

Assessment of pulp vitality: a review

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Background. One of the greatest diagnostic challenges in clinical practice is the accurate assessment of pulp status. This may be further complicated in paediatric dentistry where the practitioner is faced with a developing dentition, traumatized teeth, or young children who have a limited ability to recall a pain history for the tooth in question. A variety of pulp testing approaches exist, and there may be

confusion as to their validity or appropriateness in different clinical situations.

Aim. The aim of this paper is to provide the clinician with a comprehensive review of current pulp testing methods. A key objective is to highlight the difference between sensitivity testing and vitality testing. A biological basis for pulp testing is also provided to allow greater insight into the interpretation of pulp testing results. The rationale for, and methods of, assessing pulpal blood flow are described.

Introduction

Diagnosis in dentistry may be defined as 'the process whereby the data obtained from questioning, examining and testing are combined by the dentist to identify deviations from the normal¹. The diagnosis of dental pulp status should be seen as a synthesis of history, clinical examination, special tests, and radiological examination, and not as the outcome of any one specific test. Vitality testing is an important aid in the diagnosis of pulp disease and apical periodontitis. If the pulp is deemed to be severely compromised as a result of the diagnostic testing, then endodontic treatment, or indeed extraction, may be indicated. Ehrmann² has proposed three key uses of pulp testing in clinical practice:

1) *Prior to operative procedures:* Pulp testing may be indicated for selected teeth prior to restorative or orthodontic interventions, particularly where pulp health may be in question. The absence of symptoms or radiographic changes alone may not be taken as conclusive evidence of pulp vitality,

because pulpal degeneration can occur without accompanying symptoms³.

2) *Diagnosis of pain:* The origin of most oral pain is pulpal², but pain localization may be difficult, and may require a full range of tests as well as a careful history and examination. A number of authors have acknowledged the value of pulp testing in the diagnosis of pain in the trigeminal area^{4,5}. Furthermore, case reports have illustrated the value of pulp testing in identifying pulpal pain from other conditions such as myofascial pain dysfunction syndrome⁶ and referred pain⁷. Conversely, a normal response to pulp testing may eliminate the diagnosis of pulpal pathology in oro-facial pain of unknown aetiology.

3) *Investigation of radiolucent areas:* Radiolucent areas at the apices of teeth may be the result of periapical extension of pulpal pathology, but may also be due to other pathological processes, or may, in fact, represent normal structures. If pulpal pathology is not responsible for the lesion, the associated teeth would be expected to give a normal response to vitality testing. Periodontal lesions, cysts, fibrous lesions, congenital abnormalities, and even neoplastic processes may all produce periapical radiolucencies similar to those associated with pulp degeneration^{7,8}. The mental foramen and the incisive canal are two normal

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structures which may also present as periapical radiolucencies.

In addition to the mentioned uses, Mumford and Bjorn⁴ suggest three further uses for pulp testing:

- 1) *Post-trauma assessment*: Vitality testing forms an important part of the examination and review of traumatized teeth. However, the validity of test results is controversial and will be discussed fully in a later section. Vitality testing is also important in determining the treatment needs of teeth involved in jaw fractures⁹, and those affected by surgical trauma, such as subapical osteotomy¹⁰ or vital transplantation procedures¹¹.
- 2) *Assessment of anaesthesia*: Grossman advocated the use of pulp testers to assess whether a tooth is completely anaesthetized following injection of local anaesthetic prior to operative procedures¹². This would, however, seem unnecessary in normal clinical practice. It has also been suggested that pulp testing may be a useful adjunct in experimental studies which specifically seek to evaluate the effectiveness of different analgesic drugs⁴.
- 3) *Assessment of teeth which have been pulp capped or required deep restoration*: The prognosis of teeth which have been pulp capped or required deep restorations is clinically assessed on the basis of reported symptoms; clinical palpation; and percussion, radiographs, and pulp testing. Thus, vitality testing may play an important role in determining the outcome of various pulp-capping procedures.

