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TOPICAL REVIEW

The fluid mechanics of root canal irrigation

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Abstract

Root canal treatment is a common dental operation aimed at removing the contents of the geometrically complex canal chambers within teeth; its purpose is to remove diseased or infected tissue. The complex chamber is first enlarged and shaped by instruments to a size sufficient to deliver antibacterial fluids. These irrigants help to dissolve dying tissue, disinfect the canal walls and space and flush out debris. The effectiveness of the procedure is limited by access to the canal terminus. Endodontic research is focused on finding the instruments and clinical procedures that might improve success rates by more effectively reaching the apical anatomy. The individual factors affecting treatment outcome have not been unequivocally deciphered, partly because of the difficulty in isolating them and in making the link between simplified, general experimental models and the complex biological objects that are teeth. Explicitly considering the physical processes within the root canal can contribute to the resolution of these problems. The central problem is one of fluid motion in a confined geometry, which makes the dispersion and mixing of irrigant more difficult because of the absence of turbulence over much of the canal volume. The effects of treatments can be understood through the use of scale models, mathematical modelling and numerical computations. A particular concern in treatment is that caustic irrigant may penetrate beyond the root canal, causing chemical damage to the jawbone. In fact, a stagnation plane exists beyond the needle tip, which the irrigant cannot penetrate. The goal is therefore to shift the stagnation plane apically to be coincident with the canal terminus without extending beyond it. Needle design may solve some of the problems but the best design for irrigant penetration conflicts with that for optimal removal of the bacterial biofilm from the canal wall. Both irrigant penetration and biofilm removal may be improved through canal fluid

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agitation using a closely fitting instrument or by sonic or ultrasonic activation. This review highlights a way forward by understanding the physical processes involved through physical models, mathematical modelling and numerical computations.

Keywords: irrigation, root canal, endodontics, fluid dynamics, viscous flows

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Periapical disease is an inflammatory response around root canal termini to intra-radicular bacterial infection. In 1992, over £43 million were spent on root canal treatment in the general dental services of the National Health Service in the UK (Dental Practice Board 2005). This consistent trend, which does not take account of an increasing amount of care provided under private contract by specialist endodontists, is mirrored in the USA (Wayman *et al* 1994, Boykin *et al* 2003) and even in the low caries rate adult Danish population (Bjørndal and Reit 2005). The problem has posed a substantial economic and manpower burden to modern society (Figdor 2002) and is a frequent cause of work absence and cost to industry. The reported success rates of root canal treatment, defined by complete resolution of periapical bony radiolucency, vary widely from 31% to 100% (Ng *et al* 2007) but even where guideline standard treatment is performed, the mean success rates only reach 75%. The respective mean success of root canal retreatment reaches a similar 77% (Ng *et al* 2008). The presence of pre-operative infection strongly influences success rates (Ng *et al* 2008), whilst treatment procedure factors have lesser impact, indicating considerable room for improvement. The relative lack of sensitivity of radiographic assessment to detect subtle signs of inflammation around root apices underestimates the true prevalence of persistent periapical disease. Technological developments over the last 20 years have considerably enhanced dentists' ability to mechanically sculpt the internal tooth form to allow the delivery of fluid irrigants to wash out residual pulp tissue, planktonic bacteria, biofilm complexes and to kill remaining bacteria. The treatment-related factors having the most profound influence on periapical healing were accuracy of extension of instrumentation to the apical canal termini, the degree of bacterial load reduction (dependent on the chemical nature of the irrigant) and control over root filling and restoration placement (Ng *et al* 2008). The outcome studies provide strong inferential evidence that the main factor hindering success is the inability of treatment protocols to satisfactorily and predictably reach and control the apical infection. Given the inability of metal instruments to directly plane the walls of the complex internal surface geometry of teeth, the key issue is the ability of antibacterial fluids to reach this space and surfaces to effect bacterial biofilm removal.

The science to understand the process of irrigant delivery already exists, but is not fully exploited by clinical dental practice. The aim of this *inter-disciplinary* review is to integrate the science that underpins the physical behaviour of fluid within root canals with current clinical expertise. The *relevant* literature, in the dental and fluid dynamics disciplines is reviewed to derive an informed synthesis of the knowledge and its remaining deficiencies. A further aim is to allow fluid engineering expertise to inform and re-define key clinical parameters, to facilitate appropriate further development of the treatment procedure; as such the structure of the remaining review may seem at variance with traditional clinical dogma and is structured as follows.

(1) The structure of teeth and the clinical context.
(2) The role and efficacy of irrigation during various stages of root canal preparation.
(3) Understanding clinical approaches to irrigation.
(4) Application of physical principles to clinical procedures.
(5) Concluding statements.

2. Structure of teeth and the clinical context

2.1. Structure of teeth and the root canal system

Teeth are formed by foci of specialized embryonic tissue, a part of which becomes encapsulated by the formed tooth and is then called the dental pulp. Apart from the formative function of the specialized cells (odontoblasts), the dental pulp is a highly vascular connective tissue that serves a protective function helping to defend the tooth from bacterial, chemical, and mechanical assault. The outer odontoblastic layer secretes the mineralized hard tissue, dentine, which forms the bulk of the tooth. The odontoblasts interface with its secreted shell by virtue of their extension of a cellular process into its respective secreted tubule. Dentine is therefore a specialized connective tissue that contains thousands of tubules radiating outwards from the dental pulp to the enamel in the crown and the cementum in the root, each with its own odontoblastic process. The dentinal tubules make up 20–30% of the volume of dentine. The diameter of the tubules is about 3 μm near the pulp and less than 1 μm peripherally (Gulabivala 2004) (figure 1(a)).

The average root canal system volumes (table 1), corono-apical lengths (table 2) and apical diameters (table 3) indicate their minute proportions without conveying the enormous complexity and irregularity of the internal form, which can be seen in figure 2 for a typical tooth: the root canals are curved, pointed, non-circular, have irregularly varying cross-sections (figure 3) and side channels and chambers (figure 4). The characteristics of root canals are variable and are dictated by racial origin, tooth type, disease history and age (Gulabivala *et al* 2001, 2002, Ng *et al* 2001, Alavi *et al* 2002).

2.2. Nature of the disease

Normal wear and tear of teeth in function, disease processes (tooth decay and tooth surface loss) and dentists' attempts to repair the resulting defects lead to progressive inflammation of the dental pulp, sometimes leading to its death, leaving a zone inside the teeth that is incapable of defending against the entry of bacteria from the mouth. Such infection may lead to abscess

Table 1. Mean volumes (mm^3) of dental pulp cavities (data extracted from Fanibunda (1986)).

Tooth type	Maxillary	Mandibular
Central incisor	12.4 (±3.3)	6.1 (±2.5)
Lateral incisor	11.4 (±4.6)	7.1 (±2.1)
Canine	14.7 (±4.8)	14.2 (±5.4)
First premolar	18.2 (±5.1)	14.9 (±5.7)
Second premolar	16.5 (±4.2)	14.9 (±6.3)
First molar	68.2 (±21.4)	52.5 (±8.5)
Second molar	44.3 (±29.7)	32.9 (±8.4)
Third molar	22.6 (±3.3)	31.1 (±11.2)

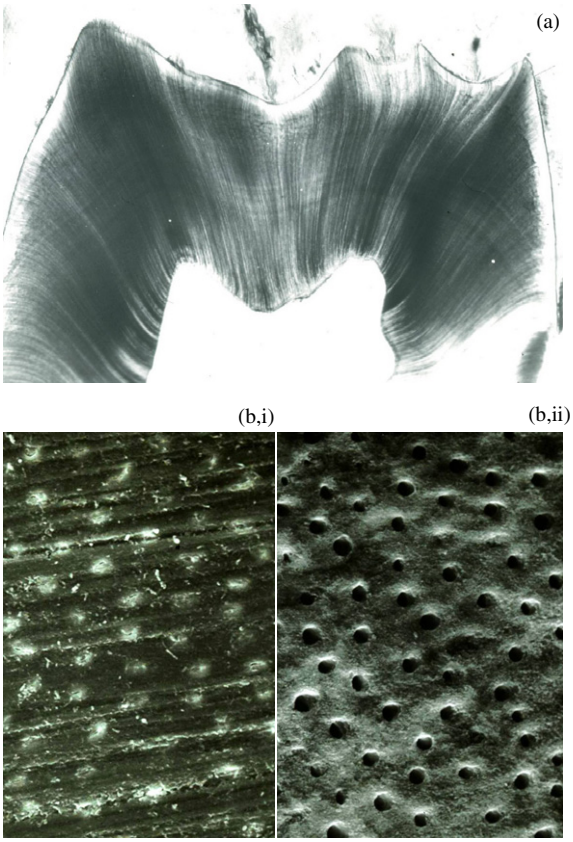

Figure 1. (a) Ground section of the crown of a tooth showing its dentinal tubular structure. (b) SEM images of the internal surface of a root canal. In (b(i)) the root canal surface is instrumented and covered by a smear layer, while in (b(ii)) the smear layer has been dissolved. The inner (pulpal) diameter of the tubules is about 3 μm.

Table 2. Average corono-apical lengths of teeth (mm) (data extracted from Walker (2004)).

Tooth	Maxillary	Mandibular
Central incisor	22.5	20.7
Lateral incisor	22.0	21.1
Canine	26.5	25.6
First premolar	20.6	21.6
Second premolar	21.5	22.3
First molar	20.8	21.0
Second molar	20.0	19.8

and cyst formation in the periradicular tissues (ligament and bone surrounding the root) at the junction where the *intra-radicular space* communicates with the *peri-radicular* tissues, principally but not exclusively at the root tip. The disease may cause pain and gum and/or facial swelling. Pulpal (inside tooth) and periapical (outside tooth) diseases are therefore

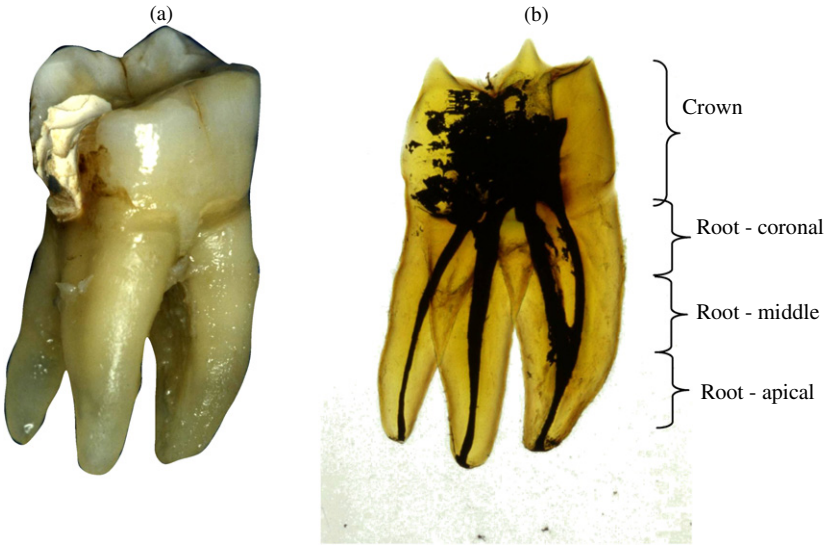

Figure 2. (a) Photograph of an extracted tooth. The relatively simple canal anatomy in this case is shown in (b), after the tooth has been rendered transparent by a process called 'clearing'.

Table 3. Diameters (μm) of apical foramina by tooth and root type (data extracted from Morfis *et al* (1994)).

Tooth/root type	Diameter of apical foramen (μm)
Maxillary incisors	289.4 ± 120.9
Mandibular incisors	262.5 ± 190.2
Maxillary premolars	210.0 ± 170.9
Mandibular premolars	368.3 ± 183.9
Maxillary molars	
Palatal root	298.0 ± 62.1
Mesial root	235.1 ± 101.0
Distal root	232.2 ± 66.09
Mandibular molars	
Mesial root	257.5 ± 343.3
Distal root	392.0 ± 77.5

inflammatory responses to bacterial infection inside teeth. In biological terms, the transition from pulpitis to apical periodontitis represents a continuum of inflammation spread from inside the tooth to the surrounding ligament and bone. The transition from one to the other is therefore marked by the loss of alveolar bone around the canal exits, radiographically evident as periapical radiolucency. The infection is polymicrobial in nature, with a variable diversity (Bergenholtz 1974, Wittgow and Sabiston 1975, Sundqvist 1976) and complex, adherent, community structure known as a biofilm. The biofilm is a bacterial layer on the internal dentine wall of variable thickness and composition and is abutted by dying or necrotic pulp tissue or migrating host defence cells, polymorphs and macrophages (Nair 1987, Richardson *et al* 2009). The hydrated biofilm is composed of bacterial cells, variable amounts of a

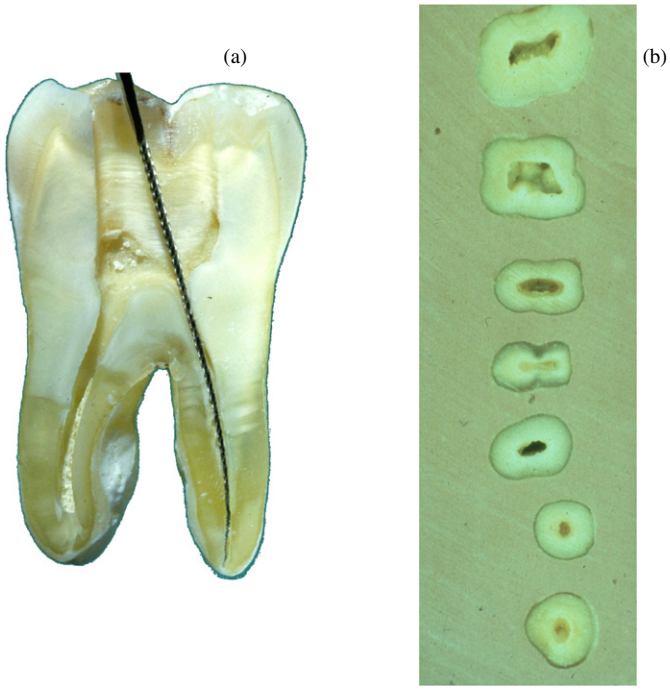

Figure 3. (a) Root canal instrument negotiating the length of a gently curved root canal. The cross-sections of un-instrumented root canals are shown in (b). The cross-section of the root is generally non-circular.

polysaccharide extracellular matrix, metabolites and other minor excreted products. The bacterial biofilm may also penetrate into dentinal tubules by a variable distance but not all tubules are so invaded (Love and Jenkinson 2002).

2.3. Role of intervention

The clinical aims of root canal treatment have been described by the European Society of Endodontology (2006). Root canal treatment is the dental procedure used to either (1) prevent apical periodontitis by early treatment of diseased or infected soft tissue contained in the hollow space inside teeth or (2) help resolve apical periodontitis, when the dental pulp is necrotic and the hollow space infected. Root canal 'retreatment' may be performed to treat persistent 'post-treatment' apical periodontitis due to treatment failure (European Society of Endodontology 2006). The complicating feature of the treatment is that the biofilm-coated internal surface has an enormously complex and irregular spatial configuration.

