors will not cease to respond when the cold stimulation is still in force.[14]

The variation of fluid flow velocity during thermal stimulation may explain the experimentally observed phenomena shown in Fig. 4a and b. We observed a high outward fluid flow rate at the initial stage of cold stimulation (<1 s) and fast velocity decrease with time (dashed line, Fig. 4c). The change of fluid flow velocity during cooling explains well the neural discharge responses of Fig. 4a and b. An initially high rate of fluid flow may induce sufficiently high shear stresses on nerve terminals, resulting in the mechanical activation of mechano-sensitive receptors and consequently neural discharge.[5,6,11,18] The quick drop of fluid flow velocity dramatically reduces the shear stresses and thus the neural discharge, which ceases finally. After a long latency (~30 s), the neural response (dull, burning pain) to cold stimulation may be attributed to the activation of thermo-sensitive receptors[16,27]: by then the temperature around the receptors may exceed the threshold.

The responses of intradental nerve fibres under cooling with preceded heating significantly differ from those under

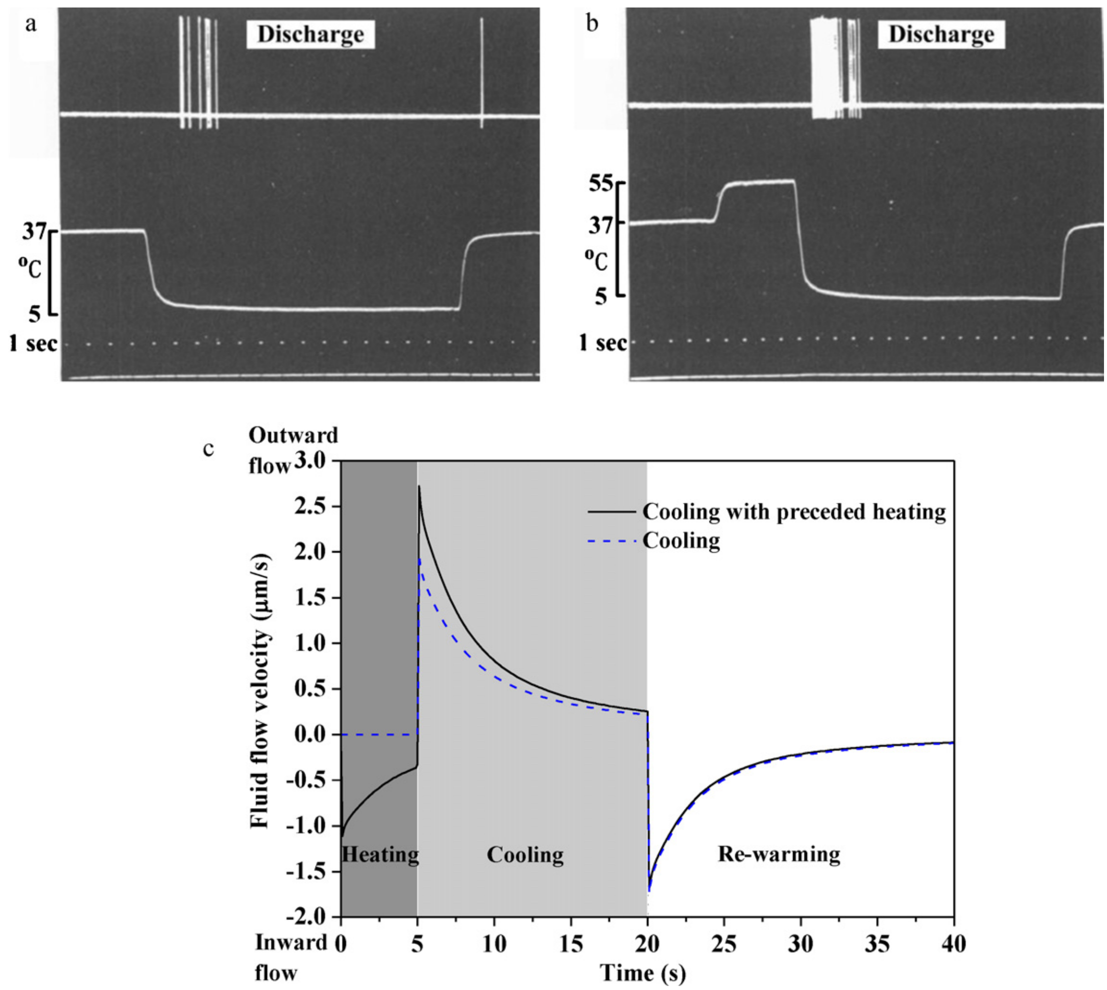

Fig. 4 – Neural discharge patterns and corresponding dentinal fluid flow: (a) without preceded heating and (b) with 5 s preceded heating, both adapted from Ref. 15. (c) Simulated fluid flow velocity as a function of time during thermal stimulation. Cooling: 5 °C, 15 s duration; preceded heating: 55 °C, 5 s duration; re-warming: 37 °C.

pure cooling (without preceded heating). As compared with pure cooling, with preceded heating (55 °C, 5 s duration),[15] a higher rate of neural discharge was observed at the initial stage of cooling, Fig. 4b. The simulated results of Fig. 4c (solid line) may explain such distinct difference. At the beginning of cooling after preheating, we observed an outward fluid flow velocity of 140% larger than that induced by pure cooling. When cooling (5 °C) was applied with 5 s preceded heating, the larger rate of temperature change leads to faster structural deformation and consequently a higher fluid flow velocity, evoking a higher neural discharge frequency.