Vitality assessment methods

The ideal pulp test should provide a simple, objective, standardized, reproducible, non-painful, non-injurious, accurate, and inexpensive way of assessing the condition of the pulp tissue. In endodontics, pulp testing strategies may involve sensitivity tests such as thermal or electric pulp testing (EPT) which assess whether there is response to a stimulus. These are the most common methods employed by clinicians. The other form of pulp testing is to evaluate the tooth's vascular supply by using laser Doppler flowmetry (LDF) or pulse oximetry.

Pulpal innervation

It is important to have an understanding of pulpal innervation characteristics in order to appreciate the rationale for, and mechanisms involved in, tests of pulpal sensitivity. Within the coronal pulp, nerve bundles diverge and branch out towards the pulpo-dentine border, and emerge from their myelin sheaths¹³⁻¹⁵. Nerve divergence continues until each bundle loses its integrity and smaller fibre groups travel towards the dentine. This course is relatively straight until the nerve fibres form a loop and a resultant mesh termed the nerve plexus of Rashkow. Terminal axons exit from their Schwann cell investiture and pass between the odontoblasts as free nerve endings¹⁵. This nerve plexus is most well developed in the peripheral pulp along the lateral wall of coronal and cervical dentine, and along the occlusal aspect of the pulp chamber.

Two types of sensory fibres are present in the pulp: the myelinated (A fibres) and unmyelinated C fibres. The A fibres predominantly innervate the dentine and are subgrouped according to their diameter and conduction velocities into A β and A δ fibres. The A β fibres may be more sensitive to stimulation than the A δ fibres, but functionally these fibres are grouped together. Approximately 90% of A fibres are A δ fibres. The C fibres innervate the body of the pulp. The A δ fibres have lower electrical thresholds than the C fibres, and respond to a number of stimuli which do not activate C fibres¹⁶. A δ fibres mediate acute, sharp pain and are excited by hydromechanical events in dentinal tubules such as drilling or air-drying¹⁷.

The C fibres mediate a dull, burning, and poorly located pain, and are activated only by stimuli reaching the pulp proper^{18,19}. C fibres have a high threshold and can be activated by intense heating or cooling of the tooth crown. Once activated, the pain initiated by C fibres can radiate throughout the face and jaws. C fibre pain is associated with tissue injury and is modulated by inflammatory mediators, vascular changes in blood volume and flow, and increases in pressure²⁰.

As the intensity of the stimulus increases, more sensory nerves are activated, and this

results in a progressive increase in the sensory response. The response to a given stimulus will be greatest where neural density is the highest. Key variables known to affect the response to pulp testing are the thickness of the enamel and dentine, and the number of nerve fibres in the underlying pulp. Lilja²¹ found that the highest concentration of neural elements was in the pulp horn region. A progressive decrease in the number of nerve fibres in the cervical and radicular areas was observed. Similar findings were reported by Byers and Dong²². Presumably, the direction of the dentinal tubules is also important in establishing pulp test responses in various parts of the tooth crown. The dentinal tubules run an almost straight course from the incisal edge of anterior teeth to the pulp horn. In multi-cuspal teeth, the course of tubules is somewhat curved and resembles an 'S' shape. Because it is principally the fluid in the tubules that conducts electrical impulses from the pulp tester electrode to the pulp, the shorter the distance between the electrode and the pulp, the lower the resistance to the flow of current²³.

Sensitivity testing

Currently, the most widely used vitality testers assess the integrity of the A δ nerve fibers in the dentine–pulp complex by briefly applying a stimulus to the outer surface of the tooth. If the A δ nerve fibres are successfully stimulated, the patient will respond by acknowledging a short, sharp sensation/tingling from the tooth. A positive response indicates that the nerve fibres are functioning (to some degree), but does not give any indication of pulpal blood flow. If there is no vascular supply to the pulp, it will rapidly become anoxic and the A δ fibres will cease to function. It should be noted, however, that there may be instances, such as following trauma, where there is a blood flow to the pulp, but the A δ nerve fibres are not functioning.

Thermal testing

These tests involve the application of cold and heat stimuli to a tooth, to determine sensitivity to thermal changes. Although both are tests of

sensitivity, they are actually conducted for different diagnostic reasons. A response to cold usually indicates a vital pulp, regardless of whether that pulp is normal or abnormal. In contrast, an increased response to heat is suggestive of pulpal or periapical pathology that may require endodontic intervention²⁴.

