Fluid dynamics of syringe-based irrigation to optimise anti-biofilm efficacy in root-canal disinfection

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_Bacterial biofilm as a therapeutic target

A mature bacterial biofilm is composed of multiple layers of bacteria embedded in a self-made matrix formed of extracellular polymeric substance. This substance has the potential to modify the response of the resident bacteria to antimicrobials by acting as a shield against the chemical effects of antimicrobials. There is also a localised high density of bacterial cells in a biofilm structure. This spatial arrangement will expose the cells in the deeper layers of the biofilm to less nutrients and redox potential than the cells on the biofilm surface. Since the degree of nutrient and gas gradients increases with the thickness and maturity of a biofilm, the influence of growth rate and oxygen on the antimicrobial resistance is particularly marked in aged biofilm. The resistance associated with biofilm bacteria is further associated with the slow growth rate (starvation) and/or due to the adoption of resistant phenotypes in bacteria residing in a biofilm. It is recognised that no single mechanism may account for the general resistance to antimicrobials in a biofilm. It is apparent that different mechanisms may act in concert within the biofilm, and amplify the effect of small variations in the susceptible phenotypes (Dunne et al. 1993; Costerton et al. 1994). Thus from a clinical perspective, bacteria are observed to demonstrate considerably high resistance to antimicrobials when they are in a biofilm (Kishen 2012).

The current concepts in endodontic microbiology emphasise endodontic disease as a biofilm-mediated infection. Ricucci and Siqueira (2010) found a very high prevalence of bacterial biofilms in the apical root canals of both untreated and treated teeth with apical periodontitis. The pattern of arrangement of bacterial communities in the root canal is noted to be consistent with the acceptable criteria for including apical periodontitis in the set of biofilm-mediated diseases. They also suggest that the biofilm morphology/structure varied from case to case, and no unique pattern for endodontic infections was determined. Elimination or significant reduction of endodontic bacterial biofilms is essential for successful outcomes of endodontic treatment (Fig. 1). However, clinical studies have demonstrated that even after meticulous chemomechanical disinfection and obturation of the root canals bacteria may persist in the un-instrumented portions and anatomical complexities of the root canal (Nair et al. 2005). It is vital to comprehend that the limitations in endodontic disinfection are not just due to the biofilm mode of bacterial growth in the root canals. The complexities of the root-canal system, in addition to the structure and composition of the root dentine, play a decisive role in limiting the efficacy of endodontic disinfection. Nair et al. (2005) demonstrated that following one-visit conventional endodontic treatment the teeth revealed microbial biofilm in the inaccessible recesses and diverticula of instrumented main canals, the intercanal isthmus and accessory canals. The main limiting factors in conventional irrigation are the complexity of the root-canal anatomy, the ultrastructure of the dentine and the characteristics of the bacterial biofilms (Kishen 2010). Attempts to surmount these limitations have recently led to renewed interest in understanding the fluid dynamics associated with different root-canal irrigation techniques through numerical and experimental investigations.

_General considerations of fluid dynamics in irrigation

Endodontic irrigants are primarily liquid anti-microbials used to combat microbial biofilms within the root-canal system. The process of delivery of irrigants within the root canal is called irrigation, and irrigation dynamics deals with how irrigants flow, penetrate and exchange within the root-canal space, and the forces produced by them. Hence, in endodontic disinfection, the process of delivery is as important as the antibacterial characteristics of the irrigants. The overall objectives of root-canal irrigation are (a) to inactivate bacterial biofilms, in-activate endotoxins, and dissolve tissue remnants/smear layer (chemical effects) from the infected root canals; and (b) to allow the flow of irrigant throughout the root-canal system in order to de-tach the biofilm structures and loosen/flush out the debris from the root canals (mechanical effects).

