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REVIEW

Review of pulp sensibility tests. Part I: general information and thermal tests

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Abstract

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A major, and essential, part of the diagnostic process for pulp disease is the use of pulp sensibility tests. When diagnosing pulp pain, these tests can be used to reproduce the symptoms reported by the patient to diagnose the diseased tooth as well as the disease state. However, a major shortcoming with these tests is that they only indirectly provide an indication of the state of the pulp by measuring a neural response rather than the vascular supply, so both false positive and false negative results can occur. 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 papers published between November 1964 and January 2009 in all languages. Thermal tests have been used as an integral part of dental examinations. Two types of thermal tests are available, one uses a cold stimulus and the other uses a hot stimulus, and each has various methods of delivery. If these tests are used properly, injury to the pulp is highly unlikely. A review of the literature regarding the rationale, indications, limitations, and interpretation of thermal tests, the value of these diagnostic tests, as well as a discussion of the important points about each of these tests is presented.

Keywords: cold, diagnosis, heat, pulp, sensibility test, thermal test.

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Introduction

Before commencing any treatment, one must first assemble all the available information regarding the symptoms and history of the disease. These should then be combined with the findings of the clinical examination (the signs) and the results of relevant diagnostic tests. Once the information has been gathered and interpreted, the clinician can formulate a differential diagnosis made up of all possible disease entities that are consistent with the history, examination, and the results of the tests. For this purpose, the clinician must have a thorough knowledge of the examination procedures and tests as well as their limitations (Ingle *et al.* 2002).

A major, and an essential, part of the diagnostic process for pulp disease is the use of pulp sensibility tests. When diagnosing pulp pain, these tests can be used to reproduce the symptoms reported by the patient to diagnose the diseased tooth as well as the disease state. There are several pulp tests available, and these can be grouped as either sensibility tests or vitality tests. Pulp sensibility tests include thermal tests (heat and cold stimuli), electric pulp tests (EPTs), and a test cavity. Pulp vitality tests include laser Doppler flowmetry (LDF), pulse oximetry, and tooth temperature measurement. These tests can be used in conjunction with other clinical tests such as periodontal probing,

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percussion, palpation, mobility, transillumination, and anaesthetic tests to aid the diagnostic process (Jafarzadeh *et al.* 2008, Jafarzadeh 2009, Jafarzadeh & Rosenberg 2009, Udoye & Jafarzadeh 2010).

No single element of the diagnostic process should be relied upon to make even what appears to be an uncomplicated diagnosis. Hence, before commencing any treatment, there should be at least two independent diagnostic test results that correlate to indicate the disease process. Pulp tests alone are usually not adequate for establishing a diagnosis but can provide useful information (Dachi *et al.* 1967, Fulling and Andreasen 1976a,b). The purpose of this review is to discuss the rationale, indications, limitations, and interpretation of pulp sensibility tests, as well as the value of these tests.

Search strategy

A literature search for relevant articles on pulp sensibility tests in the context of endodontics up to January 2009 was performed using PubMed and MEDLINE database searches. The search was performed using different keywords ('pulp test' or 'pulpal test' or 'pulpal testing' or 'pulp testing' or 'electric pulp tester' or 'vitality test' or 'endodontic tests' or 'thermal test' or 'cold test' or 'heat test' or 'cavity test' or 'palpation test' or 'percussion test' or 'laser doppler' or 'pulse oximetry'). This search identified papers published between November 1964 and January 2009 in all languages. After removing duplicates, the remaining papers were retrieved, and their reference lists were checked to identify any other articles/textbooks relevant to the topic, which might have provided additional information.

Terminology

There appears to be considerable confusion amongst dentists and in the literature regarding the terminology used to describe pulp tests. It is common to see the use of inappropriate terms, which suggest that the authors or users of those terms do not fully understand the test being used or described. If the nature of the test is not understood, then the results cannot be accurately determined or interpreted, which can lead to incorrect treatment decisions. Hence, to clarify the terminology used in this study, the following definitions are provided.

Sensibility is defined as the ability to respond to a stimulus (http://www.Dictionary.com) (Accessed online on 13 March 2009). Tests such as thermal tests and electric pulp tests are sensibility tests because they are assessing whether the pulp's nerve fibres can respond to a stimulus when applied to the tooth. In clinical situations, an assumption is then made on the basis of the results of these tests regarding the state of the pulp, whether it is alive or necrotic. That is, the results of these tests are extrapolated to imply a state of health or disease of the pulp. Thus, sensibility tests are used to determine whether a pulp is likely to be alive (with response) or necrotic (without response).

Sensitivity is a condition of being very responsive to a stimulus. Thus, when testing a tooth to determine whether it has pulpitis (a condition that is very responsive to certain stimuli, as reported by the patient), sensibility tests are used to test the sensitivity of the pulp. However, they are still regarded as sensibility tests.

The term 'hypersensitivity' implies a condition of being even more responsive to a stimulus than a very responsive (i.e. sensitive) tooth; it is subjective and difficult to define or compare between patients. Therefore, the term 'hypersensitivity' should not be used because 'sensitivity' defines the state of the pulp and the prefix 'hyper-' is not required.

Vitality implies that a blood supply is present within the tissues. Hence, only a test that actually measures or assesses pulp blood flow can be called a vitality test. Currently, the only true vitality tests that have been reported in the literature are the laser Doppler flowmetry (LDF) and pulse oximetry tests. However, these tests are not commonly used in dental practice owing to the costs, time, and clinical procedures required for use (LDF) (Jafarzadeh 2009) and uncertain results (pulse oximetry) (Jafarzadeh & Rosenberg 2009).

Pulp sensibility tests

The common methods for pulp sensibility testing are thermal stimulation (cold and heat), electrical stimulation, or direct dentine stimulation (cavity test). These tests indicate whether there is a neural response from the pulp. A major shortcoming with these tests is that they do not indicate the state of health of the pulp and that in some situations, the responses might be unreliable – such as when teeth have temporarily or permanently lost their sensory function (for example, traumatized teeth, immature teeth, or teeth that are in proximity to moving jaw components in orthognathic surgery) but still might have intact vasculature

(Bhaskar & Rappaport 1973, Evans *et al.* 1999). Also, the nerve tissue, being highly resistant to inflammation, might remain reactive long after the surrounding pulp tissue has degenerated. Pulp sensibility tests also do not indicate the vitality of the pulp, that is, whether there is an adequate vascular circulation (Noblett *et al.* 1996, Radhakrishnan *et al.* 2002).

Some authors have reported inconsistencies between pulp symptoms and responses when compared with the histological findings. A criticism of these tests is that they have only shown a correlation between the test results and necrotic pulps or pulpless teeth (Seltzer *et al.* 1963a, Tyldesley & Mumford 1970, Dummer *et al.* 1980). These studies suggest that such tests should only be used to assess whether a pulp is alive or necrotic because they do not quantify disease or health and should not be used to judge the degree of pulp disease. However, when used appropriately, thermal pulp sensibility tests are useful when patients report symptoms of pulpitis because they can be used to identify the diseased tooth by reproducing the symptoms.

Pulp testing schemes should be performed initially on pain-free teeth, away from the area of the chief complaint. The preferred sequence is to test disease-free contralateral teeth first, opposing teeth second, then presumably healthy teeth within the thermally painful quadrant, and finally, the most suspicious tooth. This strategy allows the clinician to appreciate the range of normal responses exhibited by asymptomatic teeth in that particular patient. It also allows the patient to learn what to expect with the test. Importantly, performing repetitive tests will tend to relax the patient, build confidence, and reduce the probability of a false response (Cohen & Hargreaves 2006). To improve objectivity, the tests should be repeated after a recovery period of 1 min, unless too much discomfort has been caused (Ruddle 2002a, Pitt Ford & Patel 2004).

Thermal tests are highly subjective as they are wholly dependent on the patient's response to the stimulus. There is no accurate or objective method of assessing how responsive the tooth under investigation is to any particular test or of comparing with a previous measurement. In contrast, EPTs have numerical displays, which allow the report to be compared with previous readings (Pitt Ford & Patel 2004) although many clinicians do not believe these readings are reproducible and simply look for a response or no response (Cohen & Hargreaves 2006). No studies have demonstrated whether the readings shown on the numerical display have any particular meaning or whether they are reproducible.

The ideal technique for the evaluation of pulp status should be noninvasive, painless, standardized, reproducible, reliable, inexpensive, easily completed, and objective (Chambers 1982). However, pulp sensibility tests that are currently used have the potential to produce an unpleasant sensation, and therefore, there will be a subjective element to their interpretation (Bhaskar & Rappaport 1973, Klein 1978).

Rationale of the tests

The rationale for innervation of any structure in the body is to provide a warning of damage that is occurring or impending (Cohen & Hargreaves 2006). With this understanding, sharp, nonlingering pain with the application of thermal stimulation is normal and a part of the patient's protective defence system. An exaggerated response can indicate a lowered threshold (Cohen & Hargreaves 2006).

In general, the amount of stimulus required to activate A-δ afferent fibres is only 25% of that required to activate C fibres; therefore, most clinical pulp testing activates only the A-δ fibres (Virtanen 1985, Hargreaves & Goodis 2002).

Thermal tests

Sensory response to thermal stimuli occurs before there is a temperature change in the pulpo–dentinal junction (PDJ) area, where sensory nerve endings are located (Trowbridge *et al.* 1980, Ingle *et al.* 2008). Thus, it appears that the sensory response is not initiated by temperature changes in the receptors (Trowbridge *et al.* 1980). Instead, thermal tests activate hydrodynamic movement of fluid within dentinal tubules, which excites the A-δ fibres (Cohen & Hargreaves 2006). The C fibres are not activated by these tests unless they produce injury to the pulp (Fuss *et al.* 1986). Another reason for proving that the understanding of pain responses to thermal stimuli is based on the hydrodynamic theory is that there are no thermosensing nerve endings in the pulp tissue (Cohen & Hargreaves 2006). Thus, the pain sensation the patient experiences requires some pulp tissue, including odontoblasts. These odontoblasts should be intact for the function of hydrodynamic mechanism (Berman & Hartwell 2006).

Cold stimulates the fast-conducting A-δ fibres, which produces a sharp localized pain (Ingle & Bakland 2002). Continued heat application, on the other hand, will more likely stimulate the slower conducting C fibres, located deeper in the pulp, resulting in dull pain of longer duration (Bender 2000). Thermal stimulation provides a greater response when more extreme temperature changes occur, causing more rapid and stronger fluid movement within the dentinal tubules, stimulating receptors, and exciting A-δ fibres (Bender 2000, Ingle & Bakland 2002). However, gradual temperature changes do not produce a rapid response but will eventually produce a response by C fibres (Mengel *et al.* 1993, Bender 2000).

Electric pulp test (EPT)

Electric pulp tests deliver a current sufficient to overcome the resistance of enamel and dentine and stimulate the A-δ fibres. The nonmyelinated C fibres do not respond to the conventional EPTs because significantly more current is needed to stimulate them (Närhi *et al.* 1979). The pulp is assumed to be responsive or at least partially alive if a sensation is felt by the patient when a gradually increasing level of electrical current is transmitted through the tooth. A positive response to the EPT is the result of ionic shift in dentinal fluid within the tubules causing local depolarization and subsequent generation of action potential from intact nerves (Pantera *et al.* 1993).

EPTs assess the integrity of the A-δ fibres by briefly applying the stimulus to the outer surface of the tooth. If the A-δ fibres are successfully stimulated, the patient will respond by acknowledging a brief sharp sensation or a tingling from the tooth. If there is no blood flow in the pulp tissue, it will become anoxic and the A-δ fibres will cease to function (Pitt Ford & Patel 2004).

Indications for pulp sensibility tests

Indications for the use of pulp sensibility tests include:

1. When diagnosing pain in the trigeminal area, including when referred pain is present, it is important to assess the status of the pulp of individual teeth before considering treatment (Mumford & Björn 1962, Harris 1973, Ehrmann 1977).

2. The pulp status is important when periodically monitoring teeth that have been subjected to trauma (Mumford & Björn 1962, Cooley *et al.* 1984). Pulp sensibility tests have questionable predictive value of the state of the pulp, so endodontic treatment should be delayed following trauma to the teeth (Bhaskar & Rappaport 1973). After trauma, the lack of a response to pulp tests may not be indicative of the pulp's blood supply because of shock of the pulp, whereas a response may have no prognostic value and may serve only as a base line that can be compared with subsequent test results during the follow-up period (Teitler *et al.* 1972). Periods of 1–8 weeks can lapse before a normal response can be elicited. However, longer observation periods might be required (Andreasen & Andreasen 1994). The transition from obtaining no response to having a response at a later time might be considered a sign of a pulp that is recovering following trauma, whilst the repetitious finding of a response might be taken as a sign of a healthy pulp (Bhaskar & Rappaport 1973, Andreasen & Andreasen 1994). In contrast, the transition from having a response to not obtaining a response might be taken as an indication that the pulp is undergoing degeneration, and the persistence of no response would suggest that the pulp was necrotic, but even this is not absolute and might be transient (Bhaskar & Rappaport 1973). The EPT has been shown to be reliable in differentiating between pulps that are alive and those that are necrotic following trauma (Ingle *et al.* 2002).