Cold tests

Cold thermal testing causes contraction of the dentinal fluid within the dentinal tubules, resulting in a rapid outward flow of fluid within the patent tubules^{25,26}. This rapid movement of dentinal fluid results in 'hydrodynamic forces' acting on the A δ nerve fibres within the pulp–dentine complex, leading to a sharp sensation lasting for the duration of the thermal test²⁷. A variety of cold tests may be employed, the major difference between them is the degree of cold that is applied to the tooth.

The most common pulp testing method employed by practitioners is to seek a response to a cold stimuli. Ideally, cold testing should be used in conjunction with an electric pulp tester so that the results from one test will verify the findings of the other test. If a mature, non-traumatized tooth does not respond either to EPT or cold, then the tooth may be considered non-vital²⁸. However, caution should be exercised when testing multi-rooted teeth, as they may respond positively to cold, even though only one root actually contains vital pulp tissue.

The cold test may be used to differentiate between reversible and irreversible pulpitis. It should be noted, however, whether stimulus application produces a lingering effect or if the pain subsides immediately on removal of the stimulus from the tooth. If the patient feels a lingering pain, even after the cold stimulus is removed, a diagnosis of irreversible pulpitis may be reached. Conversely, if the pain subsides immediately after stimulus removal, a diagnosis of reversible pulpitis is more likely. The clinician should also take into consideration other factors such as a history of pain on lying down and the duration of pain. The diagnosis of reversible/irreversible pulpitis is only a clinical diagnosis and may not correlate with a histological diagnosis.

A simple means of applying a cold stimulus to a tooth is to wrap a sliver of ice in wet gauze and place it against the buccal surface, comparing the reaction between the test tooth and a control tooth. Pencils of ice can be made by filling a plastic straw with water and freezing it in an upright position in a refrigerator.

Ethyl chloride (boiling point – 41 °C) may be sprayed onto a cotton pledget, resulting in the formation of ice crystals, prior to application to the tooth. Dichlorodifluoromethane (DDM) (boiling point – 0 °C) is a compressed refrigerant spray, which can similarly be sprayed onto a cotton pledget for cold testing. More recently, ozone-friendly non-chlorofluorocarbon sprays have been introduced in certain countries²⁹.

Another effective cold stimulus is frozen carbon dioxide (CO₂), also known as 'dry ice' or 'carbon dioxide snow' (boiling point – 72 °C). For testing purposes, a solid stick of CO₂ gas is prepared by delivering CO₂ gas into a custom-made plastic cylinder and the stick is applied to buccal surface of the tooth. This investigation is particularly effective when trying to assess teeth that have been restored with full-coverage metal restorations³⁰. Rickoff³¹ reported that CO₂ snow applied to a tooth for 5 min did not jeopardize the health of the pulp³², nor does it damage the surface of the enamel. On the other hand, CO₂ may cause pitting of the surface of porcelain restorations when applied for as little as 5 s³³. When testing with a cold stimulus, one must begin with the most posterior tooth and advance towards the anterior teeth. Such a sequence will prevent any melted ice water dripping in a posterior direction which may cause stimulation of other teeth, thereby giving a false response.

Ice-cold water is another useful and inexpensive test. The tooth under investigation should be isolated with rubber dam and then bathed with water from a syringe²⁹. Cold tests should be applied until the patient definitely responds or the stimulus has been applied for a maximum of 15 s³⁴. Overall, cold tests appear to be more reliable than heat tests^{2,35}. Furthermore, there is a general consensus that the colder the stimulus, the more effective the assessment of tooth innervation status^{29,30,34}.

Heat test

Heat testing can be undertaken using a stick of heated gutta-percha or hot water. A gutta-percha stick, preferably base-plate gutta-percha, is heated with a naked flame or an electric heater until it becomes soft and glistens³⁶. It is then applied to the vaseline-coated surface of the test tooth. It is purported that a tooth surface temperature as high as 150 °C can be achieved with this technique³⁷: gutta-percha softens at 65 °C and may be heated in delivery devices up to 200 °C. This test may be difficult to use on posterior teeth because of limited access. A further disadvantage is that excessive heating may result in pulp damage³⁸. Prolonged heat application will result in bi-phasic stimulation of A δ fibres initially, followed by the pulpal C fibres¹⁸. Activation of C fibres may result in a lingering pain, therefore heat tests should be applied for no more than 5 s. However, inadequate heating of the gutta-percha stick could result in the stimulus being too weak to elicit a response from the pulp³⁹.