3.3.2. *Fluid flow in response to hot stimulation*

When hot stimulation (55 °C) was applied on exposed dentine, a relatively long latency (>10 s)[14,15] of neural responses was observed (Fig. 5a and b). During this stage, no neural discharge could be detected[14,15] though there exists an initially rapid response in inward fluid flow (dashed line, Fig. 5c). These results do not contradict the discussion presented above for the case of cold stimulation. The associated nerve fibres are much "less sensitive" to inward fluid flow than outward fluid flow; in other words, relative to inward fluid flow, a much higher rate of inward fluid flow is required to evoke intradental nerve responses.[6,18] The appearance of neural discharge after a relatively long latency is attributable to the fact that temperatures around the thermo-sensitive receptors would eventually reach the pain threshold.[15] The subsequent application of cold stimulation (37 °C) at $t = 12$ s results in a high rate of outward fluid flow (dashed line, Fig. 5c). At this moment, pain sensation may be contributed by the activation of both mechano-sensitive and thermo-sensitive receptors.

In the case of heating with preceded cooling (5 °C, 12 duration), the mechanism underlying the long latency in neural discharge after subsequent heating was applied[15] also holds in the case of pure heating (without preceded cooling). The experimentally measured rate of neural discharge shown in Fig. 5b,[15] however, was considerably slower than that of pure heating, Fig. 5a. Rather than fluid flow velocity (Fig. 5c, solid line), a lower temperature in the case of heating with preceded cooling than that with pure heating may explain such difference.