Root canal treatment requires access to this complex internal surface and space and it begins with entry to the internal aspect of the tooth by drilling through the top of the crown (figures 2 and 3). The narrow extensions of the space into the roots, called canals, are accessed by specialized metal instruments (files, reamers (figure 5(a))). These are used to enlarge and sculpt the canal space into a tapering form, sufficiently to allow disinfecting agents (fluids) to reach and have contact with its entire surface. The irrigants and irrigation have multiple roles, some of which dominate at different stages of the treatment procedure. In order to effectively reach these surfaces, the fluid has to adequately flush out the canal space of residual pulp tissue and dentine and bacterial debris, which may even have been compacted

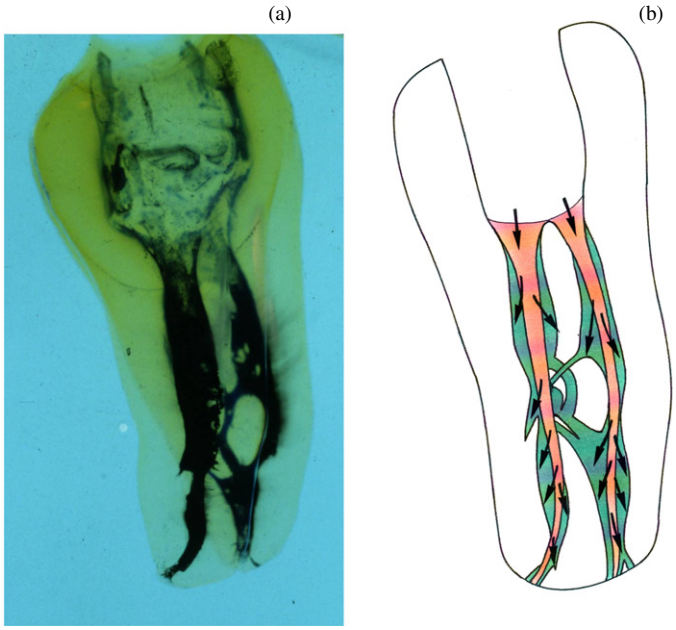

Figure 4. (a) Photograph of a cleared tooth showing complex canal anatomy filled with Indian ink. (b) Schematic of the tooth in (a). The central tapering channels represent the instrumented canals within the original root canal anatomy and through which irrigant penetrates to the peripheries of the root canal system chamber (indicated by arrows).

and displaced into the outer and distal lying spaces of the root canal system. One of the roles of the irrigant at this stage is to help dissolve the residual organic tissue and bacterial biofilm. As the instruments do not plane the entire irregular root canal system surface, 30–50% remaining un-instrumented, one of the roles of the irrigant is to help remove the residual biofilm from the un-instrumented surface and another is to remove the smear layer formed over the instrumented surface (a property of the hydroxyapatite which forms the mineral component) (figure 1(b)). The antibacterial fluid delivered into the canals must retain its potency as it reaches the target to facilitate the removal and killing of the bacteria. Once the canal system is considered to be sufficiently decontaminated (judged by bacterial culture tests and/or absence of signs and symptoms of disease), it is filled with an inert material such as gutta-percha together with a paste-like sealer to prevent bacterial recontamination. This process of finding, placing instruments into, enlarging, irrigating and filling the root canal space consists of a series of highly skill-dependent and inter-dependent procedures, taking time and patience. The outcome of the treatment is monitored clinically and with radiographs to ensure that the periapical tissues heal. The healing involves bone repair that can take anything from 6 months to 4 years and sometimes longer, probably because of the residual apical infection (Wada *et al* 1998, Nair *et al* 2005, Ng *et al* 2008).

3. The role and efficacy of irrigation during various stages of root canal preparation

The irrigant and irrigation fulfil multiple roles during root canal preparation, and although many of these processes occur simultaneously, conceptually one of these functions of irrigation takes on a dominant role in each of the different phases of root canal preparation.

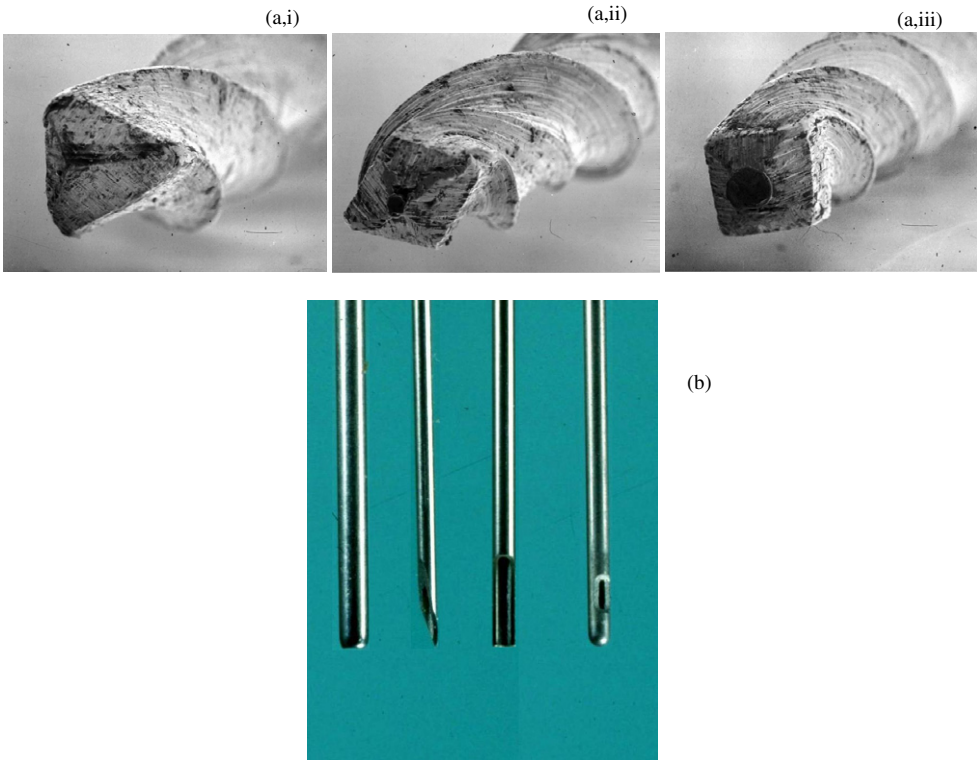

Figure 5. Summary of the instruments used in root canal treatment. In (a), SEM images show the tips of three endodontic files (a(i) file; a(ii) flexofile; a(iii) reamer). In (b) a variety of needle types are shown. From left-to-right, these are flat open-ended (FOE), bevelled open-ended (BOE), side-cut open-ended (SCOE) (Monojet, Sherwood Medical, St Louis, USA), closed-end single side-opening CE-SSO (Endovage Dental from p 9), respectively. The recommended needle types are the last two designs.

3.1. Irrigant role and delivery and their relationship with the mechanics of canal preparation

Root canal treatment may be divided into three distinct phases by the dominant role of irrigation.

3.1.1. Canal negotiation phase. After initial entry into the tooth via the access cavity, the clinical goal is to locate and negotiate the identifiable canals using instruments small enough to achieve penetration to their full length. At this stage, the irrigant may only be delivered predictably as far as the pulp chamber or coronal third of canal depending on the extent of penetration of the irrigating needle (figure 5(b)). A clinical tactic to enable further direct apical penetration of the irrigant at an earlier stage in canal preparation involves pre-flaring of the upper part of the canal (coronal preflaring or crowndown approach). The irrigant may facilitate such canal negotiation and equally the act of file negotiation may help to drag the fluid interface further apically through surface tension effects. An initial problem to overcome may be the presence of gas bubbles ahead of the advancing front of the irrigant; this has been described as the 'vapour lock effect' by Gu *et al* (2009). Agitation with a file may help break up the gas bubbles, as may the use of liquids with lower surface tension. Some clinicians believe that lubricating gels may help facilitate penetration of the instruments (Buchanan 1991).

3.1.2. Canal enlargement phase. Once the main canals have been negotiated to their full verified lengths, the mechanical enlargement or shaping of the canals can be undertaken. Mechanical shaping or enlargement of the canal at the expense of the dentine may help free up tags of pulp tissue and will also generate dentine debris, which is released into the fluid reservoir within the canal cavity. As the metal instruments negotiate and enlarge the canal space, it progressively becomes easier to inject the fluids further apically into the canal system. The primary role of the irrigant at this stage is to flush out this debris with the frequent injection of irrigant in between filing and reaming. If the files are inserted to the full length of the canal from the outset, dentine debris is generated throughout the length of the canal but the replacement of the spent, debris-laden irrigant is only effective in the coronal part of the canal where the irrigant needle is able to reach (the difficulty of accessing the apical region of the root canal is clear in figure 3(a)). The dissolving organic pulp contents mix with the dentine debris and may lead to the progressive increase in the viscosity of the irrigant fluid, to the point where it may begin to behave as a paste, clinically known as dentine 'mud' and be pushed by the piston action of the increasingly larger files into the as yet un-debrided and still contaminated apical anatomy. This process leads to apical blockage of the canal and eventually, forcing of metal instruments by the clinician in the hope of regaining length; this forcing of instruments may in turn cause 'transportation' (deviation of the instrumented channel from the original canal) and uncontrolled shaping of the canal walls. To prevent this problem, the suspended debris is flushed out by delivering the irrigant as far apically into the canal as possible with a needle but during the initial phases of canal preparation, deposition of the irrigant sufficiently apically is limited by the lack of access of the irrigating needle to near the terminus of the canal. To help flush out debris from the apical part, the freshly replaced coronal irrigant is mixed with the still debris-laden fluid in the apical part by apical transference and mixing using a small file, a process called 'recapitulation' (figure 6). Passing the file beyond the canal terminus to prevent its blockage is called 'patency filing'. The frequency of replenishment of the coronal irrigant, which with progressive canal preparation allows irrigant delivery further and further apically, as well as the frequency of recapitulation, is crucial in the ability to maintain the apical canal anatomy patent (Buchanan 1991).

3.1.3. Active canal irrigation phase. Once the canal shaping is complete as judged by the achievement of the pre-defined continuous tapering form, the entire root canal system (including the instrumented and un-instrumented surfaces) should be accessible for final washing by the irrigant. The irrigant is again delivered by injection through a needle into the prepared part of the canal and the process completed by means of agitation, pumping and mixing to drive the irrigant into the 'unshaped' part of the canal system (figure 4). This final phase of irrigation is relatively poorly adopted in general dental practice because of the lack of awareness of its importance. The actual practice may vary in terms of volume of irrigant used, the nature of agitation accompanying it and the duration of soak-time employed. Some practitioners will also alternate between a number of chemically distinct solutions in the belief that the practice synergizes the chemical effects.

The dominant roles of the irrigant and irrigation in the three phases may therefore be summarized as follows:

(1) to *lubricate* the insertion and negotiation of root canal instruments to the root canal termini;

(2) to *flush out* the root canal system of loosened debris generated during root canal filing or reaming and

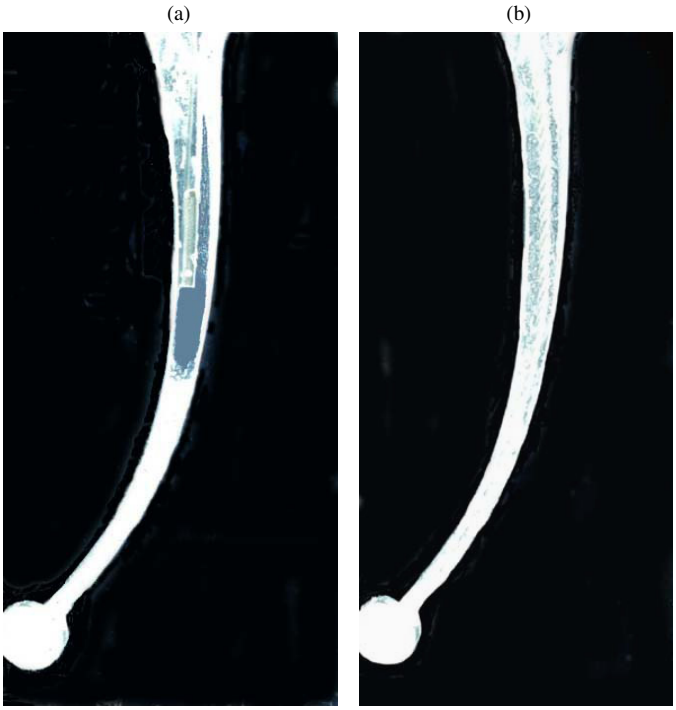

Figure 6. Simulated prepared root canal in an EndoVu block, which has the same physical dimensions as a tooth. Prepared root canal diameter varies from 0.9–2.0 mm coronally to 0.3 mm at the root apex. In (a), water is injected through a 27-gauge needle into a suspension containing debris generated by filing the canal. In (b) the fluid column is mixed by the vertical agitation of a file ('recapitulation') which extends the whole length of the canal.

(3) to *dissolve and disrupt* bacterial biofilm and pulpal tissue, kill bacteria and denature toxins to the outer-most reaches of the root canal system.

3.2. Efficacy of root canal treatment procedures

A variety of outcome measures in both laboratory and clinical studies have been used to test the efficacy of mechanical instrumentation in conjunction with organic tissue-dissolving, antibacterial and neutral irrigating agents.

3.2.1. Neutral irrigation solutions (saline, water). Neutral solutions in conjunction with mechanical preparation are insufficient to debride canals free of pulp tissue, debris, smear layer or bacterial content. The assessment is often divided into coronal, middle and apical portions of the root. As a general observation, given the tapering shape of the canals, and the need to remove more dentine coronally than apically, the greatest cleaning effect is evident coronally and the minimal effect is evident apically (Walton 1976, Biffi and Rodrigues 1989, Baumgartner and Cuenin 1992, Evans *et al* 2001).

Monitoring changes in root canal bacterial load and relative proportion of bacterial species following each stage of root canal treatment has been a valuable tool for testing the efficacy of such procedures even though the available methods require an additional laboratory step.

Both reduction in bacterial cell numbers and the proportion of teeth with negative cultures have been used as surrogate outcome measures.

The most influential microbiological evidence for contemporary root canal treatment was provided by a series of studies from Sundqvist and colleagues (Byström and Sundqvist 1981, 1983, 1985, Byström *et al* 1985, Sjögren and Sundqvist 1987, Sjögren *et al* 1991). They evaluated the effect of various root canal treatment procedures on the microbiota, both qualitatively and quantitatively, using standardized methodology. Mechanical preparation with *water or saline* irrigation proved to be the least effective way of reducing the bacterial load and achieving negative cultures.

Considering a range of studies collectively, negative cultures were achieved after using water or saline irrigation in 4.6%–75% (mean of 25%) of cases (Ingle and Zeldow 1958, Nicholls 1962, Grahnén and Krasse 1963, Zeldow and Ingle 1963, Byström and Sundqvist 1981, Ørstavik *et al* 1991, Dalton *et al* 1998). Taking account of these data together with the fact that mechanical instruments only plane up to 61% of the canal surface (Mannan *et al* 2001, Peters *et al* 2001), the considered role of canal preparation has undergone a shift from one of fulfilling a prime debriding function to one regarded more as a radicular access for the irrigant and root-filling materials to the complex root canal systems (Gulabivala *et al* 2005). An important role of root canal irrigation is to help remove the residual bacterial biofilm from the inaccessible, un-instrumented surfaces.