The chemical effectiveness will depend upon the concentration of the antimicrobial irrigant, the area of contact and the duration of interaction between irrigant and infected material. The mechanical ef-fectiveness will depend upon the ability of irrigation to generate optimum streaming forces within the entire root-canal system. Mechanical effects can be produced even by inert irrigants (e.g. water, saline), but chemical effects are only exerted by chemically active solutions (e.g. sodium hypochlorite). The final efficiency of endodontic disinfection will depend upon its chemical and mechanical effectiveness (Gulabivala et al. 2005; Haapasalo et al. 2005). Currently, there is no consensus on the relative impor-tance of these effects for the overall success of root-canal treatment; therefore, efforts to maximise both effects seem justified. Even the most powerful irri-gant will be of no use if it cannot penetrate the api-cal portion of the root canal, interact with the root-canal wall and exchange frequently within the root-canal system (Druttman & Stock 1989; Mott 1999; Tilton 1999; White 1999; Seal et al. 2002). However, over-enthusiastic efforts to deliver the irrigant may result in its inadvertent extrusion towards the periapical tissue (Hülsmann et al. 2009). Depending on the irrigant, severe tissue damage, pronounced symptomatology and possibly delayed healing may develop, as documented in a number of case re-ports (e.g. Hülsmann & Hahn 2000; Gernhardt et al. 2004; Bowden et al. 2006; Pelka & Petschelt 2008; Behrents et al. 2012). Therefore, irrigant penetra-tion should be kept within the confines of the root-canal system and a critical balance should always be maintained between efficient cleaning and pre-vention of irrigant extrusion (Haapasalo et al. 2010), especially when chemically active irrigants are used.
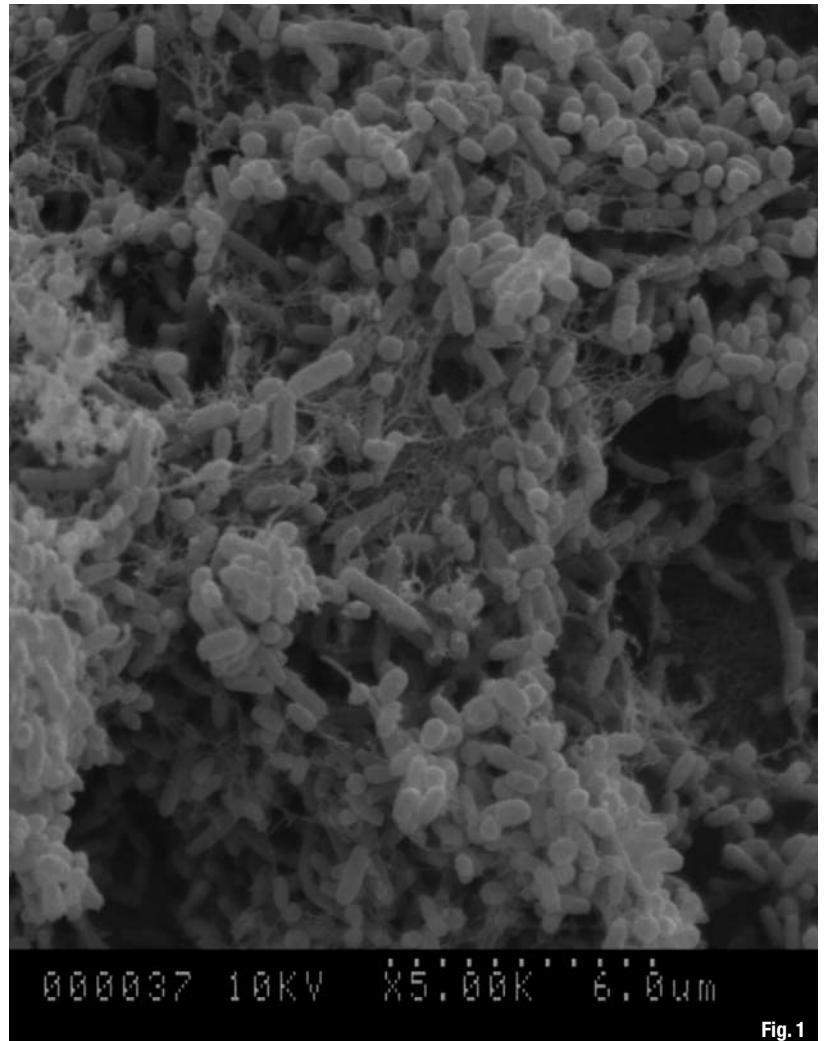

Fig. 1

Fig. 1_Multispecies bacterial biofilm grown on root-canal dentine *in vitro*.

In general, root-canal irrigation can be regarded as the flow of a liquid (irrigant) within an irregularly shaped domain (root-canal system). Consequently, a fluid dynamics approach would be appropriate for elucidating the procedures of root-canal cleaning and disinfection. The above-mentioned objectives of root-canal irrigation can be restated briefly in terms of fluid dynamics as:

_flow of the irrigant to the full extent of the root-canal system and subsequently to the canal orifice in order to come in close contact with microbes, debris and tissue remnants, and carry them away;
_frequent refreshment and mixing of the irrigant in order to retain a high concentration of its ac-tive component(s) and compensate for its rapid consumption (for chemically active irrigants);
_application of force to the canal wall (wall shear stress) in order to detach/disrupt microbes/biofilm, debris and tissue remnants;
_restriction of the flow within the confines of the root canal and prevention of irrigant extrusion towards the periapical tissue (Boutsioukis 2010).
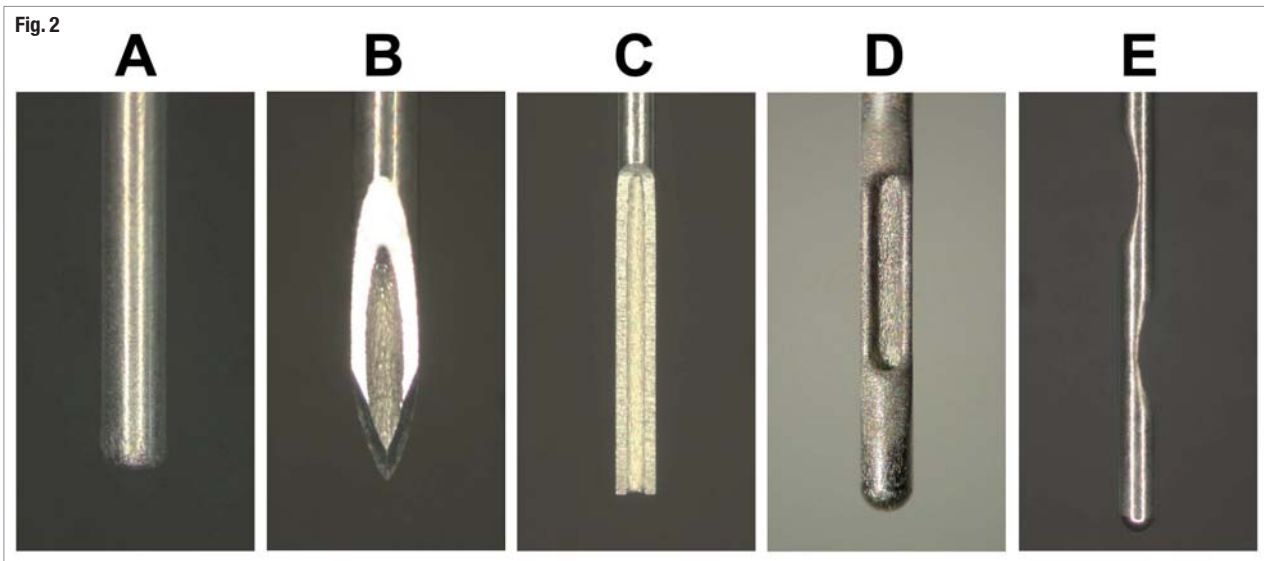
Fig. 2