3. Before restorative dental procedures on a tooth, it is essential to ascertain whether the pulp is healthy, using sensibility tests (Bender & Seltzer 1961, Ehrmann 1977). Moreover, pulp status is important when examining a potential prosthetic abutment tooth to help assess its long-term prognosis (Cooley *et al.* 1984).

4. It is desirable to periodically test the pulp in teeth that have undergone pulp preservation procedures, such as a partial pulpotomy, and those that have had extensive restorations (Mumford & Björn 1962, Cvek 1978).

5. Pulp tests are an integral part of the diagnostic process when differentiating periapical radiolucencies from normal landmarks and nonodontogenic lesions (Hare 1969, Harris 1971, Ehrmann 1977, Cooley *et al.* 1984), although it is important to understand that even if a radiograph reveals a normal periapical appearance, a root canal system might be infected because the cancellous bone might be lost without this becoming apparent radiographically (Bender & Seltzer 1961, Ehrmann 1977).

6. Pulp sensibility tests can be a valuable tool in predicting potential anaesthetic problems in restorative dentistry (Certosimo & Archer 1996), as well as endodontic procedures (Dreven *et al.* 1987, Cohen *et al.* 1993, Hsiao-Wu *et al.* 2007). The lack of a response to a pulp test is usually indicative of profound anaesthesia, and it is then likely that the treatment will be painless. A lack of response to a cold test is more effective in assessing pulp anaesthesia compared to soft tissue signs of anaesthesia (Dreven *et al.* 1987, Cohen *et al.* 1993, Certosimo & Archer 1996, Hsiao-Wu *et al.* 2007). When using these tests as an indicator of the effectiveness of local anaesthesia, all teeth to be treated should be pulp-tested preoperatively to determine whether they respond. After injection of local anaesthetic, traditional parameters of anaesthesia such as lip numbness are verified. The teeth should then be retested with the same pulp test, and the results should be recorded. Then, the teeth can be prepared for endodontic therapy/restoration, and the patient's level of anaesthesia can be screened by other means such as a visual analogue scale (Certosimo & Archer 1996).

Mumford & Björn (1962) noted that pulp tests have also been used in studies to compare and evaluate analgesic drugs. Also, Carnes *et al.* (1998) compared the changes in pain threshold caused by meperidine, naproxen sodium, acetaminophen, and placebo using an EPT. They showed that acetaminophen may significantly elevate the pain threshold, but no elevation of the threshold occurred with narcotic drugs and nonsteroidal anti-inflammatory drugs.

7. The EPT can be a suitable device for evaluating the pulp status of transplanted teeth, especially if the EPT responses subsequent to transplantation increase numerically over time (Clark *et al.* 1955, Reade *et al.* 1973, Bolton 1974, Altonen *et al.* 1978, Hardy 1982, Pogrel 1987, Robinson 1987, Andreasen *et al.* 1990, Waikakul *et al.* 2002) (Table 1).

Table 1 The association between tooth transplantation and EPT responses

Authors/year	Type of transplanted teeth	Examination period	Probability of positive response	Sample size	Major findings
Clark *et al.* 1955	Mandibular third molars	5 months 8 months	43% 85%	19 teeth 18 patients	A correlation existed between the EPT response and lamina dura formation
Reade *et al.* 1973	Maxillary canines	>6 months	39%	50 teeth 37 patients	Autotransplanted canines can survive for many years
Bolton 1974	All kinds of teeth	1–7.5 years	83% (Easy transplant) 60% (Moderate transplant) 21% (Difficult transplant)	68 teeth 60 patients	If the transplantation process is difficult, the possibility of positive response to EPT is decreased
Altonen *et al.* 1978	Maxillary canines	6–37 months	10.7%	28 teeth 22 patients	Significantly better results in younger patients than in older patients when assessing the pulp response to EPTs
Hardy 1982	Maxillary canines	12–108 months	15%	132 teeth 110 patients	In the absence of reaction to the EPT, a decrease in the size of the coronal pulp chamber or root canal on radiograph is a more reliable sign of the pulp survival
Pogrel 1987	Various kinds of teeth	≥2 years	14%	416 teeth 368 patients	A success rate of over 70% was reported
Robinson 1987	Maxillary canines	N/A	Monopolar stimuli: 39% Bipolar stimuli: 45%	33 teeth	Responses returned between 7 weeks and 26 months after transplantation
Andreasen *et al.* 1990	Premolars	8 weeks 6 months 1 year	2% 90% 95%	370 teeth 195 patients	Pulp responses in transplanted teeth became normal with time
Waikakul *et al.* 2002	Third molars	3 months 6 months 9 months 12 months After 1 year	55% 82% 91% 95% Unchanged	22 teeth 14 patients	No significant association between the EPT response and bone formation

8. Sensibility tests, particularly the EPT, can be used after Le Fort type fractures/osteotomies. Most teeth return to normal responses around 7–11 months after surgery (Roed-Petersen & Andreasen 1970, Tajima 1975).

Limitations of pulp sensibility tests

1. A major limitation of sensibility tests is that these tests are subjective and measure only pulp nerve responses and not pulp blood flow (Gazelius *et al.* 1986, Schnettler & Wallace 1991).
2. Thermal tests require dentinal tubules to be open to allow fluid to flow according to the hydrodynamic theory. Thus, these tests may not be effective in elderly patients where it is more likely that teeth will have closed tubules and substantial secondary dentine formation (Reynolds 1966).
3. Electric pulp tests are less reliable in teeth with immature apices because development of the Raschkow's plexus does not completely occur until the final stages of root development (Fulling & Andreasen 1976a, Fuss *et al.* 1986). They are also unreliable following traumatic injuries, when there may be no response to cold and electric pulp tests even if blood circulation is restored (Ohman 1965, Bhaskar & Rappaport 1973). The traumatized immature tooth with an open apex and thin dentinal walls is particularly difficult from a diagnostic and treatment perspective because there is even more subjectivity in young individuals to sensibility tests (Tronstad 1988, Yanpiset *et al.* 2001).
4. Another limitation of pulp tests is the lack of correlation with the histological status of the pulp. Many studies have evaluated the results of sensibility tests alongside the histological status of the pulp but have found no clear correlation (Mumford & Björn 1962, Seltzer *et al.* 1963a,b, Dummer *et al.* 1980). In addition, some studies have found a poor correlation between clinical symptoms and histopathological findings when the pulp diagnosis was subdivided into specific categories (Baume 1970, Garfunkel *et al.* 1973, Iqbal *et al.* 2007). In contrast, Hill (1986) found some relationship between the pulp state and responses to ethyl chloride.
5. Sensibility tests are difficult to administer or inconclusive when used with children (Peters *et al.* 1994). Children cannot always describe subjective symptoms or a response to a stimulus (Ingle & Bakland 2002). False responses, particularly, occur if the dentist asks the child a leading question (Cohen & Hargreaves 2006). Furthermore, these tests are perceived as unpleasant, as children adapt their behaviour to avoid a painful stimulus, and their ability to properly respond to pulp testing is limited (Kennedy *et al.* 1987). Also, it has been stated that sensibility to electrical stimulation is directly related to the stage of root development (Klein 1978). There are conflicting opinions about pulp testing teeth in the primary dentition with some authors stating that thermal tests are generally unreliable (Berman & Hartwell 2006). However, Asfour *et al.* (1996), in a study on the maxillary canines of 100 children aged 7–10, reported that EPTs or ethyl chloride were valid for pulp testing in the deciduous dentition (in this study, 5% lignocaine paste was used on the gingival margin to prevent gingival detection of the stimulus).
6. The reduced neural components of aged pulps, their reduced volume, and changes in character of the ground substance create an environment that may result in responses that are different to the stimulation of younger pulps (Cohen & Hargreaves 2006). There are fewer nerve branches in older pulps, which may be attributable to the retrogressive changes resulting from mineralization of the nerves and nerve sheaths (Berman & Hartwell 2006, Cohen & Hargreaves 2006). Consequently, the response to stimuli might be weaker than in the more innervated younger pulp tissues (Berman & Hartwell 2006).
7. Extensive restorations, pulp recession, and excessive calcifications create limitations in both performing and interpreting pulp test results (Pantera *et al.* 1992).
8. Patients might respond differently to sensibility tests on different days and at different hours of the same day, that is, they lack reproducibility (Reiss & Furedi 1933).

Interpretation of test results when making a diagnosis

When performing a test, the clinician should evaluate the immediacy, the intensity, and duration of the response. The immediacy and intensity of a response can vary substantially depending on many factors including the individual patient's response to any form of stimulus, the depth of caries, the placement of a new restoration, recent periodontal surgery, etc (Ingle & Bakland 2002, Cohen & Hargreaves 2006). Importantly, it is the duration of the response, compared to the baseline that has been established by testing other teeth in the same patient, which may be the most helpful aid to diagnosis, especially when testing a tooth for pulpitis (Ingle & Bakland 2002).

When a cold test is applied to a healthy pulp, it usually results in a sharp localized sensation for the duration of the applied test and for a few seconds after removal of the stimulus (Cohen & Hargreaves 2006). A pulp response that lingers for some time (although how long is indeterminate for any particular patient and pulp) after the stimulus has been removed is frequently interpreted as indicating an irreversibly inflamed pulp. No response from the tooth to such stimulation is normally regarded as an indication of pulp necrosis or that the tooth has become pulpless (Pitt Ford & Patel 2004, Cohen & Hargreaves 2006). The outcome of such testing is never absolutely certain, and that is why diagnosis must not rely on a single test (Pitt Ford & Patel 2004). It should be emphasized that there is no particular response to either heat or cold that is unique to specific pathologic states of the pulp although there are general trends (Seltzer *et al.* 1963a).

Clinically normal pulp

This condition is asymptomatic and produces a mild to moderate transient response to cold and electrical stimuli (Cohen & Hargreaves 2006). Such stimuli do not cause the patient distress. When the stimulus is removed, the response subsides within a few seconds (Berman & Hartwell 2006). Clinically normal pulps do not usually respond to heat tests (Cohen & Hargreaves 2006).

Reversible pulpitis (localized inflammation)

Thermal stimuli (usually cold) cause a sharp pain that subsides as soon as the stimulus is removed or within a few seconds (Berman & Hartwell 2006).

Irreversible pulpitis (advanced inflammation)

In this condition, the acutely inflamed pulp is usually associated with severe symptoms, whereas the chronically inflamed pulp is either asymptomatic or has only mild symptoms from time to time (Seltzer *et al.* 1963a, Ingle *et al.* 2008). The apical extent of the inflammation cannot be determined clinically until the periodontal ligament is affected and the tooth becomes tender to biting and/or percussion. Temperature changes (usually cold) elicit a sharp pain followed by a dull prolonged ache that might last up to an hour or so in some cases. EPTs are of little value in the diagnosis of this condition because the inflamed pulp is still responsive to it and the intensity of the response cannot be quantified or compared with clinically normal pulps (Seltzer *et al.* 1963a, Rowe & Pitt Ford 1990). As long as the disease is still limited to the pulp, the use of EPTs followed by thermal testing is a commonly recommended sequence of testing (Seltzer *et al.* 1963a, Dummer *et al.* 1980, Rowe & Pitt Ford 1990, Peters *et al.* 1994) although there seems little point in using an EPT in these cases. The use of a thermal test is most valuable because the dentist is able to apply the stimulus that is reported by the patient as causing pain and thereby the pain can be reproduced and assessed (Cohen & Hargreaves 2006).

Pulp necrosis

The difficulty with the use of the term necrosis is that the blood supply of a pulp cannot be determined with electrical and thermal stimulation. Ideally, the use of a test such as LDF would help to overcome this limitation (Jafarzadeh 2009). It has been proposed that the EPT is the instrument of choice for determining pulp necrosis (Ingle *et al.* 2002), but other studies have shown cold pulp tests, especially carbon dioxide snow, to be reliable and useful (Linsuwanont *et al.* 2008).

Although it is not possible to determine the histopathological status of the pulp on the basis of the pulp sensibility tests alone (Reynolds 1966, Lundy & Stanley 1969), there is a significant relationship between the lack of response to these tests and pulp necrosis (Marshall 1979, Seltzer & Bender 1984). Because nerve fibres of the pulp are relatively resistant to necrosis and will be the last part of the pulp to die (Mullaney *et al.* 1970, England *et al.* 1974), the necrotic pulp may continue to respond to stimulation for some time (Fuss *et al.* 1986). However, essentially no response will be obtained with EPTs and thermal tests from teeth with pulp necrosis. In addition, it must be remembered that pulp tests are not able to indicate whether the root canal system has become infected, and therefore, the history and other clinical and radiographic findings must be combined to complete the diagnosis (Cohen & Hargreaves 2006).

Pulp necrobiosis

This condition is sometimes referred to as partial pulp necrosis, but 'Necrobiosis' is more appropriate as it has been defined as the condition when some of the pulp has necrosed and become infected whilst the remainder of the pulp is inflamed (i.e. has pulpitis, presumably irreversible) (Ingle *et al.* 2002). Necrobiosis may be difficult to diagnose because the patient's report of symptoms suggests that he/she has pulpitis but the pulp tests results may suggest pulp necrosis. In some cases, a vague response to EPTs and/or cold tests may be obtained (Ingle *et al.* 2002).