3.2.2. Antibacterial irrigation solutions (sodium hypochlorite, chlorhexidine gluconate, Biosept). The role of antibacterial irrigants is to help reduce the bacterial load in the root canal system. Bacterial load reduction is improved by the addition of sodium hypochlorite (0.5%) irrigation and further by alternate irrigation with ethylenediaminetetraacetic acid (EDTA) and 5.0% sodium hypochlorite solution (Byström and Sundqvist 1983). The irrigation regimes reduce the residual bacterial load from an initial range of 10^2–10^8 cells per unit sample to 10^2–10^3 cells after initial debridement. Based collectively on a range of studies, the frequency of negative culture (25%–98%) (mean of 75%) increases substantially when sodium hypochlorite (concentration of 0.5%–5.0%) is used as the irrigant during mechanical preparation (Cvek *et al* 1976, Byström and Sundqvist 1981, 1983, 1985, Sjögren and Sundqvist 1987, Yared and Bou Dagher 1994, Gomes *et al* 1996, Shuping *et al* 2000, Peters *et al* 2002, Kvist *et al* 2004, Vianna *et al* 2006, Siqueira *et al* 2007a, 2007b, 2007c). The wide range of outcomes may be attributable to variation in the pre-operative condition of the teeth, the concentration, volume and method of delivery of the irrigant solution, the size and shape of the root canal system, as well as the microbiological methods used for detection.

The findings on the influence of size of apical preparation on bacterial load reduction have been inconsistent. Some groups have shown more effective bacterial debridement with larger compared to smaller apical preparation sizes (Parris *et al* 1994, Rollison *et al* 2002, Card *et al* 2002), whereas others have failed to show a difference (Yared and Bou Dagher 1994, Coldero *et al* 2002, Wang *et al* 2007). The discrepancies may again be attributed to the factors listed above, but there is a lack of clarity in the literature about the precise reasons.

The additional use of ultrasonic agitation of the sodium hypochlorite irrigant (Sjögren and Sundqvist 1987, Carver *et al* 2007) and alternate irrigation between EDTA and sodium hypochlorite (Byström and Sundqvist 1985) during mechanical preparation achieves an even higher frequency of negative bacterial cultures. The adoption of the chlorhexidine gluconate (concentration of 0.12%–2.5%) solution as an antibacterial agent for irrigation was suggested 10 years previously (Kuruvilla and Kamath 1998); it had gradually begun to gain acceptance. However, the number of negative cultures achieved using chlorhexidine irrigation was similar (Waltimo *et al* 2005, Siqueira *et al* 2007c) to or lower (Vianna *et al* 2006) than that

achieved with sodium hypochlorite irrigation; a finding also corroborated in retreatment cases (Schirrmeister *et al* 2007). Biosept®, a quaternary ammonium compound, used for irrigation in the 1960s gave 32% (Grahnén and Krasse 1963) and 40% (Engström 1964) negative cultures, respectively.

The adoption of multiple chemical agents to irrigate the root canal system has resulted in the possibility of synergism between them to enhance bacteria killing in the case of NaOCl and EDTA (Byström and Sundqvist 1985), with the potential of increased clinical success rates (Ng 2008). It has, however, also raised the spectre of neutralizing chemical reactions between chlorhexidine and NaOCl (Basrani *et al* 2007, Bui *et al* 2008) which reduce their combined effect and the potential for toxic precipitation and associated reduced clinical success rates (Ng 2008). Finally, it is worth remembering that the physical mixing of different chemicals as well as chemical interactions may alter the rheology of the irrigant, thereby altering the fluid dynamics.

Triangulation of these diverse sources of clinically oriented data indicate that whilst biofilm disruption and bacterial killing may be relatively easily achieved in laboratory tests (Spratt *et al* 2001, Bryce *et al* 2009), albeit with their own set of variations, it is relatively more difficult to achieve the same within tooth infection models (Gulabivala *et al* 2004) and in teeth, clinically. It is intuitively evident that a principal reason for this is the problem of delivery of irrigant agents to the complex apical anatomy, where reside the last vestiges of the root canal biofilm (Nair *et al* 2005, Ng *et al* 2007, 2008).

3.3. Irrigant extrusion into periapical tissues

Ironically, although the chief problem of irrigation is irrigant delivery to the complex apical anatomy of the root canal system, it is likely that in most cases there may be some seepage or diffusion of the spent irrigant into the periapical tissues (Martin and Cunningham 1982), which probably causes little or no harm. Very occasionally extrusion of a sufficient volume of irrigant into the periapical tissues may cause adverse reactions, particularly when using NaOCl (Hülsmann and Hahn 2000). Studying the causes of extrusion is very difficult in the clinical situation with reliance having to be placed on surrogate outcome measures or alternatively on the use of *in vitro* models.

Extrusion of NaOCl irrigant during routine canal instrumentation using dynamic syringe irrigation (achieved with a 23-gauge needle extending as deep as possible into the canal without binding) has been found to be significantly worse than when using static irrigation (achieved by flooding the access cavity with irrigant) (Brown *et al* 1995). Using a different outcome measure, an overall reduction in post-operative discomfort was found when using needles with closed-end, multiple side-openings for irrigation (Goldman *et al* 1979). Positioning of the needle appears to have an important effect on extrusion (Williams *et al* 1995).

The potential for extrusion when using negative pressure, sonic or ultrasonic systems has been investigated using extracted tooth models with pre-prepared canals. Irrigant was found not to be extruded using the negative pressure EndoVac® system, but a minimal amount was extruded using the sonic EndoActivator™. Both these techniques had significantly less extrusion than manual dynamic irrigation, automated dynamic irrigation (RinsEndo® handpiece) or ultrasonic active irrigation (Desai & van Himel 2009). Williams *et al* (1995) and Hauser *et al* (2007) found that although irrigant delivered through the RinsEndo handpiece penetrated deeper into the dentinal tubules, there was also a higher risk of apical extrusion than irrigant delivered manually through syringe irrigation. Ultrasonic irrigation during canal preparation was found to result in significantly more extrusion than dynamic syringe irrigation,

although extrusion could be reduced by limiting the extension of the ultrasonic file to 1 mm short of the canal terminus (Martin and Cunningham 1982).

Interestingly, and counter-intuitively, enlarging the apical terminus of the canal reduced extruded material, but it is highly likely that this was due to the use of instruments short of the enlarged canal termini (Lambrianidis *et al* 2001). The finding was corroborated in a separate study where size of apical foramen was not found to have a significant association with the amount of extruded irrigant (Williams *et al* 1995).

Clinically, therefore there is a balance to be struck between effectively delivering the irrigant to the complex apical anatomy, whilst preventing its extrusion periapically.

4. Understanding clinical approaches to irrigation

4.1. Irrigant actions in clinical operations

Irrigant is introduced into a root canal system during and after canal preparation in order for it to be dispersed throughout and to help disinfect its surfaces and space, to exert shear stress on the walls to remove the adherent biofilm and smear layer, and to remove from the canal cavity, debris generated by instrumentation. These objectives may be satisfied through developing equipment and techniques for the introduction of irrigant and for its agitation. There are two separate processes by which these objectives are attained: first the dentist delivers the fluid and then as a separate step agitates it *in situ* using either the needle or another instrument (including sonic and ultrasonic devices).

4.1.1. Methods for the introduction of irrigant. Irrigant is commonly delivered continually from a syringe through a needle. The key variables are the rate of irrigant delivery (Q), which varies tremendously amongst operators ($Q = 0.01$–1.25 mL s^{-1}) (Boutsioukis *et al* 2007a) and the volume of irrigant (V) used for each treatment ($V = 6$–42 mL) (Falk and Sedgley 2005, Nguy and Sedgley 2006, Nielsen and Baumgartner 2007). The method of delivery may be manual (for instance, using a syringe) or automated (using one of several commercially available devices). For manual injection, the volume of the syringe used may vary between 3 and 5 mL. There is a tendency for Q to be higher for male than female operators with a negative correlation between clinical experience and volume of irrigant delivered, regardless of needle used (Boutsioukis *et al* 2007a). Automated delivery systems can be categorized into several types: continuous delivery of irrigant through one needle (Quantec-E®), continuous delivery and evacuation achieved through two needles (EndoVac®), pulsating injection from one needle (RinsEndo®), and alternating delivery and evacuation through outer and inner tubings (non-instrumentation technique (NIT)), respectively.

Of central importance to the introduction of irrigant is the size and design of the needle used. The internal d_I and external d_E diameters of needles are usually expressed in terms of standard gauge sizes and are presented in table 4, along with their range. The internal and external needle diameters decrease as the gauge number increases. A survey of endodontic irrigation needles revealed that few needles complied with the ISO nominal size but all were within tolerance limits (Boutsioukis *et al* 2007b). Gauge 23 or 25 needles were widely used before the 20th century, whereas the current emphasis is to use gauge 27 or 30. Root canals are typically 0.5–2 mm in diameter at the crown and taper down to less than 0.3 mm in mature roots. A 27-gauge needle will therefore penetrate to the apical third at the end of the canal preparation. Increasing the needle gauge has two main effects on clinical treatment. First, smaller needles are able to penetrate deeper into the root canal and secondly, for equivalent delivery rates of irrigant, the viscous effects (elaborated further in section 5.2) are weaker for

Table 4. Medical stainless steel needle specifications according to ISO 9626:1991/Amd.1:2001 (ISO 9626 2001) (adopted from Boutsioukis *et al* (2007b)).

Gauge size	Designated metric size (mm)	Range of external diameters (mm)		Internal diameter (mm)
		Min	Max	Min
21	0.8	0.800	0.830	0.490
23	0.6	0.600	0.673	0.317
25	0.5	0.500	0.530	0.232
27	0.4	0.400	0.420	0.184
30	0.3	0.298	0.320	0.133

narrower needles because the flow is faster. Both contribute to more effective removal of debris and bacteria (Baker *et al* 1975, Abou-Rass and Piccinino 1982, Sedgley *et al* 2005). However, finer needles require increased effort to inject the irrigant and result in higher pressure within the barrel, up to 400–550 kPa (Boutsioukis *et al* 2007b).

Commercially available irrigation needle tips are modified so that the exit does not face the canal terminus and remains blunt in order to reduce the risk of canal binding and irrigant displacement into the periradicular tissues. The range of different needle designs available is shown in figure 5(b); they are categorized as flat open-ended (FOE), bevelled open-ended (BOE), side-cut open-ended (SCOE) and those with closed-end and single side-openings (CE-SSO). The recommended types are the SCOE and CE-SSO (the last two designs in figure 5(b)) (Moser and Heuer 1982). Other types are available such as a needle with a closed-end and multiple side-openings (National Patent Development, NY, USA, Goldman *et al* 1976).

In the two-needle irrigation systems, the finer evacuation needle penetrates further than the delivery needle; the needle gauges are 30 and 27, respectively. The ends of delivery and evacuation needles are placed 3 and 12 mm from the apical end of the root, respectively. Irrigant is delivered at a typical rate of 0.05 mL s^{-1} (Fukumoto *et al* 2006). In pulsating injection systems, such as the RinsEndo, the flow rate is 0.1 mL s^{-1} and is pulsed with a frequency of 1.6 Hz. The main difference between the commercial systems is the form and size of the needle type for evacuation of irrigant at the apical portion of the canal, as well as the flow rates.

4.1.2. Agitation of irrigant. Agitation takes place by 'activating' irrigant through the introduction of an instrument into the canal and moving it within the canal with a reciprocating, oscillating or rotating action so that the irrigant is dispersed and debris is removed from the extremities of the canal. There are several methods by which this can be achieved (figure 7): (1) manual reciprocation of the instrument within a canal by the dentist; (2) sonic or ultrasonic activation to achieve oscillation of the instrument and (3) introduction into the canal of a mechanically driven rotary instrument.

4.2. Measuring the effectiveness of irrigation regimens

Many methods have been used to measure the effectiveness of various root canal irrigation and therefore treatment procedures. Clinical trials and *ex vivo* models are attractive and relevant as they deal with the actual organ or problem in question (the material and shape of the canal

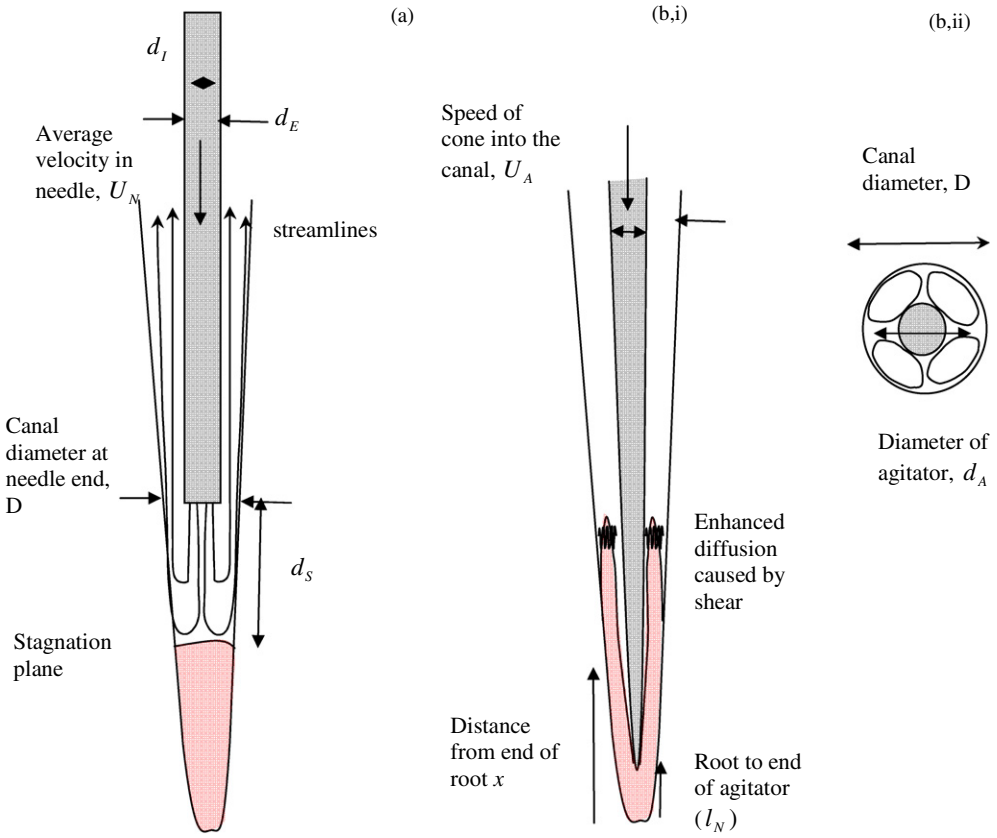

Figure 7. Schematic diagram of geometry and notation based on experimental results for: (a) injection of irrigant into the root canal by a single needle; and (b) agitation by (i) the vertical motion of a file or gutta-percha cone or (ii) in plane displacement of instrument by ultrasonic vibration. In b(ii) $\leftrightarrow$ = direction of oscillation

are particularly important). The latter models also allow measurement of the state of the canal before and after treatment. The clinically relevant outcome measures used to evaluate the effectiveness of treatment include measurements of: periapical healing (Ng *et al* 2008), tooth survival (Ng *et al* 2010), quantitative and qualitative changes in the cultivable microbiota (Byström and Sundqvist 1981) and residual bacterial biofilm (Nair *et al* 2005).

Ex vivo models have been used to gain additional mechanistic insight through assessment of debris, smear layer or bacterial reduction (Gulabivala *et al* 2005). Such measurements, whilst clinically important and relevant, do not shed light on the transient physical or chemical phenomena leading to the final outcome. Furthermore, data from clinical or *ex vivo* studies may be difficult to interpret and compare. The uncontrolled variables inherent in such systems also complicate evaluation of the effect of canal systems, teeth and patients on outcome. As an example, the volume flux of the irrigant delivered varies by more than a factor of 50 between different studies. These difficulties can be alleviated by using simplified *in vitro* models (where the canals are simulated by holes in an artificial medium such as Perspex), which allow the canal geometry to be specified and controlled. Furthermore, such models also allow physical or chemical outcome measures to be tracked with a suitable frequency, or indeed

continuously to allow depiction of the physical processes. Unfortunately, discrepancies in the results between *in vitro* or *ex vivo* models and clinical trials may lead clinicians to discount the former as being irrelevant to the complexity of natural systems. The interpretation of data from simple systems and their application to progressively more complex systems require a fundamental scientific insight, in order to achieve a synthesis of outcomes that could model and help explain the physical behaviour in real systems. Nowhere are these problems more evident, and the principles more pertinent, than in the literature on root canal irrigation.