The use of hot water, administered through an irrigating syringe under rubber dam isolation, has also been described as a means of thermal testing⁴⁰. Frictional heat may be generated by using a rubber cup intended for prophylaxis (without paste) against the buccal aspect of a tooth^{40,41}. The normal use of thermal tests on teeth has been shown not to be harmful to healthy pulp tissue^{31,42}.

Electric pulp test

The objective of EPT is to stimulate intact A δ nerves in the pulp–dentine complex by applying an electric current on the tooth surface. A positive result stems from an ionic shift in the dentinal fluid within the tubules causing local depolarization and subsequent generation of an action potential from intact A δ nerves⁴³.

The electric pulp tester is a battery-operated instrument, which is connected to a probe that is applied to the tooth under investigation. It functions by producing a pulsating electrical stimulus, the initial intensity of which should be at a very low value to prevent excessive stimulation and discomfort. The intensity of the electric stimulus is then increased steadily at a pre-selected rate, and a note is made of

the read-out on the digital display when the patient acknowledges a warm or tingling sensation. The read-out is not a quantitative measurement of pulp health, but simply provides evidence that the A δ fibres are sufficiently healthy to function^{44,45}.

The electric pulp tester is technique sensitive and has a number of limitations^{46,47}. The requirements of an EPT are: an adequate stimulus, an appropriate application method, and careful interpretation of results. Tooth isolation during EPT is essential. Drying the enamel, placement of an interproximal plastic strip, and use of rubber dam can prevent the spread of electrical impulses to adjacent teeth or gingival tissue^{48,49}. Electric current can also be transferred between adjacent teeth through contacting metallic restorations⁴⁹. A conducting medium should also be used to ensure that maximum current passes from the electrode to the tooth surface^{50,51}. A laboratory study by Martin and co-workers⁵² concluded that the interface medium made no appreciable difference to either the voltage or the electric current transmitted. However, a more recent study did demonstrate that different media influence the responses gained from electric testing⁵³.

There are several considerations regarding optimal placement of the tester electrode. The response threshold is reached when an adequate number of nerve terminals are activated to attain, what is termed a summation effect^{54,55}. An area of high neural density should have a relatively fast and strong response, and requires the least electric current²³. Therefore, the most desirable area of assessment in incisor teeth is at the incisal edge, where the enamel is thinnest or absent. The tester should be applied on the tooth surface adjacent to a pulp horn, as this receives the highest nerve density within the pulp^{16,22,56}. This position equates to the incisal third region of anterior teeth and the mid-third region of posterior teeth. The threshold for response may be influenced by the thickness of the enamel and dentine overlying the pulp^{18,57}. Thus, the response threshold for healthy teeth may be lowest in incisors, slightly greater in premolars, and greatest in molar teeth. A recent study has revealed that the optimum site for tester electrode placement on molars is on the tip of the mesiobuccal cusp⁵⁸.

Test cavity preparation

This test may serve as a last resort in testing for pulp vitality. It is only considered when the results of all other tests have proved inconclusive. Its value in clinical practice has been largely anecdotal as there is no evidence base to support its effectiveness. The test cavity is made by drilling through the enamel–dentine junction of an unanaesthetized tooth with good isolation. This may be achieved under rubber dam with a small round diamond bur in a high-speed handpiece with adequate coolant. The patient is asked to respond if any painful sensation is felt during the drilling procedure. If the patient feels pain once the bur contacts the sound dentin, the procedure is terminated and cavity is restored.