Acute apical periodontitis

This condition is usually a sequel to an infected root canal system, and therefore, the use of pulp sensibility tests is essential to the diagnostic process (Berman & Hartwell 2006). In some patients, there may be acute apical periodontitis associated with pulpitis, and therefore, a full and accurate assessment of the pulp status is required before any treatment can be considered. The pulp tests might have different results in this condition.

Acute apical abscess and acute lateral periodontal abscess

The symptoms of a lateral periodontal abscess may mimic those of the acute periradicular abscess (Ehrmann 1977). However, these conditions can usually be differentially diagnosed from each other largely through the use of appropriate pulp sensibility tests and radiographs (Cohen & Hargreaves 2006). In the case of a lateral periodontal abscess, the tooth would be expected to respond to pulp sensibility tests (assuming there is no concurrent pulp disease), and therefore, the pulp can be diagnosed as being clinically normal (Ingle *et al.* 2008). In contrast, a tooth with an acute apical abscess would not be expected to respond to pulp sensibility tests as they are a sequel to a necrotic and infected pulp, a pulpless infected root canal system, or a previously root filled tooth that has become infected (Ehrmann 1977, Cohen & Hargreaves 2006).

Chronic apical periodontitis

This condition is usually a sequel to an infected root canal system, and therefore, the use of pulp sensibility tests in addition to the radiographs is essential to the diagnostic process (Berman & Hartwell 2006).

False responses

False negative responses (teeth with normal pulps that do not respond to the tests), associated with both thermal tests and EPTs, are more often misleading than a false positive response (Seltzer *et al.* 1965, Grossman *et al.* 1988).

The patient is unlikely to respond to a cold pulp test but may respond to an EPT if the pulp space has significantly calcified (Klein 1978, Grossman *et al.* 1988). In these cases, more electric current is often needed to elicit a response because there is an increased dentine layer and a diminishing pulp cavity or a fibrotic pulp (Klein 1978, Grossman *et al.* 1988). However, Peters *et al.* (1994) showed that most teeth with calcified pulp chambers and presumably atrophic pulps responded to EPTs or cold tests. This correlated with the findings of Seltzer *et al.* (1963a) who reported that only 19% of atrophic pulps did not respond to EPTs and only 3% did not respond to heat and cold.

No response to a test might occur when the patient has been pre-medicated with sedative, tranquillizing, analgesic or anti-inflammatory medications, or alcohol (Degering 1962, Grossman *et al.* 1988, Ruddle 2002a), when the tooth has been involved in a recent episode of trauma or when the tooth has an immature apex (Mumford 1976, Grossman *et al.* 1988). Cold testing of immature teeth with refrigerant spray or carbon dioxide snow appears to be more reliable than EPTs (Fulling & Andreasen 1976a, Fuss *et al.* 1986).

Teeth that have had root canal treatment would not be expected to respond to pulp sensibility testing although occasionally a response can be obtained, especially to heat tests (Ruddle 2002a). A canal may be missed during root canal treatment that might contain inflamed or infected pulp tissue and so respond to the pulp tests.

Other factors that might affect the response to pulp tests include when extensive restorations and pulp-protecting bases have been placed (Peters *et al.* 1994), patients with unusual high pain threshold (Grossman *et al.* 1988), following activation of fixed orthodontic appliances (a lack of response was found to the EPT for up to 2 months after activation of the appliances; however, thermal testing appeared more reliable) (Burnside *et al.* 1974, Sailus *et al.* 1987, McDonald & Pitt Ford 1994, Hall & Freer 1998), and patients with psychotic disorders (Cooley & Robison 1980). A defect with the EPT device, discharged batteries, or a poor electrical contact can also induce a false negative response (Peters *et al.* 1994).

Some studies have shown a high incidence of false positive results (i.e., teeth with necrotic pulps or pulpless root canal systems responding to a pulp sensibility test), particularly with EPTs (Seltzer *et al.* 1965, Dummer *et al.* 1980). Several explanations for this phenomenon have been proposed:

1. The response may be caused by conduction of the current to the adjacent gingival or periodontal tissues (Ziskin & Wald 1938, Ziskin & Zegarelli 1945, Greenwood *et al.* 1972, Matthews & Searle 1974, Matthews *et al.* 1974, Närhi *et al.* 1979, Cooley *et al.* 1984). However, Björn (1946) reasoned that the risk involved in the activation of non-pulp nerve fibres is minimal if reasonable current strength and proper techniques are used.
2. Canal moisture from putrescence of the pulp tissue (also called moist gangrene) or the presence of inflamed pulp tissue in a partially necrotic, infected pulp might be a factor (Seltzer *et al.* 1965, Grossman *et al.* 1988).
3. The breakdown products associated with localized necrosis might be capable of conducting electrical current to adjacent inflamed pulp tissue (Dummer *et al.* 1980).
4. The calcified tooth structure might be capable of conducting an electrical current to tissue apical to an area of pulp necrosis (Ziskin & Wald 1938, Mumford 1976, Närhi *et al.* 1979).
5. The electrical current might be conducted to adjacent teeth through contacting Class II restorations, especially if they are metallic (Elfenbaum 1968, Myers 1998). In such cases, a piece of rubber dam or a celluloid strip can be placed between the teeth to avoid electrical conductance (Cooley *et al.* 1984).
6. A multi-rooted tooth might have inflamed pulp tissue in a canal, whilst the pulp chamber and other canals might be necrotic and infected (Grossman *et al.* 1988).
7. Pulp sensibility tests are reliant on the patient's response, and therefore, a false positive response might occur in anxious or young patients (Cooley & Robison 1980).

It is much rarer to have a false positive response to cold tests than to the EPT (Peters *et al.* 1994). This conforms to the theory of progressive breakdown and necrosis occurring within the pulp. The ability to cause a response to temperature changes via the tissue that has already broken down is lost much sooner for cold stimuli than for electric stimulation (Peters *et al.* 1994, Ingle *et al.* 2008). A response to a cold test requires more live tissue in the coronal aspect of the tooth than does a response to an EPT, so cold stimulation is not possible via fluids or necrotic pulp tissue (Peters *et al.* 1994).

Peters *et al.* (1994) reported that false positive responses to EPTs were spread evenly throughout all types of teeth, whereas false positive responses to cold tests occurred in multi-rooted teeth only. It was extremely rare to have false negative responses to EPTs if more than one surface or part of each tooth was tested carefully (Peters *et al.* 1994). With EPTs, the incidence of obtaining a response when testing one part of the tooth and another part not responding was not high. However, when a cold test was applied and only one area responded, it was significantly more frequently the cervical area.

Value of diagnostic tests

A perfect diagnostic test would always provide a response in the presence of disease and no response in the absence of disease. However, false negative or false positive results do occur (Ransohoff & Feinstein 1978).

Two classes of descriptors that can be used for determining the value of diagnostic tests are variability and precision. All tests have certain potential for variability of results or for the lack of precision where the precision of a test refers to the tendency of repeated measurements on the same sample to yield the same result. Possible causes of variability include differences in test interpretation amongst clinicians or by the same clinician at different times, equipment malfunction, and subjective responses from the patient (Hyman & Cohen 1984, Petersson *et al.* 1999).

The extent to which a test correctly classifies a patient's response defines its accuracy (Ransohoff & Feinstein 1978, Hyman & Cohen 1984, Iqbal *et al.* 2007) (Fig. 1). Even when functioning at the greatest possible level of precision, every test will misclassify a certain percentage of patients, that is, some disease-positive patients will have a negative test result, and some patients without disease will have a positive result. The concepts of sensitivity, specificity, and positive and negative predictive values (NPVs) have been developed to characterize test accuracy and to

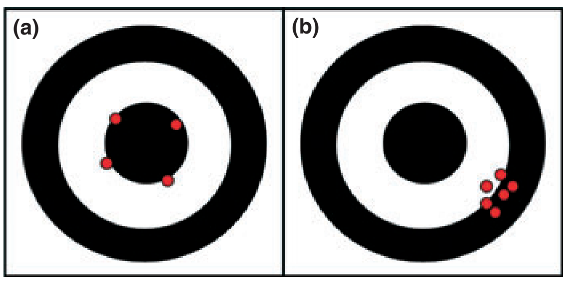

Figure 1 The accuracy versus the precision of a test. a: High accuracy versus low precision; b: High precision versus low accuracy.

		Condition		
		Clinically normal pulp	Necrotic pulp or pulpless tooth	
Test outcome	Positive	True positive (TP)	False positive (FP)	⇨ Positive predictive value [TP/(TP+FP)]
	Negative	False negative (FN)	True negative (TN)	⇨ Negative predictive value [TN/(TN+FN)]
		⇩ Sensitivity [TP/(TP+FN)]	⇩ Specificity [TN/(TN+FP)]	Accuracy [(TP+TN)/(TP+TN+FP+FN)]

Figure 2 Definition of the sensitivity, specificity, positive and negative predictive value, and accuracy of the pulp tests.

describe the benefits of test usage (Fig. 2) (Ransohoff & Feinstein 1978). As the calculations are based on comparison of the test results and true disease status, identification of this true status becomes an important part of the evaluation of the status of the pulp (Hyman & Cohen 1984, Petersson *et al.* 1999).

When a diagnostic test can be used as a gold standard, determining the accuracy rates of other tests can be determined (Ransohoff & Feinstein 1978, Hyman & Cohen 1984, Iqbal *et al.* 2007). Unfortunately, when diagnosing pulp status, a standard is not available to determine the accuracy of other tests as there is no consistently reported relationship between clinical symptoms and histopathological findings (Seltzer *et al.* 1963a,b, Garfunkel *et al.* 1973, Dummer *et al.* 1980) and patients experiencing identical clinical symptoms may exhibit different histological states (Iqbal *et al.* 2007).

Sensitivity denotes the ability of a test to detect disease in patients who actually have the disease, for example, a test with a sensitivity of 0.60 has a 60% chance of returning positive results when teeth with pulp disease are tested. In contrast, specificity is the ability of a test to detect the absence of disease. Hence, a test with specificity of 0.80 has an 80% chance of returning negative results when performed on teeth without disease. The specificity and sensitivity of most tests are inversely related. As the test is calibrated to detect more disease (i.e. sensitivity is increased), it returns a positive value in more disease-free persons (i.e. specificity is decreased) (Lilienfeld & Lilienfeld 1980, Hyman & Cohen 1984).

Although sensitivity and specificity describe test performance in relation to patients with known disease states, the actual interest is in evaluating test responses of patients with unknown disease states. This is measured by predictive values. Positive predictive value (PPV) is the probability that a positive test result actually represents a disease-positive tooth, whereas negative predictive value is the probability that a tooth with a negative test result is actually free from disease. PPV is more responsive to changes in specificity than in sensitivity, whilst the reverse is true for NPV (Williams 1982, Hyman & Cohen 1984).

A few studies on the accuracy of pulp sensibility tests were found in the literature (Fuss *et al.* 1986, Peters *et al.* 1994, Evans *et al.* 1999, Petersson *et al.* 1999, Gopikrishna *et al.* 2007) (Table 2). However, whereas sensitivity and specificity are independent of disease prevalence in the population, PPV is directly related to the prevalence and NPV is inversely related, so the predictive values cannot be directly compared in studies with different disease prevalence (Hyman & Cohen 1984).

It should be emphasized that EPTs and thermal tests are simple non-invasive tests, but they are not completely reliable. Heat has a relatively high sensibility but is the least accurate overall of the three common pulp tests owing to its low specificity (Petersson *et al.* 1999), whereas the cold test is more accurate than the EPT (Moody *et al.* 1989, Peters *et al.* 1994). Some studies have indicated that if adult teeth with no history of trauma do not respond to both EPTs and cold tests, then there is a high probability that the tooth has a necrotic pulp or it is pulpless (Seltzer *et al.* 1963a, Peters *et al.* 1994).

Thermal tests

The most common tests for assessing the status of the pulp are thermal pulp sensibility tests. Stimulation of the pulp with thermal tests is one of the oldest methods to evaluate health of the pulp and its ability to respond to external stimulation (Jack 1899). These tests have often been called 'vitality tests', but this term is inappropriate because these tests are unable to determine or demonstrate whether a tooth has a viable blood supply (Jafarzadeh *et al.* 2008, Jafarzadeh 2009, Jafarzadeh & Rosenberg 2009).

Two types of thermal tests are available, cold and hot stimuli; although these tests may not be considered as sophisticated as an EPT, they are often more reliable

Table 2 The accuracy of pulp tests

Authors/year	Tested teeth	Kinds of tests	Sensitivity	Specificity	Positive predictive value	Negative predictive value	Accuracy
Fuss *et al.* 1986	Premolars	EPT	Not stated	0.90	Not stated	Not stated	Not stated
		CO_2 snow		0.97			
		DDM		0.99			
		Ethyl chloride		0.49			
		Ice stick		0.33			
Peters *et al.* 1994	Complete dentition	CO_2 snow	0.94	Not stated	Not stated	Not stated	Not stated
		EPT	0.66				
Petersson *et al.* 1999	Various teeth	Ethyl chloride	0.83	0.93	0.89	0.90	0.86
		Hot gutta-percha	0.86	0.41	0.48	0.83	0.71
		EPT	0.72	0.93	0.88	0.84	0.81
Evans *et al.* 1999	Anterior teeth	Ethyl chloride	0.92	0.89	Not stated	Not stated	Not stated
		EPT	0.87	0.96			
Gopikrishna *et al.* 2007	Single-rooted incisors, canines, and premolars	EPT	0.71	0.92	0.91	0.74	0.81
		TFE	0.81	0.92	0.92	0.81	0.86

EPT, Electric pulp tester; DDM, Dichlorodifluoromethane spray; TFE, Tetrafluoroethane spray.

