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REVIEW

Review of pulp sensibility tests. Part II: electric pulp tests and test cavities

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Abstract

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The electric pulp test (EPT) is one type of pulp sensibility test that can be used as an aid in the diagnosis of the status of the dental pulp. However, like thermal pulp sensibility tests, it does not provide any direct information about the vitality (blood supply) of the pulp or whether the pulp is necrotic. The relevant literature on pulp sensibility tests in the context of endodontics up to January 2009 was reviewed using PubMed and MEDLINE database searches. This search identified articles published between November 1964 and January 2009 in all languages.

The EPT is technique sensitive, and false responses may occur. Various factors can affect the test results, and therefore it is important that dental practitioners understand the nature of these tests and how to interpret them. Test cavities have been suggested as another method for assessing the pulp status; however, the use of this technique needs careful consideration because of its invasive and irreversible nature. In addition, it is unlikely to be useful in apprehensive patients and should not be required because it provides no further information beyond what thermal and electric pulp sensibility tests provide – that is, whether the pulp is able to respond to a stimulus. A review of the literature and a discussion of the important points regarding these two tests are presented.

Keywords: diagnosis, electric pulp test, endodontics, test cavity.

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Introduction

Ideally, any method used to assess the state of the dental pulp should be non-invasive, objective, painless, reliable, reproducible, standardized, easily performed and inexpensive. The most popular clinical tests are pulp sensibility tests, such as thermal and electric tests. However, these tests do not provide any direct information regarding the state of the pulp's blood supply, which is what is required to truly assess pulp vitality (Chambers 1982, Jafarzadeh *et al.* 2008, Udoye & Jafarzadeh 2010). The use of thermal pulp sensibility tests has been discussed in Part 1 of this series of articles (Jafarzadeh & Abbott 2010).

Electric pulp testing (EPT) is a commonly used method to test pulp sensibility. Probably, the first recognition of electrical current as a means of stimulating the pulp took place when intermittent electrical current was applied as a means of anaesthesia (Lobb 1859). After that, an Evaluation Committee of the British Royal College of Dental Surgeons reported electricity to be painful when applied to the teeth and more a distraction than an anaesthetic (Editorial Board of Journal 1859). However, the earliest application of electrical current to stimulate the pulp tissue has been attributed to Magitot (1878) in his *Treatise on Dental Caries*, published in France, in which he referred to the use of electricity for localizing painful teeth with

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carious lesions. After that, Marshall (1891) used electrical current for the differential diagnosis of what he termed vital and non-vital teeth. These early reports suggest that the use of electricity as an aid in the diagnosis of pulp diseases is older than the use of radiography in dentistry (Reynolds 1966).

Although some reports indicate that EPTs may not give reliable results (Kaletsky & Furedi 1936, Ziskin & Zegarelli 1945, Mumford & Björn 1962), other studies (Degering 1962, Reynolds 1966) have indicated that it is superior to thermal tests, in terms of its accuracy, reliability and reproducibility. EPT is particularly effective in older patients and in teeth that have limited fluid flow through the dentinal tubules as a result of dentine sclerosis and calcification of the pulp space because thermal pulp tests are usually inadequate in these teeth (Ehrmann 1977). However, based on its reported shortcomings, EPT should not be considered as the primary instrument of choice for the assessment of pulp status because a positive cold test provides a more accurate response and it is easier to perform and interpret (Cohen & Hargreaves 2006). Moreover, it has been reported that EPT is of little value in testing healthy teeth over repeated trials (Lado *et al.* 1988).

A test cavity has been suggested as a 'last resort' form of pulp test, as it is an invasive and irreversible procedure. In addition, it is unlikely to be useful in apprehensive patients as they would be less receptive to a procedure that may intentionally cause pain. Because a test cavity provides no further information beyond what thermal and electric pulp sensibility tests provide (that is, whether the pulp is able to respond to a stimulus or not), its use should not be required, and therefore the clinical recommendations for this technique need careful consideration.

This review will address the physiological basis of the EPT, types of EPTs, correlation between EPT results and histological status, technique of usage, circuit completion against barrier techniques, variation in readings/creation of a false response, considerations regarding EPT usage and reliability of EPT after cold testing, as well as important points about the test cavity.

Search strategy

A literature search for relevant articles up to January 2009 was reviewed using PubMed and MEDLINE database searches. The search was performed using different keywords, including 'pulp test' or 'pulpal test' or 'pulpal testing' or 'pulp testing' or 'electric pulp test' or 'endodontic tests' or 'cavity test'. This search identified articles published between November 1964 and January 2009 in all languages. After removing duplicates, the remaining articles were retrieved and their reference lists checked to identify any other articles/textbooks relevant to the topic, which may have provided additional information.

Physiological basis

The sensation the patient feels when an electric current is passed through the tooth structure is the result of direct stimulation of the pulp nerve fibres. However, it cannot reasonably indicate that these fibres are present in intact and healthy tissue. Necrotic and disintegrating pulp tissue often leaves electrolytes in the pulp space, which can conduct the electricity to the nerves further down the pulp space, simulating an apparently normal response (Apfel & Gerstein 1973).

