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ORIGINAL ARTICLE

Quantitative sensory testing of dentinal sensitivity in healthy humans

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ABSTRACT
Objective The study was to provide information on quantitative sensory testing (QST) of normal teeth to establish a sensory profile and investigate the possible gender and regional differences. **Materials and methods** A modified QST protocol was applied on both left and right upper-jaw incisors and pre-molar sof 14 healthy men and 14 age-matched healthy women (18–25 years). Mechanical stimulus sensitivity (MSS), cold detection threshold (CDT), cold pain threshold (CPT), warm detection threshold (WDT), heat pain threshold (HPT), electrical detection threshold (EDT) and electrical pain threshold (EPT) were determined from the four teeth (labial side of incisor and buccal side of the first premolar). The QST parameters were analysed by ANOVA. **Results** The applied mechanical or thermal stimuli did not evoke any pain sensation. A normal tooth did not seem to be able to distinguish between the warm or cold stimuli applied. No significant differences were found between genders ($p > 0.099$) or teeth ($p > 0.053$) regarding mechanical and thermal stimuli. The EDT and EPT were significantly higher in the pre-molar compared with incisor ($p < 0.002$) without gender differences ($p > 0.573$). *Conclusion*: The established methods and results provided important information on diagnosis and treatment evaluation of dentinal hypersensitivity.

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Quantitative sensory testing; dentinal sensitivity; dentinal hypersensitivity; evaluation research; gender difference

Introduction

Dental pulp usually responds to various stimuli as nociceptive sensations. The exact mechanism of stimuli transmission is still unclear. Several hypotheses on dental pain transmission have been proposed including hydrodynamic mechanisms, odontoblastic transduction, and dentine innervation.[1] The hydrodynamic theory enjoys the most popularity.[2] Based on this theory, dentinal hypersensitivity, which is a very common and bothersome nuisance, is caused by movement of fluids within open dentine tubules. It is assumed that, when a stimulus is applied on the exposed dentine surface, it causes movement of tubular fluid, which in turn activates mechanoreceptor nerves, eliciting pain and discomfort.[3]

The dental pulp contains both large myelinated A fibres and smaller unmyelinated C fibres.[4] The assessment of the dentinal hypersensitivity usually depends on subjective responses to clinically applied stimuli, i.e., cold air, cold water, mechanical tactile pressure, etc. The treatment effects are evaluated depending on the clinical assessment. However, the evidence is somehow insufficient to permit the development of evidence-based guidelines for the evaluation of dentinal hypersensitivity due to the lack of standardization of the testing methods.

In recent years Quantitative Sensory Testing (QST) has been developed significantly and is widely applied in human experimental and clinical studies.[5] The full QST battery consists of 13 different stimuli, including mechanical, thermal and vibration stimuli at a single point, establishing a profile of the sensory function of the tested point. QST provides psychophysical methods systematically documenting alterations and re-organization in the function of the nervous system and, in particular, the nociceptive system. QST is defined as the determination of thresholds or stimulus response curves for sensory processing under normal and pathophysiological conditions. The modern concept of advanced QST for experimental pain/sensitization assessment is a multi-modality, multi-tissue approach where different pain/sensitization modalities (thermal, mechanical, electrical and chemical) are applied to different tissues (skin, muscles and viscera).[6] The responses are assessed by psychophysical methods on the thresholds and stimulus-response functions. However, the QST has not yet been applied on teeth for a dentinal sensitivity test.

The aims of this study were to apply a modified QST method on the teeth of healthy humans to establish a sensory profile and investigate the possible gender and region differences of normal human dental tissue to standardized mechanical, thermal and electrical stimuli. The results were to provide important clinical information on the diagnosis and an evaluation of the treatment of dentinal hypersensitivity and dental pain.