(Weine 1996). However, neither cold nor heat is totally reliable in all cases (Rowe & Pitt Ford 1990, Weine 1996). Each method of pulp testing has its place and they are often complementary. A major advantage of thermal tests over EPTs is that the equipment required is usually inexpensive and easy to use (Rowe & Pitt Ford 1990, Weine 1996), especially if the patient is complaining of thermal sensitivity because the tests can reproduce the patient's pain.

It is recognized clinically that thermal sensitivity is a sign of pulp inflammation; thus, the use of thermal sensibility tests is a standard means of assessing the state of the pulp (Rickoff *et al.* 1988). The presence of thermal sensitivity indicates the development of pulp disease, and the symptoms typically follow a consistent scenario. As a rule, cold sensitivity is apparent initially, whilst continuing pulp deterioration leads to heat sensitivity, whereas cold sensitivity disappears. Eventually, cold stimuli might relieve the heat-induced pain (Sommer *et al.* 1962, Morse 1974). The diseased pulp also usually demonstrates changes in response to electrical stimulus (Udoye *et al.* 2010), so a full diagnostic procedure will most likely utilize both electrical and thermal testing (Selden 2000).

Selection of a cold test or a heat test should be based on the patient's chief complaint. If the patient does not report any history of thermal pain, then, usually for ease and reliability, a cold test is selected (Ruddle 2002a). However, it has been claimed that thermal stimuli are of value only in teeth that are sensitive to temperature changes (Degering 1962), but the temperature and duration of thermal tests are not well controlled, so thermal tests are somewhat variable, with a degree of subjectivity in distinguishing a normal from an abnormal response (Linsuwanont *et al.* 2008).

Thermal pulp tests rely on fluid flow through the dentinal tubules (Trope & Debelian 2005). When cold or heat is placed on a tooth surface, the fluid movement in these tubules will result in irritation of the peripheral tissues, including the A-δ fibres, which results in a sharp pain (Cohen & Hargreaves 2006). If the pulp is severely inflamed, it is also likely that the expansion from heat stimulation, or possibly the contraction from cold stimulation, of the pulp tissue might induce stimulation of the centrally placed C fibres (Trope & Debelian 2005).

Damage to the soft and hard tissues of the tooth

It has been reported that cold tests do not injure the pulp (Ingram & Peters 1983, Rickoff *et al.* 1988), whereas heat tests have a greater potential to cause injury (Cohen & Hargreaves 2006). However, if tests are used correctly, injuries are rare (Cohen & Hargreaves 2006).

Some studies have shown that cold tests can cause pulp degeneration if tissue freezing occurs (Langeland *et al.* 1969, Dowden *et al.* 1983). However, freezing has been shown to result only when a cold probe maintained a temperature lower than −10 °C for 5–20 min (Frank *et al.* 1972). The mechanism of this injury might involve intracellular ice crystal formation coupled with ischaemic necrosis resulting from vascular injuries (Frank *et al.* 1972, Dowden *et al.* 1983). Langeland *et al.* (1969) concluded that an applied temperature of −22 °C, which lowered the temperature of the pulp to 11 °C, caused no damage to the pulp but that an application of an extreme cold stimulus of −160 °C for 3 min caused extensive pulp damage. Dowden *et al.* (1983) reported that when temperatures below −80 °C are applied to teeth for 1, 2, or 3 min, the temperature of the pulp was lowered (ranged from 0 to −30 °C) and an increasing degree of pulp damage occurred, but all of the pulps remained alive and able to respond to thermal tests. The response of the pulp was predictable and characterized by a distinct layer of coronal secondary dentine with odontoblast destruction, cellular inclusions, and microvascular injuries. The pulp within the root remained essentially healthy and without inflammation, but some periodontal and root surface damage was observed.

Barker *et al.* (1972) examined teeth before and after application of a cold stimulus of −196 °C for two periods of 5 min each. They saw no changes in the surface status of the crown, but the extreme temperature changes created new cracks in the teeth. Moreover, some other studies with the aid of permeating dye and standardized fluorescence UV-photography have demonstrated that dry ice and refrigerant sprays may create new fissures in the enamel (Lutz *et al.* 1974, Bachmann & Lutz 1976).

Some studies reported that dry ice applied to a tooth did not jeopardize pulp health (Schiller 1937, Ingram & Peters 1983, Rickoff *et al.* 1988). They revealed structurally intact pulp tissue exhibiting no evidence of injury. However, Dowden *et al.* (1983) showed that minor pulp injury occurred but the tissue recovered within 47–63 days.

Some have indicated that no new cracks or fissures could be seen after application of dry ice. This proved true even when used for significantly longer periods of time than that normally used clinically (2 min vs. <15 s). Clinically, most teeth respond to the cold test in <5 s (Ingram & Peters 1983, Peters *et al.* 1983, 1986). If a tooth is going to respond, it almost always occurs within this time (Ingram & Peters 1983, Peters *et al.* 1983). These findings are in contrast with several other studies, which determined that dry ice created fissures/cracks (Lutz *et al.* 1974, Bachmann & Lutz 1976). Also, it might cause surface pitting of porcelain when applied for as little as 5.4 s (Krell *et al.* 1985). Some delay in response of the patient to this test might be considered as normal, and this might be explained by a delayed cold transfer process (Linsuwanont *et al.* 2008).

This method must be used with caution on teeth forming part of a bridge if the bridge includes metal retainers. A cold stimulus applied to a tooth whose pulp may itself be necrotic may be felt by an adjacent tooth because the coldness is conducted through the metal part of the bridge (Ehrmann 1977).

Some clinicians worry that a piece of dry ice that falls inadvertently into the mouth could have a deleterious effect on the mucosa with which it comes into contact. However, it is fortunate that this is not the case because when CO_2 falls into the mouth it is surrounded by an insulating layer of gaseous CO_2, which does not harm the mucosa. This is known as 'film boiling' or the 'Leidenfrost phenomenon' (Fig. 3) (Ehrmann 1977). In contrast to this, some authors believe that owing to the extremely cold temperature, burns of the mucosa it contacts can occur (Cohen & Hargreaves 2006), but these claims have not been substantiated.

Cold tests

Records, including the Edwin Smith Surgical Papyrus, have referred to the use of cold stimuli as a form of pulp testing since 2500 BC (Rand *et al.* 1968). Since 1938, experiments in hypothermia have shown that cold temperatures cause minimal irreversible tissue effects unless crystal formation occurs (Rand *et al.* 1968). Frank *et al.* (1972) have confirmed this claim in respect to pulp tissues.

It has been stated that cold tests, in general, are more accurate methods of testing pulps than heat tests (Ehrmann 1977, Shabahang 2005). However, a cold test to determine the state of the pulp (e.g. pulp necrosis versus a healthy pulp) is not always reliable because teeth with calcified pulp spaces might have normal and healthy pulps but the cold stimuli might not be able to excite the nerve endings owing to the insulating effect of the thicker layer of dentine, which

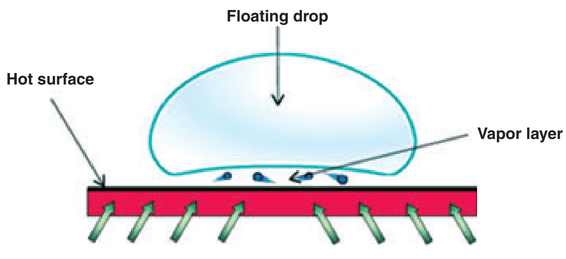

Figure 3 Leidenfrost phenomenon.

is a result of secondary and reactionary dentine formation (Ehrmann 1977, Ingle *et al.* 2008). Calcification of the pulp space can usually be identified by radiographic examination, and this highlights the essential need to always and only interpret pulp test results in conjunction with viewing a periapical radiograph. Cold tests can also be used to differentiate between reversible and irreversible pulpitis (Cohen & Hargreaves 2006). In general, the response to a cold stimulus is measured as a positive or negative reaction (Ehrmann 1977), but the quality of the response is also important, particularly whether it reproduces the pain reported by the patient. Typically, if the pulp is inflamed, the patient will report short, sharp pain that might disappear rapidly once the stimulus is removed or it might become a dull ache that lingers after the stimulus is removed. When the pain disappears rapidly, this usually indicates reversible pulpitis, whereas the dull lingering ache indicates irreversible pulpitis (Cohen & Hargreaves 2006).

Cold tests are presumed to be more reliable than EPTs in teeth with incomplete root formation. As thermal tests are not 100% accurate, an EPT is especially beneficial for confirming a questionable diagnosis (Shabahang 2005). However, cold tests should be used in conjunction with the EPT, so the results from one test can verify the findings of the other test, and radiographs must also be viewed.

The A-δ fibres are neurons that are initially stimulated during cold testing. At 22 °C, A-δ transmission is abolished, whereas C fibre sensitivity remains (Douglas & Malcolm 1955). For dentinal pain, the PDJ must cool to 29 °C (Naylor 1964, Pantera *et al.* 1993). If neurons are directly stimulated by temperature changes, it is possible to cause anaesthesia. However, the temperature needed for anaesthesia is much lower than that needed to induce pain (Naylor 1964). Clinically, a cold stimulus is removed when the patient feels the sensation, so it is unlikely that the PDJ temperature would decrease to the level needed for anaesthesia (Naylor 1964, Pantera *et al.* 1993). Several methods such as ice sticks, refrigerant sprays, carbon dioxide snow (CO_2), ethyl chloride, and cold water baths are available, with the major difference between them being the temperature produced by each test (Pitt Ford & Patel 2004).

Ice sticks

Ice sticks have been used as a cold test. The ice produces a temperature of 0 °C, but it is not considered accurate, especially in adult teeth, posterior teeth, and in teeth with severe deposition of secondary or reparative dentine (Ehrmann 1977, Augsburger & Peters 1981). Also, the use of ice appears to be of limited value when testing teeth under crowns and splints (Fulling & Andreasen 1976b).

Ice sticks can be formed by freezing water in the plastic covers of hypodermic needles or in used local anaesthetic cartridges after sterilization. The ice stick should be placed in gauze to prevent warmth from the operator's fingers from prematurely melting the ice (Ruddle 2002a). It is placed towards the cervical (Ruddle 2002a) or middle (Cohen & Hargreaves 2006) third of the buccal or lingual aspect of the crown of the tooth, or on any exposed metal surface and quickly moved back and forth (Fig. 4) (Ruddle 2002a). The ice stick should be kept in contact with the tooth for 5 s or until the patient begins to feel pain (Cohen & Hargreaves 2006). Testing should begin with the most posterior tooth and then advance towards the anterior teeth. This prevents melting ice water from dripping in a posterior direction and possibly touching a tooth that has not yet been tested but that could give a false response. A cotton pellet should be placed just distal to the tooth being tested to prevent any cold water from contacting the posterior teeth (Ruddle 2002a). The melting ice might also stimulate nerves within the surrounding gingiva of the tooth being tested or that of adjacent or nearby teeth, which can result in false responses that may lead to an incorrect diagnosis.

It has been indicated that the application of an ice stick for a period of 5 s is a reliable and valid method (Dachi *et al.* 1967), Under these situations, the error in predicting which teeth will be bothersome to the patient whilst eating cold food is reduced by 20–50%, depending upon which tooth is involved (Dachi *et al.* 1967), A major disadvantage of the ice stick test is that it is simply not cold enough and, hence, CO_2 dry ice or refrigerant sprays might be better choices (Dachi *et al.* 1967, Ehrmann 1977). A recent study showed that ice can stimulate the pulp less effectively than other cold tests (Linsuwanont *et al.* 2008).

Refrigerant sprays

A common method for cold testing is to use a refrigerant spray (Ingle *et al.* 2008). It is probably the most convenient and easiest to use and ranks just behind CO_2 dry ice for overall efficacy and accuracy (White & Cooley 1977, Ingle *et al.* 2008). It can provide reliable and reproducible results (White & Cooley 1977). Different refrigerant sprays are available,

Figure 4 Application of ice sticks for cold testing.

and they are based on dichlorodifluoromethane (DDM), tetrafluoroethane (TFE), or a propane–butane mixture (PBM). There are also sprays used to clean and test electronic circuits, which have the same composition as those used for pulp tests (Ingle *et al.* 2008, de Morais *et al.* 2008). The temperature decrease offered by such products varies according to their composition and ranges from −20 to −50 °C, according to the manufacturers (de Morais *et al.* 2008).