Enamel and dentine have high resistance against the conduction of electrical current. The energy can be consumed in these hard tissues, leaving a low level of stimulation for the nerves within the pulp tissue. As the effective resistance of the enamel [that is, the impedance or resistance to alternating current (AC)current] depends on both its electrical properties and the presence of cracks, caries and crown restorations, it follows that voltage measurements cannot indicate the current value.

The principle of the EPT, whether it be a type that measures voltage or current, is to raise the electrical potential through the enamel and dentine into the pulp to provoke a measurable response from the pulp (Michaelson *et al.* 1975). The basic requirements for this include adequate stimulation, appropriate technique of use and careful interpretation of the results (Mumford & Björn 1962). Cooley & Robison (1980) used a battery-powered pulp tester (Digilog; Demetron Research Corp, Danbury, CT, USA) and reported that both the voltage and current increased as the control dial was advanced from 1 to 9 (except for the last two settings); but probably the current was more important for eliciting a response from the pulp.

The stimulus may be in the form of direct current (DC) or AC, and both may be applied with different frequencies (Cohen & Hargreaves 2006). DC can have various durations, and it has been reported that pulsating DC with duration of 5–15 ms provided the best nerve stimulation (Björn 1946, Mumford & Björn 1962).

The optimal stimulation is gained when the cathode is applied as the stimulant. The faster the current rises, the more effective will be the stimulation, and less compensation would be observed in the pulp nerves (Ingle & Bakland 2002, Cohen & Hargreaves 2006). In other words, Ohm's law ($E = R \times I$) (E = electromotive force, R = resistance, and I = current flowing through resistance) is applicable to this test, although this phenomena most likely is a combination of the impedance and resistance (Cohen & Hargreaves 2006).

Electrical stimulation of nerves within the pulp depends on the rate of current increase, its strength (voltage and current), duration and frequency (Michaelson *et al.* 1975). Current density also plays an important role. Increasing the surface area of the electrode requires greater current to produce a sensation, and, over any given electrode area, shorter pulse widths require greater current to produce a sensation (Mumford 1959, Mumford & Newton 1969). The production of nerve excitation depends on the current density, which is the current fraction that passes the excitable tissue elements. This depends on both the current strength and the cross-sectional area of the path taken by the current (Mumford & Björn 1962).

Each stimulation should have a certain minimum intensity/strength to excite, and this is called the threshold stimulus. Different tissues require stimulation with different strengths to reach the threshold of excitation (Mumford & Björn 1962).

The duration of current is also important in the production of excitation. Current strength and duration have a definite relationship to one another, as the shorter the duration, the higher the stimulus intensity that is required to elicit a response (Mumford & Björn 1962).

Figure 1 A benchtop style digital electric pulp tester (the Vitality Scanner 2006). A fine probe tip for testing under crown margins is shown in the foreground. (Photograph courtesy of http://www.sybronendo.com).

Figure 2 A handheld style digital electric pulp tester (Digitest) (Photograph courtesy of http://www.parkell.com).

Figure 3 A handheld style analog electric pulp tester (Gentle-Pulse) (Photograph courtesy of http://www.parkell.com).

Types of EPTs

Early EPTs were large and cumbersome (Cooley *et al.* 1984) but modern testers are efficient, battery-powered and easily controlled. Some are 'benchtop' devices whilst others are handheld (Figs 1–3). In contrast to the older EPT, new devices produce no or little discomfort to the patient, even when used by inexperienced practitioners (Cohen & Hargreaves 2006). Two modes of EPTs exist, monopolar (or unipolar) and bipolar, with each being divided into two categories: those with a mains power connection and those that work with batteries (Ehrmann 1977, Närhi *et al.* 1979).

Until the mid-1950s, most EPTs were bipolar and some had double electrodes that had to contact the tooth. The electrical current flowed from one electrode to the other through the tooth, and if the patient felt pain or a tingling sensation then the tooth was considered to have pulp tissue. However, this method was extremely unreliable (Cohen & Hargreaves 2006). In another method, one electrode was applied to the tooth, whilst the other was held in the hand of the patient (Ingle & Bakland 2002, Cohen & Hargreaves 2006). Nowadays, most EPTs are monopolar with the anode often placed on the lip and the cathode on the tooth. When the electrode is applied to the tooth surface, the circuit is completed through the body of the patient via the lip clip. Alternatively, the circuit can be completed through the body of the practitioner who is holding the alternate end of the probe. In this situation, it is essential for the dentist to touch the patient with the opposite hand not holding the EPT. To ensure a suitable contact, the hand should preferably be moistened; it is possible for the practitioner to feel the current passage through his/her own hands (Matthews *et al.* 1974a, Ehrmann 1977). All monopolar devices currently available produce a high-frequency current with changeable amperage. Application of two electrodes on the tooth surface by this system is difficult, and for this reason bipolar EPTs are not popular in clinical practice (Matthews *et al.* 1974a, Jacobson 1984).