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Materials and methods

Subjects

A total of 28 healthy subjects (14 men and 14 women, aged 20–25) were recruited for the study. All subjects had natural dentition without any signs of dentinal hypersensitivity. The subjects had no history of dental pulpal treatment and no restoration on any of the tested teeth. Further, the subjects did not suffer from jaw muscle pain, headaches or other symptoms of pain in the craniofacial region or other parts of the body. All subjects were students at Aalborg University. The study was approved by the local ethics committee (N-20100058) in accordance with the Helsinki Declaration II. Written informed consent was obtained from all participants before they were included in the study.

Experimental protocol

The experiment was performed in a quiet room at a steady room temperature (22–23 °C). The subject was sitting in an upright relaxed position in a dental chair. Modified QST batteries, including mechanical thermal stimuli and electrical stimuli, were randomly applied. The thermal stimuli were applied on the four test sites: labial side of left and right incisor and buccal side of left and right of the first premolar. The mechanical stimuli were applied on one side only of the incisor and premolar. The randomization of thermal/mechanical/electrical and left/right side was made by the research assistant (YL). All testing procedures were performed by one examiner (KW). The modified QST batteries are described below. The devices for giving the mechanical, thermal and electrical stimuli are shown in Figure 1(A–C).

Mechanical testing

The mechanical stimulus sensitivity (MSS) was measured using a set of five custom-made spring pinprick stimulators (flat contact area with a diameter of 0.2 mm) (Figure 1A). The stimulators were able to apply five grades of fixed stimulus intensities with different strengths of the spring. The applied forces were calibrated as 50, 100, 200, 400 and 800 gr. The mechanical sensitivity was tested with a metal probe scratching longitudinally along the tooth surface, 1 mm away from the gingival margin, moving towards the edge. The stimulus was repeated three times with each force in a randomized manner. The subjects were asked to evaluate the different intensities of the stimuli with a 0–10 numeric rating scale (NRS: 0 = no sensation, 5 = pain threshold, 10 = maximal pain imaginable). The three NRS scores obtained from each pressure stimulus were averaged and plotted in a stimuli-response curve (S-R curve) corresponding to the five individual pressure stimuli.

Thermal testing

The tests of the thermal sensation were performed using a thermal sensory device, TSA 2001 II (CHEPS-MEDOC, Israel). The baseline temperature was pre-set at 32 °C. The temperature was increased or decreased by ramped stimuli of 1 °C/s.

