Abstract: Canal irrigation during root canal treatment is an important component of chemo-mechanical debridement of the root canal system. Traditional syringe irrigation can be enhanced by activating the irrigant to provide superior cleaning properties. This activation can be achieved by simple modifications in current technique or by contemporary automated devices. Novel techniques are also being developed, such as the Self-adjusting File (Re-Dent-Nova, Ra’anana, Israel), Ozone (Healozone, Dental Ozone, London, UK), Photo-activated Disinfection and Ultraviolet Light Disinfection.

This paper reviews the techniques available to enhance traditional syringe irrigation, contemporary irrigation devices and novel techniques, citing their evidence base, advantages and disadvantages.

Clinical Relevance: Recent advances in irrigation techniques and canal disinfection and debridement are relevant to practitioners carrying out root canal treatment.

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Endodontic treatment encompasses a range of procedures for the prevention or treatment of apical periodontitis. These include treatments to maintain the health of the vital pulp, and to treat teeth of which the pulps are irreversibly damaged or necrotic, with the aim of retaining functional tooth units. This ultimately presents clinicians with the challenge of negotiating, disinfecting, debriding and filling anatomy that is complex and infected with a plethora of microorganisms and that may be inaccessible to conventional instruments.

The challenges of removing micro-organisms and their substrate

Complex and altered anatomy

There are many challenges involved with achieving disinfection of the root canal system. Root canal anatomy is highly varied and often presents with many difficulties in terms of allowing access to the whole canal system. A recent study investigated the effect of anatomical factors on working length accessibility and found, unsurprisingly, that complex anatomy significantly increased the difficulty of achieving working length. Other variations include multiple and lateral canals, apical deltas and variations in the transverse plane such as C-canals. Peters et al showed that mechanical instrumentation left between 36% and 57% of the canal surface uninstrumented which, of course, harbour pathogenic organisms.

Iatrogenic complications can further complicate anatomy and affect working length accessibility. Complications produced during canal instrumentation can include transportation (alteration in canal curvature and ledge formation), perforations, stripping and broken instruments. Gorni and Gagliani found that teeth with altered root canal morphology had significantly poorer root canal retreatment success rates.

Retreatment cases can be particularly challenging as not only do these teeth have the potential iatrogenic complications associated with previous canal instrumentation, but they also have the difficulty of achieving access through extra-coronal restorations, posts and canals filled with gutta-percha. Ng et al
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found the apical extent of the root filling to have a significant effect on endodontic retreatment success rates, with long root fillings having poorest prognosis. One significant factor which they cited was the presence of a more resistant biofilm, that was likely to be composed of micro-organisms such as Enterococcus faecalis.

Biofilm and microbial resistance

Micro-organisms can exist in two main forms, either as loose collections/suspensions (planktonic) or as dense plaque-like aggregates (biofilm). Biofilms form through a series of events, starting with the deposition of a macromolecule conditioning film. Adhesion and cohesion of micro-organisms then occurs, followed by their multiplication and metabolism, leading to the development of a structurally organized mixed microbial community. Biofilms are organized in micro-colonies of micro-organisms, often forming tower or mushroom shapes, embedded in an extracellular polysaccharide matrix containing open water channels. Endodontic biofilms have mainly been discussed with regard to root tip surfaces in non-vital teeth in cases of refractory periapical pathology. Biofilms inside root canals have been less extensively studied, perhaps due to their inaccessible nature. However, we know micro-organisms in biofilms are generally more resistant to antimicrobials, compared to planktonic micro-organisms, with rates of 2−1000 times being reported. Several hypotheses for this have been suggested. Firstly, the slow penetration of antimicrobials through the biofilm with absorption by the extracellular matrix and de-activation. The redox potential of the biofilm could also have an effect, with oxygen being completely consumed, producing stable anaerobic conditions in the depth of the biofilm. Some antibiotics require aerobic conditions and hence deeper micro-organisms may be protected. Biofilm bacteria are also more likely to be in a non-growing state and hence resistant to antimicrobials that target growing states, eg cell wall synthesis. It has also been suggested that bacteria in a biofilm can form a phenotypic state, having a significant resistant to antimicrobials. Apical periodontitis in untreated root canals typically consists of a polymicrobial mix of gram-positive and gram-negative obligate or facultative anaerobes, whereas post-treatment disease is predominantly facultative gram-positive organisms with a very limited species distribution, perhaps even being monoinfections. This can be illustrated in part by the high detection rates of Enterococcus faecalis. This organism has numerous survival and virulence factors. It has been recovered from a high proportion of teeth with post-treatment disease, and has been implicated as a significant pathogen in 67−77% of studies when using contemporary molecular identification techniques. When dentine blocks were inoculated with E. faecalis, it was found to be difficult, if not impossible, to kill, even with a prolonged period of incubation in calcium hydroxide and NaOCl. This bacterium has been shown to have an ability to survive prolonged starvation at high pH levels as a result of a proton pump and antibiotic resistance.