_Syringe irrigation

Irrigant delivery techniques are frequently categorised as positive-pressure or negative-pressure, according to the mode of delivery employed (Brunson et al. 2010). In positive-pressure techniques, the pressure difference that is necessary for irrigant flow is created between a pressurised container (e.g. a syringe) and the root canal, where the pressure remains much lower (nearly atmospheric). Irrigant is delivered deep inside the root canal, usually by a needle, and then flows towards the canal orifice, where it is evacuated by a suction system. In negative-pressure techniques, the irrigant is delivered passively near the canal orifice at nearly atmospheric pressure and a suction tip placed deep inside the root canal creates a pressure difference. The irrigant then flows from the orifice towards the apex, where it is evacuated.

Perhaps the most traditional method of positive-pressure irrigant delivery is by a syringe and a needle. Despite the development of various irrigation systems, conventional syringe irrigation remains widely accepted (Ingle et al. 2002; Peters 2004; Dutner et al. 2012). However, over the years it has been argued that the performance of root-canal irrigation is limited mostly because syringes and needles fail to deliver the irrigant to all the parts of the complex root-canal system (Ram 1977; Rosenfeld et al. 1978; Druttman & Stock 1989; Haapasalo et al. 2005). A detailed evaluation of the irrigant flow developed during syringe irrigation could provide some insight into this problem.
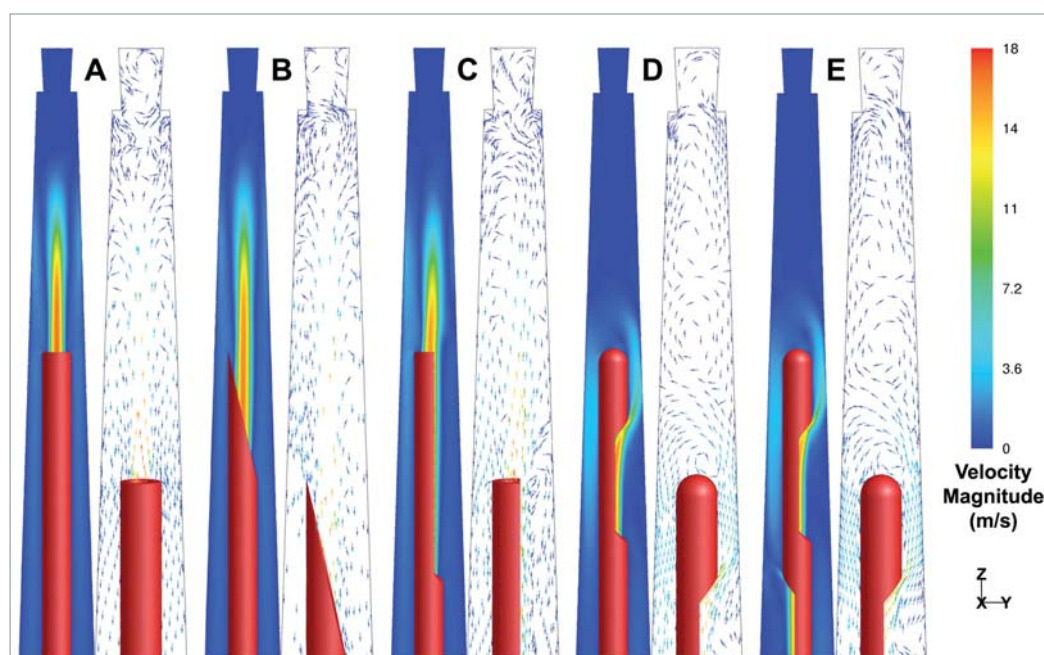
Fig. 3

_Irrigant flow during syringe irrigation

Most studies on root-canal irrigation have focused on the direct outcomes of irrigation, that is debridement, tissue dissolution, antimicrobial action or removal of the smear layer, employing a trial-and-error approach and speculating on the aetiology. Few studies have actually attempted to evaluate directly the flow developed within the root canal (e.g. Teplitsky et al. 1987; Druttman & Stock 1989; Kahn et al. 1995; Bronnec et al. 2010a; Boutsioukis et al. 2009; Shen et al. 2010), which is probably the dominant phenomenon during root-canal irrigation and the primary cause of both the chemical and mechanical effects.

The flow of irrigants is affected by their physical properties, mainly density and viscosity (White 1999). "Density" describes the amount of mass present in a certain volume of the irrigant, and "viscosity" describes the resistance of the irrigant to motion (Mott 1999; Tilton 1999; White 1999). For commonly used endodontic irrigants, these properties are very similar to those of distilled water (Guerisoli et al. 1998; Van der Sluis et al. 2010), which can be explained by the fact that irrigants are mainly sparse aqueous solutions. The surface tension of endodontic irrigants and its decrease by wetting agents (surfactants) has also been studied extensively, under the assumption that it may have a significant effect on irrigant penetration in dentinal tubules and accessory root canals (Abou Rass & Patonai 1982; Taşman et al. 2000) and on dissolution of pulp tissue (Stojicic et al. 2010). However, while density and viscosity affect the flow in all cases, *the effect of surface tension is important only at the interface between two immiscible fluids* (e.g. between irrigant and an air bubble, but not between irrigant and dentinal fluid; White 1999; Kundu & Cohen 2004). Should an air bubble occupy the apical part of the root canal (Tay et al. 2010), surface tension effects could be important, but it is unlikely that bubble entrapment is a common issue during root-canal irrigation. Recent studies have also confirmed that surfactants do not enhance the ability of NaOCl to dissolve pulp tissue (Clarkson et al. 2012; Jungbluth et al. 2012) or the ability of common chelators to remove calcium from dentine (Zehnder et al. 2005) or to remove the smear layer (Lui et al. 2007; De-Deus et al. 2008).