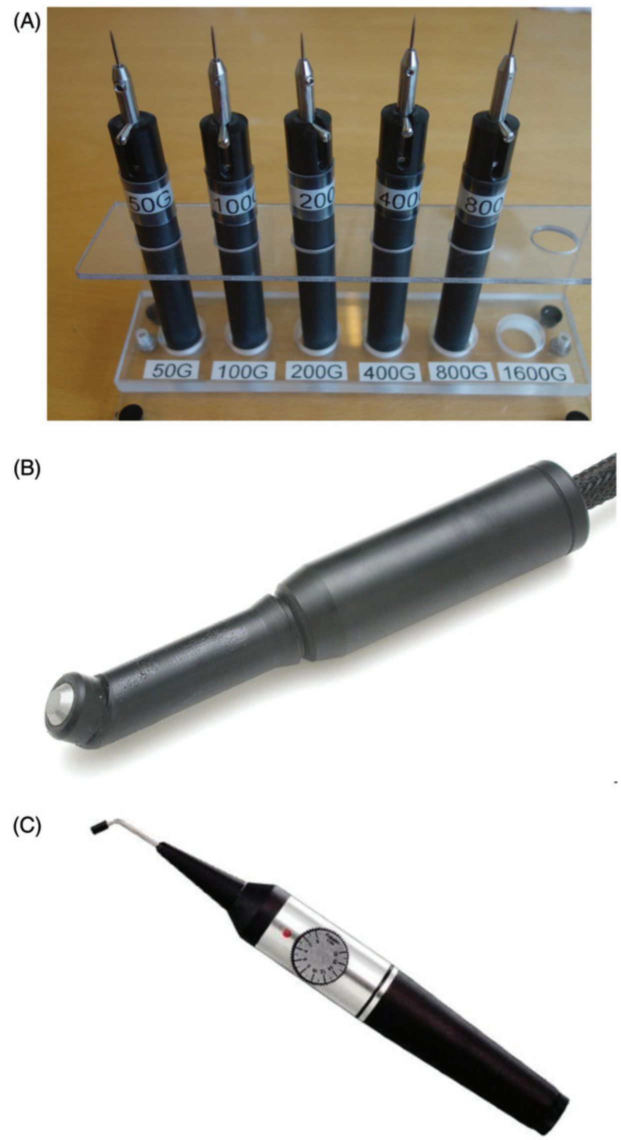

Figure 1. (A) A set of five custom-made spring pinprick stimulators (flat contact area with a diameter of 0.2 mm). The stimulators were able to apply five grades of fixed stimulus intensities with different strengths of the spring. The applied forces were calibrated as 50, 100, 200, 400 and 800 g. (B) The intra-oral thermode. The flat contact area of the probe is 6 × 6 mm. (C) An electrical stimulator. The stimulator tip is 2 × 2 mm.

The test was terminated when the subject pressed a button. The subjects were asked to press a button when a thermal sensation (cold/warm) was perceived. First, cold and warm detection thresholds (CDT, WDT) were measured followed by cold and heat pain thresholds (CPT, HPT). The mean threshold temperature of three consecutive measurements was calculated. The intra-oral thermode, with a contact area of 6 × 6 mm (Figure 1B), was always placed on the centre of the tooth surface during the testing. Cut-off temperatures were 0 °C and 50 °C and the verbal instructions given to the subjects were virtually identical to those used by the German Research Network on Neuropathic Pain.[5] During the experiment the tested tooth was isolated from the oral tissues by a gauze and rubber dam. The subjects were not able to see the computer screen, in order not to affect the behaviour of the subject.

Electrical testing

An electrical stimulator (Pulppen 2000, Denmark, Output: 274 volt and 0.25–250 μA) was employed to test the electrical detection threshold (EDT) and electrical pain threshold (EPT) (Figure 1C). The stimulator tip (2 × 2 mm) was placed on the dried target tooth surface (middle part of the tooth surface, 3 mm from gingival margin). When the tester touched the sensor button with the index finger, the stimulator emitted electronic pulses through the tooth at a regularly increasing amplitude, as indicated by the pulsating red indicator light (LED).

First the EDT was tested and the subject was asked to give a signal with the hand as soon as a tingling sensation from the target tooth was detected. The EPT was tested by asking the subject to give a signal only when a pain sensation was evoked from the target tooth. The LED displayed the stimulus level from 0.25–250 μA and was automatically re-set at zero before a new measurement. The mean threshold values of three consecutive measurements were calculated for EDT and EPT.

Analysis

The mean values and standard deviation of all parameters for gender and each test tooth were calculated. Two-way analysis of variance (ANOVA) with repeated measures was performed. The distribution was checked for all data of the QST parameters. Normality plots and tests (Kolmogorov-Smirnov test) were performed on each parameter by groups and testing sites. All non-normally distributed data were transformed logarithmically before the ANOVA was performed. The factors in the ANOVA were gender and testing tooth (incisor left, incisor right, pre-molar left and pre-molar right). Post-hoc comparisons were calculated using Bonferroni tests. The significance level for each test was set at 5%. All statistical calculations were performed by using the statistical package of SigmaStat and were presented as mean values and standard error of mean (SEM).

Results

Mechanical stimulus

The normal tooth was not sensitive to the mechanical stimuli. The response evaluation to the mechanical stimuli (50–800 g) was 0.5–4 on average in the 0–5–10 NRS. The evoked sensation was significantly increased ($p < 0.023$) on both incisor and premolar when the force was increased. No pain sensation was reported from the subjects. No significant differences were detected between men and women ($p = 0.617$) or between incisors and pre-molars ($p = 0.053$). There was no statistically significant interaction between gender and testing tooth ($p = 0.770$). See the S-R curve in Figure 2A and B.

