Root Canal Irrigants

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Abstract

Local wound debridement in the diseased pulp space is the main step in root canal treatment to prevent the tooth from being a source of infection. In this review article, the specifics of the pulpal microenvironment and the resulting requirements for irrigating solutions are spelled out. Sodium hypochlorite solutions are recommended as the main irrigants. This is because of their broad antimicrobial spectrum as well as their unique capacity to dissolve necrotic tissue remnants. Chemical and toxicological concerns related to their use are discussed, including different approaches to enhance local efficacy without increasing the caustic potential. In addition, chelating solutions are recommended as adjunct irrigants to prevent the formation of a smear layer and/or remove it before filling the root canal system. Based on the actions and interactions of currently available solutions, a clinical irrigating regimen is proposed. Furthermore, some technical aspects of irrigating the root canal system are discussed, and recent trends are critically inspected. *(J Endod 2006;32:389–398)*

Key Words

Chelators, chlorhexidine, interactions, irrigants, review, sodium hypochlorite

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We are living in the age of evidence-based medicine. Any new concepts and techniques to be used in the clinic should ideally be assessed in randomized controlled clinical trials against their respective gold standards. This, however, poses a major problem in endodontic research. A favorable outcome of root canal treatment is defined as the reduction of a radiographic lesion and absence of clinical symptoms of the affected tooth after a minimal observation period of 1 yr (1). Alternatively, so-called surrogate outcome (dependent) variables yielding quicker results, such as the microbial load remaining in the root canal system after different treatment protocols, can be defined. However, these do not necessarily correlate with the "true" treatment outcome (2). Endodontic success is dependent on multiple factors (3), and a faulty treatment step can thus be compensated. For instance if cultivable microbiota remain after improper canal disinfection, they can theoretically be entombed in the canal system by a perfect root canal filling (4), and clinical success may still be achieved (5). On the other hand, in a methodologically sound clinical trial, single treatment steps have to be randomized and related to outcome. Otherwise, the results do not allow any conclusions and no causative relationships may be revealed (6).

The above issues may be viewed as the reason (or as an excuse) for the fact that no randomized controlled clinical trials exist on the effect of irrigating solutions on treatment outcome in the endodontic literature. As of yet, we largely depend on data from in vitro studies and clinical trials with microbial recovery after treatment as the surrogate outcome. Clinical recommendations based on such findings are merely deductive and need to be interpreted with care. Nevertheless, individual problems can be singled out in these investigations and basic information can be gained.

It was the purpose of this article to present an overview on irrigating solutions in endodontics, their actions and interactions. Based on data derived from basic science studies, results obtained in clinical investigations are discussed and some general recommendations are given.

Facing the Challenge

There can be no doubt today that microorganisms, either remaining in the root canal space after treatment or re-colonizing the filled canal system, are the main cause of endodontic failure (7, 8). The primary endodontic treatment goal must thus be to optimize root canal disinfection and to prevent re-infection.

Infection of the root canal space occurs most frequently as a sequela to a profound carious lesion (9). Cracks in the crown structure extending into the pulp chamber can also be identified as a cause of endodontic infection (10). Regardless of the microbial entryways, it should be differentiated between vital and nonvital cases (11). Pulpitis is the host reaction to opportunistic pathogens from the oral environment entering the endodontium (12). Vital pulp tissue can defend against microorganisms and is thus largely noninfected until it gradually becomes necrotic (9). In contrast, the pulp space of nonvital teeth with radiographic signs of periapical rarefaction always harbors cultivable microorganisms (13). Consequently, the treatment of vital cases should focus on *asepsis*, i.e. the prevention of infection entering a primarily sterile environment, which is the apical portion of the root canal. *Antisepsis*, which is the attempt to remove all microorganisms, is the key issue in nonvital cases. Vitality cannot always be predictably assessed with current sensitivity tests and radiologic methods before treatment (14). Once the pulp space is entered during access cavity preparation, however, the clinician can clearly discern between vital and nonvital pulp tissue (15), and further treatment decisions can be made accordingly.

Aseptic principles such as correct rubber dam placement and coronal disinfection of the tooth to be treated have long been accepted (16). Although asepsis is not the topic of the current communication, it is interesting to note that the majority of general practitioners disregard the most basic principles in that they do not place rubber dam for root canal treatment (17). Because of the complex anatomy of root canal systems, with their multiple fins and ramifications (18), antisepsis in necrotic teeth and teeth with failed root canal treatments is more challenging than in vital counterparts, both from a technical and a microbiologic point of view. The specifics of root canal infection are discussed below.

Root Canal Infection

As the host defense loses its access to the necrotic pulp space, opportunistic microorganisms selected by harsh ecological conditions and the low-oxygen environment aggregate in the root canal system (19). These microbial communities may survive on organic pulp tissue remnants and exudate from the periodontium (20, 21). Consequently, clusters of microorganisms in necrotic teeth and teeth with failed root canal treatments are typically found in the apical root canal area, where they have access to tissue fluid (19). In long-standing infections, root canal bacteria can invade the adjacent dentin via open dentinal tubules (22, 23).