Monopolar stimulation will excite periodontal nerves at a level of stimulus below threshold for some pulp nerves, but they cannot be excited with bipolar stimulation even when intensities 15 times greater than the highest threshold of the pulp nerves are applied (Greenwood *et al.* 1972). When bipolar stimulation is used, the current flows from the cathode to the anode, but the current path is confined to the coronal part of the tooth (Mumford 1957), which probably explains why the periodontal nerve fibres are not stimulated.

Some researchers have indicated that bipolar EPTs can provide more reliable and more consistent results than monopolar testers (Hannam *et al.* 1974, Mumford & Bowsher 1976, Virtanen *et al.* 1984, Virtanen 1985), although in contrast, some other studies have shown that monopolar EPTs were more reliable than bipolar ones (Kaletsky & Furedi 1935, Matthews & Searle 1974, 1976).

It has been shown that variable current devices are more reliable than variable voltage EPTs because of the high and variable electrical resistance of the enamel (Matthews & Searle 1976). Also, both DC and AC EPTs are available, although there is little difference between them (Mumford 1956, Carrotte 2004).

Correlation between EPT results and histological status

The most important point regarding the use of EPTs is the interpretation of the results in conjunction with the patient's history, findings from the clinical examination and radiographs, and by comparison with control teeth (Millard 1973), because many studies have shown no correlation between positive responses to the EPT and the histological status of the pulp (Reynolds 1966, Mumford 1967b, Matthews *et al.* 1974b, Cooley & Robison 1980). A positive response simply indicates that there are sensory fibres present within the pulp that can respond to the electrical stimulus (Reynolds 1966, Mumford 1967b, Matthews *et al.* 1974b, Cooley & Robison 1980, Lado *et al.* 1988). Attempts to correlate the numerical readings of EPTs with the histological pulp status have not yielded conclusive results (Marshall 1891, Seltzer *et al.* 1963, Hare 1969, Lado 1983). Hence, dentists should not try to quantify or compare the responses between teeth because other variables may exist (Cooley *et al.* 1984). Despite this, there is a significant relationship between the failure of a tooth to respond to an electrical pulp test and histological evidence of total necrosis (Seltzer *et al.* 1963, Reynolds 1966), so this technique should be only used to determine whether or not there is viable pulp tissue present in the tooth tissues and not to assess the health or vitality (that is, the presence of blood supply) of the pulp tissue (Lado 1983). If the test is conducted properly, a lack of response to the EPT suggests the lack of responding nerve fibres, and this usually means that there is likely to be necrosis of the pulp (Björn 1946).

Technique of use

It should be emphasized that the EPT is technique sensitive and must be performed carefully (Millard 1973, Cooley & Robison 1980). Before commencing the electric pulp test, removal of supragingival calculus may be required, particularly in mandibular incisors, to gain complete access to the cervical area of the tooth. After that, the exterior surface of the tooth should be dried; ideally, the teeth should be isolated with a rubber dam although in practice this is rarely performed (Ingle & Bakland 2002). If the teeth contain any proximal metallic restorations, these must be insulated from each other by inserting celluloid strips or pieces of rubber dam through their contact points (Millard 1973, Myers 1998). These preparatory steps are important because, as a high electrical potential is used, the current may be conducted to an adjacent tooth or it may flow along wet tooth surfaces to the gingival tissue to give false positive responses (Mumford 1956, Millard 1973, Cooley *et al.* 1984, Bender *et al.* 1989, Myers 1998, Pitt Ford *et al.* 2002).

Prior to applying the device to the tooth, it should be checked using the probe on the skin of the hand to determine that current is completely passing through the probe (Grossman *et al.* 1988). The circuit should be completed by a special lip clip or any other suitable way. The main electrode should be coated with a suitable interface/conducting media (such as toothpaste), and then it can be applied to the middle third of the facial/labial surface of the tooth (Grossman *et al.* 1988). Direct contact with the tooth structure is necessary, which may be a problem with some extensively restored teeth. However, a small tip is commercially available (Mini-Tip; Analytic Technology, Redmond, WA, USA), which may be used instead of the standard tip, and this may allow contact with the tooth structure below a crown margin if there has been slight recession of the gingival tissue (Pitt Ford & Patel 2004).

All EPTs have a rheostat that shows the relative amount of current applied on various scales – such as 1–10, 1–15 or 1–80 (Weine 1996). The current flow should be increased slowly to allow the patient enough time to respond before warmth or tingling sensation becomes painful. Slowly increasing current gives more accurate results (Abdel Wahab & Kennedy 1987). The dentist must explain the nature of the test, the procedure that will be followed and the diagnostic value of the test to the patient. The sensation may be noted by the patient as a tingling sensation, warm, stinging, full or hot (Grossman *et al.* 1988). The probe tip should not be applied to any restorations because this might lead to a false response. If a response is not obtained, then ideally the tip should be applied to different locations on the tooth, such as on the lingual/palatal and labial/buccal surfaces to ensure that the lack of response is not the result of poor electrode positioning (Pitt Ford & Patel 2004). Each tooth should be tested two or three times to ensure consistency, and the average result recorded (Bender *et al.* 1989) even though Mumford (1965) found that the average of two or more readings did not reflect a more accurate pain reception threshold than that obtained by the first recorded value. Testing the reliability of the responses can also be achieved using the EPT with the current switched off or by changing the sequence of the teeth being tested to prevent the results from being affected by the patient's reaction because of his/her bias and/or anxiety (Grossman *et al.* 1988).