Syringes of variable capacity, ranging from 1 to 10 ml (Abou-Rass & Piciccino 1982; Kahn et al. 1995; Ram 1977; Moser & Heuer 1982; Chow 1983; Sabins et al. 2003; Lee et al. 2004; Sedgley et al. 2005), have been used. Although little attention has been given to the size of the syringe, it can affect the force needed to irrigate at a certain flow rate (Boutsioukis et al. 2007a). The flow rate is defined as the volume of irrigant delivered per unit time. (Mott 1999). A common error among clinicians, which is also reproduced in several irrigation studies, is that delivery of the irrigant at a high flow rate is erroneously termed "forceful delivery" or "delivery under pressure". During syringe irrigation, a clinician applies force to the plunger of the syringe. This force is transmitted to the irrigant in the syringe, where pressure builds up. A clinician will need to apply different amounts of force and will feel different levels of difficulty in pushing the plunger when syringes of different size are used, even if the pressure actually developed is identical (Tilton 1999). Larger syringes are more difficult to depress. Hence, the clinician cannot draw reliable conclusions about the pressure.

Fig. 4_Triads of time-averaged contours (left), vectors (middle) of velocity and streamlines (right) in the apical part of the root canal for a closed-ended (top) and open-ended needle (bottom) positioned at 1 to 5 mm short of WL, respectively. Needles are coloured in red. (Reprinted with permission from Boutsioukis et al. 2010c.)

Fig. 4
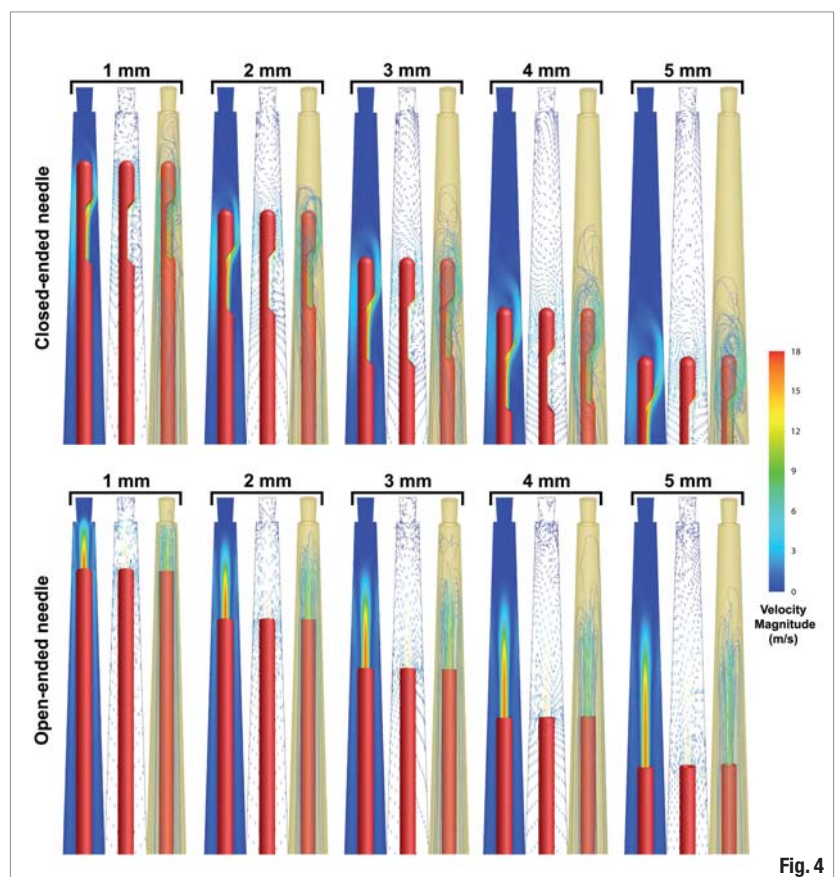
The pressure difference between the syringe and the tip of the needle is the cause of irrigant flow from the syringe through the needle and into the root canal. Irrigant flow rate is proportional to this difference, but is also affected by the size of the needle and several other parameters (Tilton 1999). Therefore, for the same pressure difference, the flow through a smaller needle will be much less than through a larger needle. Therefore, irrigant flow is not described accurately either by the force of the clinician or by the pressure developed in the syringe, but by the flow rate of the irrigant (Boutsioukis et al. 2007a, 2009), which can also be estimated clinically. A 5 ml syringe
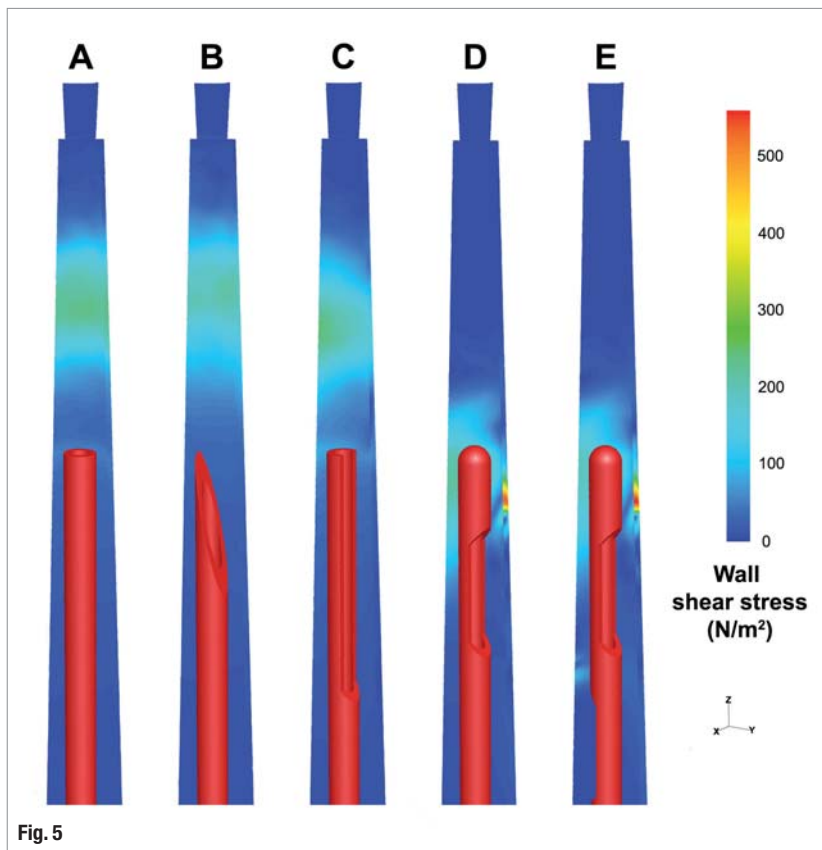
Fig. 5