A wide variety of methods using a combination of real, simulated or theoretical canal models have been developed to assess the effectiveness of needle designs and agitation methods. The effectiveness of needle design and placement has been assessed using the fraction of irrigant in the root canal being replaced (Ram 1977), degree of penetration of the irrigant (Goldman *et al* 1976, Khademi *et al* 2006) or removal of canal contents or wall surface coatings as outcome measures. The latter have included flushing out of artificial particles (Chow 1983), debris (Goldman *et al* 1979, Abou-Rass and Piccinino 1982) or bacterial cells (Falk and Sedgley 2005) from the canal space and removal of simulated 'biofilm' (Huang *et al* 2008) and smear layer (Goldman *et al* 1979) from the root canal surfaces. These methods have also been used to measure the effect of different root canal irrigation variables on selected outcomes, including the effect of agitation.

In order to tackle the problem systematically, it helps to visualize the full extent of the root canal system problem in its three-dimensional complexity and scalar dimensions and to resolve it into its simpler component parts. The accuracy of the complex depiction at the one extreme and the resolved simplicity at the other end should improve the probability of revealing innate mechanisms underpinning any interaction between the simpler component parts. As an example, it is thought that agitation encourages the mixing of root canal fluids, allowing freshly injected irrigant to replace the resident fluid already occupying the canal (figures 6 and 7); it may also facilitate penetration of the irrigant into lateral canals and chambers beyond the prepared canal (figure 4). The intended outcome of the agitation should be to disperse newly introduced irrigant throughout the root canal system and also to dilute the resident debris by flushing it out through its displacing motion. The effectiveness of this process will be dependent upon the extent of the fluid volume agitated within the cavity, as well as the transport processes used to place or remove the bolus of fluid. In addition, it is also hoped that the stresses generated by the agitation would encourage the removal of material bound or adherent to the canal walls. Measurement of the ultimate clinical outcomes is insufficient to reveal the processes that lead to the clinical outcomes. It is therefore necessary to specifically identify and demarcate the nature of subordinate physical processes likely to influence and improve the clinical outcomes. In order to achieve this aim, expertise and insight from the physical and engineering sciences can be harnessed to elucidate the nature of fundamental fluid-flow processes inherent in such systems.

4.3. Reported effectiveness of irrigation

There have been many *ex vivo* studies of the effectiveness of different irrigation regimens utilizing various injection needle designs and techniques.

4.3.1. Irrigant introduction. The difficulty in reconciling the outcomes from multiple *ex vivo* investigations is illustrated by the results of four separate studies evaluating the effect of various needle geometries on irrigation effectiveness but using different outcome measures: irrigant penetration (Goldman *et al* 1976); efficacy of bacterial removal (Vinothkumar *et al* 2007);

efficacy of *in situ* smear layer and debris removal (Goldman *et al* 1979) and efficacy of artificial debris removal (Moser and Heuer 1982). Goldman *et al* (1976) found that using a closed-end needle with multiple side-openings (CE-MSO) placed within 2 mm of the apex produced a more widespread and uniform distribution of the irrigant in the canal than using a closed-end needle with a single-side opening (CE-SSO). Consistent with this observation, Boutsioukis *et al* (2009) studied the irrigant flow pattern within a prepared root canal computationally and reported that the irrigant *flow pattern* for the CE-SSO needle was influenced by the flow rate but the irrigant replacement was limited to 1–1.5 mm apical to the needle tip, regardless of the flow rate. Goldman *et al* (1979) used scanning electron microscopy to examine the extent of residual *in situ* smear layer and debris during serial instrumentation of canals in freshly extracted teeth; they concluded that irrigation with the sodium hypochlorite solution using the CE-MSO needle was more effective than using the conventional 23-gauge needle with a BOE. In contrast, using simulated canals, Moser and Heuer (1982) showed that a CE-MSO needle was less effective in removing artificial debris than a SCOE needle, where in both cases the needle was 23 gauge. More recently, Vinothkumar *et al* (2007) apparently contradicted Moser and Heuer (1982) by showing that CE-SSO 25-gauge needles were more effective than CE-MSO or BOE needles in removing bacteria from root canals with a specified size (apical size 0.60 mm; 0.04 taper). The contradictions could be attributed to differences in a number of factors, including test model design, size and taper of the canal, size of needle and the rate of irrigant delivery. Irrigant delivery was standardized at a rate of 0.2 mL s^{-1} by Vinothkumar *et al* (2007) but was unspecified by Moser and Heuer (1982), however, they did report that the average time necessary to empty a 2 to 3 mL syringe with the approximation of the forces used clinically was 60 s, a much slower rate than that used by Vinothkumar *et al* (2007). These examples illustrate the benefit of comprehensive data recording of inherent variables to account for differences, always assuming that the likely influencing factors had been anticipated and incorporated into the study design.

An example of an *ex vivo* study attempting to record data comprehensively is that of Huang *et al* (2008), who undertook a systematic evaluation of the influence of canal size and geometry (apical size 0.20 or 0.40 mm, taper 0.04 or 0.08) and irrigant volume on the fraction of simulated biofilm removed. A CE-SSO needle was used with the direction of the single-side opening location fixed in all the tests on single-rooted extracted teeth with single canals. The bacterial biofilm was simulated using dyed rat-tail collagen (First Link Ltd, Birmingham, UK), which was applied in multiple layers to the root canal walls. The 30-gauge needle was inserted to 4.5 mm short of the root apex and delivered the sodium hypochlorite solution at a rate of 0.1 mL s^{-1}. After every 9 mL of irrigant had been delivered (up to a total of 36 mL), the percentage of the canal surface covered with residual stained collagen was measured from the images. It was found that the efficacy of biofilm simulant removal was improved by increasing the apical size and taper of the canal, the volume of irrigant used and the orientation of the side opening of the needle (Huang *et al* 2008). The percentage of canal surface coverage with residual collagen increased from the apex coronally. Complete removal was not achieved in any of the samples. The finding on the effect of canal preparation size was consistent with the report by Falk and Sedgley (2005) who used the alternative methodology of measuring removal of artificially introduced bioluminescent bacteria from extracted teeth. Using the same test model, Nguy and Sedgley (2006) showed that canal curvature and size also greatly affected irrigation. For canals with a curvature of less than 20°, the canal size had no effect on irrigation efficacy, but this increased significantly with canal size where the canal curvature was between 24° and 28°. In contrast, the efficacy of removal of artificially placed debris in the canal space was not affected by the apical size (0.25 versus 0.40 mm in diameter) of flared canal preparations (Abou-Rass and Piccinino

1982). The features of these studies that allow appropriate interpretation and intuitive synthesis include control of canal topology, the use of a direct physical measurement and the use of an outcome measure (e.g., erosion of the wall-adherent film) that could be tracked over time.

Similar *ex vivo* extracted tooth models have been used to study the effect of commercially available automated systems for introducing irrigants. There is evidence that such automated systems can be superior to the conventional syringe/needle systems for removal of pulp tissue (Braun *et al* 2005), killing of *Enterococcus faecalis* (Muselmani *et al* 2005), removal of dyed collagen film from the canal surface (McGill *et al* 2008) and removal of a smear layer (Fukumoto *et al* 2006). The commercial systems show an improvement in debris removal within 1 mm from the root apex, but there was no observable improvement 3 mm from the apex, as compared to syringe injection (Nielsen and Baumgartner 2007). Again, these studies suffer from the measurement of final effects only and give little direct insight about the processes that could be manipulated to effect improvements. Measurement of the processes may help to decipher the features of the automated systems that confer real benefit and help elucidate the mechanisms involved.

An example of clouded understanding resulting from the lack of such insight into fundamental operating processes is provided by experiments on the assisted introduction of irrigant by the 'non-instrumentation technology' (NIT) developed by Lussi *et al* (1993). This method claimed to deliver the irrigant whilst circumventing the need for mechanical enlargement of the root canal system. The authors recommended irrigation with the sodium hypochlorite solution under alternating pressure fields, which they claimed produced hydrodynamic turbulence that enabled perfusion of even the most minute ramifications of the root canal system. *In vitro* experiments on NIT canal irrigation with the sodium hypochlorite solution of freshly extracted teeth with vital pulps apparently resulted in significantly cleaner apical canals than with dynamic syringe irrigation following conventional canal enlargement (Lussi *et al* 1999). The device is putatively still under development (Lussi *et al* 1995, 1999) and not available for clinical use. There is an absence of any definitive demonstration of the claimed physical processes underlying the observed effect in the published literature and from a physical perspective it would be surprising if the device was indeed able to generate turbulence throughout such a confined system.

4.3.2. Manual agitation. Gu *et al* (2009) have recently reviewed the contemporary irrigant agitation techniques. The simplest method for agitating canal fluid is to introduce an instrument into the canal and to manually redistribute it along the canal with a reciprocating action. Appropriately sized instruments or devices are likely to be readily available in practice at no extra cost. Such agitation of canal irrigant may be achieved using hand files (Cecic *et al* 1984), irrigation needles (Druttman and Stock 1989), 'well-fitting' tapered gutta-percha points (Huang *et al* 2008) or brushes (Gu *et al* 2009).

There is evidence that manual irrigation can be effective. Agitation of the canal irrigant using hand files or irrigation needles removed significantly more test albumin (Cecic *et al* 1984) and allowed better apical irrigant replacement (Druttman and Stock 1989). The notion was reinforced by unpublished data and video footage from simulated canals in clear plastic blocks by Machtou (2003, personal communication), which graphically showed that active irrigation (push-pull reciprocal agitation with a well-fitting, tapered gutta-percha point) can improve the penetration and exchange of irrigant apically as compared to dynamic syringe irrigation. This was confirmed experimentally by Huang *et al* (2008) using a dyed collagen film model where gutta-percha points were typically displaced to within 1 mm of the terminus of the canal and then retracted at a frequency of 1 Hz. Once

practiced, this procedure is neither time consuming nor laborious but may be perceived by busy dentists to be so. It does however have a slightly increased risk of apical extrusion (Alexander *et al* 2010).

4.3.3. Sonic and ultrasonic devices. Automated systems specifically designed for agitation of the irrigant within the root canal system (Gu *et al* 2009) include sonic (Sabins *et al* 2003, Ruddle 2007) and ultrasonic (Cunningham and Martin 1982, Cunningham *et al* 1982, Sabins *et al* 2003) devices. Activation of irrigant with sonic or ultrasonic devices involves the agitation of either a syringe-delivered bolus of fluid in the canal or by simultaneous delivery (via a custom reservoir) and agitation. The sonic devices available for irrigant agitation include the Sonic Air Endo Handpiece (Micromega 1500, Besancon, France) and the EndoActivator® system (Advanced Endodontics, Santa Barbara, CA, USA). The former is driven by air pressure to produce vibration frequencies (manufacturer data: 1500–3000 Hz) and which also drive stainless steel files to aid simultaneous canal preparation and irrigation. The EndoActivator® is electrically driven and is reputed by the manufacturer to work at the much lower frequencies of 33, 100 and 167 Hz but a recent study measured the putative frequencies to be 160, 175 and 190 Hz, respectively (Jiang *et al* 2010). The instrument was designed to use polymer tips of various sizes (ISO size 15, 25, 35) and tapers (0.02, 0.04) for agitation of the irrigant (Ruddle 2007) to avoid the potential risks of instrument separation associated with metal files, ledge formation and canal transportation (Hülsmann and Stryga 1993). Preliminary data on debris and smear layer removal were promising from Ruddle (2007) but conflicting from Uroz-Torres *et al* (2010). The outcome measure of dye penetration into dentinal tubules in the apical 5 mm of the root found ultrasonic activation to be best, manual activation the worst and sonic activation of intermediate value (Paragliola *et al* 2010). Further more systematic research is awaited.

The much higher frequencies of ultrasonic vibration (20–40 kHz) are achieved with either magnetostrictive or piezoelectric devices. *Magnetostrictive transducers* produce an elliptical motion at the working tip, whilst *piezoelectric* transducers produce longitudinal or transverse linear motions (Cracknell 1980). Ultrasonic agitation of irrigant allowed better penetration of irrigant apically than manual syringe irrigation when a viscous irrigant (viscosity approaching 5.8× that of sodium hypochlorite) was used (Teplitsky *et al* 1987). When the irrigant viscosity was close to that of sodium hypochlorite, the benefit from ultrasound was only evident in narrow canals (smaller than ISO size 30), but canal curvature had no influence on irrigant penetration (Teplitsky *et al* 1987). The beneficial effect of higher viscosity irrigants during ultrasonic irrigation was also demonstrated in a preliminary study using the '*ex vivo* dyed collagen film model' (Merivale *et al* 2009) from our group.

A number of approaches have been used to measure the influence of sonic and ultrasonic vibration on irrigation. The outcome measures evaluated have included the visual measurement of mixing, removal of dye from the canal wall, irrigant replacement, irrigant penetration into secondary/accessory canals, removal of artificially placed debris and histological evaluation of residual pulp tissue and residual biofilm.

The efficacy and efficiency of such agitation in removing material at the walls of the canal has been estimated by dyeing the material and measuring the degree of removal. Endosonic irrigation removed dye from canals quickly compared with syringe irrigation (23-gauge needle); the latter was effective in removing all the dye only when the canal was flared and enlarged to an apical size 40 (Teplitsky *et al* 1987). Irrigant replacement was, however, found to be equally and highly effective regardless of whether syringe (27-gauge needle), sonic (Micromega 1500) or ultrasonic (Electro-magnetic device, Cavi-Endo) irrigation was used in canals of size 30 or 35 (Kahn *et al* 1995). As expected, irrigant replacement in

simulated canals within resin blocks could be improved by increasing the number of ultrasonic file activation cycles (Druttman and Stock 1989).

An electrochemical approach has also been used to measure the extent of irrigant penetration into secondary canals (Nanzer *et al* 1989). The study model used transparent acrylic cells with a main cylindrical canal and secondary horizontal or inclined canals branching off at various levels. Electrolyte was introduced into the canal and agitated by an ultrasonically activated file. The transfer of ions by diffusion and convection due to ultrasonic agitation from the bulk of electrolyte to the electrodes embedded in the secondary canals was measured. Preliminary data showed that the propagation of ultrasonic waves into lateral canals was greatly hindered by the inclination of the lateral canals, and irrigation apical to the file extremity was poor as no convection was induced in the vertical direction (Nanzer *et al* 1989). This study provides an example of laboratory simulation that requires extrapolation of the results to a clinical scenario. An actual study evaluating similar parameters but using the outcome measure of dissolution of bovine pulp tissue placed into simulated accessory canals resulted in contradictory findings; ultrasonic agitation of the sodium hypochlorite solution in the main canal was effective in dissolving the pulp tissue regardless of the position and angulation of the accessory canals (Al-Jadaa *et al* 2009). The contradictory findings may only be reconciled through an understanding of the physical processes inherent in ultrasonic agitation of the fluid *in situ*.