Local anaesthetic test

When dental symptoms are poorly localized or referred, an accurate diagnosis is extremely difficult. Sometimes, patients may not even be able to specify whether the symptoms are from the maxillary or mandibular arch. In such cases, and where pulp testing has proved inconclusive, an anaesthetic test may be helpful. The technique is as follows: using either infiltration or an intraligamentary injection, the most posterior tooth in the area suspected of causing the pain is anaesthetized. If pain persists once the tooth has been fully anaesthetized, the tooth immediately mesial to it is then anaesthetized, and so on, until the pain disappears. If the source of the pain cannot be even localized to the upper or lower jaw, an inferior alveolar nerve block injection is given; cessation of pain indicates involvement of a mandibular tooth. This approach has an advantage over a test cavity, which may incur iatrogenic damage.

Limitations of sensitivity testing

False positive results

A false positive response is where a non-vital tooth appears to respond positively to testing. This may occur in anxious or young patients who may report a premature response because they are anticipating an unpleasant sensation^{23,51}.

Necrotic breakdown products in one part of a root canal system can conduct electric currents to viable nerve tissue in adjacent areas, thereby resulting in a false positive result⁵⁹. Contact with metal restorations may also result in conduction of the current to the periodontium, giving a false vital response; the same may occur with inadequately dried teeth⁶⁰.

False negative results

A false negative result means that a vital tooth has not responded positively to testing. This may be seen in teeth with incomplete root development, which have a higher threshold to testing, and require a stronger stimulation than normal to elicit a response⁶¹. This is because teeth erupt and become functional before completion of neural development^{62,63}. In these conditions, cold testing has proved more reliable than EPT^{34,61}.

Following injury, traumatized teeth may not respond to thermal or EPT due to nerve rupture⁶⁴. The pulps of these teeth, however, may still be vital as their blood vessels remain intact or have revascularized. Therefore, traumatized teeth should always be carefully monitored at periodic intervals as their nerve fibres may subsequently regain function. Interestingly, orthodontic tooth movement has been shown to produce changes in tissue respiration with a resultant reduction in blood flow and possible anoxia of Aδ nerves⁶⁵. Cave and co-workers reported that orthodontic force increased the response threshold to EPT. The effect was almost instantaneous and could persist for up to 9 months following treatment⁶⁶.

Patients with psychotic disorders may not respond to pulp testing⁵¹. It has also been reported that individuals who are under the influence of sedative drugs/alcohol may either not respond or respond to stronger stimulation due to their increased threshold to nerve excitation⁶⁷.

Sensitivity and specificity

Sensitivity denotes the ability of a test to detect disease in patients who actually have the disease⁶⁸. Thus, the sensitivity of a pulp

vitality test indicates the test’s ability to identify non-vital teeth. It is defined as the ratio of the number of persons with a positive test result who have the disease divided by the total number of persons with the disease who were tested⁶⁸. A test with a sensitivity of 0.80 therefore has an 80% chance of achieving a positive result when individuals with the disease are tested.

Specificity, on the other hand, describes the ability of a test to detect the absence of disease⁶⁸. Thus, specificity of a pulp vitality test indicates the test’s ability to identify vital teeth. It is defined as the ratio of the number of patients with a negative test result who do not have disease divided by the total number of tested patients without the disease⁶⁸. A test with a specificity of 0.80 has an 80% chance of returning negative results when performed on persons without the disease.

The sensitivity and specificity of cold, EPT, and pulse oximetry⁶⁹ are given in Table 1.

Correlation with pulp histopathology

Conservative procedures, aimed at preserving pulp vitality, can only be effective if the status of the pulp is accurately assessed^{35,59}. Responses to vitality testing, however, correlate poorly with histological findings. Seltzer *et al.*³⁵ described a ‘sense of inadequacy, often bordering on frustration’ accompanying attempts to predict the pathological state of the pulp. Numerous studies have confirmed the lack of correlation between various pulp testing methods and the actual histological condition of the pulp^{2,39,59,70–74}.

Despite the acknowledged lack of correlation between test threshold and the specific histological state of the pulp, it has been found that there is a statistically significant relationship

Table 1. Sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) for the cold test, electric test, and pulse oximeter test.

Test	Sensitivity	Specificity	PPV	NPV
Cold	0.81	0.92	0.92	0.81
Electrical	0.71	0.92	0.91	0.74
Pulse oximeter	1.00	0.95	0.95	1.00

between the absence of a response to pulp testing and the presence of a completely necrotic pulp^{35,39,74,75}. The traditional view that a lowered threshold to pulp testing indicates hyperaemia or acute pulpitis, and an increased threshold indicates chronic pulpitis is questionable⁷⁶. It must also be remembered that there is a poor correlation between symptoms and pulpal histopathology^{77,78}.