Fig. 5_Time-averaged distribution of shear stress on the root-canal wall in the apical part of a size 45 root canal with a 0.06 taper during syringe irrigation using various needle types: open-ended (A–C), closed-ended (D & E). Only half of the root-canal wall is presented to allow simultaneous evaluation of the needle position. Needles are coloured in red. (Reprinted with permission from Boutsioukis et al. 2010b.)

combined with a 30G needle may be a reasonable compromise between effectiveness, ease of use and less frequent refilling, and can be used to reach flow rates of up to 0.20 to 0.25 ml/s (Boutsioukis et al. 2007a). High pressures may develop within the syringe during irrigation, so a Luer-lock connector is always necessary to avoid sudden detachment of the needle.

When investigating irrigation, it should be emphasised that the root canal behaves mostly like a closed-end system, thus in most cases the apical foramen should be considered non-patent (Hockett et al. 2008; Boutsioukis et al. 2009; Bronnec et al. 2010a; Parente et al. 2010; Tay et al. 2010). The apex being closed results in a significantly more complicated flow pattern compared with a simple tube open from both sides, even if we consider a simplified root-canal shape (White 1999; Boutsioukis et al. 2010a; Verhaagen et al. 2012). For very low flow rates, in the order of 0.01 ml/s, a steady laminar flow is developed within the root canal (Boutsioukis et al. 2009; Verhaagen et al. 2012). For higher flow rates, the flow becomes unsteady (changing as a function of time) but remains laminar up to a flow rate of approximately 0.26 ml/s (Boutsioukis et al. 2009, 2010a; Verhaagen et al. 2012). For higher flow rates, turbulence may develop in some areas of the root canal, mainly close to the tip of the needle, where irrigant velocity is higher (Boutsioukis et al. 2009).

In order to increase the efficiency of syringe irrigation, different needle types have been proposed (Moser & Heuer 1982; Kahn et al. 1995; Yamamoto et al. 2006; Vinothkumar et al. 2007; Boutsioukis et al. 2010b; Shen et al. 2010; Fig. 2). The type of the needle has a significant effect on the flow pattern developed (Fig. 3), while other parameters such as needle insertion depth, root-canal size and taper have only a limited influence (Boutsioukis et al. 2010a, 2010b, 2010c, 2010d, 2010e). Based on the resulting flow, the available needle types can be categorised into two main groups, namely closed-ended and open-ended (Boutsioukis et al. 2010b). Both needle groups create a jet at their outlet, but the shape of the outlet determines the orientation and, to some extent, the intensity of the jet.

In the case of open-ended needles (flat, bevelled, notched), the jet is very intense and extends along the root canal to their tip. Within a certain distance, which also depends on the geometry of the root canal and the insertion depth of the needle, the jet appears to break up gradually. Reverse flow towards the canal orifice occurs near the canal wall. The jet formed by the flat and bevelled needle is slightly more intense and extends farther apically than the notched needle. The overall performance of the bevelled and the notched needle is slightly inferior to that of the flat needle. Furthermore, the bevelled needle was originally designed for injections and its sharp tip poses a significant risk of injury to both the patient and the dentist, combined with an increased possibility of wedging inside the root canal, so it should not be used for root-canal irrigation (Boutsioukis et al. 2010b).

In the case of closed-ended needles (side-vented, double side-vented), the jet of irrigant is formed near the apical side of the outlet (the one proximal to the tip for the double side-vented needle) and is directed apically with a small divergence. The irrigant mainly follows a curved path around the tip and then towards the coronal orifice. A series of counter-rotating vortices (rotating flow structures) are formed apical to the tip. Their size, position and number may differ according to needle insertion depth, root-canal size and taper, and flow rate. The velocity of the irrigant inside each vortex decreases significantly towards the apex. The distal outlet of the double side-vented needle has only a minor influence on the overall flow pattern because most of the irrigant flows out through the proximal outlet, so it provides no significant advantage (Boutsioukis et al. 2010b). Contrary to previous reports (Kahn et al. 1995), turbulence is not developed at flow rates up to 0.26 ml/s, but it may develop at higher, clinically unrealistic flow rates (Boutsioukis et al. 2009, 2010a; Verhaagen et al. 2012). It is possible that formation of vortices and unsteady flow were mistaken for turbulence in the past.