Smear layer

Another challenge in allowing complete canal disinfection is the smear layer produced during canal instrumentation, with debris being spread over the canal walls. This is composed largely of inorganic dentine but also contains organic matter, such as odontogenic processes, micro-organisms and necrotic pulp material. Smear layer formation is greatest during motorized canal preparation compared to hand filing. The smear layer can potentially have several adverse effects on root canal treatment outcomes. The smear layer could compromise the coronal and apical seal, leading to microleakage. The layer may act as a substrate for bacteria and, indeed, can contain bacteria, their by-products and necrotic tissue. It also blocks dentinal tubules and limits optimum penetration of disinfecting irrigation solutions. Some have suggested that the smear layer may be beneficial and should be retained as it prevents the exchange and penetration of bacteria into dentinal tubules. A systematic review evaluating leakage of root-filled teeth and smear layer removal concluded that 41% of the papers were in favour of smear layer removal, 5% in favour of keeping it and 54% found no significant difference.

The potency of optimal chemo-mechanical preparation has been demonstrated in mechanical papers by Byström and Sundqvist. In their initial study, they irrigated canals with physiologic saline during instrumentation, which left 53% of the root canals infected. In subsequent studies, they irrigated with 0.5% NaOCl, leaving 20% of the canals infected and then placed calcium hydroxide as an intracanal dressing, leaving under 3% of the canals infected.

This paper aims to review canal irrigation techniques and methods for optimizing irrigation. Traditional syringe irrigation will be discussed, along with contemporary methods of enhancing irrigant penetration and dynamics. Novel techniques will also be considered.

Traditional methods of cleaning (disinfecting and debriding) root canals

Irrigation

Intra-operative disinfecting solutions or irrigants have three main roles; lubrication during instrumentation of the canals, flushing out instrumentation debris and to dissolve and disrupt the bacterial biofilm and remaining pulpal tissues. All three roles are crucial in delivering a patent root canal which is free from pathogenic levels of micro-organisms.

Irrigation of a small complex space, such as the root canal, is challenging. The confined geometry limits turbulence over much of the canal volume, making dispersion and mixing of irrigant difficult. Root canals can be described as ‘closed systems’ and difficulty in achieving adequate canal cleaning has been described.

Irrigants have both chemical and physical actions. Physical actions are largely comprised of shear stresses generated by fluid flow during irrigation. The shear stresses produced by injecting irrigant into a root canal are small and unlikely to disrupt the biofilm or smear layer significantly.

Several irrigants are available including:

- Saline;
- Chlorhexidine (CHX);
Alcohol;
- Hydrogen peroxide;
- Citric acid;
- Ethylenediamine tetra-acetic acid (EDTA);
- Proteolytic enzymes; and
- Sodium hypochlorite (NaOCL).

Sodium hypochlorite is the irrigant of choice owing to its tissue-dissolving properties and antibacterial effects.22 Synergic and antagonistic effects have been reported when using NaOCl and EDTA. Byström and Sundqvist found enhanced bacteria killing 23 but, more recently, Clarkson et al showed significant reductions in the amount of active chlorine available from NaOCl when used with EDTA.24 Care should be taken with CHX and NaOCl as neutralizing chemical reactions occur with a reduced combined effect, and also the potential for the production of a toxic precipitation.25

Surfactants have been added to irrigation solutions to reduce the surface tension and attempt to enhance the cleaning ability of the solution. Smear Clear (SybronEndo, Orange, CA, USA) contains 17% EDTA, cationic and anionic surfactants. However, studies have shown Smear Clear to give statistically similar results to EDTA alone.26,27

Syringe irrigation

Syringe irrigation has been the mainstay of treatment for many years and studies have shown it to provide disinfection and debridement of the root canal system.28,29 There are, however, challenges with syringe irrigation and studies have shown that irrigant rarely passes 1 mm deeper than the needle tip,30 forming a stagnation plane of non-irrigated canal31 (Figure 1b).

Needle tip designs can be divided into side-venting or open-ended flat needles. The latter deliver better apical penetration and a smaller stagnation plane but are not commonly used for the risk of apical extrusion. Side-venting needles have poorer apical penetration but concentrate the irrigant flow against the canal walls and produce high local velocity gradients, increased shear stresses and greater biofilm disruption.21,31 However, this is limited to straight regions of the canal which have sufficient width to accommodate the irrigation needle.