Primary root canal infections are polymicrobial, typically dominated by obligately anaerobic bacteria (20). The most frequently isolated microorganisms before root canal treatment include Gram-negative anaerobic rods, Gram-positive anaerobic cocci, Gram-positive anaerobic and facultative rods, *Lactobacillus* species and Gram-positive facultative *Streptococcus* species (20). The obligate anaerobes are rather easily eradicated during root canal treatment. On the other hand, facultative bacteria such as nonmutans Streptococci, Enterococci, and Lactobacilli, once established, are more likely to survive chemomechanical instrumentation and root canal medication (24). In particular *Enterococcus faecalis* has gained attention in the endodontic literature, as it can frequently be isolated from root canals in cases of failed root canal treatments (25, 26). In addition, yeasts may also be found in root canals associated with therapy-resistant apical periodontitis (27).

It is likely that all of the microorganisms able to colonize the necrotic root canal system cause periapical inflammatory lesions. Enterococci can survive in monoculture (Fig. 1), but cause only minor lesions (28). Certain Gram-negative taxa appear to be more virulent (20). The outer membrane of Gram-negative bacteria contains endotoxin, which is present in all necrotic teeth with periapical lesions (29), and is able to trigger an inflammatory response even in the absence of viable bacteria (30). Furthermore, the levels of endotoxin in necrotic root canals are positively correlated to clinical symptoms such as spontaneous pain and tenderness to percussion (31). Virulent Gram-negative anaerobic rods depend on the presence of other bacteria in their environment to survive and establish their full pathogenic potential (28). Such aggregations of microorganisms in an extracellular polysaccharide matrix associated with a surface (in our case the inner root canal wall) are called biofilms (32). There is convincing evidence that microorganisms organized in this manner are far less susceptible to antimicrobial agents than their planktonic counterparts, which have traditionally been used to test the antimicrobial efficacy of substances in vitro (33, 34). If a bacterially inoculated broth is confronted with an antimicrobial fluid, the efficacy of that agent can appear to be very convincing, similar as with agar-diffusion tests. However, in the root canal system biofilms and infected dentinal tubules make disinfection much more difficult and thus study models such as standardized infected bovine dentin blocks (35) or in vivo models appear to be more valid than the above mentioned study designs. Furthermore, it has been shown that organic and inorganic dentin components, which are suspended in the irrigant during chemomechanical instrumentation, inhibit most antimicrobial agents (36, 37).

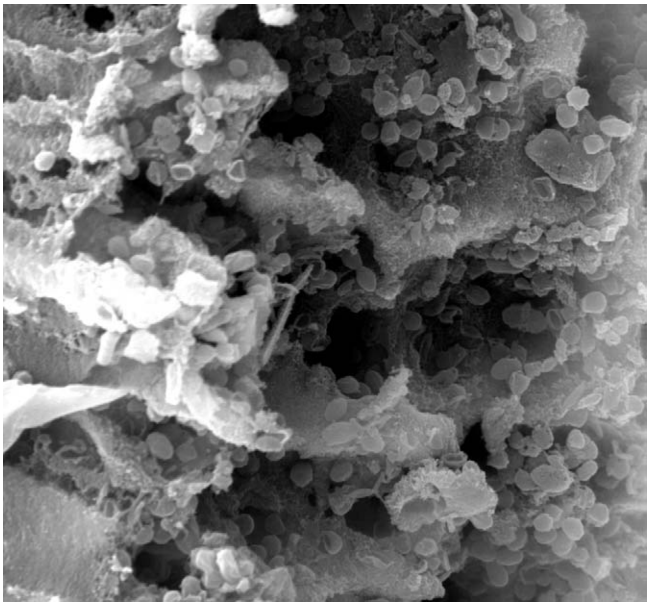

Figure 1. SEM image of a canal wall of a human premolar monoinfected with *E. faecalis* in tryptic soy broth for 2 weeks. Note the cell aggregations and the entering of the bacteria into dentinal tubules. Original magnification ×20,000.

In conclusion, the biofilm concept and the specific conditions in the pulpless root canal microniche cannot be overestimated when considering the actions of different irrigating solutions.

Root Canal Instrumentation

The main purpose of instrumentation is the mechanical debridement of the root canal system and the creation of a space for delivery of antimicrobial substances. Furthermore, a well-shaped root canal system facilitates the proper placement of a tight root canal filling to prevent re-colonization by oral microbiota (38). There have been attempts to perform endodontic treatment without mechanical instrumentation by means of a vacuum device and hypochlorite perfusion of the root canal system (39). Canal cleanliness obtained with this method, however, is still unacceptable when used clinically (40), and further research is indicated to improve this interesting approach.