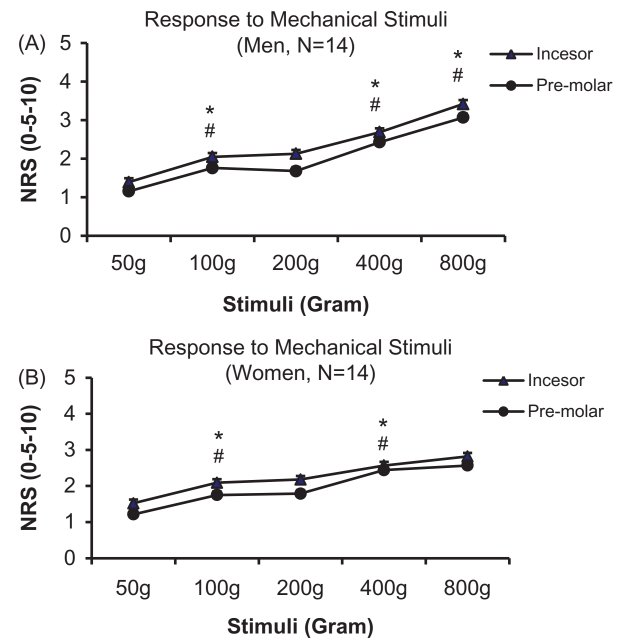

Figure 2. A stimuli-responses curve (S-R curve) corresponding to the mechanical stimuli from 14 men (A) and 14 women (B). NRS, Numeric Rating Scale. The evoked sensation was significantly increased compared to the previous force level. *Incisor, #premolar. No significant differences were found between genders and teeth.

Thermal testing

The healthy tooth was not sensitive to the applied thermal stimulus between 0–50 °C. Approximately 70% of the subjects (20 out of 28) could detect the cold detection threshold (CDT). Only 20% of the subjects (6 out of 28) could detect the warm detection threshold (WDT). In addition, the subjects could not detect the warm sensation, but reported a cold sensation when receiving the warm stimulus. It is an interesting finding that the tooth itself cannot distinguish between the cold and warm stimuli. No significant differences were found between genders ($p > 0.099$) and tooth type ($p > 0.243$) (Figure 3A and B). The cold pain threshold (CPT) or heat pain threshold (HPT) was not detected within the temperature range of 0–50 °C at any of the teeth.

Electrical testing

All teeth responded to the electrical stimulus. At first, a ‘tingling sensation’ was reported with the stimulus level increasing; then a pain sensation was evoked when the stimulus level was further increased. Both EDT and EPT were detected at a significantly different level ($p < 0.001$). In addition, pre-molars had a significantly higher threshold than incisors ($p < 0.002$). No gender difference was found ($p > 0.573$). Further, no statistically significant interaction was found between gender and testing teeth ($p = 0.395$) (Figure 4A and B).

Discussion

This is the first study to employ QST on the teeth. The applied mechanical stimuli evoked proportionally increased responses, but no pain sensation was reported. Only a number of the teeth detected the applied thermal stimuli, but they did not seem to be able to identify whether the stimuli were cold or warm. The electrical stimuli evoked both detection and pain sensation in all teeth and a regional difference was found.

Responses to mechanical stimuli

The exact mode of transmission of stimuli across the dentin is still unclear. According to the hydrodynamic hypothesis,[7] the contents of the dentinal tubules act as hydraulic linkages between the external environment and the pulpal nerve endings. Mechanical stimuli generate movement of tissue fluid within the dentinal tubules and the movement excites the nerve terminals.[8] However, enamel is an acellular tissue protecting the dentine of the crown from varying stimuli during function.