Manually activated irrigation is simple and cost-effective, utilizing existing endodontic armamentarium. Techniques such as agitation of a well-fitting master gutta-percha point enhances mixing of the canal fluids and increases the shear stress on the canal walls.22,32 Likewise, moving the irrigation needle34 or other endodontic instruments in a reciprocating corono-apical motion will have similar effects.35 Factors such as proximity of the irrigation needle to the apex, larger irrigation volume and smaller-gauge irrigation needles can improve irrigant efficacy.36

Entrapment of gas at the apical end of the canal may prevent irrigant penetrating fully to the apex (vapour lock effect).37 This gas could be air, gases such as chlorine formed when NaOCl dissolves organic tissue, or from microbial metabolism. It has been shown that, if fluid is left in the canal, it will eventually flood the whole canal and displace the gas. However, this takes hours to days, a time frame not practical clinically. A simple solution is to place a well-fitting master GP point to working length. This removes the air by displacement and carries a film of irrigant to the working length. This simple procedure is shown in Figure 1. A similar effect will occur with passage of files, but these are rarely so well fitting. Manually activated irrigation using a GP point has been shown to be superior to static irrigation and an automated system (RinsEndo system, Durr Dental Co, Germany) in removing a stained collagen bio-molecular film from root canal walls in ex-vivo models.32,33 The GP point should be moved in 3 mm coronal-apical motions at a rate of 33 Hz which translates to 100 strokes/30 seconds.32 As described by McGill et al33 ‘some clinicians balk at the laborious nature of such a task while others applaud its utter simplicity and cost effectiveness’. There are concerns regarding apical extrusion, with a ex-vivo study finding significantly greater apical extrusion with dynamic irrigation compared to static irrigation methods.38
Contemporary automated methods for activating irrigation

Sonic and ultrasonic irrigation systems

Sonic and ultrasonic instrumentation transmits energy from an oscillating instrument to the irrigant in the root canal by means of sonic or ultrasonic waves and induces acoustic streaming and cavitation of the irrigant (Figure 2). Cavitation is the growth and subsequent violent collapse of small gas bubbles formed due to a drop in pressure in the fluid. Acoustic streaming is the phenomenon of bulk movement of a fluid when pressure waves are projected through it, forming a circular or vortex-like motion around a vibrating object. Both of these effects allow the irrigant to be activated.

Acoustic streaming can produce sufficient shear forces to dislodge debris in instrumented canals and causes de-agglomeration of bacterial biofilms, rendering the resultant planktonic bacteria more susceptible to the NaOCl.

Cavitation might cause temporary weakening of the cell membrane and increase permeability to NaOCl.

In addition to the effect of acoustic streaming and cavitation, heat is produced by the ultrasonic instruments and a temperature rise seen in the irrigant. Heating of NaOCl leads to improved effectiveness with improved tissue dissolving properties and enhanced antibacterial effect.

Powerful ultrasonic systems have been shown to be more efficient than sonic irrigation systems, with more dentine debris removal and higher acoustic streaming velocity. Sonic devices, such as the Vibringe (Vibringe BV Corp, Amsterdam, Netherlands), have been developed for endodontic irrigation and been shown to be more effective than syringe irrigation, but not as effective as ultrasonic systems, at removing artificially placed dentine debris.

Ultrasonic instruments are widely used in several areas of dentistry and most dental surgeries will have ready access to a unit. Ultrasonic units can be either piezoelectric or magnetostrictive systems. The piezoelectric system transfers more energy to the files and generates little heat, hence not needing handpiece cooling. Specially shaped tips are available for the piezoelectric systems which can be used for conservative removal of dentine/pulp stones from pulp chambers and canals. They have the advantage that the tips are small and visibility is significantly increased over a conventional bur. Additionally, ultrasonic units can be used to provide activated irrigation through files, smooth wires, plastic inserts or irrigation needles.

Ultrasonic irrigation is described as 'passive' because the intention is for the file not to engage the canal walls, which could lead to uncontrolled and irregular dentine cutting. Passive ultrasonic irrigation (PUI) has been shown to be effective in removing pulp tissue and the smear layer, with the action being most effective when the file is loose and allowed to oscillate freely in the canal. Hence PUI should be completed after canal preparation and enlargement to allow the free movement of the file.