DDM (R-12), usually sold under the brand name Freon-12, is a chlorofluorocarbon halomethane, which has been shown to be an effective and uncomplicated agent for cold testing of teeth (http://en.wikipedia.org/wiki/Dichlorodifluoromethane) (Accessed November 4, 2007). It is commercially packaged for dental use as a compressed spray (Endo-Ice) (−50 °C) (Coltène/Whaledent, Switzerland) (Fig. 5a) (Augsburger & Peters 1981, Fuss *et al.* 1986). The production of DDM was prohibited by the Clean Air Act in the United States in January 1996, because of environmental concerns regarding its effect on the ozone layer of the atmosphere. Moreover, it might act as an irritant if inhaled by the patients, nurses, or the dentists. However, some researchers feel that the amount used to test pulps might not be of any real significance with respect to these potential hazards (Cohen & Hargreaves 2006), but others believe that DDM can create new fissures or cracks in enamel (Bachmann & Lutz 1976).

White & Cooley (1977) showed that DDM can produce a more rapid thermal change than either an ice stick or a cold water bath. Fuss *et al.* (1986) also showed that DDM and CO_2 dry ice produced a greater decrease in temperature than either an ice stick or ethyl chloride. DDM produced the greatest reduction in intrapulpal temperature when applied by a saturated cotton pellet rather than via a cotton tip applicator (Jones 1999).

DDM was less efficient than CO_2 dry ice when testing multiple teeth (Augsburger & Peters 1981). However, one study showed that at least three teeth could be tested with DDM before having to respray the cotton pellets (Fuss *et al.* 1986).

DDM has been replaced by the manufacturer with 1,1,1,2-tetrafluoroethane (TFE) because of the above-mentioned concerns. TFE is commercially available as Green Endo-Ice (−26.2 °C) (Coltène/Whaledent) (Fig. 5b) and has also been chemically called R-134a, Freon 134a, Genetron 134a, or HFC-134a. It is a haloalkane refrigerant without ozone-depletion potential and has thermodynamic characteristics similar to DDM (http://en.wikipedia.org/wiki/Dichlorodifluoromethane) (Accessed November 4, 2007). It is easy to use with rapid results (Ingle *et al.* 2008). The material is sprayed onto a cotton pellet which is then applied to the middle third of the facial/labial surface of the crown. It should be kept in contact with the surface for 5 s or until the patient begins to feel pain (Cohen & Hargreaves 2006).

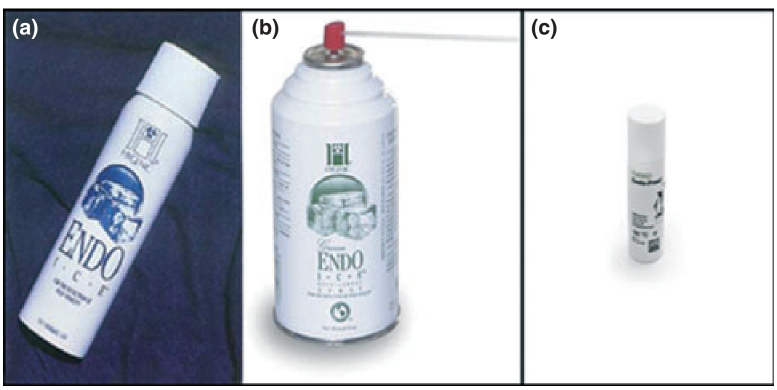

Figure 5 Endo-Ice for cold testing (Reproduced with permission from Johnson WT (2002) *Color Atlas of Endodontics*. Philadelphia: W.B. Saunders) (a), Green Endo-Ice for cold testing (Courtesy of http://www.coltenewhaledent.biz) (b), and Endo-Frost for cold testing (Courtesy of http://www.coltenewhaledent.biz) (c).

Jones *et al.* (2002) concluded that TFE and CO_2 dry ice were equivalent in producing a pulp response regardless of the tooth type and the presence/absence of restorations, but the response from TFE was faster.

Miller *et al.* (2004) reported that in intact teeth and teeth restored with porcelain-fused-to-metal (PFM) crowns or all-ceramic restorations, TFE produced a more rapid and effective initial temperature reduction than CO_2 dry ice. Application of TFE on a saturated cotton pellet was the most effective technique for producing a temperature reduction in these cases.

PBM, commercially available as Endo-Frost (−50 °C) (Coltène/Whaledent) (Fig. 5c), usually contains 30–50% propane, 30–50% butane, and 10–20% isobutane. It is a nontoxic cold spray, which is recommended for freezing cotton pellets and small cotton rolls. A recent study showed that PBM and TFE induced lower temperatures than dichlorofluoroethane-containing sprays when measured immediately after application on a cotton swab. However, temperatures inside the pulp chamber had similar decreases, no matter which spray was used (de Morais *et al.* 2008).

Carbon dioxide snow (dry ice)

Carbon dioxide (CO_2) is a chemical compound composed of two oxygen atoms bonded to a single carbon atom. It is a gas, but in its solid state, it is often called 'dry ice', and it is commonly used as a versatile cooling agent (http://en.wikipedia.org/wiki/Carbon_dioxide) (Accessed November 4, 2007). The low temperature and direct sublimation to a gas at atmospheric pressure make it an effective coolant, because it is colder than ice and leaves no moisture as it changes state. Fischer (1972) regarded it as the only satisfactory method of pulp testing.

In 1835, the French chemist Charles Thilorier (1835) published the first account of the use of dry ice. Upon opening the lid of a large cylinder containing liquid CO_2, he noted much of the CO_2 rapidly evaporated leaving solid dry ice in its container. Dry ice was first introduced into dentistry by Back (1936) whose apparatus was modified by Obwegeser & Steinhauser (1963) to collect the dry ice in a thin Plexiglas tube that could then be used in a pencil-like form.

The temperature of dry ice has been reported to be −78 °C (Bachmann & Lutz 1976); however, applying it as used clinically directly to a temperature probe produced a less cold reading of −56 °C (Augsburger & Peters 1981), which is still effective for decreasing pulp temperature and to elicit a painful response (Augsburger & Peters 1981, Fuss *et al.* 1986). The sensory response to the application of dry ice is rapid, usually being <2 s (Fuss *et al.* 1986).

Mechanism

Application of dry ice for 5 s can reduce the temperature at the PDJ to <2 °C (Rickoff *et al.* 1988). This further supports the hydrodynamic theory concerning the sensory response of the teeth to thermal stimulation. According to this theory, application of heat or cold to a tooth results in rapid movement of dentinal fluid that mechanically stimulates the sensory terminals located in the region of the PDJ (Brännström & Johnson 1970). However, a recent study reported that thermal contraction and expansion of dentinal fluid might not be the complete explanation for dentinal fluid movement in intact teeth. Enamel might serve not only as a temperature transfer medium, but it might also expand or contract when subjected to thermal stimulation (Linsuwanont *et al.* 2007).

Technique

For pulp sensibility testing, CO_2 is released into a special tube inside the Plexiglas container in which it forms the 'snow' (Figs 6 and 7). It is compacted with a plugger and the 'pencil' or 'stick' of dry ice is expressed slightly from the tube and then applied immediately to the middle third of the facial surface of the crown of the tooth and kept in contact for 2–5 s or until the patient feels pain (Fig. 8) (Cohen & Hargreaves 2006).

Advantages

Clinically, testing with CO_2 snow is accurate, reliable, consistent, fast, and uncomplicated (Ehrmann 1977). A complete dentition can be tested in 1–2 min without any requirement for isolation of the teeth (Obwegeser & Steinhauser 1963, Ehrmann 1977, Augsburger & Peters 1981). It is preferred for pulp testing because it does not affect the adjacent teeth and because it gives an intense, reproducible response (Augsburger & Peters 1981, Ingram & Peters 1983, Peters *et al.* 1983, Fuss *et al.* 1986). It has been shown that the accuracy of dry ice is greater than that of EPTs (Back 1936, Obwegeser & Steinhauser 1963, Fulling & Andreasen 1976a). It is also effective for testing teeth with full coverage crowns (Ehrmann 1977, Augsburger & Peters 1981, Grossman *et al.* 1988, Cohen & Hargreaves 2006). PFM crowns can be tested by applying the dry ice to the metal part of the crown (Ehrmann 1977). Although Riedel & Fichter (1966) found CO_2 to be less effective when

Figure 6 Dry ice maker.

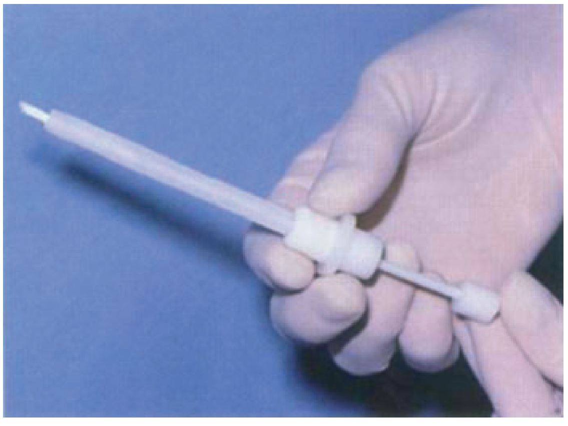

Figure 7 Dry ice stick with holder and plugger (Reproduced with permission from Johnson WT (2002) *Color Atlas of Endodontics*. Philadelphia: W.B. Saunders).

testing through acrylic or porcelain restorations, it can still be used when these restorations are present as long as the clinician recognizes the potentially

Figure 8 Application of dry ice.

different response to be expected. Notwithstanding this, CO_2 is considered to be more reliable than other forms of pulp sensibility tests when these types of restorations are present (Ingle *et al.* 2008).

When testing teeth after trauma for their response to cold, the CO_2 snow test is the most effective test (Fulling & Andreasen 1976b, Ehrmann 1977, Ingle *et al.* 2008). It gives more accurate responses than ice because the intense cold penetrates the tooth and any covering splints or restorations and will reach the deeper areas of the tooth/pulp, so it can be used on individual teeth under splinted abutments (Fulling & Andreasen 1976b, Ehrmann 1977). In the case of splints and temporary crowns, dry ice can also provide reliable responses, unless applied on the incisal edge (Fulling & Andreasen 1976b).

Other advantages of CO_2 snow include no false positive readings in cases of pulp necrosis and in cases of early pulpitis where there is a sustained or lingering painful response, which is quite different from that exhibited by normal pulps (Fulling & Andreasen 1976b, Ehrmann 1977, Ingle *et al.* 2008). It also may be used to test teeth undergoing orthodontic treatment using fixed appliances where an EPT is not possible (Fulling & Andreasen 1976b, Ehrmann 1977) because the metallic wires, brackets, and bands might result in conduction of the electric current to another tooth other than the one being tested.

Disadvantages

One disadvantage of the dry ice test is that it is not effective with calcified pulps or in elderly patients where there has been considerable secondary dentine formation (Ehrmann 1977). Also, the apparatus is more expensive to purchase than ethyl chloride or ice sticks (Weine 1996).

Comparative studies

Fuss *et al.* (1986) concluded that dry ice and DDM were more dependable than ethyl chloride and ice in producing a positive response in premolars and that the rate of temperature decrease was greater for dry ice and DDM than for either ethyl chloride or ice. Their findings are in agreement with those of Fulling & Andreasen (1976a) who found that 100% of the incisors tested responded positively to dry ice, whereas only 70% responded to the ice stick test. The lower incidence of positive response in the study of Fuss *et al.* (1986), compared with the study of Fulling & Andreasen (1976a), may be attributable to the total thickness of enamel and dentine being greater in premolars than in incisors.

According to Fuss *et al.* (1986), the reaction to CO_2 snow and DDM was rapid (i.e. only 1–2 s). Characteristically, DDM evoked a sharp pain almost immediately, whereas it usually took CO_2 snow somewhat longer to elicit a response. This difference may be owing to the cotton pellets saturated with DDM covering a greater surface area of enamel than that covered by the CO_2 snow 'pencil'. It has been hypothesized that that CO_2 snow makes less contact with the tooth surface (Ingle *et al.* 2008).

When comparing CO_2 snow and DDM, Fuss *et al.* (1986) found no difference between the young and adult groups. This is in accordance with the results of other studies (Fulling & Andreasen 1976a, Ehrmann 1977) where CO_2 snow was reported to be more reliable than an EPT in determining the pulp status of immature teeth. Therefore, it seems that the statement by Mumford (1967) that the EPT is more reliable than thermal tests is correct with regard to tests using ice and ethyl chloride but not to those utilizing CO_2 snow and DDM.

Linsuwanont *et al.* (2008) indicated that CO_2 snow and refrigerant sprays provided more consistent stimuli when compared with cold water and ice, so these tests might be considered as the stimulus/test of choice.

Ethyl chloride

Ethyl chloride (chloroethane), with a temperature of −12.3 °C, is a colourless, flammable gas or refrigerated liquid with a faintly sweet odour, available as a compressed spray and commonly used in medicine as a skin refrigerant (Fig. 9) (Augsburger & Peters 1981). It is a prescription drug in the United States of America, where it is supplied as a liquid in a spray bottle propelled by its own vapour pressure. It acts as a mild topical anaesthetic when sprayed on skin, such as when removing splinters in a clinical setting. The heat absorbed by the boiling liquid on tissues produces a rapid and deep chill, but as the boiling point is well above freezing, it usually presents no danger of frostbite (http://en.wikipedia.org/wiki/Ethyl_chloride) (Accessed November 4, 2007).