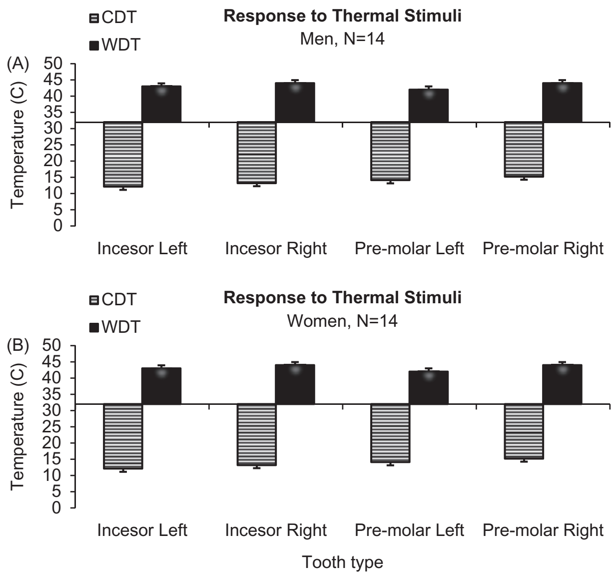

Figure 3. Responses to the thermal stimuli from all responded teeth recorded from the thermal stimulator. The exact temperature was shown on the sensory device. The cut-off temperatures were set at 0 °C and 50 °C. No significant differences were found between genders and teeth.

General dental practitioners usually scratch the surface of the tooth with a dental probe to detect the dentinal hypersensitivity. The force applied by the probe is difficult to standardize and quantify. In the present study the calibrated 5-grate force probes were applied for the quantified mechanical stimulation. In addition, the mechanical stimulation was applied with a metal probe scratching the tooth surface instead of probing only, as used in previous clinical studies.[9] When the dentin surface is mechanically probed, a dental explorer tine or another probe is pushed into the dentin. This produces a compression of dentin beneath the probe proportional to the applied compressive stress. The scratching may involve applying the same compressive stress, but the probe is dragged across the dentin, producing a mechanical stimulation of a much larger surface.[10] Theoretically, the tooth surface should be more sensitive to scratching than to probing at the same force. The subjects' responses to the mechanical stimuli were 'being touched', 'being pressed' or 'being scratched'. The applied mechanical stimuli (50–800 g) did not evoke any pain sensation on the normal teeth, but the sensation was proportionally increased when the force was increased. However, during the mechanical scratching on the tooth surface, not only the pulp nerve but also the proprioceptors in the periodontal tissues were stimulated. The psychophysical response evoked by the mechanical stimulation could be a