Two irrigating methods have been discussed with PUI:

- A continuous flush of irrigant from the ultrasonic handpiece; or
- An intermittent flush from a syringe between activations, similar to the technique used between files in conventional root treatment.

Van der Sluis et al found both the methods to be equally effective at removing dentine debris from grooves he had cut into canal walls in vitro. For the intermittent flush technique, he activated 2% NaOCl ultrasonically for 3 minutes, delivering 2 mL by syringe every 30 seconds.

Carver et al developed a continuous flush device which is essentially a clamp attaching an irrigation needle to an ultrasonic tip, transferring the ultrasonic motion to the irrigation needle. It has been shown to have a high ultrasonic output, producing cavitation in instrumented canals. It has been reported that significantly cleaner canals resulted from using this method, with significant reductions in colony-forming units and positive cultures. A contributory factor may be the continuous delivery of fresh active irrigant into the canals. NaOCl loses its tissue dissolution properties rapidly and hence, for optimal effect, it should be constantly replenished. A concern with this technique is the extrusion of irrigant through the apex.

A key point to note with ultrasonic activation is that acoustic streaming and cavitation can only occur in liquids and hence, if an apical gas bubble exists and the tip passes into this, there will be no effect in this region. This air bubble should be eliminated using a well-fitting master GP point, as previously described.

There are specially designed, non-cutting nickel-titanium inserts that can be fitted to conventional ultrasonic devices, eg ESI ENDO SOFT (EMS Optident (UK) Limited, Ilkley, West Yorkshire, UK) or Irrisafe Tips (Figure 3) and Saltelec piezoelectric scaling unit (Satelec ACTEON, St Neots, UK). Alternatively, normal endodontic instruments, such as files and irrigation needles, can be ‘engaged’ and ‘indirectly activated’ by an ultrasonic scaler tip, transferring the ultrasonic action to the instrument.

There are also several specifically produced devices, including the EndoActivator (Dentsply Tulsa Dental Specialties, York, USA) (Figure 4) and the

Figure 2. Ultrasonic mechanisms of action: (a) cavitation and (b) acoustic streaming. (Figures kindly provided by EMS, Electro Medical Systems.)
ProUltra®PiezoFlow™ (Dentsply Tulsa Dental Specialties, York, USA) (Figure 5). MiniEndo II (SybronEndo, California, USA) is an ultrasonic unit specially designed for endodontic procedures.

**EndoActivator**

The EndoActivator is a sonically driven canal irrigation system (Figure 4). It is presented with a portable handpiece and disposable non-cutting polymer tips. It has been shown to have significantly better debris removal and opening of lateral canals when compared to conventional syringe irrigation and passive ultrasonic irrigation. The smooth polymer tips have the advantage of being non-cutting and hence reducing the risk of creating iatrogenic damage. The knowledge that this tip is non-cutting allows the operator to provide additional up and down vertical strokes in addition to the sonic motion, a factor which may explain why studies have found this sonic technique to be superior to the more powerful ultrasonic techniques. The tips, however, have been criticized for being radiolucent; a potential problem in the event of future fracture.

**ProUltra®PiezoFlow™**

The ProUltra®PiezoFlow™ is an ultrasonic irrigation device. It consists of a disposable irrigation needle which is fitted to an ultrasonic headpiece. Irrigant is flown through the needle from either a handheld Luer-lock syringe or mechanical syringe pump (Figure 5). This is not currently available in the UK.

**Future developments**

**Contemporary irrigation systems**

A recent systematic review looking at factors for endodontic success found insufficient direct evidence relating irrigation type to endodontic success. However, procedural factors, such as instrumentation to the apex and bacterial load reduction, did have significant improvements on endodontic success and good quality root canal irrigation will, of course, play a crucial role in both of these.

With a greater knowledge of biofilm mechanics and fluid dynamics, new instrumentation systems have been developed, with the premise of allowing greater biofilm disruption, in the hope that this will lead to more predictable healing and tooth survival. However, evidence is currently lacking in this field and simply agitating a GP point may be as effective as these novel techniques.

**Negative and positive pressure irrigation**

Negative and positive pressure irrigation devices attempt to overcome the difficult balance between trying to ensure the canal is completely immersed in irrigant on the one hand, eliminating any air entrapment and, on the other hand, ensuring the canal is not over filled with irrigant, risking extrusion through the apex. Lussi et al first experimented in this area and developed a ‘non-instrumentation’ alternating pressure device that was able to achieve cleaner root canals than conventional step-back preparation with static irrigation. Unfortunately, this was not considered safe during in vivo animal studies and was not developed further.