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	ISO 9626:1991/Amd.1:2001 (Medical needles)				ISO 3630–1:2008 (Endodontic instruments)		
Gauge size	Designated Metric size (mm)	External diameter (mm)		Internal diameter (mm)	Size	Tip diameter (mm)	
		min	max	min		min	max
21	0.80	0.800	0.830	0.490	80	0.760	0.840
23	0.60	0.600	0.673	0.317	60	0.580	0.620
25	0.50	0.500	0.530	0.232	50	0.480	0.520
27	0.40	0.400	0.420	0.184	40	0.380	0.420
28	0.36	0.349	0.370	0.133	40	0.380	0.420
29	0.33	0.324	0.351	0.133	35	0.330	0.370
30	0.30	0.298	0.320	0.133	30	0.280	0.320
31	0.25	0.254	0.267	0.114	25	0.230	0.270

Irrigation needles are available in various sizes, which are most frequently described by the gauge system (Boutsioukis et al. 2007b). These units are not directly comparable to clinically related units like the size of endodontic files and obturation materials; thus, an intermediate conversion to millimetres may be useful (Table 1). In the past, large needles (21–25 G) were commonly employed (Brown & Doran 1975; Ram 1977; Salzgeber & Brilliant 1977; Chow 1983; Teplitsky et al. 1987). Such needles could hardly penetrate beyond the coronal third of the root canal, even in wide root canals. More recently, the use of finer-diameter needles (28 or 30 G) has been advocated (Sedgley et al. 2004; Zehnder 2006; Huang et al. 2008; Bronnec et al. 2010b), mainly because they can reach farther into the canal, even to working length (WL), and thus may result in better irrigant exchange and cleaning (Ram 1977; Chow 1983; Druttman & Stock 1989), but also because they may be more effective than larger-diameter needles even when positioned at the same depth (Chow 1983; Bronnec et al. 2010b).

Assuming other parameters are kept constant, the use of a larger needle would result in a decrease in the space available for irrigant flow between the needle and the root-canal wall. This decrease has been associated with either increased apical pressure for open-ended needles or decreased irrigant refreshment apical to the tip for closed-ended needles, as will be explained below in the relevant sections (Boutsioukis et al. 2010d, 2010e). Therefore, the use of a larger needle would not provide any advantage, apart from decreasing the clinician's effort in pushing the syringe plunger (Boutsioukis et al. 2007a).

The effect of tooth orientation (mandibular, maxillary, horizontal) on irrigant flow has been found to result in only minor differences in the resulting flow (Boutsioukis 2010; Boutsioukis et al. 2010a, 2010b). In a single-phase system, such as a root canal completely filled with the irrigant, gravity affects the flow through hydrostatic pressure. The latter is very low compared with the dynamic pressure developed owing to the flow of the irrigant. A noteworthy case in which tooth orientation may be important is when an air bubble is trapped in the apical part of the root canal (apical vapour lock), so a two-phase system is created (air and irrigant; De Gregorio et al. 2009; Tay et al. 2010; Vera et al. 2011, 2012). The air bubble could block irrigant penetration and, since air has a lower density than irrigants, it would tend to remain apical in a maxillary oriented root canal, if undisturbed, owing to buoyancy. However, routine trapping of air bubbles in the apical part of the root canal during endodontic treatment has not been shown and remains a speculation.

_Irrigant refreshment

Irrigant exchange in the various parts of the root-canal system is a crucial requirement for ensuring adequate chemical effect, since irrigants are rapidly inactivated when they come into contact with tissue remnants or microbes (Moorer & Wesselink 1982; Druttman & Stock 1989; Haapasalo et al. 2005). Needle type appears to have a significant effect on the extent of apical irrigant exchange. Earlier reports argued that closed-ended needles are more efficient than open-ended ones (Kahn et al. 1995; Vinothkumar et al. 2007). However, recent studies have clarified the limitations in the irrigant refreshment apical to closed-ended needles and clearly proven their inferiority (Zehnder 2006; Boutsioukis et al. 2009, 2010b, 2010c, 2010d, 2010e; Verghaagen et al. 2012) No significant difference has been detected between various types of closed-ended needles or between various types of open-ended needles (Vinothkumar et al. 2007; Boutsioukis et al. 2010b).

A general trend has been well documented in the literature: needle placement closer to WL results in more efficient irrigant exchange, regardless of needle type (Chow 1983; Sedgley et al. 2005; Hsieh et al. 2007; Boutsioukis et al. 2010c; Bronnec et al. 2010b; Fig. 4). An increase in the preparation size or taper allows penetration of the needle closer to WL (Abou-Rass & Piccinino 1982) and leads directly to more efficient irrigant refreshment (Chow 1983; Falk & Sedgley 2005; Hsieh et al. 2007; Huang et al. 2008; Bronnec et al. 2010a; Boutsioukis et al. 2010d, 2010e). It seems that enlargement to size 25 does not allow effective irrigant flow and apical refreshment even in 0.06 tapered root canals (Hsieh et al. 2007; Boutsioukis et al. 2010d). Enlargement to size 30 allows effective replacement 2 mm apical to an open-ended needle when combined with at least a 0.06 taper (Boutsioukis et al. 2010e), while size 35 combined with a 0.05 to 0.06 taper leads to significant irrigant refreshment almost 3 mm apical to the needle tip (Hsieh et al. 2007; Boutsioukis et al. 2010d). For closed-ended needles, it appears that irrigant replacement extends almost 1 mm apical to their tip in a root canal of size 30 and at least a 0.06 taper, while a further increase in the size or taper has only a minimal additional effect (Hockett et al. 2008;