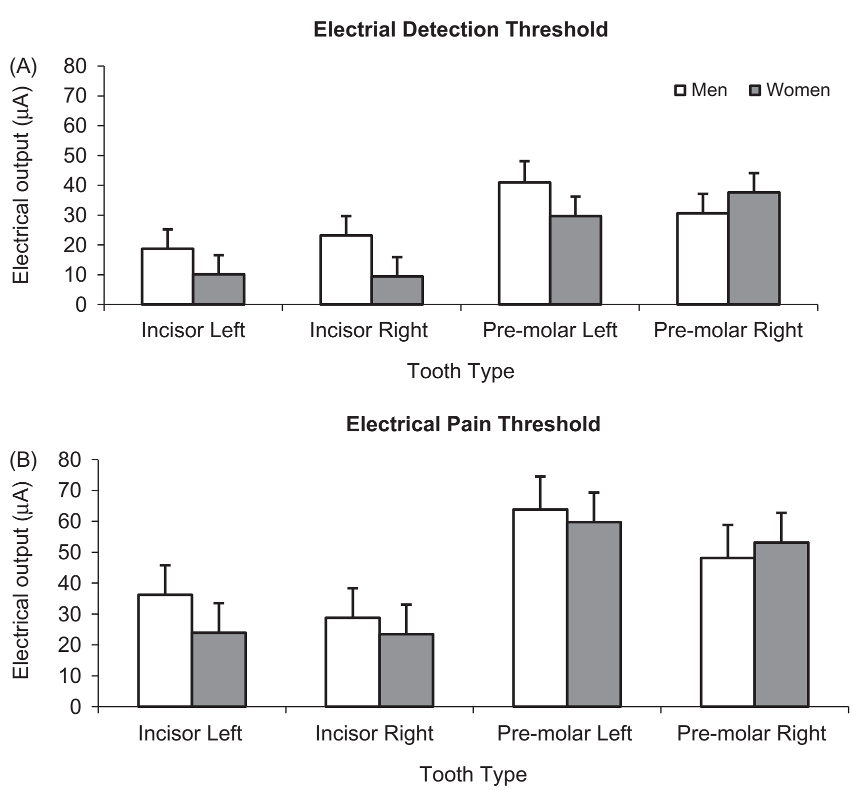

Figure 4. (A) Electrical Detection Threshold (EDT) and (B) Electrical Pain Threshold (EPT) were detected in all the tested teeth. Pre-molars had a significantly higher threshold than incisors. The EDT and EPT were tested in significantly different levels. No gender difference was found.

combined sensation from both the pulp nerve and the periodontal proprioceptor.

Responses to thermal stimuli

According to the hydrodynamic theory, the thermally induced expansion/contraction of the dentinal fluid within the dentinal tubules activate the pulpal nociceptors, resulting in dental pain.[7,11] Thermal stimulation, i.e., mediated by ice, cold water, hot water, heated gutta-percha and ethyl chloride, is routinely used as a clinical testing method to assess the pulpal status.[12] However, these methods lack quantification and standardization of measurements. For the first time the quantitative thermal stimulator (CHEPS-MEDOC) was employed to apply thermal stimulation on teeth in the present study. The thermal stimulator takes the quantitative sensory testing method to a new level, delivering painful and non-painful stimuli at a temperature range of 0–55 °C with a heating and cooling rate of up to 8 °C/s. The applied temperature can be controlled and programmed, thus introducing new research opportunities in testing of the dentinal sensitivity. In the present study the applied thermal stimuli did not evoke responses in all teeth (70% response to cold stimulus and 20% to warm stimulus) and no pain sensation was evoked. Surprisingly, the teeth were not able to identify the nature of the thermal stimuli, cold or warm.

The primary sensory response to thermal stimulation is due to physical changes within the dentine rather than direct nerve stimulation.[11] The hydrodynamic force was the result of dentinal fluid movement caused solely by the expansion or contraction of the dentinal fluid.[13] It is reasonable to assume that dentinal fluid movement would occur after the temperature transfers through the enamel, reaching the dentinal tissue in the intact tooth. The thermal stimuli conduction could be delayed and the applied thermal stimuli could reach the limitation (0 °C for cold and 50 °C for heat) before the responses are evoked. Repeated application of thermal stimuli will reduce the displacement rate of the fluids inside the dentinal tubules, causing less response from the pulp for a short time, which is a possible explanation why the thermal test is sometimes refractory.[4] In addition, the small contact area between the hard tooth surface and the thermode probe during the thermal application could be a possible reason for the poor response to the thermal stimulation.

Animal researchers have suggested that the dentinal fluid flow is the difference between hot and cold stimuli. A cold stimulus evokes a rapid transient sensation, whereas a hot stimulus evokes a dull lasting sensation.[14] Although the transduction mechanism is not clear, the direction of the fluid flow through dentinal tubules has been identified as an outward flow (away from the pulp) during cold stimulation and an inward flow (into the pulp) during hot stimulation.[15] Surprisingly, it was found that the human subjects were confused by the thermal stimulation, i.e., they could not detect whether the stimuli were cold or warm during most of the tests in this study.

The expression of several members of the transient receptor potential (TRP) channels has been studied in dental primary afferent neurons for their functional roles as transducers of noxious temperature or mechanical stimuli.[16] It has been indicated that TRPV1 channels are activated by capsaicin and a warm temperature above 42 °C,[17] whereas TRPM8 and TRPA1 are activated by a cold stimulus and cold receptors are expressed in the majority of the dental afferent neurons.[18] Animal studies have found that some of the dental afferents showed co-expression of TRPM8 or TRPA1 with TRPV1. In such neurons it may be difficult to discern cold or hot temperature stimuli by nerve impulses.[18] These ambiguities might be involved in the detection of the quality of thermal stimulation in teeth.