Mechanical instrumentation, on the other hand, is not unproblematic either. First, there is the risk of instrument separation and preparation errors. In infected nonvital teeth with periapical radiolucencies, technical complications such as perforations into the periodontal ligament, instrument fractures, and the inability to mechanically reach the apical portion of the root canal section have a significant negative impact on treatment outcome (41). Second, a smear layer is produced on instrumented canal walls (42), which is comprised of inorganic and organic material such as dentin filings and pulp tissue remnants (43). This deposit can be penetrated by bacteria (44) and may offer protection to biofilms adhering to root canal walls (45). Furthermore, the smear layer interferes with a tight adaptation of currently used root canal sealers to dentin walls (46), and may therefore promote microleakage (47). Third, mechanical instrumentation in combination with a chemically inert irrigating solution cannot adequately reduce viable microorganisms in the infected root canal system (48, 49), nor can the formation of a smear layer be prevented (50). With both current nickel-titanium instrumentation systems and traditional stainless-steel hand instruments almost half of the root canal walls are left unprepared (51).

TABLE 1. Overview on the features of aqueous irrigants frequently recommended for endodontic use

Compound (recommended concentration)	Type	Action on Endodontic Taxa Biofilm	Tissue Dissolution Capacity	Endotoxin Inactivation	Action on Smear Layer	Caustic Potential	Allergic Potential
Hydrogen peroxide (3%–30%)	Peroxygen	+	−	−	−	D. o. c.	−
Sodium hypochlorite (1%–5.25%)	Halogen-releasing agent	++	+++	+	++ on organic compounds	D. o. c.	+
Iodine potassium iodide (2%–5%)	Halogen-releasing agent	++	−	N. i. a.	−	−	++
Chlorhexidine (0.2%–2%)	Bisguanide	++	−	+	−	D. o. c.	+
Dequalinium acetate (0.5%)	Quaternary ammonium compound	N. i. a.	−	N. i. a.	+	−	++
Ethylenediamine tetraacetic acid (10%–17%)	Polyprotic acid	+	−	−	++ on inorg. compounds	−	−
Citric acid (10%–50%)	Organic acid	−	−	−	+++ on inorg. compounds	−	−

−: absent or minor, +: reported, ++: definitely present, +++: strong, D. o. c.: depending on concentration, N. i. a: no information available.

Desired Irrigant Actions

Historically, countless compounds in aqueous solution have been suggested as root canal irrigants, including inert substances such as sodium chloride (saline) or highly toxic and allergenic biocides such as formaldehyde (52). In this review, however, the focus is on currently used irrigating solutions; obsolete substances are not discussed. Based on the above knowledge, it appears evident that root canal irrigants ideally should:

- Have a broad antimicrobial spectrum and high efficacy against anaerobic and facultative microorganisms organized in biofilms
- Dissolve necrotic pulp tissue remnants
- Inactivate endotoxin
- Prevent the formation of a smear layer during instrumentation or dissolve the latter once it has formed

Furthermore, as endodontic irrigants come in contact with vital tissues, they should be systemically nontoxic, noncaustic to periodontal tissues and have little potential to cause an anaphylactic reaction.

Choosing the Main Irrigant

Although iodine is less cytotoxic and irritating to vital tissues than sodium hypochlorite and chlorhexidine (53, 54), it bears a much higher risk to cause an allergic reaction (55). The same is true for quaternary ammonium compounds (56, 57). Sensitivities to hypochlorite and chlorhexidine are rare (58, 59). Despite its ubiquitous use, only few cases of allergic reactions to sodium hypochlorite from a root canal irrigant have been reported (60).

Of all the currently used substances, sodium hypochlorite appears to be the most ideal, as it covers more of the requirements for endodontic irrigant than any other known compound (Table 1). Hypochlorite has the unique capacity to dissolve necrotic tissue (61–63) and the organic components of the smear layer (64–67). It kills sessile endodontic pathogens organized in biofilms and in dentinal tubules as efficiently as chlorhexidine or iodine at comparable concentration (68–70). Inactivation of endotoxin by hypochlorite has been reported (71, 72); the effect, however, is minor compared to that of a calcium hydroxide dressing (73).

In conclusion, the currently available evidence is strongly in favor of sodium hypochlorite as the main endodontic irrigant. However, the use of chlorhexidine solutions may also be indicated under certain conditions. Therefore, the reader will find a short summary on basic properties of chlorhexidine, followed by a longer elaboration on hypochlorite.

Chlorhexidine

Chlorhexidine was developed in the late 1940s in the research laboratories of Imperial Chemical Industries Ltd. (Macclesfield, England). Initially, a series of polybisguanides was synthesized to obtain anti-viral substances. However, they had little anti-viral efficacy and were put aside, only to be re-discovered some years later as antibacterial agents. Chlorhexidine was the most potent of the tested bisguanides (74). Chlorhexidine is a strong base and is most stable in the form of its salts. The original salts were chlorhexidine acetate and hydrochloride, both of which are relatively poorly soluble in water (75). Hence, they have been replaced by chlorhexidine digluconate.

Chlorhexidine is a potent antiseptic, which is widely used for chemical plaque control in the oral cavity (76). Aqueous solutions of 0.1 to 0.2% are recommended for that purpose, while 2% is the concentration of root canal irrigating solutions usually found in the endodontic literature (77). It is commonly held that chlorhexidine would be less caustic than sodium hypochlorite (78). However, that is not necessarily the case (53). A 2% chlorhexidine solution is irritating to the skin (75). As with sodium hypochlorite (see below), heating a chlorhexidine irrigant of lesser concentration could increase its local efficacy in the root canal system while keeping the systemic toxicity low (79).