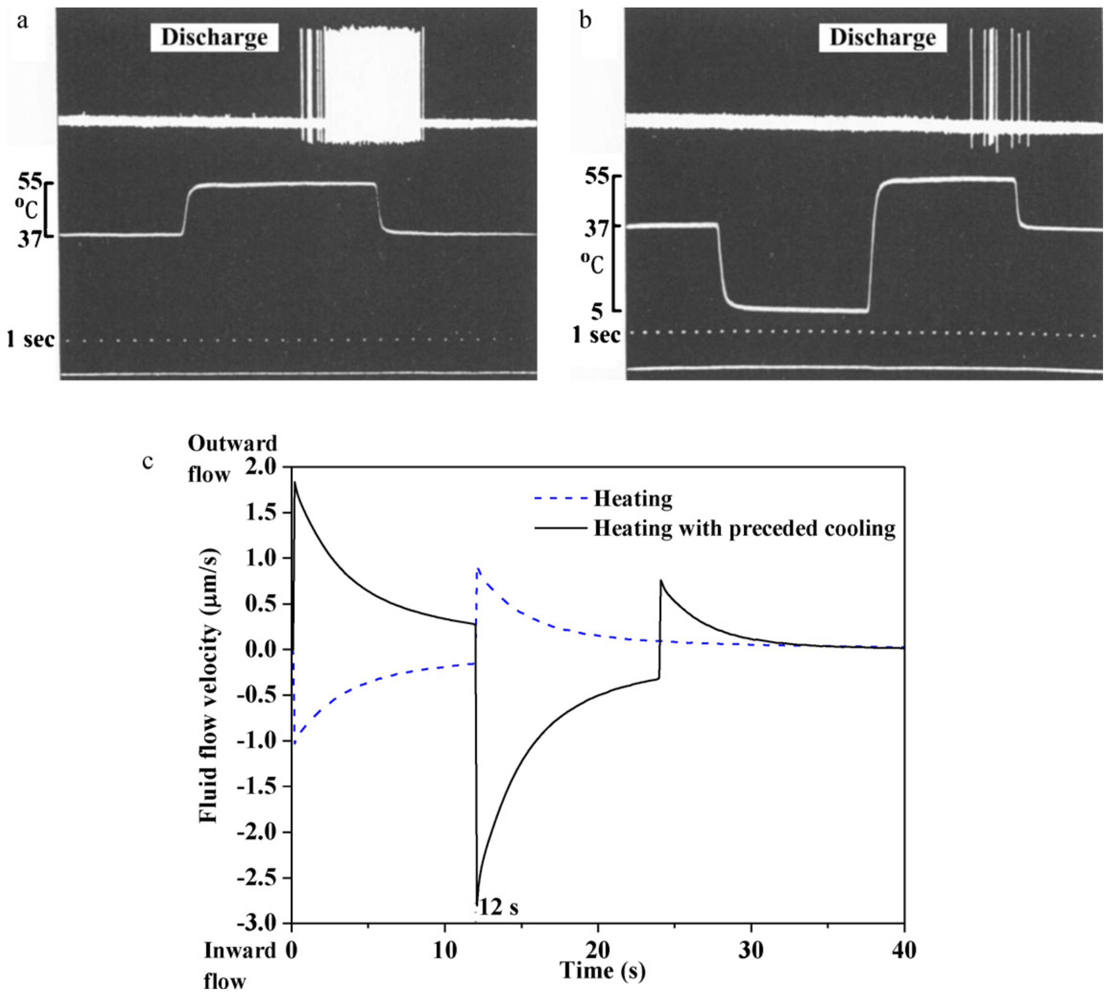

Fig. 5 – Neural discharge patterns and corresponding dentinal fluid flow: (a) without preceded cooling and (b) with 12 s preceded cooling, both adapted from Ref. 15. (c) Simulated fluid flow velocity as a function of time during thermal stimulation. Heating: 55 °C, 12 s duration; preceded cooling: 5 °C, 12 s duration; re-warming: 37 °C.

4. Conclusion

In this study, we developed a thermomechanical model to simulate thermal-induced dentinal fluid flow in a single dentinal tubule. The proposed model significantly reduces the complexity of the *in vivo* situations including tooth architecture and arrangement/shape of dentinal tubules. Although the various assumptions introduced to simplify the model might reduce the quantitative characteristics of its predictions, the results presented in this study should help to understand better a few physical mechanisms. Firstly, both dentinal tubule deformation and dentinal fluid expansion/contraction contribute to dentinal fluid flow, and that dentinal tubule deformation rather than dentinal fluid expansion/contraction is responsible for the rapid response in dentinal fluid flow under thermal stimulation. Secondly, the initially high rate of outward fluid flow under cold stimulation may mechanically activate intradental nerve terminals causing therefor neural discharge after a short latency; by contrast, the long latency in neural responses under hot stimulation may be attributed to the activation of thermo-sensitive receptors. Furthermore, neural discharges induced by complex thermal stimulations, e.g., cooling with preceded heating, heating with preceded cooling and so on, could be explained in terms of dentinal fluid flow or local temperature changes.

Author contributions

Tian Jian Lu, Feng Xu and Min Lin designed research.
Min Lin, ShaoBao Liu and Lin Niu performed research.
Min Lin, ShaoBao Liu, Lin Niu, Tian Jian Lu and Feng Xu analyzed data.
Min Lin, Tian Jian Lu and Feng Xu wrote the paper.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (10825210, 31050110125 and 81000453) and the National 111 Project of China (B06024).

Funding: This work was supported by the National Natural Science Foundation of China (10825210, 31050110125 and 81000453) and the National 111 Project of China (B06024).

Competing interests: None declared.

Ethical approval: Not required.

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