Objectivity

Ingle and Beveridge⁷⁹ have proposed that patient responses to pulp testing procedures may be considered objective. Many other authors, however, would disagree due to the subjective nature of pain^{2,5,80,81}. Thus, any attempts to correlate intensity of response with pulpal condition are complicated by this issue of subjectivity. The use of a 'control' tooth, on the opposite side of the mouth, has been proposed to remove subjectivity from an individual's response⁸². This, approach, however, is still open to criticism as there is no way of knowing whether the 'control' tooth itself is normal³⁵. Furthermore, Mumford⁵ reminds us that, as response intensity does not represent pathological state, comparative testing contributes little further information.

Reproducibility

Reiss and Furedi⁸³, and Schaffer⁸⁴ have reported that patients respond differently to pulp tests on different days, and at different hours of the same day. Reproducibility of pulp testing is therefore an area for concern and may relate to the variable state of mind of the patient¹² as well as the lack of intrinsic accuracy of several types of commercial electrical pulp testers^{51,73}.

Unpleasant sensation

All methods of pulp testing require the patient to indicate when he or she feels a sensation. Naylor⁸⁵ and Greenwood⁸⁶ consider that pain is the only sensation elicited by stimulation of pulpal nerves. This has been challenged by Mumford and Newton⁸⁷, who reported that patients use many words other than 'pain' to

describe the sensation. In most cases, however, the resultant sensation is perceived as 'unpleasant', and this is a considerable disadvantage when full-mouth vitality testing is performed².

Effect of dental development

Many authors have observed that erupting teeth show an increased threshold value to EPT^{12,59,61,76,88} or may give no response⁸⁹, even though their vitality is assured. Sensitivity to electrical stimulation appears to be related to the stage of root development⁸⁹. Kaletsky and Furedi⁷⁶ have suggested that primary teeth with resorbed roots may also have an increased threshold, but this has been disputed in children over 10 years of age⁹⁰. In contrast, Fulling and Andreasen⁶¹ found that thermal testing with carbon dioxide snow gave consistently positive responses irrespective of the stage of dental development. Nonetheless, the stage of dental development should certainly be taken into consideration when undertaking pulp testing in young patients, especially following trauma to immature permanent incisors⁸⁹.

Multi-rooted teeth

Grossman¹² has noted the problems of assessing the vitality of multi-rooted teeth when the pulp is vital in one root canal but not in another.

Effect of drugs

Several authors have stated that sedative, tranquillizing, or analgesic medications increase the threshold of stimulation of pulpal nerves in some patients^{12,91}. Interestingly, the same effect has been noted with placebo medication⁹².

Age influence

With the exception of newly erupted teeth, the age of the patient (10–73 years) appears to have no effect on thresholds to pulp testing^{93–96}. This would seem surprising in view of histological findings of pulpal nerve calcification and decreased neural density with increased age^{97,98}.

Effect of periodontal disease

There are conflicting reports as to the effect of periodontal disease on pulp testing responses. No increase in pulpal stimulus threshold has been reported in the presence of periodontal disease or bone loss^{70,94,98}. Bender and Seltzer⁹⁹, however, produced a very comprehensive paper in 1972 which examined the effect of periodontal disease on the pulp. They stated that there was strong inferential evidence that teeth with periodontal disease may have associated pulpal inflammation and degeneration.

Gender

There is no evidence for a difference in perception threshold to pulp testing according to the gender of the patient¹⁰⁰⁻¹⁰².