Despite its usefulness as a final irrigant (see "Suggested Irrigation Regimen" below), chlorhexidine cannot be advocated as the main irrigant in standard endodontic cases, because: (a) chlorhexidine is unable to dissolve necrotic tissue remnants (63), and (b) chlorhexidine is less effective on Gram-negative than on Gram-positive bacteria (74, 80, 81). This may explain why long-term application of chlorhexidine in dogs led to a domination in plaque samples of Gram-negative rods (82). It must be cautioned here that many ex vivo studies use extracted bovine or human teeth mono-infected with *Enteroccous faecalis*, a Gram-positive facultative species associated with failed root canal treatments (83). However, in primary endodontic infections, which are usually poly-microbial, Gram-negative anaerobes predominate (20). Enterococci are rarely encountered in primary endodontic infections (84). The efficacy of chlorhexidine against Gram-positive taxa in laboratory experiments may thus cause an over-estimation of the clinical usefulness of this agent. In a randomized clinical trial on the reduction of intracanal microbiota by either 2.5% NaOCl or 0.2% chlorhexidine irrigation, it was found that hypochlorite was significantly more efficient than chlorhexidine in obtaining negative cultures (85). This was especially the case for anaerobic bacteria, while the difference for facultative taxa was less significant. Furthermore, more culture reversals from negative to positive were found with chlorhexidine than with hypochlorite. The authors attributed this phenomenon to the inability of chlorhexidine to dissolve necrotic tissue remnants and chemically clean the canal system.

Hypochlorite

Natural Occurrence

Chlorine is one of the most widely distributed elements on earth. It is not found in a free state in nature, but exists in combination with sodium, potassium, calcium, and magnesium (86). In the human body, chlorine compounds are part of the nonspecific immune defense. They are generated by neutrophils via the myeloperoxidase-mediated chlorination of a nitrogenous compound or set of compounds (87).

History of Chlorine-Releasing Agents

Potassium hypochlorite was the first chemically produced aqueous chlorine solution, invented in France by Berthollet (1748-1822). Starting in the late 18th century, this solution was industrially produced by Percy in Javel near Paris, hence the name "Eau de Javel". First, hypochlorite solutions were used as bleaching agents. Subsequently, sodium hypochlorite was recommended by Labarraque (1777-1850) to prevent childbed fever and other infectious diseases. Based on the controlled laboratory studies by Koch and Pasteur, hypochlorite then gained wide acceptance as a disinfectant by the end of the 19th century. In World War I, the chemist Henry Drysdale Dakin and the surgeon Alexis Carrel extended the use of a buffered 0.5% sodium hypochlorite solution to the irrigation of infected wounds, based on Dakin's meticulous studies on the efficacy of different solutions on infected necrotic tissue (88). Beside their wide-spectrum, nonspecific killing efficacy on all microbes, hypochlorite preparations are sporicidal, virucidal (89), and show far greater tissue dissolving effects on necrotic than on vital tissues (90). These features prompted the use of aqueous sodium hypochlorite in endodontics as the main irrigant as early as 1920 (91). Furthermore, sodium hypochlorite solutions are cheap, easily available, and demonstrate good shelf life (92). Other chlorine-releasing compounds have been advocated in endodontics, such as chloramine-T and sodium dichloroisocyanurate (93, 94). These, however, have never gained wide acceptance in endodontics, and appear to be less effective than hypochlorite at comparable concentration (63, 86, 95).

Concentration of Sodium Hypochlorite for Endodontic Usage

There has been much controversy over the concentration of hypochlorite solutions to be used in endodontics. As Dakin's original 0.5% sodium hypochlorite solution was designed to treat open (burnt) wounds, it was surmised that in the confined area of a root canal system, higher concentrations should be used, as they would be more efficient than Dakin's solution (96). The antibacterial effectiveness and tissue-dissolution capacity of aqueous hypochlorite is a function of its concentration, but so is its toxicity (53). It appears that the majority of American practitioners use "full strength" 5.25% sodium hypochlorite as it is sold in the form of household bleach. However, severe irritations have been reported when such concentrated solutions were inadvertently forced into the periapical tissues during irrigation or leaked through the rubber dam (97). Furthermore, a 5.25% solution significantly decreases the elastic modulus and flexural strength of human dentin compared to physiologic saline, while a 0.5% solution does not (98). This is most likely because of the proteolytic action of concentrated hypochlorite on the collagen matrix of dentin. The reduction of intracanal microbiota, on the other hand, is not any greater when 5% sodium hypochlorite is used as an irrigant as compared to 0.5% (99, 100). From in vitro observations, it would appear that a 1% NaOCl solution should suffice to dissolve the entire pulp tissue in the course of an endodontic treatment session (101). It must be realized that during irrigation, fresh hypochlorite consistently reaches the canal system, and concentration of the solution may thus not play a decisive role (102). Unclean areas may be a result of the inability of solutions to physically reach these areas rather than their concentration (103). Hence, based on the currently available evidence, there is no rationale for using hypochlorite solutions at concentrations over 1% wt/vol.