Boutsioukis et al. 2010d, 2010e). Therefore, these needles should be placed within 1 mm from WL, and a minimum apical size of 35 is required in order for a 30 G needle to reach this depth. Surprisingly, a minimally tapered root-canal preparation (size 60 and 0.02 taper) may present an advantage over tapered ones in terms of irrigant refreshment (Boutsioukis et al. 2010e). However, irrigant exchange should be evaluated together with resistance to root fracture, the possibility of iatrogenic root-canal perforation and obturation technique requirements before deciding the instrumentation strategy.

Apart from the need to enlarge the root canal so that the needle can reach within a few millimetres of WL, it is equally important to ensure adequate space around the needle for reverse flow of the irrigant towards the canal orifice. Assuming that the position and size of the needle remain constant, an increase in the apical size or taper of the root canal results in an increase in the space available between the needle and the root-canal wall. This increase leads to an increase in the irrigant refreshment in the apical part of the root canal. Effective reverse flow is also necessary for irrigant refreshment coronal to the needle tip (Boutsioukis et al. 2010d,

2010e). It has been speculated that a "dead-water" zone or stagnation zone exists apical to the needle tip (Gao et al. 2009; Shen et al. 2010). However, recent studies have disproved this assumption and have demonstrated that there are no areas in the main root canal where the irrigant is completely stagnant during syringe irrigation, but only areas where the irrigant flow is extremely slow and adequate exchange cannot be ensured within the time limitations of a root-canal treatment (Boutsioukis
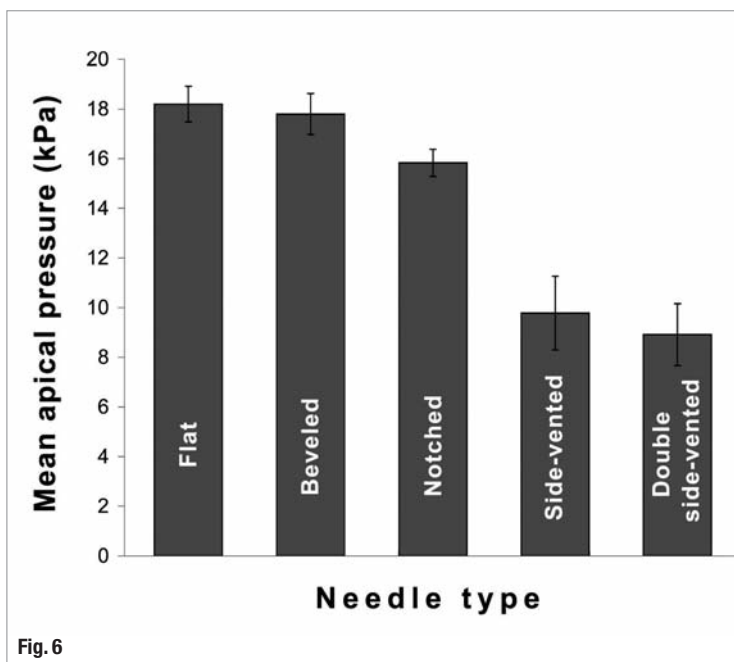

Fig. 6

Fig. 6_Time-averaged irrigant pressure at the apical foramen for various needle types: open-ended (A–C), closed-ended (D & E). Data shown as mean ± standard deviation. (Reprinted with permission from Boutsioukis et al. 2010b.)

et al. 2010a, 2010b, 2010c, 2010d, 2010e; Verhaagen et al. 2012). Increasing the volume of irrigant delivered could help to improve refreshment in such cases (Sedgley et al. 2004, 2005; Bronnec et al. 2010b) because it can be translated into irrigating for a longer time if the flow rate is constant.

Most of the data on irrigant flow and refreshment has been obtained from experiments and simulations in simple, straight root canals; however, many root canals are curved in reality. The effect of curvature on irrigant exchange has been studied indirectly by Nguy and Sedgley (2006), who reported that only a severe curvature in the order of 24 to 28 degrees impeded the flow of irrigants, delivered by a closed-ended needle near WL, even at a low flow rate. It can be assumed that if needles are positioned within 1 to 3 mm short of WL in a curved root canal, in many cases they have already bypassed most of the curvature and the remaining curvature apical to their tip is limited. Small size (30 G) flexible irrigation needles available nowadays in the market facilitate placement near WL, even in severely curved canals provided that the canal is enlarged to at least a size 30 or 35.

_Wall shear stress

During irrigant flow, frictional forces occur between the flowing irrigant and root-canal walls. These forces give rise to wall shear stress (Mott 1999; Tilton 1999; White 1999), which is of particular interest to irrigation because it tends to detach microbes/biofilm, tissue remnants or dentine debris from the root-canal wall; thus, it determines the mechanical effect of irrigation. Currently, there is no quantitative data on the minimum shear stress required for the removal of these targets. However, the overall distribution of wall shear stress provides an indication of the mechanical debridement efficacy.