Effect of trauma

Several authors have highlighted the unpredictable response of a tooth to pulp testing following trauma^{59,76,103,104}. Immediately following traumatic injury, teeth often fail to respond to conventional pulp testing methods. This temporary loss of response is caused by injury, inflammation, pressure, or tension to apical nerve fibres¹⁰⁵. It may take 8 weeks, or longer, before a normal pulpal response can be elicited^{106,107}. Bhaskar and Rappaport¹⁰⁸ found vital pulp tissue in a series of 25 teeth which has sustained trauma and did respond to conventional vitality tests. They concluded that conventional pulp tests are simply tests of sensitivity, and as such, have questionable value in predicting pulp vitality. For this reason, they recommended that endodontic therapy be delayed in the case of traumatized teeth, and the pulp tissue considered vital in the absence of a sinus tract or periapical radiolucency. A more accurate assessment of pulp vitality would be made by determining the presence of a functioning blood supply, thus allowing the healing potential to be evaluated at an earlier stage. Moreover, delay in diagnosis can lead to severe complications such as inflammatory root resorption¹⁰⁹. Therefore, it is important to determine the status of pulp in such cases to evaluate the necessity for root canal treatment.

Assessment of pulpal vascularity

Crown surface temperature

Thermography or temperature measurement has been previously used for variety of facial conditions, but it has not gained widespread acceptance. Temperature measurement, as a diagnostic procedure for human teeth, has been described with the use of thermistors, infrared thermography, and liquid crystals.

Cholesteric liquid crystals, which exhibit different colours when heated, have been previously employed to determine pulp vitality¹¹⁰. The underlying principle was that teeth with an intact pulp blood supply (vital/healthy pulp tissue) had a warmer tooth surface temperature compared with teeth that had no blood supply.

Surface temperature of teeth has also been measured over a period of time at 15 s intervals using an electric thermometer attached to a surface probe, placed in contact with the tooth^{111,112}. These studies showed that, following cooling, only vital teeth showed a subsequent rise in surface temperature.

Thermographic imaging is a non-invasive and highly accurate method of measuring the body's surface temperature. It has been used to demonstrate that, following cooling, non-vital teeth were slower to rewarm than vital teeth¹¹³. The disadvantage of using this technique is that the teeth must be isolated with rubber dam, after which a period of acclimatization is necessary prior to imaging¹¹⁴. The technique is complex and requires the subjects to be at rest for 1 h prior to testing¹¹⁴.

Transmitted light photoplethysmography (TLP)

TLP is a non-invasive technique used to monitor pulpal blood flow, and has been successfully applied in animal and human studies^{115,116}. It has been suggested that TLP incurs less signal contamination from the periodontal blood flow than is the case for LDF.

Laser Doppler flowmetry

LDF is another non-invasive method for assessing blood flow in microvascular systems. Its

use in teeth was first described by Gazelius and co-workers in 1986¹¹⁷. Since then, the technique has been widely used to monitor dynamic changes in pulpal blood flow in response to pressure changes and following administration of local anaesthesia.

The technique utilizes a beam of infrared light produced by a laser that is directed into the tissue. As light enters the tissue, it is scattered and adsorbed by moving red blood cells and stationary tissue elements. Photons that interact with moving red blood cells are scattered and frequently shifted according to the Doppler principle. Photons that interact with stationary elements are scattered but are not Doppler shifted. A portion of the light is returned to the photon detector, and a signal is produced. Because red blood cells represent the vast majority of moving objects within the tooth pulp, measurement of Doppler-shifted backscattered light is interpreted as an index of pulpal blood flow^{117,118}.

Gazelius and colleagues proved that LDF can reliably differentiate between healthy and non-vital teeth¹¹⁷. Furthermore, LDF readings have proved extremely accurate in predicting revascularization in experimentally replanted dog teeth¹¹⁹. Indeed, using this methodology, pulp revascularization has been shown to re-establish at around 4 weeks following tooth replantation, which is much earlier than would be expected from standard sensitivity tests^{119,120}. It is generally agreed that LDF assessment for human teeth should be performed at 4 weeks following the initial trauma, and repeated at regular intervals up until 3 months. The disadvantage of LDF relates to motion artefact due to uncontrolled movement of the probe when placed against the tooth. Thus, there may be a need for a modified mouthguard or splint to stabilize the measuring probe on the tooth surface in order to obtain more accurate and reproducible readings. Blood pigments within a discolored tooth crown can also interfere with laser light transmission. Care must also be taken to ensure that the false positive results are not obtained from the stimulation of supporting tissues.