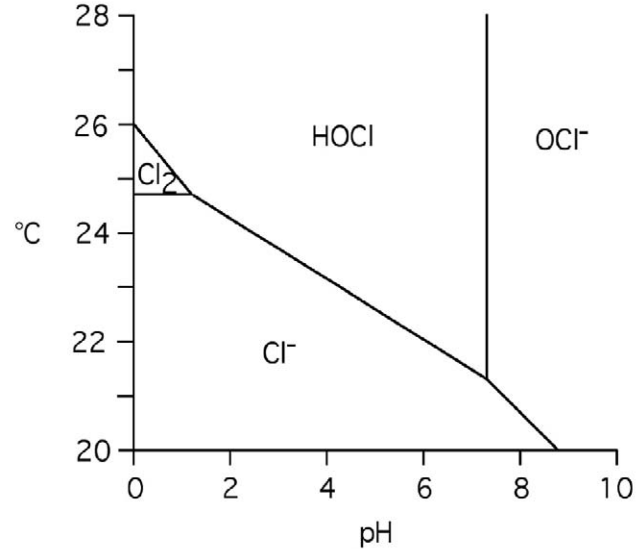

Figure 2. Different states of chlorine found in water, depending on pH and temperature. (Taken from (178) with the permission of the copyright holders; calculations for this figure were kindly performed by Beat Müller, PhD, Swiss Federal Institute for Environmental Science and Technology, Kastanienbaum, Switzerland.)

Increasing the Efficacy of Hypochlorite Preparations

Reactive chlorine in aqueous solution at body temperature can, in essence, take two forms: hypochlorite (OCl^-) or hypochlorous acid (HOCl). The concentration of these can be expressed as available chlorine by determining the electrochemical equivalent amount of elemental chlorine (86). According to the following equations:

$$C1_2 + 2e^- = 2C1^- \text{ and} \quad (1)$$

$$OC1^- + 2e^- + 2H^+ = C1^- + H_2O \quad (2)$$

Therefore, 1 mol of hypochlorite contains 1 mol of available chlorine. The state of available chlorine is depending on the pH of the solution (Fig. 2). Above a pH of 7.6, the predominant form is hypochlorite, below this value it is hypochlorous acid (104). Both forms are extremely reactive oxidizing agents. Pure hypochlorite solutions as they are used in endodontics have a pH of 12 (92), and thus the entire available chlorine is in the form of OCl^-. However, at identical levels of available chlorine, hypochlorous acid is more bactericidal than hypochlorite (105). One way to increase the efficacy of hypochlorite solutions could thus be to lower their pH. It has also been surmised that such solutions would be less toxic to vital tissues than nonbuffered counterparts (88, 106). However, buffering hypochlorite with bicarbonate renders the solution unstable with a decrease in shelf life to less than 1 week (106). Depending on the amount of the bicarbonate in the mixture and therefore the pH value, the antimicrobial efficacy of a fresh bicarbonate-buffered solution is only slightly higher (106) or not elevated at all compared to that of a nonbuffered counterpart (107). Finally, the caustic potential of hypochlorite solutions appears to be influenced mainly by the available chlorine rather than by pH or osmolarity (107).

One alternative approach to improve the effectiveness of hypochlorite irrigants in the root canal system could be to increase the temperature of low-concentration NaOCl solutions. This improves their immediate tissue-dissolution capacity (108–110). Furthermore, heated hypochlorite solutions remove organic debris from dentin shavings more efficiently than unheated counterparts (111). The antimicrobial properties of heated NaOCl solutions have also been discussed. As early as 1936, the effect of NaOCl temperature on *Mycobacterium tuberculosis* survival was demonstrated (112). With the taxa tested so far, bactericidal rates for sodium hypochlorite solutions are more than doubled for each 5°C rise in temperature in the range of 5 to 60°C (86). This was corroborated in a recent study using steady-state planktonic *E. faecalis* cells; a temperature raise of 25°C increased NaOCl efficacy by a factor 100 (101). The capacity of a 1% NaOCl at 45°C to dissolve human dental pulps was found to be equal to that of a 5.25% solution at 20°C (101). On the other hand, with similar short-term efficacy in the immediate environment, i.e. the root canal system, the systemic toxicity of preheated NaOCl irrigants should be lower than the one of more concentrated nonheated counterparts as a temperature equilibrium is reached relatively quickly (109). However, there are no clinical studies available at this point to support the use of heated sodium hypochlorite.