Disconnection of the circuit by the patient after a threshold level stimulation is reached depends on two factors. First is the neural pathway for pain perception, which is transferred through the afferent fibres of the pulp tissue to the central nervous system (CNS). The second factor is the manual switching off of the EPT by the patient or the dentist. Hence, some delay will occur, which may result in discomfort for the patient (Allen & Pronych 1997, Nam *et al.* 2005) and a higher level of reading on the EPT.

In some clinical situations, EPT of a tooth covered fully by gold or porcelain may be imperative because other pulp sensibility tests have been equivocal. In these cases, a cavity can be prepared through the restoration without any local anaesthesia until the dentine is reached. During the cavity preparation, penetration to the dentine may be sufficient to elicit a response. If not, the EPT probe can be placed directly on the dentine and the response can be observed. In such a situation, contact between the probe and any metal of the restoration must be avoided – this can be carried out with a small piece of rubber dam or using a very small tip that has been introduced by some manufacturers for this purpose (Mini tip; Analytic Technology, Redmond, WA, USA) (Cohen & Hargreaves 2006). Alternatively, a small dental instrument such as an endodontic file may reliably be used as a bridging instrument (Pantera *et al.* 1992).

Small deviations of the readings of EPTs (e.g. 1–2 units on a scale of 10) are considered to be insignificant. Only when the response between a control tooth and the affected tooth is highly different and when combined with other sensibility tests is the EPT of any value in the diagnostic process.

Circuit completion whilst using barrier techniques

To stimulate the pulp nerve fibres, the current must be able to traverse a circuit from the electrode tip through the tooth structure, through the patient's body and back to the electrode. Prior to the routine use of rubber gloves by dentists, their ungloved fingers typically completed the circuit by contacting both the electrode handle and the patient's face, usually on the cheek or lip. However, over the last two decades, the use of rubber gloves by dentists has become an important part of the standard of patient care (Editorial Board of Journal 1988). The use of rubber gloves with EPTs not only results in current blockage to the tooth but also possible contamination of the probe tip and/or handle from the powder or other components of the glove (Lado 1983, Cooley *et al.* 1984). To solve this problem, one method of completing the circuit whilst the practitioner is wearing gloves is to use a metal lip clip which is placed on the patient's lip and then attached to the probe handle (Guerra *et al.* 1993). This method has an important disadvantage in that when the clips are disinfected between patients, they may lose their retentiveness and ability to provide reliable contact with the probe handle from repeated removal and insertion (Guerra *et al.* 1993).

Another method for completing the electrical circuit is for the patient to touch the probe handle with his/her finger (Devin & Weisenseel 1987, Anderson & Pantera 1988). This method has the advantage of giving more control to the patient as he/she can lift the finger off the electrode handle as soon as a sensation is felt, and this will immediately interrupt the current. This method has been reported to be a more satisfactory and successful method (Devin & Weisenseel 1987, Anderson & Pantera 1988, Kolbinson & Teplitsky 1988, Cailleteau & Ludington 1989).

Other methods have also been proposed, such as to modify the EPT by adding a metal rod that is connected to the handle of the probe by a conductive wire (Matthews & Searle 1974) – the patient holds this rod during the test to complete the circuit and he/she can let it go when the current if felt. This method allows the dentist's hands to remain gloved. No significant difference between this technique and the conventional ungloved procedure was observed in one study (Anderson & Pantera 1988). Another method is for the cuff of the dentist's gloves to be rolled down to allow contact of the dentist's wrist with the EPT handle and with the patient's face. However, this may potentially compromise protection of the dentist and the patient (Treasure 1989).

Some authors have introduced innovative solutions for electrical tests whilst wearing gloves. For example, Butel & DiFiore (1991) described a method that allows the use of rubber gloves and contact by the patient to the handle via a custom-made patient-held contact device. The entire handle, including the attachment of this device on the handle, should be protected with a disposable plastic wrap. The sterilized tip is inserted to the wrapped handle which eliminates cross-contamination of the handle during usage. Response readings were more accurate when EPT was used with this technique than when used in the conventional manner without gloves. A barrier technique has been described by Guerra *et al.* (1993) who cut a small stabilization groove about 1 mm deep at an acute angle along the proximal surface of the probe tip. A protective current-conductive sleeve that fits over the probe tip was made by sectioning a new saliva ejector. This sleeve was then inserted over the tip so the wire on one end of the sleeve fitted into the groove, and the wire on the other end made contact with the tooth surface. This technique is not proposed to practitioners because it is not user friendly and the cutting process on the probe is not reversible.

Variation in readings/creation of a false response

Correlating EPT readings with pulp health is impractical and impossible, because there are so many reasons for variations in readings. The two major reasons are failure to complete the circuit and patient-related factors (Cooley & Robison 1980, West 1982). However, some of these reasons may only apply to one or two instrument types and may be irrelevant to modern instruments.