Recently, extracted tooth and simulated plastic root canal models were designed by Wu and Wesselink's group to specifically investigate the factors influencing the efficacy of debris removal using ultrasonic irrigation (Lee *et al* 2004a, 2004b, van der Sluis *et al* 2005a, 2005b, 2006). Removal of artificially created dentine debris placed in simulated un-instrumented extensions and irregularities in straight, wide root canals was found to be significantly more effective with ultrasonic irrigation than with dynamic syringe irrigation (27-gauge needle at 2 mm short of the apical foramen) using 50 mL of 2% sodium hypochlorite solution (Lee *et al* 2004a). Canal taper (van der Sluis *et al* 2005b) and mode of irrigant delivery (continuous delivery through the ultrasonic device or intermittent delivery through the hand syringe) (van der Sluis *et al* 2006) were found to have no significant influence on the efficacy of artificial debris removal. However, the volume of irrigant used was different rendering any direct comparison of the two modes of delivery inconclusive. In contrast, Lee *et al* (2004b) found that ultrasonic irrigation removal of artificially placed dentine debris from simulated resin canals (apical size 20) was significantly improved with a larger canal taper. The precise reasons for the contradictory findings are not clear but may be attributed to the difficulty of controlling the size and shape of canals in real teeth, which have enormously variable canal anatomy. The efficacy of debris removal from simulated resin canals was not influenced by the surface configuration (smooth or fluted) of the ultrasonically activated k-file (van der Sluis *et al* 2005a), in agreement with a similar *ex vivo* study (Munley and Goodell 2007).

One group (Meyers, Beck and Reader) has perfected the use of histological evaluation of extracted mesial roots of mandibular teeth to evaluate the role of irrigation regimens in removal of residual pulp tissue and dentine debris from the apical parts of canal systems and their isthmuses. A series of studies have demonstrated the efficacy of various ultrasonic activation regimens (Goodman *et al* 1985, Lev *et al* 1987, Hiadet *et al* 1989, Archer *et al* 1992, Gutarts *et al* 2005, Burleson *et al* 2007).

The efficacy of removal of root canal bacteria using ultrasonic agitation has been compared with syringe irrigation in an *in vitro* study (Briseno *et al* 1992), where it was significantly more effective, and in a randomized controlled clinical trial (Carver *et al* 2007), where in contrast, it was significantly less effective. As previously explained, the contradictory findings could be attributed to the difficulty in controlling the many different variables inherent in the two

different study types. The innate differences may be enumerated as follows: the nature of root canal infection (artificial versus real); the concentration of the sodium hypochlorite solution (1–2% versus 6%); the type of ultrasonic instrument (25 k-file versus 25-gauge needle); the duration of ultrasonic activation (20 versus 60 s) and the type of ultrasonic machine (electro-magnetically driven Cavi-Endo unit versus piezo-electrically driven Mini-Endo unit). A further study using the same outcome measure but different interventions revealed no significant difference in the efficacy of bacterial elimination when comparing ultrasonic with manual file agitation of sodium hypochlorite irrigant (Siqueira *et al* 1997).

5. Application of physical principles to clinical procedures

Clinical trials and laboratory (*ex vivo* and *in vitro*) experiments are both important and complementary in providing evidence for the development of good clinical practice. However, bridging the gap between the relatively uncontrolled clinical scenario (with the possibility of unmeasured factors) and the definitively controlled *in vitro* experiments may prove a challenge as demonstrated above. The gap between these study types may be bridged by a further class of experiments that reveal the underlying physical processes; in the case of the problem under discussion, this means the nature of the flow field within the root canal system. These often require further abstraction of the clinical setting and the isolation of the physical processes that dominate the flow field. This allows a general model of these processes to be built up and then applied to particular circumstances. Techniques for this approach include use of (a) scaled laboratory experiments; (b) computational fluid dynamics (CFD) and (c) analytical models or scaling analysis. The behaviour predicted by such models may be validated in controlled *in vitro* and *ex vivo* experiments. Such validated outcomes should allow extrapolation to realistic, clinical situations and prediction of the likely outcome of different interventions. In addition, they should also allow interpretation of the outcomes of clinical and *ex vivo* trials.

There is a large body of well-tested techniques for modelling flow situations to both understand flows and refine experiments. In particular, the use of scale models to measure complex flow fields round engineering objects is very well developed (e.g. White 1999, Douglas 1969). The value of the use of scaled models is that measurements become practically possible. The models are easier to construct to specification and instrument, and allow the flow field to be visualized and measured. Model testing relies on dynamic similarity, which allows the scale-up of the experiments from the size of the tooth to a larger size. The process requires not only the physical form of the root canal to be scaled, but also the non-dimensional groups controlling the behaviour to be identical in the scaled-up experiment.

A particularly important non-dimensional number is the Reynolds number,

$$Re = \frac{\rho U L}{\mu}, \tag{1}$$

where ρ is the density of a fluid, μ its viscosity, U its velocity and L is a characteristic length scale. It expresses the ratio of inertial forces to viscous forces. So, flows with low Reynolds numbers are dominated by viscous forces and are laminar in nature, whilst those with high Reynolds numbers, by the effects of mass are turbulent in nature. In an experimental model of a root canal, it is possible to preserve the right balance between inertial and viscous forces when the Reynolds numbers of the irrigant in the root canal and the scaled-up experimental tube are matched; the increase in scale results increases L, and this can be compensated for by ensuring that the fluid in the experiment has a higher viscosity compared with the root canal irrigant or the average flow speed, U, is reduced.

Mixing, in a broad sense, describes the spreading of an initial patch of material over a larger area. This can also be broadly characterized by the dimensionless group, the Peclet number, defined by

$$Pe = \frac{UL}{D_M}, \tag{2}$$

where $D_M \sim 10^{-8}$ m^2 s^{-1} is the molecular diffusivity of sodium hypochlorite, L is a characteristic length scale and U is a characteristic velocity scale. This is the ratio of mechanical mixing of newly introduced fluid (i.e. it is physically mixed with the existing fluid by the flow field) to molecular diffusion; so, for high *Pe,* mixing is mediated through the displacement of the irrigant by stretching and folding, which leads to the spread of the fresh irrigant over a greater volume, while for low $Pe(<1)$, diffusion is important and the effect of advection weak.

In many applications, the mixing of fluids is achieved by generating high Reynolds numbers so that turbulence is produced, and this generates a flow field that promotes mixing and achieves high Peclet numbers. At low *Re* and high *Pe*, turbulence is not generated, and material distant from the boundaries of the space is passively advected by the streamlines. This type of agitation is reversible such that a blob of dyed liquid is stretched out when the fluid is moved, but if the fluid movement is reversed, the blob will be retrieved; the fluid is therefore ineffectively mixed (a striking demonstration of this can be seen in the film by Taylor (1967)). For mixing to be effective in viscously dominated systems, the fluid flow needs to be unsteady, so that the fluid tracks at different times look different and cross each other (Sturman *et al* 2006). This can be achieved by the performance of a series of transformations on the bolus so that it is drawn into a filament, distorted, folded or cut (e.g., the 'baker's transformation'). Several of these operations repeated in succession should result in a well-mixed system. Such mixing is irreversible and known as chaotic mixing because the path of any portion of fluid within a mixing region is sensitive to its initial position. It is possible for unsteady flows to have some regions that are well mixed and others that are not (Sturman *et al* 2006). Mechanical methods for the introduction of irrigant, such as the RinsEndo®, may generate an unsteady flow field in the root canal, allowing mixing between the new irrigant and the resident canal fluid, which is in contrast to the scenario with straightforward injection.

The effect of boundaries is important for mixing, especially for high *Pe*. Owing to the action of friction, at a solid boundary the fluid velocity is zero. Because of this, in confined channels large velocity gradients (or shear) can be generated in a fluid flow. The effect of shear is to enhance cross-stream diffusion so effectively that the longitudinal dispersivity is dominated by diffusion. In the limit of large *Pe*, this results in an effective streamwise diffusivity, that is D_M/Pe, which is much larger than D_M. This process is called the Taylor–Aris dispersion (Stone and Brenner 1999). There are many engineering approaches to mixing fluids in small cavities so that *Re* is small, but most rely on designing the walls of the channel to encourage chaotic mixing (e.g. Liu *et al* 2000). However, this method has limited application for root canal systems, so unsteady flow fields have to be generated by other means, either through the delivery of the irrigant or by its agitation by tools.

5.1. Delivery of irrigant

Figure 6(a) shows a schematic diagram of the injection of irrigant through a needle into a slowly tapering root canal. The canal radius at the end of the needle is defined as D and U_N is the average liquid speed in the needle:

$$U_N = \frac{4Q}{\pi d_I^2}, \tag{3}$$

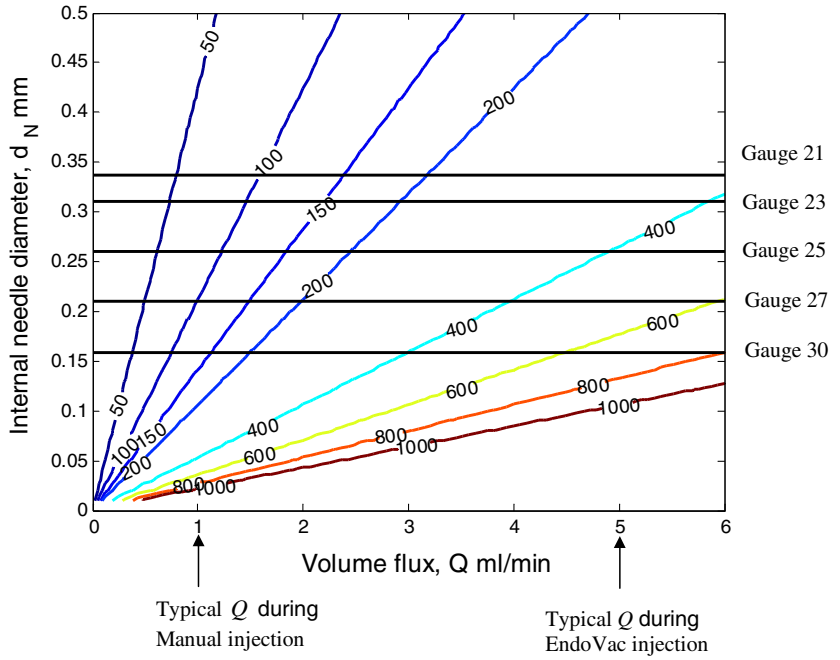

Figure 8. Contour plot (generated using MatLabs Contour Command) showing the variation of Reynolds number Re_N (equation (7)) with internal needle diameter d_N and volume flux of irrigant (Q mL s^{-1}).

where Q is the injection rate of the irrigant and d_I is the internal diameter of the needle. By considering the parameters that are available to affect mixing,

$$Pe = f(\alpha, Re), \tag{4}$$

where α is the relative size of the needle to the canal hole and geometry of the needle tip,

$$\alpha = \frac{D - d_E}{D} \tag{5}$$

and the needle Reynolds number is

$$Re_N = \frac{U_N d_I}{\upsilon}, \tag{6}$$

where $\upsilon = \mu/\rho$ is the kinematic viscosity of the fluid, U_N is the average velocity of the irrigant in the needle and d_E is the external diameter of the needle. Combining (3) and (4), we have

$$Re_N = \frac{4Q}{\pi d_I \upsilon}. \tag{7}$$

The variation of Re_N with the internal needle diameter and injection flux is shown in figure 8. For a 30-gauge needle, recommended manual injection rates give an approximate value of $Re_N \sim 150$, while for automated injection, this increases to $Re_N \sim 1500$. For continuous injection, fresh irrigant largely displaces the irrigant–debris mixture. The physics of mixing changes with Reynolds numbers. Typically, for $Re_N \sim O(100)$, the mixing is expected to be relatively weak with the transport tending to be through advection, except in certain circumstances, as discussed later. When Re_N is typically large, the flow at the exit of the needle is likely to be unsteady and may even be on the verge of being turbulent, though the

flow within the needle and that exhausting up the canal is likely to be steady and laminar. The effect of additives to the irrigant is usually to increase its viscosity and so reduce its Reynolds number. Surfactants have also been added to the irrigant and have been found to improve the efficacy of simulated-biofilm removal (Merivale *et al* 2009). Since surfactants tend to affect the interface between air and irrigant, it is more likely that any positive effect on biofilm removal was either through their chemical action on the biofilm or through the presence of thickeners, which increase irrigant viscosity.

A well-designed needle would perform several functions, including (a) ensure that the irrigant penetrates as far as possible into the root canal system; (b) exert large shear stresses on the canal walls, to remove adherent smear layer, debris or biofilm and (c) efficiently flush out debris from the canal space. Physical, life-sized models of root canals can be made to examine the flow field generated during the injection process, but it can be difficult to manufacture them accurately and take measurements of the flow field. These difficulties can be avoided through the use of scaled-up models. Some illustrative examples are presented here for 20 mm holes drilled in polycarbonate to represent the canal where scaled-up needles ($d_{\mathrm{I}} = 8$ mm, $d_E = 12$ mm) are used for delivery of water as the working irrigant into them. The injection volume flow rate through the needle was controlled to obtain $Re = 265$. Further insight was obtained from computational fluid dynamics (CFD) using conservation equations for a Newtonian fluid.

5.1.1. Irrigant penetration. A common feature of all these flows is the presence of a stagnation plane, a distance d_S from the needle tip, beyond which fresh irrigant will not penetrate after injection. Figure 8 shows the effect of injecting fresh irrigant into a simulated root canal at $Q = 0.02$ mL s^{-1} using a gauge 30 ISO needle.

The presence of the stagnation plane is anticipated even for extremely slow flows ($Re_N \sim 1$) and is an example of Moffatt's corner vortices (Moffatt 1964). Blake (1979) examined the forcing of a Stokes flow in a circular cylinder and showed the presence of a series of viscous toroidal eddies rotating in alternate directions, with a stagnation plane lying at a distance $d_S/D \sim 0.5$ from the forcing. The velocity decreases so quickly with distance from the end of the needle that the series of re-circulating vortices usually cannot be identified experimentally. This anticipated result was reflected in a study measuring the efficacy of replacing a radio-opaque (Hy-Paque—50%) solution in root canals of human extracted teeth (Ram 1977). Teeth filled with a radio-opaque solution were irrigated once with 5 mL of a saline solution through a syringe with a 25-gauge needle placed loosely within the coronal third of the canals. It was found that the irrigation left the apical half of most canals (diameter 0.25 mm) undisturbed, although increasing irrigation time and pressure caused an additional 2 mm of the radio-opaque solution to be replaced. In contrast, the radio-opaque solution in wider canals of 0.4 and 0.6 mm diameter was mostly completely replaced.