Ultrasonic activation of sodium hypochlorite has also been advocated, as this would "accelerate chemical reactions, create cavitational effects, and achieve a superior cleansing action" (113). However, results obtained with ultrasonically activated hypochlorite versus irrigation alone are contradictory, both in terms of root canal cleanliness (114–117) and remaining microbiota in the infected root canal system after the cleaning and shaping procedure (118, 119). The observed effects of ultrasonic activation, if any, were relatively minor. Furthermore, the nature of these effects is unclear (120). An ISO-size 15 endosonic file connected to an ultrasonic handpiece introduced 1 mm short of working length has been advocated for passive irrigant activation (121). Using this set-up, cavitation—the growth and subsequent collapse of small gas bubbles in the bulk fluid—was not observed under laboratory conditions in rectangular glass containers (114). Hence, the hypochlorite activation has been attributed mainly to sonic (acoustic) streaming, i.e. the vortex-like fluid movement about the endosonic file (114). On the other hand, in simulated root canals steady streaming and stable cavitation both occurred to varying degrees, depending on the file-to-wall contact (122). However, the streaming patterns in the confined environment of the root canal system with its complex inner surface and unpredictable wave reflection patterns remain unclear (123). In none of the above studies was the temperature of the irrigant controlled. Ultrasonic energy may simply produce heat (124), thus rendering the hypochlorite slightly more active. Nevertheless, a direct ultrasound effect on canal debridement has been reported (125, 126). If ultrasonic activation of the hypochlorite irrigant is to be used, it appears important to apply the ultrasonic instrument after the canal preparation has been completed. A freely oscillating instrument will cause more ultrasound effects in the irrigating solution than a counterpart that binds to canal walls (122). In addition, ultrasonic files can cause uncontrolled cutting of the canal walls, especially if used during preparation (127). Therefore, it appears best to insert a slim, noncutting instrument in a controlled fashion after canal preparation (50, 126). As of recently, smooth wires fitting to an ultrasonic device have been commercially available. However, clear guidelines regarding their risk/benefit ratio cannot be given at this point.

In this context, it should also be noted that *time* is a factor that has gained little attention in endodontic studies (119). Even fast-acting biocides such as sodium hypochlorite require an adequate working time to reach their potential (89). This should especially be considered in view of the fact that rotary root canal preparation techniques have expedited the shaping process (51). The optimal time that a hypochlorite irrigant at a given concentration needs to remain in the canal system is an issue yet to be resolved.

Chelator Solutions

Although sodium hypochlorite appears to be the most desirable single endodontic irrigant, it cannot dissolve inorganic dentin particles and thus prevent the formation of a smear layer during instrumentation (128). In addition, calcifications hindering mechanical preparation are frequently encountered in the canal system. Demineralizing agents such as ethylenediamine tetraacetic acid (EDTA) (129) and citric acid (130) have therefore been recommended as adjuvants in root canal therapy. These are highly biocompatible and are commonly used in personal care products (131). Although citric acid appears to be slightly more potent at similar concentration than EDTA, both agents show high efficiency in removing the smear layer (132). In addition to their cleaning ability, chelators may detach biofilms adhering to root canal walls (Kishor Gulabivala, personal communication). This may explain why an EDTA irrigant proved to be highly superior to saline in reducing intracanal microbiota (133), despite the fact that its antiseptic capacity is relatively limited (134). Albeit never shown in a randomized clinical trial, an alternating irrigating regimen of NaOCl and EDTA may be more efficient in reducing bacterial loads in root canal systems than NaOCl alone (100). Antiseptics such as quaternary ammonium compounds (EDTAC (129)) or tetracycline antibiotics (MTAD (135)) have been added to EDTA and citric acid irrigants, respectively, to increase their antimicrobial capacity. The clinical value of this, however, is questionable. EDTAC shows similar smear-removing efficacy as EDTA, but it is more caustic (134). As for MTAD, resistance to tetracycline is not uncommon in bacteria isolated from root canals (136). Generally speaking, the use of antibiotics instead of biocides such as hypochlorite or chlorhexidine appears unwarranted, as the former were developed for systemic use rather than local wound debridement, and have a far narrower spectrum than the latter (89).

Chelating agents can be applied in liquid or paste-type form (137). The origin of paste-type preparations dates back to 1961, when Stewart devised a combination of urea peroxide with glycerol (138). Later, based on the results of that first preliminary study and the successful introduction of EDTA to endodontic practice (129), urea peroxide and EDTA were combined in a water-soluble carbowax (polyethylene glycol) vehicle (139). This product has since been commercially available. Similar paste-type chelators containing EDTA and peroxide have later been marketed by other manufacturers. However, none of these pastes should be used, as they are inefficient in preventing the formation of a smear layer (137). Furthermore, instead of lowering physical stress on rotary instruments as advocated, carbowax-based lubricants, depending on instrument geometry, have either no effect or are even counterproductive (140).

One important aspect related to currently available irrigating solutions, i.e. EDTA and citric acid, is that they strongly interact with sodium hypochlorite (141). Both citric acid and EDTA immediately reduce the available chlorine in solution, rendering the sodium hypochlorite irrigant ineffective on bacteria and necrotic tissue (132). Hence, citric acid or EDTA should never be mixed with sodium hypochlorite. The same goes for paste-type EDTA preparations: at a 1:10 ratio, they immediately rid a 1% sodium hypochlorite solution of all hypochlorite (142). The "bubbling effect" or effervescence used to advocate for such products is only proof of the chemical reaction that takes place between hypochlorite on the one hand and EDTA and hydrogen peroxide (if contained in the paste-type chelating product) on the other hand, resulting in evaporating gas (141). Oxygen evaporates from aqueous peroxide-hypochlorite mixtures, and chlorine and oxygen gas from corresponding mixtures of NaOCl with EDTA or citric acid (141). Despite clinical folklore, a physical cleaning effect of this reaction has never been shown. In his landmark study on the use of sodium hypochlorite in 1921 (61), Blum wrote (translated from German): "I should not forget to mention that the efficacy of hypochlorite in the tooth can be enhanced by the use of a heated needle. I have found a lesser benefit from adding a drop of acid. The immediate foaming can feign a strong effect. However, this is not the case, as the hypochlorite solution is instantly lost and rendered completely ineffective. The time the hypochlorite is allowed to act will have a major impact on treatment outcome."