Figure 9 Ethyl chloride spray (Courtesy of Gebauer Company, Cleveland, Ohio, USA).

Like other chlorinated hydrocarbons, ethyl chloride is a central nervous system depressant, albeit a less potent one than many other similar compounds. Breathing its vapours at <1% concentration in air usually produces no symptoms; however, in higher concentrations, victims usually exhibit symptoms similar to those of alcohol intoxication. Breathing its vapours at a concentration of ≥15% is often fatal (http://en.wikipedia.org/wiki/Ethyl_chloride) (Accessed November 4, 2007).

Moody *et al.* (1989), using ethyl chloride and monopolar and bipolar EPTs, reported that the best prediction of the pulp status was with the ethyl chloride. Also, Mumford (1964) showed that the results using ethyl chloride were better than hot Gutta-percha for both consistency of the response and the lower number of teeth that did not respond. However, he showed that reproducible results could not be obtained with ethyl chloride.

The use of ethyl chloride in pulp testing is no longer recommended because it has been found to be less effective than dry ice or DDM (Augsburger & Peters 1981). Although it provides a good source for lowering tooth temperature, the temperature obtained is normally not sufficient enough for pulp stimulation in teeth with very extensive restorations or full crown coverage restorations (Cohen & Hargreaves 2006).

Cold water bath

For cold testing, a tooth or a group of teeth can be isolated with a rubber dam, and iced water can be syringed onto each tooth (Fig. 10). This cold water bath can be an effective method of pulp testing because it is the only technique that immerses the tooth in chilled water. Although more time-consuming, this kind of cold testing is effective at simultaneously bathing the entire crown of the tooth, which is why this is a reliable method for testing thermal sensitivity, and stimulating an inflamed pulp (Cohen & Hargreaves 2006). It is clearly superior in its accuracy compared to ice sticks. Even when the tooth has a full crown restoration, sufficient contact between the tooth and the cold water is made to allow cooling of the pulp. In addition, it prevents damage to the tooth caused by excessive temperature changes. This method is effective for evaluating teeth with full coverage restorations, either metal or porcelain. The sensory response of teeth is refractory to repeated thermal stimulation. Another benefit of this method is that it needs no armamentarium except for rubber dam (Ruddle 2002a).

Heat tests

When a cold stimulus is applied to a tooth with a normal pulp, it creates a response quickly but the stimulus does not last long. If the pulp has only a mild and local inflammation, the patient feels a sharper reaction to it (Ingle *et al.* 2008). Heat application in these cases produces a similar sensation, but more slowly. Heat causes the fluid to expand, stimulating the A-δ fibres; however, when heat is applied to an inflamed pulp, the pressure increase can stimulate the C fibres and produce a long lasting pain (Grossman 1981). Because cold might relieve the pain in irreversibly inflamed pulps and because the response to cold is by the A-δ fibres and not the C fibres, heat testing might give better results for true diagnosis (Cohen & Hargreaves 2006).

Figure 10 Cold water bath (Reproduced with permission from Johnson WT (2002) *Color Atlas of Endodontics*. Philadelphia: W.B. Saunders).

Pain precipitated by heat usually shows an acutely inflamed or a partially necrotic pulp (Cohen & Hargreaves 2006). Necrotic tissue frequently harbours bacteria that can produce gasses that potentially expand against tissue encased inside the unyielding dentinal walls. This may cause sensory nerve fibres to transmit pain. Hence, in the case of a small pulp abscess, heat can increase the symptoms, and cold can relieve the pain (Seltzer *et al.* 1963a). It has also been proposed that the heat might cause sufficient thermal expansion to push infected material from the pulp space into the periapical tissues (Mumford 1964, Mumford & Jedynakiewicz 1988).

Heat tests have many methods of delivery, such as heated Gutta-percha, warmed instruments, electrical heat sources, frictional heat, and hot water baths. However, heat tests are infrequently performed because of the difficulties associated with tooth isolation and obtaining a consistent heat stimulus (Ingle & Bakland 2002). As studies indicate that the diagnostic accuracy of heat tests is low, heat should not be used as a single test of the pulp status (Petersson *et al.* 1999, Bergenholtz *et al.* 2003). It has been shown that thermal stimuli are highly variable in terms of the rate of thermal transfer through the tooth, the stimulus temperature, and the extent of temperature change within the tooth structure (Linsuwanont *et al.* 2008).

Heated Gutta-percha (Grossman's method)

Application of warmed sticks of gutta-percha (120–140 °C) is one method of performing a heat test. To use this technique, the tooth surfaces and the surrounding area should firstly be dried with cotton rolls (Rosenberg 1991). The teeth to be tested should be protected with a light coating of petroleum jelly to prevent the heated gutta-percha from sticking to the tooth surface (Cohen & Hargreaves 2006). The gutta-percha stick is then warmed over a flame until it becomes soft and begins to glisten, but not so that it slumps and becomes too limp for application (Grossman 1981, Tronstad 2003). Mumford (1964) found that if the gutta-percha stick was held in the flame for 2 s, only 14% of the anterior teeth tested gave a positive response, whereas Trowbridge *et al.* (1980) found that all teeth gave a positive response, generally within <2 s.

One disadvantage of heating gutta-percha over a flame is the difficulty in controlling the temperature obtained (Rickoff *et al.* 1988). As its temperature may be as high as 76 °C when applied to the tooth surface (Trowbridge *et al.* 1980), some concerns have been expressed that such high temperatures might damage a healthy pulp. However, one study indicated that it does not jeopardize the pulp health as the 5-s application only increased the temperature at the PDJ by <2 °C (Rickoff *et al.* 1988). Special care should be taken not to damage the pulp tissue with an excessive or prolonged heat stimulus that could result in pulp damage (Mumford 1964), because it will result in biphasic stimulation, initially of the A-δ fibres and then subsequently the C fibres, resulting in a lingering pain. Therefore, heat tests should be applied to the tooth surface for no more than 5 s. However, and in contrast, inadequate heating of the gutta-percha stick might result in a weak stimulus, which might not elicit a response from the pulp (Närhi 1985).

Application to the middle third of the facial/labial surface of the crown usually results in a response within <2 s (Cohen & Hargreaves 2006) (Fig. 11). If the patient complains that the heat test produces a severe ache, the clinician must be ready to apply a cold stimulus immediately to the tooth to relieve the pain (Ingle & Bakland 2002).

Reproducible results cannot be obtained by testing pulps with heated gutta-percha. Moreover, teeth that fail to respond to this test are mainly canines, and this is attributed to their greater bulk that permits only a small change in temperature for the amount of heat applied (Mumford 1964). The temperature at the site where excitation occurs (either in the dentine or in the pulp) depends not only on the amount of heat transferred from the gutta-percha but also on the amount of heat present in the gutta-percha to begin with and furthermore on the area of contact with the tooth. The latter in turn depends on the original diameter of the gutta-percha stick, its plasticity, and the force with which it is applied (Mumford 1964). In addition, the thickness, thermal conductivity, and thermal diffusivity of the enamel and dentine, and the presence and extent of caries or restorations may modify the final stimulus and response (Braden 1963, Mumford 1964, Mumford & Jedynakiewicz 1988).

Figure 11 Grossman's method.

A recent study showed that heated gutta-percha is a strong but less consistent stimulus in terms of both initial temperature and the temperature change during testing (Linsuwanont *et al.* 2008). Overall, the use of heated gutta-percha appears to be of limited value in sensibility testing of teeth under splints and temporary crowns (Fulling & Andreasen 1976b). It may also be difficult to use on posterior teeth because of the limited access (Ehrmann 1977).

Warmed hand instruments

A popular but not very reliable and relatively poorly assessed method for heat testing of the teeth is through using a heated dental hand instrument such as a ball burnisher. The instrument is heated over a flame and then applied close to the buccal surface of the crown without actually contacting the tooth, thus relying on the radiant heat produced from the heated instrument (Fig. 12). Because of the difficulty in controlling the temperature of the heated instrument and the potential safety problems associated with using heated instruments in the patient's mouth, this type of heat test is not generally recommended. In addition, it cannot be considered as being reliable or reproducible (Walton & Torabinejad 2002).

Electrical heat sources

There are several devices that might be used to apply a hot stimulus to teeth, including the Touch'N Heat (SybronEndo, Orange, CA, USA) or the System B devices (SybronEndo). Each of these devices has a handpiece designed to receive various inserts such as

Figure 12 Application of warmed hand instruments for heat testing.

Figure 13 Application of frictional heat for heat testing.

the Hot Pulp Test Tip. Regardless of the device chosen, the continuous heat mode is selected, and the intensity is set at the manufacturer's recommendation for performing the heat test on the surface of the tooth, provided it has been lubricated to prevent sticking and burning of the enamel. As an example, when using the System B device, the temperature is set at 150 °F. This test can be performed without damage to hard and soft tissues of the tooth (Ruddle 2002a, Ingle *et al.* 2008).

Frictional heat

Frictional heat can be generated using a rubber cup, such as those intended for prophylaxis, applied to the buccal aspect of a tooth without prophylactic paste and rotated within a dental handpiece to produce frictional heat (Fig. 13). This method is considered to be the best, easiest, and safest technique of performing a heat test (Walton & Torabinejad 2002), especially when testing a tooth with a gold crown (Weine 1996). Despite this, frictional heat tests are seldom used today (Cohen & Hargreaves 2006).

Hot water bath

The simplest method of testing for heat sensitivity is to bathe the tooth in hot water (Trope & Debelian 2005). This is performed by placing the patient in a supine position and applying rubber dam on the most posterior tooth in the quadrant using a single-tooth isolation technique. The tooth is then bathed in very hot water syringed onto it for 5 s or until the patient begins to feel pain. If the patient's chief complaint is pain associated with heat, then the temperature can be gradually increased if no response is obtained, rather than producing unnecessary pain by beginning with excessively hot liquid. If this test does not reproduce the patient's symptoms, the rubber dam is removed and then placed on the next tooth anterior to the first tooth tested and the hot water test is repeated using fresh hot water. This protocol is repeated on one tooth at a time, moving further anteriorly until the patient's presenting pain is replicated (Ruddle 2002b, Trope & Debelian 2005). This technique produces a greater thermal change than heated gutta-percha, a warmed hand instrument, or a rotating rubber cup (White & Cooley 1977) because the entire crown of the tooth is bathed with the hot water.

The advantage of this method is attributable to the hot water instantaneously bathing the entire clinical crown, which improves conductivity and more closely replicates the way heat naturally contacts the tooth during drinking of hot liquids (Ruddle 2002a). Also, because the hot water is contained within the rubber dam, the response is limited to the one tooth being tested (Grossman *et al.* 1988) although this will be dependent on the thickness of the rubber dam (i.e. thick or heavy body dam is more effective than thinner grades of dam) and on how well the tooth is isolated because any marginal gaps between the dam and the tooth may allow the hot water to diffuse through the gaps and then stimulate the adjacent tooth or gingivae. Heat testing by hot water bathing may be more effective in penetrating PFM crowns, and it may also prevent damage to the tooth caused by excessive temperature changes (Ingle *et al.* 2008).

The disadvantage of this test is the cooperation required to comfortably place a rubber dam clamp on one tooth at a time and the time required to perform this test on several teeth (Ruddle 2002a). Although this method is time-consuming, it is superior in its accuracy compared to other heat tests (Cohen & Hargreaves 2006, Ingle *et al.* 2008).

Important technical points about thermal pulp tests

Before initiating thermal tests, it is important to inform the patient of the nature of the test(s) and what is to be achieved. The patient must be aware of when the operator requires them to respond and how they can indicate their response; hand signals are an effective means of achieving this, but it is essential to establish a reliable report. The patient should be instructed to raise his/her hand when they first feel the sensation from the thermal stimulus in the tooth, to keep their hand up as long as this sensation lingers and to lower their hand when the sensation dissipates. In the event that the patient does not perceive any sensation in the tooth after 5–6 s, then the stimulus should be removed. Because some pulpally involved teeth may not be stimulated immediately by the thermal test, the operator should wait for several seconds after the stimulus is removed from the tooth to see whether any pain is elicited before placing the stimulus on the next tooth. Some teeth with irreversible pulpitis require repeated stimuli to reach the threshold that provokes pain (Mumford & Jedynakiewicz 1988, Trope & Debelian 2005, Cohen & Hargreaves 2006, Ingle *et al.* 2008). Also, it should be remembered that once a pulp is tested with cold, there is a refractory period of several minutes before a second cold or heat stimulation can be accurately conducted on that same tooth (Mumford & Jedynakiewicz 1988, Trope & Debelian 2005).

Thermal tests are considered to be more accurate when applied to the cervical aspect of a tooth and as close as possible to the gingival margin. This location represents the thinnest aspect of enamel or a restoration and the closest distance to the pulp chamber (Peters *et al.* 1994, Ruddle 2002a). However, some studies have used the middle third of the buccal/labial or palatal/lingual aspect of the crown for thermal testing (Cohen & Hargreaves 2006). In contrast, others believe that for anterior teeth, the cold stimulus should be placed on the incisal third, and for posterior teeth on the incisal aspect of the mesiobuccal cusp. These areas approximate the pulp horns, where the pulp innervation is most plentiful (Trope & Debelian 2005). It should be remembered that the size of the pulp chamber is the most important factor in determining the thermal response, with small chambers making stimulation of the pulp difficult (Reynolds 1966). Notwithstanding all these opinions, the most important consideration is whether the tooth responds to a test, and this might be dependent on the history of caries, restorations, cracks, calcifications, etc in the tooth. Hence, teeth should ideally be tested on several surfaces to gain as much information as possible about the state of the pulp.