Failure to complete the circuit

Completion of the circuit is of paramount importance when using an EPT. Starting with the electrode tip, electrical contact must be made with enamel through the use of an electrolytic conductor; however, variations in electrolyte conductivity and the amount of electrolyte used may affect the result (Ingle & Bakland 2002). The voltage used in most EPTs is sufficient to overcome the impedance of enamel, but on the skin surface of the patient, the area of surface contacted is directly proportional to the current flow. In other words, the resistance is lowered as the contacted area becomes greater and the current flows more readily (Lado 1983).

Equipment problems

Inaccuracy or unreliability of the device may be a major cause of the inconsistencies encountered with EPTs (Cooley & Robison 1980). One such reported example occurred during evaluation of the low-battery and depleted-battery indicators (Cooley *et al.* 1984). When the voltage of the battery dropped to 4 volts on the instrument under test, the digital display continued to count upwards, but the output voltage did not increase with the display numbers. In these instances, the practitioner may think that the device is operating normally but the electrical stimulus would not be increasing. This problem can be circumvented by periodic replacement of the batteries (Cooley *et al.* 1984).

Probe placement

The optimal placement of the probe tip is necessary because the response threshold is reached when an adequate number of nerve fibres is stimulated. The response would be expected to be greatest where the density of neural distribution is the highest (Närhi *et al.* 1979, Johnsen 1985, Bender *et al.* 1989, Udoye *et al.* 2010). There is no agreement on the optimal placement site for the probe. However, several authors have shown that EPTs produce the most consistent results when the probe tip is placed on the incisal edge or on the cusp tip of teeth (Ziskin & Zegarelli 1945, Mumford 1960, Jacobson 1984, Bender *et al.* 1989, Lin *et al.* 2007).

One study showed that the lowest response for both mandibular and maxillary first molars was obtained from the mesiobuccal cusp tip. Other areas showed an increase in the level of current required from the mesiobuccal cusp surface, mesiobuccal gingival surface and the centre area of the supporting cusps (buccal of mandibular molars and palatal of maxillary molars) (Lin *et al.* 2007).

Other studies have suggested that the optimal placement for the electrode is on the incisal third of the crown (Jones 1967), the middle third of the labial surface (King 1972, Hannam *et al.* 1974, Matthews *et al.* 1974b) or the cervical third of the labial surface (Martin *et al.* 1969, West 1982). Jacobson (1984) concluded that the middle third area of the labial surface of incisors and the occlusal third area of premolars required the lowest current. In contrast with these claims, Matthews *et al.* (1974b) found no consistent relationship between the electrical threshold and the site of probe placement.

It has been proposed that multi-rooted teeth may need to be tested by placing the probe tip on more than one site, because two sites on a molar may not give a response, but a response may be obtained in another area (Ingle & Bakland 2002).

Another controversial matter is whether to choose the labial/buccal surface or palatal/lingual surface. Jacobson (1984) concluded that the labial/buccal surface of maxillary incisors and premolars required lower voltages than the palatal surfaces, but this was only significant for incisors, and not for premolars. The elevated palatal voltages for the incisors may be mechanical because the cingulum causes difficulty in establishing a good electrode-to-tooth contact on this area. The results of Jacobson (1984) are in contrast with those of others – Björn (1946) found that the buccal and palatal surfaces were similar in their measurements, and Michaelson *et al.* (1975) reported that the buccal and lingual readings were the same in 50% of their tests, whilst in 40%, the buccal readings were slightly higher than lingual readings.

The angle of placement of the tip may be another important parameter. If the electrode tip is rotated to one side, so that it is not flat against the surface of enamel, then less current and voltage would be transmitted to the tooth structure (Cooley & Robison 1980).

Interface media

A dry electrode tip and tooth may allow the electrical current to be dispersed along the crown surface and not elicit an observable response from the pulp (Ingle & Bakland 2002). Hence, the necessity of using a conducting medium (interface media) to ensure the electrical impulse is conducted through the tooth structure has been investigated and confirmed in several studies (Martin *et al.* 1969, Michaelson *et al.* 1975, Cooley & Robison 1980, Mickel *et al.* 2006).

Various materials such as toothpaste (Coolidge & Kessel 1956), concentrated salt solution (Sommer *et al.* 1962) and water-based jelly (Martin *et al.* 1969) have been advocated for use as interface media. However, other materials such as special electrode gel (Matthews *et al.* 1974a, Jacobson 1984, Petersson *et al.* 1999), fluoride gel (Bender *et al.* 1989, Dal Santo *et al.* 1992, Lin *et al.* 2007) and even a dry electrode (Ziskin & Wald 1938) have been used by various researchers. The most commonly used medium is toothpaste (Fuss *et al.* 1986, Anderson & Pantera 1988, Kolbinson & Teplitsky 1988, Cailleteau & Ludington 1989, Moody *et al.* 1989, Butel & DiFiore 1991, Pantera *et al.* 1992, Peters *et al.* 1994, Myers 1998) as it is readily available in dental surgeries and it is cheap and easy to use. However, one study showed toothpaste was less effective than water and an electrode gel (Cooley & Robison 1980).