Figure 9(a) shows a photograph of the four scaled-up needle types used to simulate the flow in a scaled-up model of the root canal. The experimental study consisted of a vertical needle located in a cylindrical root canal. Two projected views were taken as a function of time. The intensity of each image in figure 9(b) represents the integrated effect of dye on a diffuse light source behind the transparent root canal. The stagnation plane beneath the needle end is evident where $d_S/D = 6$, 4, 3.5 and 2.3 (for i, ii, iii and iv, respectively). In order of increasing d_S/D (for fixed Q), these physical analogue experiments indicate that in terms of irrigant penetration, the flat open-ended (FOE) needle is the best, followed by the BOE, SCOE and CE-SSO needle designs. The needle sides for the BOE and SCOE designs have a tendency to reduce the momentum of the flow along the canal and reduce d_S/D as compared to the flat open-ended (FOE) needle. The CE-SSO needle generates the shortest penetration distance beyond the needle end, though these differences are not considerable. Since neither

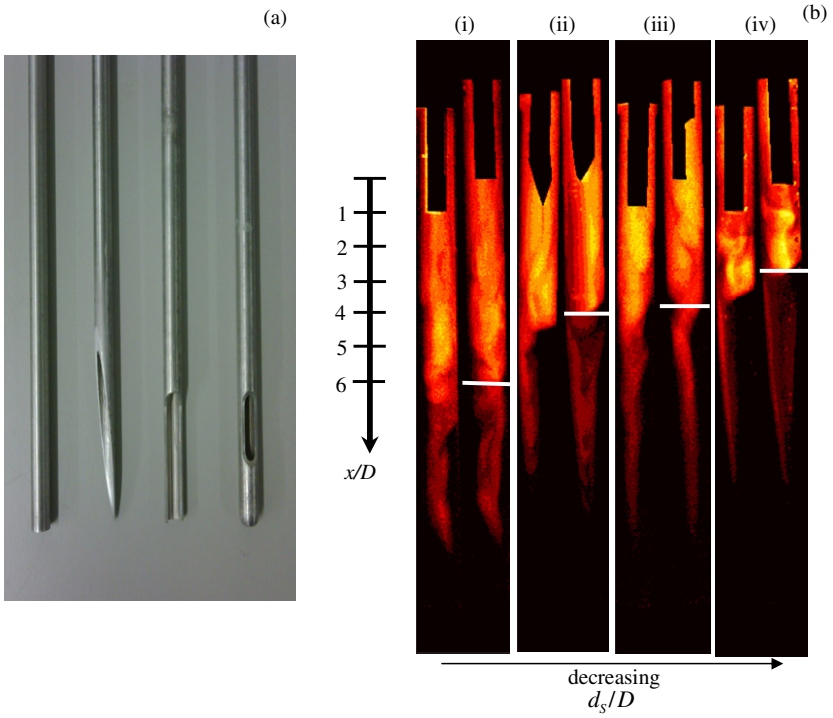

Figure 9. (a) Needle types used in a scaled laboratory experiment and (b) experimental observations of the injection of dye into a model root canal. The colour corresponds to the attenuation of the image due to the presence of dye. Two perpendicular projected views are shown. The white horizontal line shows the position of the stagnation plane for (i) flat open-ended (FOE) needle, (ii) bevelled open-ended (BOE) needle, (iii) side-cut open-ended (SCOE) needle and (iv) closed-end single side-opening (CE-SSO) needle.

the flat open-ended or BOE needles are contemporarily recommended for use in root canal treatment, the SCOE needle gives the best performance in terms of d_S/D. Reducing the length of the cut would have a tendency to increase d_S/D, as well as placing the side opening much closer to the end of the needle.

Investigation of fluid flow using the CFD approach has been recently applied to study root canal irrigation. Boutsioukis *et al* (2009) examined the flow generated by an ISO 30-gauge needle penetrating a canal. The geometry of the needle used was taken from measurements of a needle type used in practice. They considered flow rates from $Q = 0.02$– 0.79 mL s^{-1}, though the higher flow rates are rarely used in clinical practice. Their results also demonstrate the presence of a stagnation plane beyond the end of the needle, but in their simulations this distance was $d_S/D \sim 1$–1.2 (case *A*–*C*, in Boutsioukis *et al* 2009 notation). As a demonstration of this investigation method, figure 10 shows the simulated flow by the authors through a flat open-ended needle with the same geometry as the laboratory experiments for $Re_N = 100$ and 200. The numerical calculations were undertaken using CFX 5.0 (CFX Ltd, UK) at a resolution of 1 million nodes to calculate the steady axisymmetric flow due to needle injection into a cylindrical cavity. The geometry of the needle and canal were the same as the experimental study shown in figure 9. The stagnation plane is indicated as $d_S/D = 3.5$ and 6 for this range, which is comparable to the experimental measurements. This distance is much larger than $d_S/D \sim 1 - 1.2$ for side hole injection as calculated by Boutsioukis *et al* (2009), though their

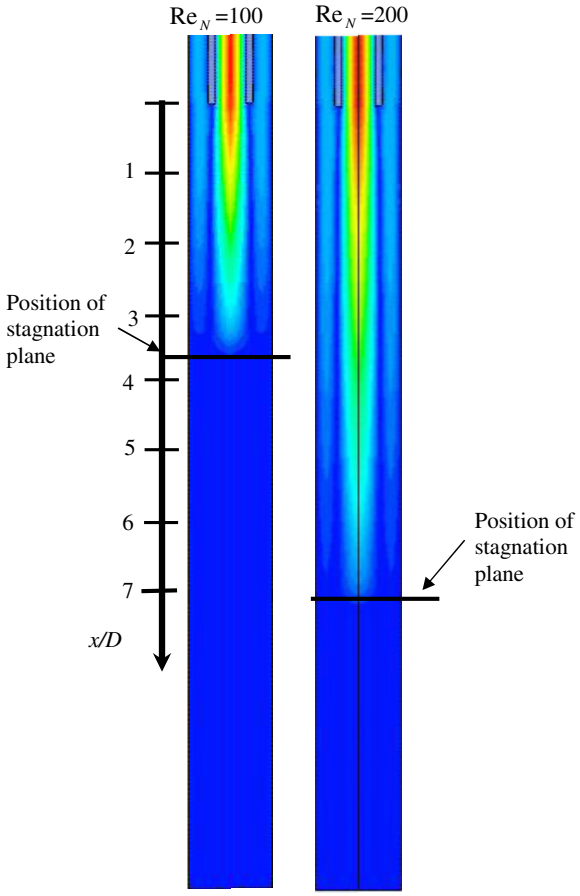

Figure 10. Isocontours of the fluid speed from a CFD calculation of the flow in a needle and root canal. The needle geometry is a straight needle type with flat open end (FOE). The position of the stagnation plane is shown for $Re_N = 100$ and 200.

needle was more loosely fitted in the canal ($d_E/D = 0.49$ rather than 0.60) and the exit hole of their needle was at a considerable distance from the needle tip.

5.1.2. Wall shear stress. Clinically, it is likely that the biofilm and smear layer are removed both by the chemical action and physical action of shear stress on the canal wall generated by fluid flow during irrigation. Wall shear stress is a difficult parameter to measure directly, but will depend on the flow velocity gradient at the wall. The order of magnitude of the shear stress on the canal wall exerted by the flow along the canal can be estimated using lubrication analysis. The shear stress for a Newtonian fluid is defined by

$$\tau = \mu \frac{\partial u}{\partial y}, \tag{8}$$

where the differential is evaluated on the root canal wall. The shear stress scales as

$$\tau \sim \mu \frac{Q}{\pi D(D - d_E)^2}, \tag{9}$$

and is estimated to lie in the range ~0.001–0.01 Pa for a flow rate of 0.02–0.2 mL s^{-1}. This indicates that the shear stress along the canal wall is quite small and is consistent with the clinical experience that fluid delivery by injection does not typically lead to biofilm or smear layer removal. It is possible to increase the shear stress by concentrating the flow against the wall, and generating high local velocity gradients; so, out of the four needle designs shown in figure 9, the side opening needle has been found to be experimentally effective in removing biofilm in the area adjacent to the side hole (Huang *et al* 2008). Designs that use multiple small holes (Goldman *et al* 1976) rather than a single large opening can generate faster flow through these nozzles and will tend to increase the shear stress on the canal wall and improve biofilm and smear layer removal; however, the addition of side ports will also dramatically reduce d_S/D (figure 9(b, iv)).

5.1.3. Irrigation replenishment. It is important that a large portion of the body of irrigant within the root canal system is replenished. It is therefore desirable to transport the irrigant from the coronal and central regions of the canal to its perimeter and the apical regions. Fluid moves relatively slowly in regions adjacent to the rigid walls, where the non-slip condition is applied, and so though debris is removed, fresh irrigant would only reach the walls through diffusion after a finite period of time. Even if the flow is inertially dominated and unsteady near the end of the needle, it will tend to be laminar along the canal wall. Assuming the flow is approximately parabolic between the needle and a cylindrical canal wall, to replenish a fraction $\beta = 99\%$ of the irrigant requires the layer of resident irrigant to have a thickness $\delta \sim (1-\beta)(D-d_E)$. This requires a volume

$$Qt = \frac{L\pi D(D-d_E)^2}{\delta} \approx \frac{L\pi D(D-d_E)}{1-\beta} \tag{10}$$

of irrigant to be injected. For low flow rates, this volume is independent of the rate of injection and is estimated to be 100 times the root canal volume or about 1 mL.

5.2. Agitation of irrigant

Analysis of the fluid mechanics shows that fresh irrigant injected into the root largely displaces resident irrigant within a displacement d_S below the end of the point of injection. Mixing of new irrigant and the liquid within a root canal can be achieved through diffusion, which takes a long time, and advection, which is confined only to the upper reaches of the canal if only injection is relied upon. Further mixing is encouraged either manually, through the application, or automatically using sonic and ultrasonic devices, but there has been little research on the mixing that occurs due to agitation in the dental field.

5.2.1. Manual agitation. Agitation by push-pull reciprocating movement of an instrument may be undertaken using hand files (Cecic *et al* 1984), irrigation needles (Druttman & Stock 1989) or 'well-fitting' tapered gutta-percha points (Huang *et al* 2008). The key aspect is that the instrument used must be tightly fitted when pushed into the hole and close to the end of the canal (Yu 2007). If the end of the canal was not close to the tip of the moving instrument or the instrument was not tightly fitted, then the instrument would merely pull liquid up and down in a reversible manner; however, when the instrument tightly fits, it forces liquid to be displaced down the tube where, if it is unable to be extruded through the canal terminus due to tissue pressure, it moves sideways and upwards through the gap between the instrument and the canal wall. It is the latter motion that generates the mixing.

This process for causing mixing can be illustrated by considering the use of a gutta-percha cone to agitate the irrigant in the canal, as shown in figure 7(b). Using this form of a circular cone, it is possible to explain some of the physical processes when it is reciprocated along the length of the root canal. The vertical movement of the conical agitator (of angle α) generates a mean flow:

$$\overline{U} = \frac{(x - l_N)^2 U_A}{l_N(2x - l_N)} \tag{11}$$

a distance $x > l_N$ from the end of the root canal, and $\overline{U} = 0$ for $x < l_N$, below the end of the agitator. The shear at the distance x from the end of root canal scales as

$$\frac{\overline{U}}{(x - l_N)\tan\alpha} \tag{12}$$

and is extremely large along the entire fluid column between the cone and the root canal wall. The Peclet number in this situation is given by

$$Pe \sim \frac{U_A(x - l_N)^3 \tan\alpha}{l_N(2x - l_N)D_I}. \tag{13}$$

This may have a high value, but this is deceptive because in the absence of diffusion, the discharged irrigant would be merely moved up and down the root canal. However, the high shear accentuates the effects of diffusion by giving rise to the Taylor–Aris dispersion. The parabolic shear profile causes an enhancement of mean streamwise diffusion with the effective Peclet number becoming

$$Pe_E = \frac{Pe}{1 + Pe^2/210} \tag{14}$$

(from Stone and Brenner (1999)).

The value of this effective Peclet number (13) is quite small, showing that the role of the cone is to enhance diffusion and therefore mixing between the fresh and resident irrigants.

The second important effect of the generation of high velocity gradients by the confined channel between the cone and the canal wall is the high shear stresses that result. The shear stress on the wall caused by the cone scales as

$$\tau \sim \frac{\mu(x - l_N)\,U_A}{l_N(2x - l_N)\tan\alpha} \sim \frac{\mu U_A}{2l_N \tan\alpha}. \tag{15}$$

For typical values of $U_A \sim 0.02$ m s^{-1}, $l_N \sim 10\ \mu$m, $\alpha \sim 0.04$, the shear stress on the root canal wall is $\tau \sim 20$ Pa. This is more than three orders of magnitude greater than that generated by fluid injection and is therefore much more likely to be effective at removing the biofilm from the canal wall.

5.2.2. Sonic and ultrasonic agitation. Sonic and ultrasonic instruments are used to 'activate' the irrigant *in situ* in the canal. The numerous studies on ultrasonic irrigation have produced conflicting data (van der Sluis *et al* 2007). Two potential physical mechanisms underlying the effect of ultrasonic debridement of root canal systems have been investigated using a photometric system, cavitation and acoustic micro-streaming (Ahmad *et al* 1987a). Cavitation is the generation of vapour within a fluid owing to a drop in pressure; however, the findings suggested that transient cavitation was unlikely to play a role in canal cleaning (Ahmad *et al* 1987a). Nevertheless, Shrestha *et al* (2009) explored the possibility of utilizing such collapsing cavitation bubbles generated by high-intensity focused ultrasound to deliver antibacterial nanoparticles into dentinal tubules.

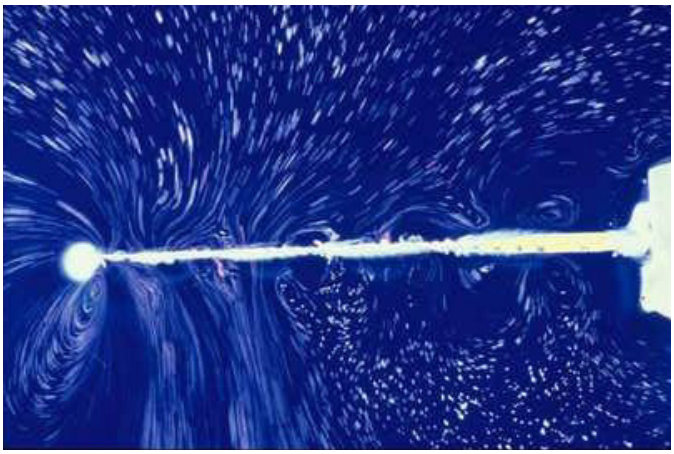

Figure 11. Ultrasonic agitation of a file at 30 000 Hz. The streaming flow set up by the motion of the file is visualized by placing the file just below a free surface on which white tracer particles are suspended. The streak patterns are seen through the long exposure time of the camera. It is uncertain, what sort of streaming patterns might develop in the constrained environment of the apical part of root canal anatomy.

Acoustic streaming is the bulk movement of a liquid, generated when pressure waves are projected through it. It can have many origins, but the main component is often generated by the dissipation of acoustic energy owing to the viscosity of the fluid, particularly close to solid boundaries (Lighthill 1978). Ahmad *et al* (1987a) proposed that acoustic micro-streaming is potentially the main mechanism involved in effecting canal debridement, and it is influenced by the size of the file and the ultrasonic power output (Ahmad *et al* 1987b). The findings of Ahmad *et al* (1987a, 1987b) were based on the nature of file oscillation in air or when submerged in large volumes of fluids and there is an absence of insight into the nature of fluid movement generated by acoustic instruments within the confined root canal system.

The use of a sonic or ultrasonic agitator has a number of different fluid mechanical aspects. First, the agitation of an instrument (perpendicular to its axis) generates a streaming motion with a thin boundary layer whose thickness scales as

$$\delta \sim (\nu/f)^{1/2}, \tag{16}$$

where f is the frequency of vibration of the instrument (Batchelor 1967, p 354). This gives a boundary layer thickness of 30 to 5 μm for $f = 1000$ to 30 kHz. The thin boundary layer and the streaming motion combine to generate a large shear stress on the surface of the instrument and root canal wall, which scales as

$$\tau \sim \frac{\mu f \varepsilon^2}{d_A \delta}, \tag{17}$$

where ε is the displacement of the agitator and d_A is the diameter of the agitator (see equation (2) from van der Sluis *et al* 2007). For typical values, this gives $\tau \sim O(10)$ Pa, indicating that ultrasonic agitation generates a significant shear stress on the walls of the root canal. This is supported by the clinical observation that ultrasonic agitation of the irrigant may be effective in helping dislodge a simulated biofilm or a smear layer. The dissipation within the flow caused by the movement of the instrument generates heat, which has been observed to locally increase the fluid temperature from 37 to 45 °C (van der Sluis *et al* 2007). This

increase in temperature may result in increased effectiveness of the sodium hypochlorite in dissolving organic matter.