Hydroxyethylidene bisphosphonate (HEBP), also called etidronate, is a decalcifying agent that shows only little short-term interference with sodium hypochlorite. It has recently been suggested as a possible alternative to citric acid or EDTA (132, 143). HEBP prevents bone resorption and is used systemically in patients suffering from osteoporosis or Paget's disease (144). However, whether this agent will improve or abbreviate endodontic irrigation will have to be shown in future studies.

Suggested Irrigation Regimen

As indicated above, the chemicals used to clean infected canals should be administered in such manner that they can unleash their full potential on their targets in the root canal rather than act on each other. Hence, a hypochlorite solution should be employed throughout instrumentation, without altering it with EDTA or citric acid. Canals should always be filled with sodium hypochlorite. This will increase the working time of the irrigant. In addition, cutting efficacy of hand instruments is improved (145) and torsional load on rotary nickel-titanium instruments is reduced (140) in fluid-filled environments compared to dry conditions. On the other hand, corrosion of instruments in prolonged contact with hypochlorite is an issue (146). Submersing instruments for hours in a hypochlorite solution will induce corrosion (147). However, no adverse effects should be expected during the short contact periods when an instrument is manipulated in a root canal filled with hypochlorite (148).

Between instruments, canals should be irrigated using copious amounts of the hypochlorite solution. Once the shaping procedure is completed, canals can be thoroughly rinsed using aqueous EDTA or citric acid. No clear-cut recommendations exist as to the time this procedure should be exercised (137). Generally each canal is rinsed for at least 1 min using 5 to 10 ml of the chelator irrigant. It must be cautioned that prolonged exposure to strong chelators such as EDTA may weaken root dentin (149), as dentin hardness and elastic modulus are functions of the mineral content of the dentin (150).

After the smear removing procedure a final rinse with an antiseptic solution appears beneficial (151). The choice of the final irrigant depends on the next treatment step, i.e. whether an intervisit dressing is planned or not. If calcium hydroxide is used for the interim, the final rinse should be sodium hypochlorite, as these two chemicals are perfectly complementary (152). It appears even advantageous to mix calcium hydroxide powder with the sodium hypochlorite irrigant rather than with saline to obtain a more effective dressing (152).

If the canal walls are perceived to be clean of debris and the plan is to fill the root canal or to place a chlorhexidine gel as an intervisit dressing (153), necrotic tissue dissolution is not an issue anymore. Hence, chemicals other than sodium hypochlorite may be employed. Chlorhexidine appears to be the most promising agent to be used as a final irrigant in this situation. It has an affinity to dental hard tissues (154), and once bound to a surface, has prolonged antimicrobial activity, a phenomenon called substantivity (155, 156). Substantivity is not observed with sodium hypochlorite (157). In a randomized clinical trial, a 2% chlorhexidine solution, used as a final irrigant, significantly decreased bacterial loads in root canals that had been irrigated with sodium hypochlorite during canal preparation (77). However, a final chlorhexidine rinse was compared to an identical procedure using sterile saline, and it is thus not clear whether this regimen is any better than using hypochlorite for the final rinse. Other clinical studies have reported on a positive effect of infiltrating the root canal system with iodine potassium iodide for 5 to 10 min after chemomechanical preparation (158, 159). Yet again, sodium hypochlorite was not used as a control. Nevertheless, a final irrigation using a chlorhexidine solution appears advantageous, especially in re-treatment cases, where high proportions of Gram-positive bacteria are to be expected in the root canal system.

If hypochlorite is still present in the canal, subsequently added chlorhexidine will precipitate in the form of a brownish-reddish mass. Copious amounts of chlorhexidine irrigant should thus be administered to secure proper action of the chlorhexidine and to prevent discoloring of the tooth by these precipitates. Alternatively, the canal can be dried using paper points before the final chlorhexidine rinse.

Technical Aspects of Irrigating Root Canals

Penetration of an irrigant into the instrumented root canal system is a function of irrigating needle diameter in relation to preparation size (160). Hence, while direct evidence is still lacking, the introduction of a slim irrigating needle with a safety tip (Fig. 3, panel *A*) to working length or 1 mm short of it is a promising approach to improve irrigant efficacy in the infected apical area of nonvital teeth with apical radiolucencies. It should be kept in mind that the solution does not reach further than 1 mm apically from the needle tip during irrigation (Fig. 3, panels *B–G*). Hence, apical preparation size becomes an issue (161). When a 30-gauge needle is used, the apical preparation should be to an ISO-size 35 to 40 to secure proper rinsing of the apical area (Fig. 3).