Martin *et al.* (1969) revealed that the conducting medium is important although the medium type was not significant as long as it had a high dielectric constant and was preferably water-based. They proposed petroleum jelly or a water-based jelly for use as an interface media because such materials do not dry out, they remain in place and they provide the necessary interface between the electrode and enamel. Michaelson *et al.* (1975) showed no appreciable difference between water-based and petroleum-based materials; however, in contrast, Mickel *et al.* (2006) reported that different interface media conduct differently. They recommended that the media should be water-based and not petroleum-based because the petroleum-based materials failed to allow electric impulses to reach the pulp. This is important because some patients may wear lip stick or lip balm, and if the tooth surface is contaminated with these products, then a false negative response may be obtained.

Patient-related factors

Tooth characteristics

The response threshold may be affected by the thickness and homogeneity of the enamel and dentine, hence, it may be lowest in incisors, higher in premolars and greatest in molar teeth (Rubach & Mitchell 1965, Närhi 1985, Dummer & Tanner 1986, Bender *et al.* 1989, Yoon & Yoon 1991). In accordance with this, tooth surface wear may have a significant effect in determining the response threshold (Ingle & Bakland 2002). As enamel has low moisture content, its resistance to the electricity flow is high, and therefore the enamel loss associated with wear may lower the response threshold (Bender *et al.* 1989).

Calcification of the root canal and pulp recession as a result of pulp irritation and/or ageing can increase the response threshold. Enamel defects, such as extensive caries and cracks, can also affect the response threshold (Davies & Rawlinson 1988, Bender *et al.* 1989, Yoon & Yoon 1991). However, one study concluded that there was no correlation between the electrical threshold and the presence of caries, diffuse pulp mineralization or pulp stones (Moody *et al.* 1989).

A greater current is needed to produce a response in teeth with larger pulp chambers (Mumford 1959). This is supported by the findings that canines have a higher response threshold than central and lateral incisors (Michaelson *et al.* 1975, Bender *et al.* 1989). Similarly, maxillary incisors tend to have higher thresholds than mandibular incisors. However, it is difficult to understand why the threshold of maxillary lateral incisors is higher than maxillary central incisors (Bender *et al.* 1989).

Traumatized teeth and orthodontically treated teeth may, at times, give little or no response to the EPTs (Hyman & Cohen 1984). At other times, they may require a greater current to elicit a response (Mumford 1959).

Apex maturation

Permanent teeth with open apices usually give little or no response to electrical testing (Hyman & Cohen 1984). Only 11% of the teeth in children with completely open apices gave a response to the EPT (Klein 1978), so it has been suggested that CO_2 'snow' can be more reliable than EPT for sensibility testing of immature teeth (Fulling & Andreasen 1976a). Therefore, it seems that the statement by Mumford (1967a) that the EPT is more reliable than thermal tests is correct but only with respect to tests utilizing ice sticks or ethyl chloride, but not to those using CO_2 'snow'.

Teeth with restorations

A false response may be obtained when EPT is used on teeth with necrotic pulps or pulpless root canal systems when they have large metallic restorations. These restorations have the ability to conduct electrical impulses to the supporting tissues. Teeth that have full crown restorations, porcelain restorations or a pulpotomy may not respond as expected to EPT because the dental materials used may prevent the current from reaching the dentinal tubules and hence the pulp (Cooley *et al.* 1984, Beer *et al.* 2006), although, in contrast, Moody *et al.* (1989) concluded that there was no correlation between the electrical threshold and the presence of restorations. When undertaking EPTs on teeth with full crowns, an EPT with a special tip that can fit between the crown and the gingival margin is available (Carrotte 2004). The use of CO_2 snow or a cold spray is the best method to test the pulps in these cases (Grossman *et al.* 1988).

Electric pulp tests should not be used on teeth that have orthodontic appliances, such as bands and arch wires (Fulling & Andreasen 1976b), and teeth involved in splints or bridges (Weine 1996) because the current can be transferred to adjacent or nearby teeth.

Dentition

Asfour *et al.* (1996) concluded that EPTs can be useful in the deciduous dentition. They assessed the reliability of children's responses to pulp testing of the maxillary deciduous canines in children aged 7–10. These children were tested with ethyl chloride or with an EPT. They concluded that usage of ethyl chloride or EPT for pulp testing of deciduous teeth resulted in reliable responses.

Supporting tissues

The response threshold of teeth with periodontal disease is lower than teeth without periodontal disease. The average value of normal teeth and periodontally diseased teeth is 36.3 and 31.4, respectively, which shows that in periodontal disease the response of the pulp to testing decreases (Hori *et al.* 1989). As there is an overlap of the thresholds of the pulp and periodontal nerve fibres, the periodontal nerves can contribute to false readings suggesting pulp sensibility (Närhi *et al.* 1979).

Teeth with an acute alveolar abscess may respond to EPT because of the presence of liquefied or gaseous elements within the root canal which can conduct the current to the periapical tissues, which respond to the stimulus (Weine 1996).

Repeated trials

Investigators have failed to note significant adaptation or habituation by patients when subjected to repeated EPTs. Results have been found to be reproducible for trials on the same day and for trials performed on different days. However, the best time of the test in a day is not clear (Yoon & Yoon 1991, Dal Santo *et al.* 1992).