Table 1. List of abbreviations in alphabetical order.

List of abbreviations
CDT: Cold detection threshold
CPT: Cold pain threshold
EDT: Electrical detection threshold
EPT: Electrical pain threshold
HPT: Heat pain threshold
MSS: Mechanical stimuli sensitivity
NRS: Numeric rating scale
QST: Quantitative sensory testing
S-R: curve: Stimuli-response curve
TRP: Transient receptor potential
WDT: Warm detection threshold

Responses to electrical stimuli

Electrical stimulation has been widely used for dental sensitivity testing.[19] In the present study the electrical testing was employed as a combined outcome of the QST parameters. Unlike thermal sensitivity testing, which most likely depends on the outward and inward movement of the dentinal fluid, electrical pulp testing depends on ionic movement.[4] An electric stimulus delivers a current on the tooth surface sufficient to overcome the thickness of enamel and dentin and then stimulates the sensory fibre (A-delta and A-beta) in the pulp.[20] The A and C afferent fibres are activated by different stimuli producing changes in the quality of pain ranging from a sharp shooting pain (A-delta) to a dull and prolonged pain (C-fibre). Because of their high thresholds, C fibres usually do not respond to electric stimulation.[4] A ‘tingling’ or pain sensation will be felt by the tested subject once the increasing currency reaches the sensation threshold, but this threshold level varies between individuals and teeth and can be affected by many other factors such as age, gender, pulp size, pain perception, tooth surface conduction and resistance.[21]

The present study indicated significant EDT and EPT between the incisor and premolar, which can be easily understood as the premolar tooth has thicker enamel providing more resistance to the electrical currency.[22] Interestingly, different thresholds were found for detection of sensation and pain sensation for both the incisor and premolar teeth in disagreement with the traditional concept that stimulation of dentine or dental pulp produces pain only and probably no other sensation.[23] It seems that the dental pulp is also sensible to stimuli below the pain threshold. The result was according to previous experimental studies where certain electrical stimuli elicited a ‘pre-pain’ sensation.[24]

The ideal dentinal sensory testing method should provide a simple, objective, standardized, reproducible and accurate way of assessing the condition of the pulp. A recent human study suggested that electrical stimuli were the most reliable and accurate pulp test.[21]

Limitations

The modified QST was applied only on incisor and premolar teeth. Further studies are required to evaluate the current responses for different tooth types and sites in relation to the pulp sensitivity and innervation pattern before being able to produce an overview of the dentinal sensory profile.

Unlike other tissues in the body, mechanical and thermal stimuli did not elicit nociception in normal intact teeth during the limited experimental conditions. The enamel of the teeth has a good insulating capacity for the mechanical and thermal stimuli. However, when enamel is decayed or abraded and dentin is exposed in various clinical situations, i.e., dentinal hypersensitivity, a light mechanical stimulus or small changes in temperature can evoke a sudden and intense sensation. It is more valuable to apply the modified QST on a tooth with dentinal hypersensitivity.

Conclusion

For the first time this study employed QST on teeth to establish basic information of the normal teeth responses to standardized mechanical, thermal and electrical stimuli. The established methods are more valuable to apply on teeth with dentinal hypersensitivity for diagnosis and treatment evaluation.