Alternative Concepts

In this communication it was aimed at presenting a simple and affordable way for the chemical debridement of root canal systems using materials that are currently available to the clinician. This does not mean that there could be no other biologically acceptable possibilities to clean root canal systems. However, the reader should be aware of the fact that new concepts usually are overrated in initial studies when compared to the gold standard (6, 135, 162). Some recent approaches to improve root canal debridement include the use of laser light to induce lethal photosensitization on canal microbiota (163), irrigation using electrochemically activated water (164), and ozone gas infiltration into the endodontic system (165). However, in terms of killing

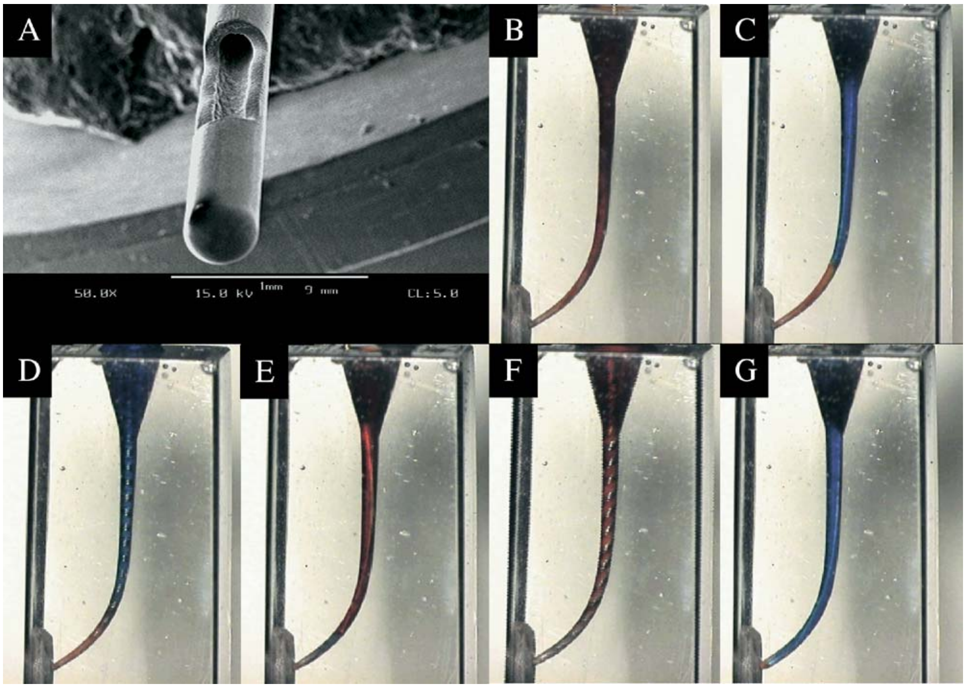

Figure 3. Two differently colored dyes were used so that the advancing penetration of the subsequent dye could be monitored (panels *B–G* were transferred from a digital film sequence, courtesy of Frank Paqué). Panel *A*: scanning electron micrograph of a 30-gauge irrigating needle with a safety tip. Panel *B*: canal instrumented to an ISO-size 30 using a .04-tapered ProFile and filled with a red liquid. Panel *C*: the 30-gauge irrigating needle scarcely reaches the apical third of the prepared canal; the blue irrigant does not reach further than 1 mm from the tip. Panel *D*: A size 35 ProFile is introduced to working length, the old and the fresh irrigants are stirred. Panel *E*: the needle still does not reach the apex, the old irrigant remains in the apical area. Panel *F*: Preparation using a size 40 ProFile to working length. Now the irrigating needle reaches the apical area, which only now can efficiently be rinsed (panel *G*).

efficacy on endodontic microbiota in biofilms, there is good evidence that none of these approaches can match a simple sodium hypochlorite irrigation (166–168).

One other idea that keeps returning is the notion that reducing surface tension by adding wetting agents would improve the effectiveness of irrigants, as they would reach better into dentinal tubules and accessory canals (169, 170). In the original study that showed a better penetration of liquids with reduced surface tension into the root canal systems of extracted molars, it was not mentioned whether these teeth were dry or had been kept in a moist environment (169). In situ root canals and adjacent dentin walls are liquid-filled (171), and surface tension of liquids to be introduced thus plays a minor role in this environment. The infiltration of dentin by chemical moieties from aqueous solutions occurs via diffusion rather than direct liquid exchange (172). Therefore, it may not come as a surprise that reducing surface tension in irrigants does not influence their capacity to remove the smear layer (143), nor does it enhance their antibacterial efficacy in the root canal (173). Moreover, reducing the surface tension in solutions used during instrumentation may actually cause an increased penetration of smear material into the dentinal tubules (174).

Finally, it should be mentioned that the irrigating concepts presented here are aimed at obtaining a clean root canal system that is ideally prepared for the classic filling technique, using gutta-percha and a sealer. In the future, other ways to fill root canal systems may evolve and/or be established, such as the use of resin-bonded systems (175), bioactive materials (176), or even the attempt to regenerate pulp tissue in necrotic cases (177). Although radical changes in the irrigating concept are not likely to occur, the specific needs for irrigants when such alternative attempts are followed are yet to be delineated.

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