Patient's psychological state

The mental and emotional status of the patient can be an important factor in stimulus perception (Cooley & Robison 1980, Kennedy *et al.* 1987), as can the cultural background (Bender *et al.* 1989, Dal Santo *et al.* 1992). However, no significant difference in the responses of men and women has been found (Bender *et al.* 1989, Lin *et al.* 2007).

Anxious and nervous patients may have a lower response threshold (Bender *et al.* 1989). In contrast, patients with psychopathic disorders may indicate little or no response to maximum levels of electrical stimulation (Cooley & Robison 1980).

Patient's physiological state

The health status of the patient can influence the test results – for example, hypertensive patients had significantly higher thresholds for EPT (Ghione *et al.* 1985), whilst some patients with endocrine imbalance (such as primary hyperparathyroidism) and some patients with diseases affecting the CNS had unpredictable EPT results (Ziskin & Zegarelli 1945, Albright & Reifenstein 1948). In contrast, in patients undergoing chemotherapy for Hodgkin's disease (Rosenthal *et al.* 1984) and those using combinations of hydrocodone and acetaminophen (paracetamol) systemically (Kardelis *et al.* 2002), there was little impact on their pulp sensibility readings.

McKinstry *et al.* (1989), in a study on six maxillary incisors, concluded that patients with unilateral and bilateral clefts had higher electrical thresholds than patients without clefts. Also, no significant difference between unilateral and bilateral cleft patients was found in their responses to the EPT. They also reported that patients with cleft palate who received orthodontic treatment within 1 year of testing had elevated electrical threshold as did non-cleft palate patients who completed orthodontic treatment within 1 year of testing.

Drugs, including narcotics, analgesics, tranquillizers, sedatives and alcohol, can also influence the EPT response (Chambers 1982). Thus, alcoholics tend to have an elevated threshold response (Ziskin & Zegarelli 1945). It has been shown that meperidine (pethidine) does not alter the EPT response but a systemic dose of acetaminophen can affect the patient response to the EPT (Carnes *et al.* 1998, Kardelis *et al.* 2002).

Considerations/limitations regarding use of EPT

Although the EPT can be a beneficial aid for the diagnosis of pulp conditions, it has some important limitations:

1 A response to an EPT does not provide any information about the health status of the pulp, its circulation, or its integrity. It only indicates that some sensory fibres are present within the pulp tissue and are capable of responding to the stimulus (Bhaskar & Rappaport 1973, Shabahang 2005).

2 The EPT is not reliable for testing immature teeth because the myelinated fibres entering the pulp may not reach their maximum number until 5 years after tooth eruption or until they have been in function for 4–5 years. Failure of immature teeth to respond may also be caused by the lack of development of the plexus of Raschkow at the pulpodentinal junction (Anderson 1963, Fulling & Andreasen 1976a, Johnson *et al.* 1983, Johnsen 1985). Also, the larger pulp of immature teeth may cause impedance to the electrical current (Mumford 1959). Unreliable results in children, because of fear, apprehension or management problems are additional drawbacks (Cohen & Hargreaves 2006).

3 Use of EPTs for teeth which have full or partial coverage with a metallic restoration can create difficulty because of the limited access to tooth structure for tip placement and the large size of many electrode tips. Small adapters for the electrode tip (Mini tip; Analytic Technology) can allow contact in these cases, but these tips are easily displaced or lost and several are required to meet infection control requirements (Pantera *et al.* 1992).

4 An electric current of about 0.2 mA applied directly to a healthy heart can cause ventricular fibrillation (Starmer *et al.* 1971). Because of the protective effects of its investing tissues, greater currents (100–500 mA, AC) are required to induce heart fibrillation *in situ*. After testing the effect of EPTs on a dog with a pacemaker, Woolley *et al.* (1974) concluded that 5–20 mA current is sufficient to modify the function of a normal pacemaker, so for some years, it led to the view that EPTs should not be used on patients with cardiac pacemakers (Woolley *et al.* 1974, Lado 1983). However, in later laboratory tests, EPTs did not interfere with pacemaker functioning. This is because newer EPTs contain improved shielding and filtering circuits (Adams *et al.* 1982, Luker 1982, Miller *et al.* 1998). Recently, Wilson *et al.* (2006), in an *in vivo* study, simulated EPT usage on patients with implanted pacemakers and showed that EPTs did not cause any interference.

Some patients who have epilepsy with pharmacologically refractory seizures may be treated with an implanted pulse generator that can electrically stimulate the left vagus nerve. This device works similarly to cardiac pacemakers, and Roberts (2002) has shown that electrical devices can be used in close proximity to these patients without any adverse effect on the stimulator function.

Reliability of EPT after cold testing

Some clinicians have proposed that using cold tests may create hypothermic anaesthesia, and thereby make the tooth less reactive to stimulation by an EPT if performed soon afterwards. However, the hydrodynamic theory suggests that electrical and cold stimulation of the pulp have two different mechanisms of action. This theory says that cold stimuli may induce neurons to act as mechanoreceptors that react to the movement from the thermal contraction of the dentinal fluid. On the other hand, electrical stimulation may cause depolarization of nerve membranes. Hence, it seems unlikely that a cold pulp sensibility test would affect electrical stimulation of the pulp tissue, and therefore the sequence of pulp tests is not critical (Gysi 1900, Trowbridge *et al.* 1980, Pantera *et al.* 1993).