Disclosure statement

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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References

[1] Yu C, Abbott PV. An overview of the dental pulp: its functions and responses to injury. Aust Dent J Suppl. 2007;52:S4–S16.
[2] Matthews B, Vongsavan N. Interactions between neural and hydrodynamic mechanisms in dentine and pulp. Arch Oral Biol. 1994;39:87S–95S.
[3] Brännström M, Linden LA, Johnson G. Movement of dentinal and pulpal fluid caused by clinical procedures. J Dent Res. 1968;47:679–682.
[4] Bender IB. Pulpal pain diagnosis-a review. J Endod. 2000;26:175–179.
[5] Rolke R, Magerl W, Campbell KA, et al. Quantitative sensory testing: a comprehensive protocol for clinical trials. Eur J Pain. 2006;10:77–88.
[6] Arendt-Nielsen L, Yarnitsky D. Experimental and clinical applications of quantitative sensory testing applied to skin, muscles and viscera. J Pain. 2009;10:556–572.
[7] Brännström M, Astroem A. A study on the mechanism of pain elicited from the dentin. J Dent Res. 1964;43:619–625.
[8] Ahlquist M, Franzén O, Coffey J, et al. Dental pain evoked by hydrostatic pressures applied to exposed dentin in man: a test of the hydrodynamic theory of dentin sensitivity. J Endod. 1994;20:130–134.
[9] Kleinberg I, Kaufman HW, Wolff M. Measurement of tooth hypersensitivity and oral factors involved in its development. Arch Oral Biol. 1994;39:63S–71S.
[10] Camps J, Salomon JP, Meerbeek BV, et al. Dentin deformation after scratching with clinically-relevant forces. Arch Oral Biol. 2003;48:527–534.
[11] Andrew D, Matthews B. Displacement of the contents of dentinal tubules and sensory transduction in intradental nerves of the cat. J Physiol (Lond). 2000;529:791–802.
[12] Gillam DG, Orchardson R, Närhi MVO, et al. Present and future methods for the evaluation of pain associated with dentin hypersensitivity. In: Addy M, Embery G, Edgar WM, et al. editors. Tooth wear and sensitivity. Martin Dunitz, London, 2000. P.283–297.
[13] Närhi M. The neurophysiology of the teeth. Dent Clin North Am. 1990;34:439–448.
[14] Jyväsjärvi E, Kniffki KD. Cold stimulation of teeth: a comparison between the responses of cat intradental A delta and C fibres and human sensation. J Physiol (Lond). 1987;391:193–207.
[15] Vongsavan N, Matthews B. The relationship between the discharge of intradental nerves and the rate of fluid flow through dentine in the cat. Arch Oral Biol. 2007;52:640–647.
[16] Patapoutian A, Tate S, Woolf CJ. Transient receptor potential channels: targeting pain at the source. Nat Rev Drug Discov. 2009;8:55–68.
[17] Caterina MJ, Schumacher MA, Tominaga M, et al. The capsaicin receptor: a heat-activated ion channel in the pain pathway. Nature. 1997;389:816–824.
[18] Park C-K, Kim MS, Fang Z, et al. Functional expression of thermo-transient receptor potential channels in dental primary afferent neurons: implication for tooth pain. J Biol Chem. 2006;281:17304–17311.
[19] Lin J, Chandler NP. Electric pulp testing: a review. Int Endod J. 2008;41:365–374.
[20] Närhi M, Virtanen A, Kuhta J, et al. Electrical stimulation of teeth with a pulp tester in the cat. Scand J Dent Res. 1979;87:32–38.
[21] Chen E, Abbott PV. Evaluation of accuracy, reliability, and repeatability of five dental pulp tests. J Endod. 2011;37:1619–623.
[22] Sarig R, Vardimon AD, Sussan C, et al. Pattern of maxillary and mandibular proximal enamel thickness at the contact area of the permanent dentition from first molar to first molar. Am J Orthod Dentofacial Orthop. 2015;147:435–444.
[23] Närhi M, Yamamoto H, Ngassapa D, et al. The neurophysiological basis and the role of inflammatory reactions in dentine hypersensitivity. Arch Oral Biol. 1994;39:23S–30S.
[24] McGrath PA, Gracely RH, Dubner R, et al. Non-pain and pain sensations evoked by tooth pulp stimulation. Pain. 1983;15:377–388.