The ultrasonic agitation of the instrument also generates a large-scale streaming pattern, as shown in figure 11. Since the dissipation caused by the ultrasonic agitation of the instrument decreases with the local radius of the instrument (which is usually tapered), the tip tends to have the largest displacement and generates the largest shear stress. The streaming flow at the end of the instrument can penetrate into the region of spent resident irrigant located at the apical portion of the root canal system and it is this that is likely to play an important role in debriding the biofilm-infected apical anatomy. If the instrument is constrained and confined in its oscillation, then it is unlikely that this process would occur.

6. Conclusions

Despite the significant advances in root canal treatment, there remains a lack of clarity about the mechanisms of irrigant delivery, replenishment, mixing, flushing and wall erosion. This review attempts to demonstrate how knowledge of the physical processes in fluid movement within root canal systems may help interpret and better explain the outcomes of *ex vivo,* microbiological and clinical studies.

The existence of a stagnation plane beyond which the irrigant cannot pass has been observed in many clinical studies but never has been so defined. The identification of the phenomenon opens the possibility of solutions to the problem; for example, the distance between the stagnation plane and the needle tip can be controlled through needle tip design, fluid flow rate and the relative size of the needle to the canal hole. Furthermore, the low Reynolds number within the root canal system helps explain the poor mixing of freshly delivered and debris-laden, spent, resident irrigant. Recognition of the physical processes allows a better understanding of why the long established clinical procedures of 'recapitulation' and 'patency filing' help achieve fluid mixing, and therefore prevent canal blockage. This simple but little regarded step in root canal treatment emerges as the single most important operator action influencing the outcome of established root canal treatment procedures. Mass dispersal of irrigant may also be effected by agitation of the irrigant with a well-fitting gutta-percha cone or by the medium of a sonically or ultrasonically activated instrument.

Since the key problem in root canal treatment is removal of a surface-adherent bacterial biofilm, which is not reached with the same degree of ease and access as that of plaque on the external surface of the tooth by a toothbrush, the action of instruments and fluids is critical. Yet, direct injection of fluids into the canal is unlikely to effect biofilm removal. However, the use of side-opening needles may be more effective than end-opening needles because the Reynolds number is higher at the exit of the side opening of a needle tip and the shear stress opposite the outlet much higher than for other needle designs. Needles with multiple openings around the circumference of the needle may provide a means to improve biofilm removal. The reciprocating action of a well-fitting cone not only enhances mixing of the fluid in the canal but also increases significantly the shear stress on the canal wall. Sonic or ultrasonic agitation of the fluid through unconstrained file oscillation can generate large shear stresses on the canal surface and streaming flow inside the root canal. The additional effect of the increased sodium hypochlorite solution temperature as a function of ultrasonic agitation may potentially also lead to increased tissue or bacterial dissolution.

This review has highlighted some of the physical processes that may help elucidate root canal irrigation but much work remains to validate analytical and numerical models of fluid behaviour, as well as considering the effects of chemical dissolution on viscosity and fluid

flow. These models may then be extended to the scale of teeth and tested through clinical trials, allowing more effective treatments to be devised.

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References

Abou-Rass M and Piccinino M V 1982 The effectiveness of four clinical irrigation methods on the removal of root canal debris *Oral Surg.* **54** 323–8

Ahmad M, Pitt Ford T R and Crum L A 1987a Ultrasonic debridement of root canals: an insight into the mechanisms involved *J. Endod.* **13** 93–101

Ahmad M, Pitt Ford T R and Crum L A 1987b Ultrasonic debridement of root canals: acoustic streaming and its possible role *J. Endod.* **13** 490–9

Alavi A, Opasanon A, Ng Y-L and Gulabivala K 2002 Root canal anatomy of Thai mandibular molars *Int. Endod. J.* **35** 478–85

Alexander I, Palmer G, Mordan N, Gulabivala K and Ng Y-L 2010 Development of an *in vitro* model to evaluate the effect of mode of irrigation on apical extrusion *Int. Endod. J.* **43** 829

Al-Jadaa A, Paqué F, Attin T and Sehnder M 2009 Necrotic pulp tissue dissolution by passive ultrasonic irrigation in simulated accessory canals: impact of canal location and angulation *Int. Endod. J.* **42** 59–65

Archer R, Reader A, Nist R, Beck M and Meyers W J 1992 An *in vivo* evaluation of the efficacy of ultrasound after step-back preparation in mandibular molars *J. Endod.* **18** 549–52

Baker N A, Eleazer P D, Averback R E and Seltzer S 1975 Scanning electron microscopic study of the efficacy of various irrigating solutions *J. Endod.* **1** 127–35

Basrani B R, Manek S, Sodhi R N, Fillery E and Manzur A 2007 Interaction between sodium hypochlorite and chlorhexidine gluconate *J. Endod.* **33** 966–9

Batchelor G K 1967 *An Introduction to Fluid Dynamics* (Cambridge: Cambridge University Press)

Baumgartner J C and Cuenin P R 1992 Efficacy of several concentrations of sodium hypochlorite for root canal irrigation *J. Endod.* **18** 605–12

Bergenholtz G 1974 Microorganisms from necrotic pulp of traumatized teeth *Odontol. Revy* **25** 347–58

Biffi J C G and Rodrigues H H 1989 Ultrasound in endodontics: a quantitative and histological assessment using human teeth *Endod. Dent. Traumatol.* **5** 55–62

Bjørndal L and Reit C 2005 The adoption of new endodontic technology amongst Danish general dental practitioners *Int. Endod. J.* **38** 52–8

Blake J R 1979 On the generation of viscous toroidal eddies in a cylinder *J. Fluid Mech.* **95** 209–22

Boutsioukis C, Lambrianidis T and Kastrinakis E 2009 Irrigant flow within a prepared root canal using various flow rates: a computational fluid dynamics study *Int. Endod. J.* **42** 144–55

Boutsioukis C, Lambrianidis T, Kastrinakis E and Bekiaroglou P 2007a Measurement of pressure and flow rates during irrigation of a root canal *ex vivo* with three endodontic needles *Int. Endod. J.* **40** 504–13

Boutsioukis C, Lambrianidis T and Vasiliadis L 2007b Clinical relevance of standardization of endodontic irrigation needle dimensions according to the ISO 9626:1991 and 9626:1991/Amd 1:2001 specification *Int. Endod. J.* **40** 700–6

Boykin M J, Gilbert G H, Tilashalski K R and Shelton B J 2003 Incidence of endodontic treatment: a 48-month prospective study *J. Endod.* **29** 806–9

Braun A, Kappes F and Jepsen S 2005 Efficiency of a novel rinsing device for the removal of pulp tissue *in vitro* (abstract) *Int. Endod. J.* **38** 923

Briseno B M, Wirth R, Hamm G and Standhartinger W 1992 Efficacy of different irrigation methods and concentrations of root canal irrigation solutions on bacteria in the root canal *Endod. Dent. Traumatol.* **8** 6–11

Brown D C, Moore B K, Brown C E and Newton C W 1995 An *in vitro* study of apical extrusion of sodium hypochlorite during endodontic canal preparation *J. Endod.* **21** 587–91

Bryce G, O'Donnell D, Ready D, Ng Y-L, Pratten J and Gulabivala K 2009 Contemporary root canal irrigants are able to disrupt and eradicate single- and dual-species biofilms *J. Endod.* **35** 1243–8

Buchanan S L 1991 Cleaning and shaping the root canal system ed S Cohen and R C Burns *Pathways of the Pulp* 5th edn (St Louis, MO: Mosby) chapter 7 pp 166–89

Bui T B, Baumgartner J C and Mitchell J C 2008 Evaluation of the interaction between sodium hypochlorite and chlorhexidine gluconate and its effect on root dentin *J. Endod.* **34** 181–5

Burleson A, Nusstein J, Reader A and Beck M 2007 The *in vivo* evaluation of hand/rotary/ultrasound instrumentation in necrotic, human mandibular molars *J. Endod.* **33** 782–7

Byström A, Claesson R and Sundqvist G 1985 The antibacterial effect of camphorated paramonochlorophenol, camphorated phenol and calcium hydroxide in the treatment of infected root canals *Endod. Dent. Traumatol.* **1** 170–75

Byström A and Sundqvist G 1981 Bacteriologic evaluation of the efficacy of mechanical root canal instrumentation in endodontic therapy *Scand. J. Dent. Res.* **89** 321–8

Byström A and Sundqvist G 1983 Bacteriologic evaluation of the effect of 0.5% sodium hypochlorite in endodontic therapy *Oral Surg. Oral Med. Oral Pathol.* **55** 307–12

Byström A and Sundqvist G 1985 The antibacterial action of sodium hypochlorite and EDTA in 60 cases of endodontic therapy *Int. Endod. J.* **18** 35–40

Card S J, Sigurdsson A, Ørstavik D and Trope M 2002 The effectiveness of increased apical enlargement in reducing intracanal bacteria *J. Endod.* **28** 779–83

Carver K, Nusstein J, Reader A and Beck M 2007 *In vivo* antibacterial efficacy of ultrasound after hand and rotary instrumentation in human mandibular molars *J. Endod.* **33** 1038–43

Cecic P A, Peters D D and Grower M F 1984 The comparative efficiency of final endodontic cleansing procedures in removing a radioactive albumin from root canal systems *Oral Surg.* **58** 336–42

Chow T W 1983 Mechanical effectiveness of root canal irrigation *J. Endod.* **9** 475–9

Coldero L G, McHugh S, MacKenzie D and Saunders W P 2002 Reduction in intracanal bacteria during root canal preparation with and without apical enlargement *Int. Endod. J.* **35** 437–46

Cracknell A P 1980 *Ultrasonics* (New York: Crane, Russak and Co.)

Cunningham W T and Martin H 1982 A scanning electron microscope evaluation of root canal debridement with the endosonic ultrasonic synergistic system *Oral Surg.* **53** 527–31

Cunningham W T, Martin H and Forrest W R 1982 Evaluation of root canal debridement by the endosonic ultrasonic synergistic system *Oral Surg.* **53** 401–4

Cvek M, Nord C-E and Hollender L 1976 Antimicrobial effect of root canal debridement in teeth with immature roots: a clinical and microbiological study *Odontol. Revy* **27** 1–10

Dalton B C, Ørstavik D, Phillips C, Pettiette M and Trope M 1998 Bacterial reduction with nickel-titanium rotary instrumentation *J. Endod.* **24** 763–67

Dental Practice Board 2005 NHS Business Services Authority, Dental Practice Division, Digest Search Results for 1992–2005 http://www.dpb.nhs.uk/gds/ddonline_index.cfm (accessed 01 /06/2007)

Desai P and van Himel 2009 Comparative safety of various intracanal irrigation systems *J. Endod.* **35** 545–9

Douglas J F 1969 *An Introduction to Dimensional Analysis for Engineers* (London: Pitman)

Druttman A C S and Stock C J R 1989 An *in vitro* comparison of ultrasonic and conventional methods of irrigant replacement *Int. Endod. J.* **22** 174–8

Engström B 1964 The significance of enterococci in root canal treatment *Odontol. Revy* **15** 87–106

European Society of Endodontology 2006 Quality guidelines for endodontic treatment: consensus report of the European Society of Endodontology *Int. Endod. J.* **39** 921–30

Evans G E, Speight P M and Gulabivala K 2001 The influence of preparation technique and sodium hypochlorite on removal of pulp and predentine from root canals of posterior teeth *Int. Endod. J.* **34** 322–30

Falk K W and Sedgley C M 2005 The influence of preparation size on the mechanical efficacy of root canal irrigation *in vitro J. Endod.* **31** 742–5

Fanibunda K B 1986 A method of measuring the volume of human dental pulp cavities *Int. Endod. J.* **19** 194–7

Figdor 2002 Apical periodontitis: a very prevalent problem *Oral Surg. Oral Med. Oral Pathol. Oral Radiol. Endod.* **94** 651–2

Fukumoto Y, Kikuchi I, Yoshioka T, Kobayashi C and Suda H 2006 An *ex vivo* evaluation of a new root canal irrigation technique with intracanal aspiration *Int. Endod. J.* **39** 93–9

Goldman L B, Goldman M, Kronman J H and Lin P S 1979 Scanning electron microscope study of a new irrigation method in endodontic treatment *Oral Surg. Oral Med. Oral Pathol.* **48** 79–83

Goldman M, Kronman J H, Goldman L B, Clausen H and Grady J 1976 New method of irrigation during endodontic treatment *J. Endod.* **2** 257–60

Gomes B P F A, Lilley J D and Drucker D B 1996 Variations in the susceptibility of components of the endodontic microflora to bio-mechanical procedures *Int. Endod. J.* **29** 235–41

Goodman A, Reader A, Beck M, Melfi R and Meyers W 1985 An *in vitro* comparison of the efficacy of the step-back technique versus a step-back/ultrasonic technique in human mandibular molars *J. Endod.* **11** 249–56

Grahnén H and Krasse B 1963 The effect of instrumentation and flushing of non-vital teeth in endodontic therapy *Odontol. Revy* **14** 167–77

Gu L, Kim J R, Ling J, Choi K K, Pashley D H and Tay F R 2009 Review of contemporary irrigant agitation techniques and devices *J. Endod.* **35** 791–804

Gulabivala K 2004 Rationale for pulp therapy *Endodontics* 3rd edn ed C Stock, R Walker and K Gulabivala (Oxford: Elsevier Mosby) pp 3–23

Gulabivala K, Aung T H, Alavi A and Ng Y-L 2001 Root canal anatomy of Burmese mandibular molars *Int. Endod. J.* **34** 359–70

Gulabivala K, Opasanon A, Ng Y-L and Alavi A 2002 Root canal anatomy of Thai maxillary molars *Int. Endod. J.* **35** 56–62

Gulabivala K, Patel B, Evans G and Ng Y-L 2005 Effects of mechanical and chemical procedures on root canal surfaces *Endod. Top.* **10** 103–22

Gulabivala K, Stock C J R, Le wsey J D, Ghori S, Ng Y L and Spratt D A 2004 Effectiveness of electrochemically activated water as an irrigant in an infected tooth model *Int. Endod. J.* **37** 624–31

Gutarts R, Nusstein J, Reader A and Beck M 2005 *In vivo* debridement efficacy of ultrasonic irrigation following hand-rotary instrumentation in human mandibular molars *J. Endod.* **31** 166–70

Hauser V, Braun A and Frentzen M 2007 Penetration depth of a dye marker into dentine using a novel hydrodynamic system (RinsEndo®) *Int. Endod. J.* **40** 644–52

Hiadet J, Reader A L, Beck M and Meyers W 1989 An *in vitro* comparison of the step-back technique versus step-back/ultrasonic technique in human mandibular molars *J. Endod.* **15** 195–9

Huang T-Y, Gulabivala K and Ng Y-L 2008 A bio-molecular film ex-vivo model to evaluate the influence of canal dimensions and irrigation variables on the efficacy of irrigation *Int. Endod. J.* **41** 60–71

Hülsmann M and Hahn W 2000 Complication during root canal irrigation—literature review and case reports *Int. Endod. J.* **33** 186–93

Hülsmann M and Stryga F 1993 Comparison of root canal preparation using different automated devices and hand instrumentation *J. Endod.* **19** 141–5

Ingle J I and Zeldow B J 1958 An evaluation of mechanical instrumentation and the negative culture in endodontic therapy *J. Am. Dent. Assoc.* **57** 471–6