Finally, several adjacent, opposing, and contralateral teeth should be tested before testing the tooth in question, so the 'normal' response for that particular patient can be determined. The response to a stimulus can vary considerably between patients, and this largely depends on the individual's perception of what constitutes pain, discomfort, or a normal feeling. The dentist should also use care not to bias a patient's response by indicating either a normal or suspect tooth is being tested (Rowe & Pitt Ford 1990).

Summary

Pulp tests include sensibility and vitality tests. Sensibility tests are the most commonly performed in clinical practice owing to their simplicity and low cost. It is essential that clinicians understand the limitations of these tests and their usefulness. They are important diagnostic aids; however, their results must be interpreted in conjunction with consideration of a detailed history, the symptoms, the clinical findings, and radiographic observations. A diagnosis of the state of the pulp can only be reached once all the information has been gathered and assessed. This clinical pulp diagnosis might not correspond to the histological state of the pulp tissues.

References

Altonen M, Haavikko K, Malmström M (1978) Evaluation of autotransplantations of completely developed maxillary canines. *International Journal of Oral Surgery* **7**, 434–41.

Andreasen JO, Andreasen FM (1994) *Textbook and Color Atlas of Traumatic Injuries to the Teeth*, 3rd edn. Copenhagen: Munksgaard.

Andreasen JO, Paulsen HU, Yu Z, Bayer T, Schwartz O (1990) A long-term study of 370 autotransplanted premolars. Part II. Tooth survival and pulp healing subsequent to transplantation. *European Journal of Orthodontics* **12**, 14–24.

Asfour MA, Millar BJ, Smith PB (1996) An assessment of the reliability of pulp testing deciduous teeth. *International Journal of Paediatric Dentistry* **6**, 163–6.

Augsburger RA, Peters DD (1981) In vitro effects of ice, skin refrigerant, and CO_2 snow on intrapulpal temperature. *Journal of Endodontics* **7**, 110–6.

Bachmann A, Lutz F (1976) Cracks in the dental enamel caused by sensitivity testing with CO2 snow and dichlorodifluoromethane–a comparative in vivo study. *Schweizerische Monatsschrift Fur Zahnheilkunde* **86**, 1042–59.

Back R (1936) Vitalitaetspruefung der zaehne mittels kohlensaeureschnee. *Praktischer Zahnarzt* **4**, 309.

Barker RE Jr, Rafoth RF, Ward RW (1972) Thermally induced stresses and rapid temperature changes in teeth. *Journal of Biomedical Materials Research* **6**, 305–25.

Baume LJ (1970) Diagnosis of diseases of the pulp. *Oral Surgery, Oral Medicine, and Oral Pathology* **29**, 102–16.

Bender IB (2000) Pulpal pain diagnosis – a review. *Journal of Endodontics* **26**, 175–9.

Bender IB, Seltzer S (1961) Roentgenographic and direct observation of experimental lesions in bone: I. *Journal of the American Dental Association* **62**, 152–60.

Bergenholtz G, Hørsted-Bindslev P, Reit C (2003) *Textbook of Endodontology*. Oxford: Blackwell Munksgaard.

Berman LH, Hartwell GR (2006) Diagnosis. In: Cohen S, Hargreaves KM, eds. *Pathways of the Pulp*, 9th edn. St. Louis: Mosby, pp. 16–20.

Bhaskar SN, Rappaport HM (1973) Dental vitality tests and pulp status. *Journal of the American Dental Association* **86**, 409–11.

Björn H (1946) Electrical excitation of teeth. *Swedish Dental Journal* **39**, 6–10.

Bolton R (1974) Autogenous transplantation and replantation of teeth: report on 60 treated patients. *British Journal of Oral Surgery* **12**, 147–65.

Braden M (1963) Heat conduction in teeth and efficiency of lining materials. *Journal of Dental Research* **42**, 1084.

Brännström M, Johnson G (1970) Movements of the dentine and pulp liquids on application of thermal stimuli. An in vitro study. *Acta Odontologica Scandinavica* **28**, 59–70.

Burnside RR, Sorenson FM, Buck DL (1974) Electric vitality testing in orthodontic patients. *Angle Orthodontics* **44**, 213–7.

Carnes PL, Cook B, Eleazer PD, Scheetz JP (1998) Change in pain threshold by meperidine, naproxen sodium, and acetaminophen as determined by electric pulp testing. *Anesthesia Progress* **45**, 139–42.

Certosimo AJ, Archer RD (1996) A clinical evaluation of the electric pulp tester as an indicator of local anesthesia. *Operative Dentistry* **21**, 25–30.

Chambers IG (1982) The role and methods of pulp testing in oral diagnosis: a review. *International Endodontic Journal* **15**, 1–15.

Clark HB Jr, Tam JC, Mitchell DF (1955) Transplantation of developing teeth. *Journal of Dental Research* **34**, 322–8.

Cohen S, Hargreaves KM (2006) *Pathways of the Pulp*, 9th edn. Louis: Mosby.

Cohen HP, Cha BY, Spångberg LS (1993) Endodontic anesthesia in mandibular molars: a clinical study. *Journal of Endodontics* **19**, 370–3.

Cooley RL, Robison SF (1980) Variables associated with electric pulp testing. *Oral Surgery, Oral Medicine, and Oral Pathology* **50**, 66–73.

Cooley RL, Stilley J, Lubow RM (1984) Evaluation of a digital pulp tester. *Oral Surgery, Oral Medicine, and Oral Pathology* **58**, 437–42.

Cvek M (1978) A clinical report on partial pulpotomy and capping with calcium hydroxide in permanent incisors with complicated crown fracture. *Journal of Endodontics* **4**, 232–7.

Dachi SF, Haley JV, Sanders JE (1967) Standardization of a test for dental sensitivity to cold. *Oral Surgery, Oral Medicine, and Oral Pathology* **24**, 687–92.

Degering CI (1962) Physiologic evaluation of dental-pulp testing methods. *Journal of Dental Research* **41**, 695–700.

Douglas WW, Malcolm JL (1955) The effect of localized cooling on conduction in cat nerves. *Journal of Physiology* **130**, 53–71.

Dowden WE, Emmings F, Langeland K (1983) The pulpal effect of freezing temperatures applied to monkey teeth. *Oral Surgery, Oral Medicine, and Oral Pathology* **55**, 408–18.

Dreven LJ, Reader A, Beck M, Meyers WJ, Weaver J (1987) An evaluation of an electric pulp tester as a measure of analgesia in human vital teeth. *Journal of Endodontics* **13**, 233–8.

Dummer PMH, Hicks R, Huws D (1980) Clinical signs and symptoms in pulp disease. *International Endodontic Journal* **13**, 27–35.

Ehrmann EH (1977) Pulp testers and pulp testing with particular reference to the use of dry ice. *Australian Dental Journal* **22**, 272–9.

Elfenbaum A (1968) The electric pulp vitality test. *Dental Digest* **74**, 168–71.

England MC, Pellis EG, Michanowicz AE (1974) Histopathologic study of the effect of pulpal disease upon nerve fibers of the human dental pulp. *Oral Surgery, Oral Medicine, and Oral Pathology* **38**, 783–90.

Evans D, Reid J, Strang R, Stirrups D (1999) A comparison of laser Doppler flowmetry with other methods of assessing the vitality of traumatised anterior teeth. *Endodontics and Dental Traumatology* **15**, 284–90.

Fischer CH (1972) *Endodontie*. Berlin: Die Quintessenz.

Frank U, Freundlich J, Tansy MF, Chaffee RB Jr, Weiss RC, Kendall FM (1972) Vascular and cellular responses of teeth after localized controlled cooling. *Cryobiology* **9**, 526–33.

Fulling HJ, Andreasen JO (1976a) Influence of maturation status and tooth type of permanent teeth upon electrometric and thermal pulp testing. *Scandinavian Journal of Dental Research* **84**, 286–90.

Fulling HJ, Andreasen JO (1976b) Influence of splints and temporary crowns upon electric and thermal pulp-testing procedures. *Scandinavian Journal of Dental Research* **84**, 291–6.

Fuss Z, Trowbridge H, Bender IB, Rickoff B, Sorin S (1986) Assessment of reliability of electrical and thermal pulp testing agents. *Journal of Endodontics* **12**, 301–5.

Garfunkel A, Sela J, Ulmansky M (1973) Dental pulp pathosis. Clinicopathologic correlations based on 109 cases. *Oral Surgery, Oral Medicine, and Oral Pathology* **35**, 110–7.

Gazelius B, Olgart L, Edwall B, Edwall L (1986) Non-invasive recording of blood flow in human dental pulp. *Endodontics and Dental Traumatology* **2**, 219–21.

Gopikrishna V, Tinagupta K, Kandaswamy D (2007) Comparison of electrical, thermal, and pulse oximetry methods for assessing pulp vitality in recently traumatized teeth. *Journal of Endodontics* **33**, 531–5.

Greenwood F, Horiuchi H, Matthews B (1972) Electrophysiological evidence on the types of nerve fibres excited by electrical stimulation of teeth with a pulp tester. *Archives of Oral Biology* **17**, 701–9.

Grossman LI (1981) *Endodontic Practice*, 10th edn. Philadelphia: Lea & Febiger.

Grossman LI, Oliet S, Del Rio CE (1988) *Endodontic Practice*, 11th edn. Philadelphia: Lea & Febiger.

Hall CJ, Freer TJ (1998) The effects of early orthodontic force application on pulp test responses. *Australian Dental Journal* **43**, 359–61.

Hardy P (1982) The autogenous transplantation of maxillary canines. *British Dental Journal* **153**, 183–6.

Hare GC (1969) Diagnostic value of vitality tests. *Journal of the Canadian Dental Association* **35**, 495.

Hargreaves KM, Goodis HE (2002) *Seltzer and Bender's Dental Pulp*, 3rd edn. Chicago: Quintessence Pub Co.

Harris WE (1971) Pseudoendodontic sinus tract: report of case. *Journal of the American Dental Association* **83**, 165–7.

Harris WE (1973) Endodontic pain referred across the midline: report of case. *Journal of the American Dental Association* **87**, 1240–3.

Hill CM (1986) The efficacy of transillumination in vitality tests. *International Endodontic Journal* **19**, 198–201.

Hsiao-Wu GW, Susarla SM, White RR (2007) Use of the cold test as a measure of pulpal anesthesia during endodontic therapy: a randomized, blinded, placebo-controlled clinical trial. *Journal of Endodontics* **33**, 406–10.

Hyman JJ, Cohen ME (1984) The predictive value of endodontic diagnostic tests. *Oral Surgery, Oral Medicine, and Oral Pathology* **58**, 343–6.

Ingle JI, Bakland LK (2002) *Endodontics*, 5th edn. London: BC Decker Inc.

Ingle JI, Heithersay GS, Hartwell GR *et al.* (2002) Endodontic diagnostic procedures. In: Ingle JI, Bakland LK, eds. *Endodontics*, 5th edn. London: BC Decker Inc, pp. 203–17.

Ingle JI, Bakland LK, Baumgartner JC (2008) *Endodontics*, 6th edn. Hamilton: BC Decker Inc.

Ingram TA, Peters DD (1983) Evaluation of the effects of carbon dioxide used as a pulpal test. Part 2. In vivo effect on canine enamel and pulpal tissues. *Journal of Endodontics* **9**, 296–303.

Iqbal M, Kim S, Yoon F (2007) An investigation into differential diagnosis of pulp and periapical pain: a PennEndo database study. *Journal of Endodontics* **33**, 548–51.

Jack L (1899) Observation of the relation of thermal irritation of the teeth to their treatment. *Dental Cosmos* **41**, 1–6.

Jafarzadeh H (2009) Laser Doppler flowmetry in endodontics: a review. *International Endodontic Journal* **42**, 476–90.

Jafarzadeh H, Rosenberg PA (2009) Pulse oximetry: review of a potential aid in endodontic diagnosis. *Journal of Endodontics* **35**, 329–33.

Jafarzadeh H, Udoye CI, Kinoshita J (2008) The application of tooth temperature measurement in endodontic diagnosis: A review. *Journal of Endodontics* **34**, 1435–40.

Jones DM (1999) Effect of the type carrier used on the results of dichlorodifluoromethane application to teeth. *Journal of Endodontics* **25**, 692–4.

Jones VR, Rivera EM, Walton RE (2002) Comparison of carbon dioxide versus refrigerant spray to determine pulpal responsiveness. *Journal of Endodontics* **28**, 531–3.

Kennedy DC, Kiely MC, Keating PJ (1987) Efficacy of electrical pulp testing. *Journal of Irish Dental Association* **33**, 41–6.

Klein H (1978) Pulp responses to an electric pulp stimulator in the developing permanent anterior dentition. *ASDC Journal of Dentistry for Children* **45**, 199–202.

Krell KV, Madison S, Jordan RD (1985) The effects of CO_2 ice on PFM restorations. *Journal of Endodontics* **11**, 146.