Similar to the irrigant flow, two basic wall shear stress patterns can be distinguished for the various needle types during syringe irrigation (Fig. 5; Boutsioukis et al. 2010b). Regarding open-ended needles, an area of increased shear stress (which can be linked to optimum debridement) is developed apical to the needle tip, in the region of jet break up. Closed-ended needles lead to almost twice as high maximum shear stress, but limited near their tip, on the wall facing the needle outlet (the proximal outlet for the double side-vented needle). The unidirectional performance of closed-ended needles has also been reported in ex vivo studies that documented the influence of needle orientation on the debridement of the root canal (Yamamoto et al. 2006; Huang et al. 2008). So, in both cases, optimum debridement is expected near the tip of the needle (Huang et al. 2008; Boutsioukis et al. 2010b); therefore, during irrigation it is necessary to move the needle inside the root canal, so that the limited area of high wall shear stress affects as much of the root-canal wall as possible.

Needle insertion depth, canal size and taper do not seem to affect the distribution of wall shear stress significantly (Boutsioukis et al. 2010c, 2010d, 2010e). The maximum shear stress decreases as needles move away from WL, or with increasing size or taper, because more space is available for the back-flow of the irrigant and the irrigant velocity decreases, but the area affected by maximum shear stress becomes larger. It could be hypothesised that over-enthusiastic enlargement of the root canal beyond a certain size or taper may in fact reduce the debridement efficacy of irrigation. Similar to irrigant refreshment, it appears that the overall distribution of wall shear stress may be slightly more favourable in canals with a large apical size and limited taper rather than canals with a small size and increased taper (Boutsioukis et al. 2010d, 2010e). No data is available on the effect of flow rate, but it can be assumed that increasing the flow rate will also increase the wall shear stress. In all cases, high shear stress may lead to the detachment of biofilm or debris from the root-canal wall but is not enough to ensure their removal from the canal space, unless there is a favourable reverse flow to carry them towards the canal orifice.

_Apical pressure—Extrusion

During root-canal irrigation, it is possible that part of the irrigant delivered will be extruded towards the periapical tissue (Vande Visse & Brilliant 1975; Hülsmann et al. 2009). A healthy periodontium seems to provide a reliable barrier against irrigant extrusion (Salzgeber & Brilliant 1977; Chu 2010). However, currently, there is insufficient data to allow a more elaborate understanding of this aspect of root-canal irrigation. In order to conduct some useful comparisons, the irrigant pressure at the apical foramen could be related to the possibility and severity of irrigant extrusion (Boutsioukis et al. 2010*b*).

In general, the open-ended needles achieve improved irrigant refreshment in the apical part of the root canal but also lead to higher pressure at the apical foramen, indicating an increased risk of irrigant extrusion; closed-ended needles develop much lower pressure (approximately 50% less; Fig. 6; Boutsioukis et al. 2010*b*). Both needle types present a similar decrease in apical pressure, as the insertion depth decreases or the preparation size or canal taper increases (Boutsioukis et al. 2010*c*, 2010*d*, 2010*e*).

The performance of open-ended and closed-ended needles is expected to be quite different in the hypothetical situation of the needle binding in the root canal. If an open-ended needle is used, the flow would be trapped apical to the needle tip without any route of escape towards the canal orifice, the apical pressure would increase rapidly and forceful irrigant extrusion would probably occur. To the contrary, binding of a closed-ended needle would limit the irrigant flow to the space coronal to its tip. Irrigant exchange apical to the tip would be impossible, but the apical pressure would be almost zero, which is a benefit of the blind tip or safe tip of closed-ended needles, providing safety in such cases (Boutsioukis et al. 2010*d*, 2010*e*).

_Concluding remarks

Anatomical complexities of the root-canal system and the existence of microbes as surface-adherent biofilm structures serve as the foremost challenges in root-canal disinfection. One way of circumventing such challenges is by combining ideal irrigants with an optimal irrigation technique to achieve maximum removal of biofilms from the root canals. Accordingly, it becomes imperative to understand the fluid dynamics of irrigation in the root-canal system. The application of Computational Fluid Dynamics (CFD) models provides information on the flow and exchange of irrigant within the root-canal system for a particular mode of irrigation. It appears that the requirements of adequate irrigant penetration and exchange, mechanical debridement and minimum risk of apical ex-

trusion contradict each other and a delicate balance needs to be maintained. Since the prevention of extrusion should precede the other requirements of irrigation, a reasonable compromise for open-ended needles would be 2 or 3 mm short of WL. Based on Computational Fluid Dynamics analyses, this can still ensure adequate irrigant exchange and high wall shear stress, while reducing the risk of extrusion, provided that the canal is enlarged to at least a size 35 with a 0.06 taper or to a larger apical size combined with a minimum taper. The development of lower irrigant pressure by closed-ended needles allows their placement within 1 mm short of WL, so that optimum irrigant exchange can be ensured.

Anatomic irregularities may create additional challenges. Syringe irrigation seems unable to prevent or remove hard-tissue debris from the isthmus between the mesial root canals of mandibular molars (Endal et al. 2011; Paqué et al. 2011) or from artificial grooves and cavities in the apical part of the canal (Rödig et al. 2010). Currently, the irrigant flow in such complicated geometries has not been studied. It can be speculated that flow into narrow spaces connected to the main root canal is dependent on adequate activation, which could force the irrigant laterally into the grooves, cavities and isthmuses (Jiang et al. 2010), while syringe irrigation is possibly unable to achieve this goal predictably under clinical conditions.

In all cases, it must be remembered that regardless of the method and equipment used, irrigation of root canals involves a series of human-controlled actions, inevitably prone to natural human variability and difficult to standardise on a clinical basis. A wide variation in irrigant flow rate, duration, volume of irrigant and force applied to the syringe has been found among endodontists, even when the participants shared a common educational background (Boutsioukis et al. 2007*a*). Thus, the human factor should also be considered in root-canal irrigation._

Editorial note: A complete list of references is available from the publisher.

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