Jiang L-M, Verhaagen B, Versluis M and Van Der Sluis L W M 2010 Evaluation of a sonic device designed to activate irrigant in the root canal *J. Endod.* **36** 143–6

Kahn F H, Rosenberg P A and Gliksberg J 1995 An *in vitro* evaluation of the irrigating characteristics of ultrasonic and subsonic handpieces and irrigating needles and probes *J. Endod.* **21** 277–80

Khademi A, Yazdizadeb M and Feizianfard M 2006 Determination of the minimum instrumentation size for penetration of irrigants to the apical third of root canal systems *J. Endod.* **32** 417–20

Kuruvilla J R and Kamath M P 1998 Antimicrobial activity of 2.5% sodium hypochlorite and 0.2% chlorhexidine gluconate separately and combined, as endodontic irrigants *J. Endod.* **24** 472–6

Kvist T, Molander A, Dahlén G and Reit C 2004 Microbiological evaluation of one- and two-visit endodontic treatment of teeth with apical periodontitis: a randomized, clinical trial *J. Endod.* **30** 572–6

Lambrianidis T, Tosounidou E and Tzoanopoulou M 2001 The effect of maintaining apical patency on periapical extrusion *J. Endod.* **27** 696–8

Lee S-J, Wu M-K and Wesselink P R 2004a The effectiveness of syringe irrigation and ultrasonics to remove debris from simulated irregularities within prepared root canal walls *Int. Endod. J.* **37** 672–8

Lee S-J, Wu M-K and Wesselink P R 2004b The efficacy of ultrasonic irrigation to remove artificially placed dentine debris from different-sized simulated plastic root canals *Int. Endod. J.* **37** 607–12

Lev R, Reader A, Beck M and Meyers W 1987 An *in vitro* comparison of the step-back technique versus a step-back/ultrasonic technique for 1 and 3 min *J. Endod.* **13** 523–30

Lighthill J 1978 Acoustic streaming *J. Sound Vib.* **61** 391–418

Liu R, Sharp K V, Olsen M G, Stremler M A, Santiago J G, Adrian R J, Aref H and Beebe D J 2000 Passive mixing in a three-dimensional serpentine microchannel *J. MEMS* **9** 190–7

Love R M and Jenkinson H F 2002 Invasion of dentinal tubules by oral bacteria *Crit. Rev. Oral Biol. Med.* **13** 171–83

Lussi A, Messerli L, Hotz P and Grosrey J 1995 A new non-instrumental technique for cleaning and filling root canals *Int. Endod. J.* **28** 1–6

Lussi A, Nussbächer U and Grosrey J 1993 A novel noninstrumented technique for cleansing the root canal system *J. Endod.* **19** 549–53

Lussi A, Portmann P, Nussbächer U, Imwinkelried S and Grosrey J 1999 Comparison of two devices for root canal cleansing by the noninstrumentation technology *J. Endod.* **25** 9–13

Mannan G, Smallwood E R and Gulabivala K 2001 Effect of access cavity location and design on degree and distribution of instrumented root canal surface in maxillary anterior teeth *Int. Endod. J.* **34** 176–83

Martin H and Cunningham W T 1982 The effect of endosonic and hand manipulation on the amount of root canal material extruded *Oral Surg.* **53** 611–3

McGill S, Gulabivala K, Mordan N and Ng Y-L 2008 The efficacy of dynamic irrigation using a commercially available system (Risendo) determined by removal of a collagen 'bio-molecular film' from an *ex vivo* model *Int. Endod. J.* **41** 602–8

Merivale C, Gulabivala K and Ng Y-L 2009 Influence of surfactant/thickener on NaOCl-induced removal of applied collagen from canal walls during ultrasonic irrigation *Int. Endod. J.* **42** 1140

Moffatt H K 1964 Viscous and resistive eddies near a sharp corner *J. Fluid Mech.* **18** 1–18

Morfis A, Sylaras S N, Georgopoulou M, Kernani M and Prountzos F 1994 Study of the apices of human permanent teeth with the use of scanning electron microscope *Oral Surg. Oral Med. Oral Pathol.* **77** 172–6

Moser J B and Heuer M A 1982 Forces and efficacy in endodontic irrigation systems *Oral Surg.* **53** 425–8

Munley P J and Goodell G G 2007 Comparison of passive ultrasonic debridement between fluted and nonfluted instruments in root canal *J. Endod.* **33** 578–80

Muselmani B, Kneist S and Glockmann E 2005 Antimicrobial effectiveness of hydrodynamic and conventional rinsing in root canal http://iadr.confex.com/iadr/eur05/techprogram/abstract_68667.htm

Nair P N, Henry S, Cano V and Vera J 2005 Microbial status of apical root canal system of human mandibular first molars with primary apical periodontitis after 'one-visit' endodontic treatment *Oral Surg. Oral Med. Oral Pathol. Oral Radiol. Endod.* **99** 231–52

Nair P N R 1987 Light and electron microscope studies of root canal flora and periapical lesions *J. Endod.* **13** 29–33

Nanzer J, Langlois S and Coeuret F 1989 Electrochemical engineering approach to the irrigation of tooth canals under the influence of a vibrating file *J. Biomed.* **11** 157–63

Ng Y-L 2008 Factors affecting outcome of non-surgical root canal treatment *PhD Dissertation* University College London, UK

Ng Y-L, Aung T H, Alavi A and Gulabivala K 2001 Root canal anatomy of Burmese maxillary molars *Int. Endod. J.* **34** 620–30

Ng Y-L, Mann V and Gulabivala K 2010 Tooth survival following non-surgical root canal treatment: a systematic review of the literature *Int. Endod. J.* **43** 171–89

Ng Y-L, Mann V, Rahbaran S, Lewsey J and Gulabivala K 2007 Outcome of primary root canal treatment: systematic review of the literature—part 1. Effects of study characteristics on probability of success *Int. Endod. J.* **40** 921–39

Ng Y-L, Mann V, Rahbaran S, Lewsey J and Gulabivala K 2008 Outcome of primary root canal treatment: systematic review of the literature—part 2. Influence of clinical factors *Int. Endod. J.* **41** 6–31

Nguy D and Sedgley C 2006 The influence of canal curvature on the mechanical efficacy of root canal irrigation *in vitro* using real-time imaging of bioluminescent bacteria *J. Endod.* **32** 1077–82

Nicholls E 1962 The efficacy of cleansing of the root canal *Br. Dent. J.* **112** 167–70

Nielsen B A and Baumgartner J C 2007 Comparison of the EndoVac system to needle irrigation of root canals *J. Endod.* **33** 611–5

Ørstavik D, Kerekes K and Molven O 1991 Effects of extensive apical reaming and calcium hydroxide dressing on bacterial infection during treatment of apical periodontitis: a pilot study *Int. Endod. J.* **24** 1–7

Paragliola R, Franco V, Fabiani C, Mazzoni A, Nato F, Tay F R, Breschi L and Grandini S 2010 Final rinse optimization: influence of different agitation protocols *J. Endod.* **36** 282–5

Parris J, Wilcox L and Walton R 1994 Effectiveness of apical clearing: histological and radiographical evaluation *J. Endod.* **20** 219–24

Peters L B, van Winklehoff A J, Buijs J F and Wesselink P R 2002 Effects of instrumentation, irrigation and dressing with calcium hydroxide on infection in pulpless teeth with periapical bone lesions *Int. Endod. J.* **35** 13–21

Peters O A, Laib A, Göhring T N and Barbakow F 2001 Changes in root canal geometry after preparation assessed by high resolution computed tomography *J. Endod.* **27** 1–6

Ram Z 1977 Effectiveness of root canal irrigation *Oral Surg.* **44** 306–12

Richardson N, Mordan N, Ng Y-L and Gulabivala K 2009 Microflora distribution in teeth associated with apical periodontitis determined by different microscopy techniques and protocols *Int. Endod. J.* **42** 908–21

Rollison S, Barnett F and Stevens R H 2002 Efficacy of bacterial removal from instrumented root canals *in vitro* related to instrumentation technique and size *Oral Surg. Oral Med. Oral Pathol. Oral Radiol. Endod.* **94** 366–71

Ruddle C 2007 Hydrodynamic disinfection: tsunami endodontics *Dent. Today* **26** 110–7

Sabins R A, Johnson J D and Hellstein J W 2003 A comparison of the cleaning efficacy of short-term sonic and ultrasonic passive irrigation after hand instrumentation in molar root canals *J. Endod.* **29** 674–8

Schirrmeister J F, Liebenow A L, Braun G, Wittmer A, Hellwig E and Al-Ahmad A 2007 Detection and eradication of microorganisms in root-filled teeth associated with periradicular lesions: an *in vivo* study *J. Endod.* **33** 536–40

Sedgley C M, Nagel A C, Hall D and Applegate B 2005 Influence of irrigant needle depth in removing bioluminescent bacteria inoculated into instrumented root canals using real-time imaging *in vitro Int. Endod. J.* **38** 97–104

Shrestha A, Fong S-W, Khoo B-C and Kishen A 2009 Delivery of antibacterial nanoparticles into dentinal tubules using high-intensity focused ultrasound *J. Endod.* **35** 1028–33

Shuping G B, Ørstavik D, Sigurdsson A and Trope M 2000 Reduction of intracanal bacteria using nickel-titanium rotary instrumentation and various medications *J. Endod.* **26** 751–5

Siqueira J F Jr , Guimarães-Pinto T and Rôças I N 2007a Effects of chemomechanical preparation with 2.5% sodium hypochlorite and intracanal medication with calcium hydroxide on cultivable bacteria in infected root canals *J. Endod.* **33** 800–5

Siqueira J F Jr, Magalhães K M and Rôças I N 2007b Bacterial reduction in infected root canals treated with 2.5% NaOCl as an irrigant and calcium hydroxide/camphorated paramonochlorophenol paste as an intracanal dressing *J. Endod.* **33** 667–72

Siqueira J F Jr, Rôças I N, Paiva S S, Guimarães-Pinto T, Magalhães K M and Lima K C 2007c Bacteriologic investigation of the effects of sodium hypochlorite and chlorhexidine during the endodontic treatment of teeth with apical periodontitis *Oral Surg. Oral Med. Oral Pathol. Oral Radiol. Endod.* **104** 122–30

Siqueira J F, Machado A G, Silverira R M, Lopes H P and De Uzeda M 1997 Evaluation of the effectiveness of sodium hypochlorite used with three irrigation methods in the elimination of *Enterococcus faecalis* from the root canal *in vitro Int. Endod. J.* **30** 279–82

Sjögren U, Figdor D, Spångberg L and Sundqvist G 1991 The antimicrobial effect of calcium hydroxide as a short-term intracanal dressing *Int. Endod. J.* **24** 119–25

Sjögren U and Sundqvist G 1987 Bacteriologic evaluation of ultrasonic root canal instrumentation *Oral Surg. Oral Med. Oral Pathol.* **63** 366–70

Spratt D A, Pratten J, Wilson M and Gulabivala K 2001 An *in vitro* evaluation of the antimicrobial efficacy of irrigants on biofilms of root canal isolates *Int. Endod. J.* **34** 300–7

Stone H A and Brenner H 1999 Dispersion in flows with streamwise variations of mean velocity: radial flow *Ind. Eng. Chem. Res.* **38** 851–4

Sturman R, Ottino J and Wiggins S 2006 *The Mathematical Foundations of Mixing. The Linked Twist Map as a Paradigm in Applications: Micro to Macro, Fluids to Solids* (Cambridge: Cambridge University Press)

Sundqvist G 1976 Bacteriologic studies of necrotic dental pulps *Dissertation* University of Umeå, Sweden

Taylor G I 1967 Low Reynolds Number Flow Film commissioned by the National Committee for Fluid Mechanics http://web.mit.edu/hml/ncfmf.html

Teplitsky P E, Chenail B L, Mack B and Machnee C H 1987 Endodontic irrigation—a comparison of endosonic and syringe delivery systems *Int. Endod. J.* **20** 233–41

Uroz-Torres D, González-Rodríguez M P and Ferrer-Luque C M 2010 Effectiveness of the EndoActivator System in removing the smear layer after root canal instrumentation *J. Endod.* **36** 308–11

Van Der Sluis L W M, Gambarini G, Wu M-K and Wesselink P R 2006 The influence of volume, type of irrigant and flushing method on removing artificially placed dentine debris from the apical root canal during passive ultrasonic irrigation *Int. Endod. J.* **39** 472–6

Van Der Sluis L W M, Versluis M, Wu M K and Wesselink P R 2007 Passive ultrasonic irrigation of the root canal: a review of the literature *Int. Endod. J.* **40** 415–26

Van Der Sluis L W M, Wu M-K and Wesselink P R 2005a A comparison between a smooth sire and a K-file in removing artificially placed dentine debris from root canals in resin blocks during ultrasonic irrigation *Int. Endod. J.* **38** 593–6

Van Der Sluis L W M, Wu M-K and Wesselink P R 2005b The efficacy of ultrasonic irrigation to remove artificially placed dentine debris from human root canals prepared using instruments of varying taper *Int. Endod. J.* **38** 764–8

Vianna M E, Horz H P, Gomes B P and Conrads G 2006 *In vivo* evaluation of microbial reduction after chemo-mechanical preparation of human root canals containing necrotic pulp tissue *Int. Endod. J.* **39** 484–92

Vinothkumar T S, Kavitha S, Lakshminarayanan L, Gomathi N S and Kumar V 2007 Influence of irrigation needle-tip designs in removing bacteria inoculated into instrumented root canals measured using single-tube luminometer *J. Endod.* **33** 746–8

Wada M, Takase T, Nakanuma K, Arisue K, Nagahama F and Yamazaki M 1998 Clinical study of refractory apical periodontitis treated by apicectomy: part 1. Root canal morphology of resected apex *Int. Endod. J.* **31** 53–6

Walker R T 2004 Root canal morphology *Endodontics* 3rd edn ed C Stock, R Walker and K Gulabivala (Oxford: Elsevier Mosby) chapter 7 pp 127–34

Waltimo T, Trope M, Haapasalo M and Ørstavik D 2005 Clinical efficacy of treatment procedures in endodontic infection control and one year follow-up of periapical healing *J. Endod.* **31** 863–6

Walton R E 1976 Histologic evaluation of different methods of enlarging the pulp canal space *J. Endod.* **2** 304–11

Wang C S, Arnold R R, Trope M and Teixeira F B 2007 Clinical efficiency of 2% chlorhexidine gel in reducing intracanal bacteria *J. Endod.* **33** 1283–9

Wayman B E, Patten J A and Dazey S E 1994 Relative frequency of teeth needing endodontic treatment in 3350 consecutive endodontic patients *J. Endod.* **20** 399–401

White F M 1999 *Fluid Mechanics* 4th edn (New York: McGraw-Hill) chapter 5

Williams C E C S, Reid J S, Sharkey S W and Saunders W P 1995 *In-vitro* measurement of apically extruded irrigant in primary molars *Int. Endod. J.* **28** 221–5

Wittgow W C and Sabiston C B 1975 Microorganisms from pulpal chambers of intact teeth with necrotic pulps *J. Endod.* **1** 168–71

Yared G M and Bou Dagher F E 1994 Influence of apical enlargement on bacterial infection during treatment of apical periodontitis *J. Endod.* **20** 535–7

Yu T 2007 Two viscous fluids mixing and efficiency evaluation *MSc Thesis* Department of Mechanical Engineering, University of Bristol

Zeldow B J and Ingle J I 1963 Correlation of the positive culture to the prognosis of endodontically treated teeth: a clinical study *J. Am. Dent. Assoc.* **66** 23–7