Langeland K, Tobon G, Eda S, Langeland LK (1969) The effect of lowered temperatures on dental tissues. *Journal of Connecticut State Dental Association* **43**, 10–26.

Lilienfeld AM, Lilienfeld DE (1980) *Foundations of Epidemiology*, 2nd edn. New York: Oxford University Press.

Linsuwanont P, Palamara JE, Messer HH (2007) An investigation of thermal stimulation in intact teeth. *Archives of Oral Biology* **52**, 218–27.

Linsuwanont P, Palamara JE, Messer HH (2008) Thermal transfer in extracted incisors during thermal pulp sensitivity testing. *International Endodontic Journal* **41**, 204–10.

Lundy T, Stanley HR (1969) Correlation of pulpal histopathology and clinical symptoms in human teeth subjected to experimental irritation. *Oral Surgery, Oral Medicine, and Oral Pathology* **27**, 187–201.

Lutz F, Mörmann W, Lutz T (1974) Enamel cracks caused by vitality tests with carbon dioxide snow. *Schweizerische Monatsschrift Fur Zahnheilkunde* **84**, 709–25.

Marshall FJ (1979) Planning endodontic treatment. *Dental Clinics of North America* **23**, 495–518.

Matthews B, Searle BN (1974) Some observations on pulp testers. *British Dental Journal* **137**, 307–12.

Matthews B, Searle BN, Adams D, Linden R (1974) Thresholds of vital and non-vital teeth to stimulation with electric pulp testers. *British Dental Journal* **137**, 352–5.

McDonald F, Pitt Ford TR (1994) Blood flow changes in permanent maxillary canines during retraction. *European Journal of Orthodontics* **16**, 1–9.

Mengel MK, Stiefenhofer AE, Jyvasjarvi E, Kniffki KD (1993) Pain sensation during cold stimulation of the teeth: differential reflection of A delta and C fibre activity? *Pain* **55**, 159–69.

Miller SO, Johnson JD, Allemang JD, Strother JM (2004) Cold testing through full-coverage restorations. *Journal of Endodontics* **30**, 695–700.

Moody AB, Browne RM, Robinson PP (1989) A comparison of monopolar and bipolar electrical stimuli and thermal stimuli in determining the vitality of human teeth. *Archives of Oral Biology* **34**, 701–5.

de Morais CA, Bernardineli N, Lima WM, Cupertino RR, Guerisoli DM (2008) Evaluation of the temperature of different refrigerant sprays used as a pulpal test. *Australian Endodontic Journal* **34**, 86–8.

Morse DR (1974) *Clinical Endodontology*. Springfield: Charles C. Thomas.

Mullaney TP, Howell RM, Petrich JD (1970) Resistance of nerve fibers to pulpal necrosis. *Oral Surgery, Oral Medicine, and Oral Pathology* **30**, 690–3.

Mumford JM (1964) Evaluation of gutta-percha and ethyl chloride in pulp-testing. *British Dental Journal* **116**, 338–42.

Mumford JM (1967) Thermal and electrical stimulation of teeth in the diagnosis of pulpal and periapical disease. *Proceedings of the Royal Society of Medicine* **60**, 197–200.

Mumford JM (1976) Stimulus-evoked pain in teeth. *Frontiers of Oral Physiology* **2**, 51–77.

Mumford JM, Björn H (1962) Problems in electrical pulp-testing and dental algesimetry. *International Dental Journal* **12**, 161–79.

Mumford JM, Jedynakiewicz NM (1988) *Principles of Endodontics*. London: Quintessence Pub Co.

Myers JW (1998) Demonstration of a possible source of error with an electric pulp tester. *Journal of Endodontics* **24**, 199–200.

Närhi MV (1985) The characteristics of intradental sensory units and their responses to stimulation. *Journal of Dental Research* **64**, 564–71.

Närhi M, Virtanen A, Kuhta J, Huopaniemi T (1979) Electrical stimulation of teeth with a pulp tester in the cat. *Scandinavian Journal of Dental Research* **87**, 32–8.

Naylor MN (1964) Studies on sensation to cold stimulation in human teeth. *British Dental Journal* **117**, 482–6.

Noblett WC, Wilcox LR, Scamman F, Johnson WT, Diaz-Arnold A (1996) Detection of pulpal circulation in vitro by pulse oximetry. *Journal of Endodontics* **22**, 1–5.

Obwegeser H, Steinhauser E (1963) Ein neues gerat zur vitalitatsprufung der zahne mit kohlensaureschnee. *Schweizerische Monatsschrift Fur Zahnheilkunde* **73**, 1001–12.

Ohman A (1965) Healing and sensitivity to pain in young replanted human teeth. An experimental, clinical and histological study. *Odontologisk Tidskrift* **73**, 166–227.

Pantera EA Jr, Anderson RW, Pantera CT (1992) Use of dental instruments for bridging during electric pulp testing. *Journal of Endodontics* **18**, 37–8.

Pantera EA Jr, Anderson RW, Pantera CT (1993) Reliability of electric pulp testing after pulpal testing with dichlorodifluoromethane. *Journal of Endodontics* **19**, 312–4.

Peters DD, Lorton L, Mader CL, Augsburger RA, Ingram TA (1983) Evaluation of the effects of carbon dioxide used as a pulpal test. 1. In vitro effect on human enamel. *Journal of Endodontics* **9**, 219–27.

Peters DD, Mader CL, Donnelly JC (1986) Evaluation of the effects of carbon dioxide used as a pulpal test. 3. In vivo effect on human enamel. *Journal of Endodontics* **12**, 13–20.

Peters DD, Baumgartner JC, Lorton L (1994) Adult pulpal diagnosis. I. Evaluation of the positive and negative responses to cold and electrical pulp tests. *Journal of Endodontics* **20**, 506–11.

Petersson K, Soderstrom C, Kiani-Anaraki M, Levy G (1999) Evaluation of the ability of thermal and electrical tests to register pulp vitality. *Endodontics and Dental Traumatology* **15**, 127–31.

Pitt Ford TR, Patel S (2004) Technical equipment for assessment of dental pulp status. *Endodontic Topics* **7**, 2–13.

Pogrel MA (1987) Evaluation of over 400 autogenous tooth transplants. *Journal of Oral and Maxillofacial Surgery* **45**, 205–11.

Radhakrishnan S, Munshi AK, Hegde AM (2002) Pulse oximetry: a diagnostic instrument in pulpal vitality testing. *Journal of Clinical Pediatric Dentistry* **26**, 141–5.

Rand RW, Rinfret AP, von Leden H (1968) *Cryosurgery*. Springfield, IL: Charles C Thomas.

Ransohoff DF, Feinstein AR (1978) Problems of spectrum and bias in evaluating the efficacy of diagnostic tests. *The New England Journal of Medicine* **299**, 926–30.

Reade P, Mansour A, Bowker P (1973) A clinical study of the autotransplantation of unerupted maxillary canines. *Australian Dental Journal* **18**, 273–80.

Reiss HL, Furedi A (1933) Significance of the pulp test as revealed in microscopic study of the pulps of 130 teeth. *Dental Cosmos* **75**, 272–83.

Reynolds RL (1966) The determination of pulp vitality by means of thermal and electrical stimuli. *Oral Surgery, Oral Medicine, and Oral Pathology* **22**, 231–40.

Rickoff B, Trowbridge H, Baker J, Fuss Z, Bender IB (1988) Effects of thermal vitality tests on human dental pulp. *Journal of Endodontics* **14**, 482–5.

Riedel H, Fichter J (1966) Ein Beitrag zur systematischen Befunder-heberg. *Deutscher Zahnärzte* **21**, 511–3.

Robinson PP (1987) A comparison of monopolar and bipolar electrical stimuli and thermal stimuli in determining the vitality of autotransplanted human teeth. *Archives of Oral Biology* **32**, 191–4.

Roed-Petersen B, Andreasen JO (1970) Prognosis of permanent teeth involved in jaw fractures. A clinical and radiographic follow-up study. *Scandinavian Journal of Dental Research* **78**, 343–52.

Rosenberg RJ (1991) Using heat to assess pulp inflammation. *Journal of the American Dental Association* **122**, 77–8.

Rowe AH, Pitt Ford TR (1990) The assessment of pulpal vitality. *International Endodontic Journal* **23**, 77–83.

Ruddle CJ (2002a) Endodontic diagnosis. *Dentistry Today* **21**, 90–2.

Ruddle CJ (2002b) *Ruddle on Clean*•Shape•Pack. 2-tape video series. Studio 2050. Santa Barbara: Advanced endodontics.

Sailus J, Trowbridge HO, Greco M, Emling R (1987) Sensitivity of teeth subjected to orthodontic forces. *Journal of Dental Research* **66**, 556.

Schiller F (1937) Ist die vitalitatsprufung mit kohlensaureschnee unschadlich? *Ost Ztschr Stomatology* **35**, 1056–63.

Schnettler JM, Wallace JA (1991) Pulse oximetry as a diagnostic tool of pulpal vitality. *Journal of Endodontics* **17**, 488–90.

Selden HS (2000) Diagnostic thermal pulp testing: a technique. *Journal of Endodontics* **26**, 623–4.

Seltzer S, Bender IB (1984) *The Dental Pulp: Biologic Considerations in Dental Procedures*, 3rd edn. Philadelphia: J. B. Lippincott.

Seltzer S, Bender IB, Ziontz M (1963a) The dynamics of pulp inflammation: correlations between diagnostic data and actual histologic findings in the pulp. *Oral Surgery, Oral Medicine, and Oral Pathology* **16**, 846–71.

Seltzer S, Bender IB, Ziontz M (1963b) The dynamics of pulp inflammation: correlations between diagnostic data and actual histologic findings in the pulp. *Oral Surgery, Oral Medicine, and Oral Pathology* **16**, 969–77.

Seltzer S, Bender IB, Nazimov H (1965) Differential diagnosis of pulp conditions. *Oral Surgery, Oral Medicine, and Oral Pathology* **19**, 383–91.

Shabahang S (2005) State of the art and science of endodontics. *Journal of the American Dental Association* **136**, 41–52.

Sommer RF, Ostrander FD, Crowley MC (1962) *Clinical Endodontics*, 2nd edn. Philadelphia: WB Saunders.

Tajima S (1975) A longitudinal study on electrical pulp testing following Le Fort type osteotomy and Le Fort type fracture. *Journal of Maxillofacial Surgery* **3**, 74–80.

Teitler D, Tzadik D, Eidelman E, Chosack A (1972) A clinical evaluation of vitality tests in anterior teeth following fracture of enamel and dentin. *Oral Surgery, Oral Medicine, and Oral Pathology* **34**, 649–52.

Thilorier C (1835) Solidification de l'Acide carbonique. *Comptes Rendus* **1**, 194.

Tronstad L (1988) Root resorption – etiology, terminology and clinical manifestations. *Endodontics and Dental Traumatology* **4**, 241–52.

Tronstad L (2003) *Clinical Endodontics: A Textbook*, 2nd edn. Stuttgart: Thieme.

Trope M, Debelian G (2005) *Endodontics Manual for the General Dentist*. London: Quintessence Publishing Co.

Trowbridge HO, Franks M, Korostoff E, Emling R (1980) Sensory response to thermal stimulation in human teeth. *Journal of Endodontics* **6**, 405–12.

Tyldesley WR, Mumford JM (1970) Dental pain and the histological condition of the pulp. *The Dental Practitioner and Dental Record* **20**, 333–6.

Udoye CI, Jafarzadeh H (2010) Xeroradiography: stagnated after a promising beginning? A historical review *European Journal of Dentistry* **4**, 95–9.

Udoye CI, Jafarzadeh H, Okechi UC, Aguwa EN (2010) Appropriate electrode placement site for electric pulp testing of anterior teeth in Nigerian adults: a clinical study. *Journal of Oral Science* **52**, 287–92.

Virtanen AS (1985) Electrical stimulation of pulp nerves – comparison of monopolar and bipolar electrode coupling. *Pain* **23**, 279–88.

Waikakul A, Kasetsuwan J, Punwutikorn J (2002) Response of autotransplanted teeth to electric pulp testing. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontics* **94**, 249–55.

Walton RE, Torabinejad M (2002) *Principles and Practice of Endodontics*, 3rd edn. Philadelphia: WB Saunders.

Weine FS (1996) *Endodontic Therapy*, 5th edn. St. Louis: Mosby.

White JH, Cooley RL (1977) A quantitative evaluation of thermal pulp testing. *Journal of Endodontics* **3**, 453–7.

Williams BT (1982) *Computer Aids to Clinical Decisions*. Boca Raton: CRC Press.

Yanpiset K, Vongsavan N, Sigurdsson A, Trope M (2001) Efficacy of laser Doppler flowmetry for the diagnosis of revascularization of reimplanted immature dog teeth. *Dental Traumatology* **17**, 63–70.

Ziskin DE, Wald A (1938) Observations on electrical pulp testing. *Journal of Dental Research* **17**, 79–89.

Ziskin DE, Zegarelli EV (1945) The pulp testing problem: the stimulus threshold of the dental pulp and the periodontal membrane as indicated by electrical means. *Journal of the American Dental Association* **32**, 1439–49.