Pulse oximetry

This is an oxygen saturation monitoring device widely used in medical practice for recording blood oxygen saturation levels during the administration of intravenous anaesthesia. It was invented by Aoyagi in the early 1970s¹²¹. Pulse oximetry is an entirely objective test, requiring no subjective response from the patient.

The pulse oximeter sensor consists of two light-emitting diodes, one to transmit red light (640 nm) and the other to transmit infrared light (940 nm), and a photodetector on the opposite side of the vascular bed. The light-emitting diode transmits light through a vascular bed such as the finger or ear. Oxygenated haemoglobin and deoxygenated haemoglobin absorb different amounts of red/infrared light. The pulsatile change in the blood volume causes periodic changes in the amount of red/infrared light absorbed by the vascular bed before reaching the photodetector. The relationship between the pulsatile change in the absorption of red light and the pulsatile change in the absorption of infrared light is analysed by the pulse oximeter to determine the saturation of arterial blood¹²¹.

Earlier studies by Schnettler and Wallace reported a correlation between pulpal and systemic oxygen saturation readings using a modified ear pulse oximeter probe on a tooth¹²². They recommended its use as a definitive pulp vitality tester. Kahan and co-investigators subsequently developed a customized probe, in conjunction with a commercial pulse oximeter, for pulp vitality testing¹²³. Unfortunately, the accuracy of the commercial instrument was disappointing, and was not considered to have predictable diagnostic value. The critical requirement of using pulse oximeter in dentistry is that the sensor should conform to the size, shape, and anatomical contours of teeth. Secondly, the sensor holder should also keep the light-emitting diode sensor and the photoreceptor as parallel as possible to each other so that the photoreceptor sensor receives the light transmitted through the tooth. Moreover, the sensor holder should allow firm placement of the sensor onto the tooth to obtain accurate measurements.

Gopikrishna and colleagues later developed and refined a pulse oximeter system for assessment of human pulp vitality¹²⁴. The group compared the accuracy of their pulse oximeter dental probe with thermal and electric pulp tests, and found that the probability of a negative test result (indicating a vital pulp) was 81% with the cold test, 74% with the electrical test, and 100% with pulse oximetry⁶⁹. The probability of a positive test result (indicating a necrotic pulp) was 92% with the cold test, 91% with the electrical test, and 95% for pulse oximeter. The investigators also compared the efficacy of a custom-made pulse oximeter dental probe with EPT and thermal testing for determining pulp vitality status of recently traumatized permanent teeth¹²⁵. They reported that the sensitivity of the pulse oximeter was 1.00, which was superior to that found for the cold test (0.81) and electric pulp test (0.71). This finding is of considerable diagnostic importance as it demonstrates that the pulse oximeter is a definitive and accurate tool for identifying non-vital teeth.

For pulse oximetry to be accurate, however, a normal arterial blood flow is required. When arterial pulsatile blood flow is low, pulse oximeter measurements are unobtainable. This may occur during hypovolaemia, hypothermia, or intense peripheral vasoconstriction¹²⁶. Apart from these medical conditions, the authors also hypothesize that pulse oximetry may have lower specificity in cases where the coronal pulp is undergoing calcific changes. This may occur following trauma, placement of deep restorations, or with physiological ageing. In such cases, a radicular vital pulp with coronal calcification could potentially cause a false negative response.

Conclusion

An accurate assessment of tooth vitality is of paramount importance in clinical practice. Although sensitivity testing is the *de facto* standard employed by the majority of clinicians, it has acknowledged limitations. Rapid advances in knowledge and applied technology relating to pulpal blood flow may lead the way for a more objective, accurate, and predictable means of pulp vitality assessment.

What this paper adds

- This study has provided a comprehensive review on the different approaches to pulp vitality assessment.
- It has highlighted the limitations of pulp testing on the basis of sensitivity, and has provided the biological basis for vitality testing on the basis of pulpal blood flow measurements.

Why this paper is important to paediatric dentists

- Diagnosis of pulp status is particularly challenging for the paediatric dentist, particularly for young children and those who have suffered dento-alveolar trauma. This paper describes the vast array of factors that may influence responses to pulp testing, and gives the clinician a valuable insight into the diagnostic value of such tests.

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