Test cavity

Occasionally, after conducting clinical testing and radiographic evaluation, there may be a diagnostic dilemma, such as when a patient reports acute, diffuse or radiating pain that cannot be localized, and so a definitive diagnosis may be difficult or even impossible to achieve (Ruddle 2002, Tronstad 2003). In these cases, it has been suggested by some authors that a cavity could be prepared in the tooth in a concealed position without anaesthetizing the tooth. The patient must be adequately apprised of what to expect and how to respond if any discomfort is felt in such a situation. This procedure has been called a 'test cavity' (Cohen & Hargreaves 2006).

When the dentino-enamel junction (DEJ) is approached during cavity preparation, or when the pulp is exposed, the patient would be expected to feel some pain if the pulp tissue was alive and had a viable sensory nerve supply. Once a response is gained, proponents of this technique state that the cavity preparation should be stopped and the cavity should be restored because this tooth is not the one causing the presenting pain. However, the response felt by the patient cannot truly be a precise indication of the degree of inflammation or the state of the pulp. On the other hand, if no response is evoked, then endodontic access cavity preparation can be continued and endodontic therapy commenced.

If a high-speed bur and handpiece are used to prepare the test cavity, it may be difficult to control the depth of penetration. Hence, it has been recommended that a more suitable way of proceeding may be to cut such a cavity with a low-speed handpiece and a small bur so the cavity can be kept shallow and only extend just into the dentine (Ehrmann 1977, Rowe & Pitt Ford 1990). When performing this test, copious water spray and light pressure should be used, although the latter is difficult to achieve if a low-speed handpiece is used.

This test has been suggested for use in cases with full crown restorations and where the margins of the crown are in contact with the gingival tissues. It may also be helpful to some extent in young teeth with immature roots that respond erratically to all other pulp sensibility tests (Tronstad 2003), although the use of such an invasive procedure in a young and possibly apprehensive patient should be questioned with respect to the long-term effects this may have on the patient's approach to further dental treatment.

A test cavity may be unreliable as the patient may give a response even though the pulp is necrotic because the nerve fibres can continue to conduct impulses for some time in the absence of blood circulation. Moreover, the value of this test is doubtful in nervous patients and even in patients who are not normally nervous about dental procedures but may be apprehensive about the lack of use of local anaesthesia in an attempt to see whether there is pain produced. Furthermore, reduced dentine innervations in geriatric patients also render this test less beneficial in these patients (Cohen & Hargreaves 2006). Other pulp sensibility tests, such as the CO_2 dry ice test, seem to reduce the need for this invasive test (Ehrmann 1977).

Although the damage because of this test can be repaired with a restoration, it is essential to note that this test is invasive and it is not reversible. It is also unlikely to provide any further information than thermal and electric pulp sensibility tests because it is testing the same aspect – that is, the ability of the pulp to respond to an irritating stimulus. The only difference is the nature of the stimulus but when weighed up against the irreversible and invasive nature of the test cavity, plus its unreliability in most patients as they are likely to be apprehensive in this situation, it is difficult to justify the need for a test cavity. A thorough understanding of the symptoms associated with and the nature of pulp and periapical diseases should enable clinicians to make a diagnosis in the vast majority of cases. Such an understanding should also include an understanding of how these diseases progress through various stages. The teeth that can be difficult to diagnose typically have pulp necrobiosis (Ingle & Bakland 2002, Abbott & Yu 2007), which is a condition where there is some necrotic and infected pulp tissue present in the coronal part of the pulp space or within one root canal, and the remainder of the pulp is irreversibly inflamed (Abbott & Yu 2007). These teeth typically present with symptoms of pulpitis but the pain cannot be reproduced, and so the tests suggest pulp necrosis. A test cavity is unlikely to provide any further enlightenment to this situation and ultimately the diagnosis depends on the skill and experience of the dentist in interpreting the patient's history and the clinical findings. Hence, test cavities are not justified in modern endodontic or dental practice and in the best interests of the patient.

Conclusions

Electric pulp tests can be a valuable aid to the diagnostic process when assessing the state of the dental pulp, although cold pulp sensibility tests are usually more reliable, more useful and much easier to perform. However, in some cases thermal tests are not reliable, and so an EPT should also be used, such as in teeth with pulp canal calcification, when equivocal results are obtained with thermal tests and when following up traumatized teeth. Test cavities have been advocated in the past as a 'last resort' form of pulp test, but this procedure can no longer be justified because of their invasive and irreversible nature, the likelihood of unreliable results and the lack of additional information that they can provide beyond thermal and EPTs. It should be remembered that the best methods to assess the state of the dental pulp are vitality tests such as laser Doppler flowmetry and pulse oximetry (Jafarzadeh 2009, Jafarzadeh & Rosenberg 2009), even though these tests are not commonly used in clinical settings due to their expense and the time involved.

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