In a similar method, negative pressure irrigation has been developed and is essentially a miniature aspirator placed at the apical region of the root canal. This could be a very fine needle attached to a dental unit suction, or there are several commercially available systems, such as the EndoVac (SybronEndo, California, USA) (Figure 6). The EndoVac has a microcannula which extends to the working length and a delivery tip which delivers irrigant into the pulp chamber. The irrigant is sucked from the orifice to the apical part of the root canal. The benefits of this system are the safety improvements with reduced risk of irrigant being extruded through the apex, avoiding the problem of air entrapment and possibly increased cleaning efficiency. Clinical data is limited but studies have shown EndoVac to be superior to syringe irrigation, with regards to debris and smear layer removal, particularly when examining closer to the working length. There are, however, limitations with the EndoVac. It is restricted to use in larger canals, requiring them to be prepared to size 35 or larger, and it would also struggle with any significant curvature. There is also a significant amount of apparatus with the EndoVac which is a challenge for the
using the SAF, compared to 55% when using conventional rotary instrumentation. Lateral laceration errors may also be reduced as the file accepts existing anatomy. One of the main advantages of the SAF is the irrigation system, with fresh irrigant being continuously fed to the canal which is then activated by the physical motion of the file (0.4 mm vertical oscillations, 5000 per minute).

This is a uniquely different technique and it is inevitable that there will be skepticism among endodontists. Shortcomings include the need for the canal to be prepared to size 20 apically before accepting the SAF, concerns regarding instrument separation, although studies have shown no mechanical failures after 29 minutes of operation, and the steep learning curve with using this new technique. The manufacturers also recommend purchasing an irrigation system (electronic pump) which, along with the handpiece and files, leads to a significant financial outlay. A manual syringe can be connected to provide irrigation, although an assistant will be required to deliver the irrigant during file activation.

The SAF is not currently available in the UK.

Ozone (Healozone, Dental Ozone, London, UK)

Ozone is a naturally occurring compound consisting of three oxygen atoms. It has been found to have powerful and reliable antimicrobial effects against bacteria, fungi, protozoa and viruses. Possible dental uses include arresting caries and remineralization, although several reviews conclude that there is a lack of reliable evidence to support its use and further clinical trials are needed. There have been a handful of in-vitro studies using ozone as a root canal disinfectant as compared to 2.5% NaOCl. The results were controversial with most of the studies concluding NaOCl was superior.

Photo-activation disinfection

Photodynamic therapy (PDT) or light-activated therapy (LAT) may have endodontic applications because of their antimicrobial effectiveness. A photoactive compound (toluidine blue O, Methylene Blue) is introduced into the root canal, preferentially localized in certain tissues (bacteria) and is then activated by exposure to a specific wavelength. This produces free radicals and singlet oxygen which have multiple antimicrobial effects. Early studies, both ex- and in-vivo, have found that if PDT/LAT is used as an adjuvant to conventional endodontic treatments, then significant further reductions in planktonic and biofilm bacterial load can be achieved, especially with regards to drug resistant bacteria. There are additional benefits of reducing bacterial resistance due to the wide spectrum of antimicrobial activity.

Ultraviolet light disinfection

Ultraviolet (UV) light is widely used for disinfection purposes, including drinking water and surfaces in operating theatres. Early studies introducing an intracanal UV diffuser into root canals in-vitro have given promising results when the UV light has been used as an additional procedure after NaOCl disinfection of the canal. One laboratory study achieved 96% teeth producing negative cultures compared to 47% when using conventional 5% NaOCl. Safety issues have also been considered, with 100 µm of dentine (the thickness of a coat of paint) allowing passage of only 1% of the UV light (<3 mJ/cm²), which is within EU safety limits. Canals with perforations and open apices may well be contra-indicated for this treatment modality, although illumination through the apex could be avoided by blocking the tip of the diffuser.

Novel irrigants

Developments are also being made with regards to irrigating solutions. Electrochemically activated water has been used to disinfect dental impressions and waterlines and has been approved and promoted as an endodontic irrigant in the United States since 2006 (Aquatine Endodontic Cleanser, Puricare, Pennsylvania, USA). Other irrigants showing potential include MTAD (Mixture of Tetracycline, Acid and Detergent, BioPure, Dentsply Tulsa Dental) and CHX-Plus (Vista Dental Products, Wisconsin, USA).

Conclusion

This paper has summarized the various techniques available to optimize

Figure 7. Self-adjusting File.
endodontic irrigation, either through manually activating syringe irrigation or through using contemporary automated devices. Novel techniques also show a varying amount of potential in providing additional disinfection and debridement of root canals.

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