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Factors affecting the viscosity of sodium hypochlorite and their effect on irrigant flow

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Abstract

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Aim To assess the influence of concentration, temperature and surfactant addition to a sodium hypochlorite solution on its dynamic viscosity and to calculate the corresponding Reynolds number to determine the corresponding flow regimen.

Methodology The dynamic viscosity of the irrigant was assessed using a rotational viscometer. Sodium hypochlorite with concentrations ranging from 0.6% to 9.6% was tested at 37 and 22 °C. A wide range of concentrations of three different surfactants was mixed in 2.4% sodium hypochlorite for viscosity measurements. The Reynolds number was calculated under each condition. Data were analysed using two-way ANOVA.

Results There was a significant influence of sodium hypochlorite concentration ($P < 0.001$) and temperature ($P < 0.001$) on dynamic viscosity: the latter significantly increased with sodium hypochlorite concentration and decreased with temperature. A significant influence of surfactant concentration on dynamic viscosity ($P < 0.001$) occurred, especially for high surfactant concentrations: 6.25% for benzalkonium chloride, 15% for Tween 80 and 6.25% for Triton X-100. Reynolds number values calculated for a given flow rate (0.14 mL s^{-1}), and root canal diameter (sizes 45 and 70) clearly qualified the irrigant flow regimen as laminar.

Conclusions Dynamic viscosity increased with sodium hypochlorite and surfactant concentration but decreased with temperature. Under clinical conditions, all viscosities measured led to laminar flow. The transition between laminar and turbulent flow may be reached by modifying different parameters at the same time: increasing flow rate and temperature whilst decreasing irrigant viscosity by adding surfactants with a high value of critical micellar concentration.

Keywords: critical micellar concentration, dynamic viscosity, irrigation, laminar flow, Reynolds number, sodium hypochlorite, surfactant, turbulent flow.

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Introduction

It is generally accepted that periapical pathosis is due to the presence of microorganisms or bacterial by-products in the root canal (Kakehashi *et al.* 1965) which must be removed to achieve success (Sjögren *et al.* 1997). However, root canal anatomy is complex with irregularities areas that contain pulpal tissues and microorganisms that cannot be approached by instruments (Paqué *et al.* 2011). Therefore, an antiseptic and proteolytic fluid is necessary to disinfect and clean these areas. The way this irrigant spreads onto the canal and reaches the non-instrumented areas is of primary importance in root canal treatment.

Much research has been undertaken to reveal the mechanisms underlying irrigant penetration so as to

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draw clinical conclusions. For example, poor penetration depth of the irrigant beyond the needle tip (Boutsioukis *et al.* 2009), limiting the disinfection of the apical part of the root canal, has been reported. However, there is still a lack of knowledge concerning irrigant penetration because various physical parameters and complex mathematical calculations oblige researchers to create simulators to approach clinical conditions (Gulabivala *et al.* 2010). Recently, irrigant flow has been studied using a computational fluid dynamics model (Boutsioukis *et al.* 2009, 2010a,b). In these publications, flow was analysed according to irrigation technique, needle design, anatomical characteristics of canals and flow rate. However, the influence of the physicochemical properties of the irrigant on its penetration depth has not yet been evaluated.

Two essential parameters must be taken into account to understand fluid dynamics in root canals. First, fluid surface tension as it influences the spreading properties of the irrigant on dentine surfaces (De Gennes *et al.* 2004, Bukiet *et al.* 2012). When adding a surfactant to an irrigant, the liquid surface tension decreases with increasing surfactant concentration, until reaching the critical micellar concentration (CMC). Above the CMC, the addition of surfactant contributes to the formation of micelles in the liquid, and the surface tension remains relatively constant; the best wetting properties are achieved at this concentration (Bukiet *et al.* 2012).

Second, fluid viscosity as it describes the internal resistance to root canal irrigant flow (Viswanath 2007) deformed by either shear or tensile stress. When flowing, the different layers of the liquid slide against each other at different velocities with a transfer of energy. In fluid dynamics, two main types of flow exist: laminar flow, characterized by smooth and constant fluid motion, and turbulent flow which has chaotic eddies, vortices and other flow instabilities. The type of flow is related to the Reynolds number (Re), a dimensionless number quantifying the relative importance of inertial and viscous forces (Guyon *et al.* 2001). In the case of a root canal, similar to a tube, Re is given by:

$$\mathrm{Re} = (\rho v D)/\mu \qquad (1)$$

Where: ρ is the fluid density (kg m^{-3});v is the fluid velocity (m s^{-1});D is the root canal diameter (m);μ is the fluid dynamic viscosity (Pa s or kg s^{-1} m^{-1})

As Re is inversely related to fluid viscosity, this factor must be taken into account when assessing the type of flow of the irrigant in a root canal. At a low Reynolds number (Re < 2300), viscous forces are dominant leading to laminar flow, whereas at high Reynolds number (Re > 4000), inertial forces are dominant leading to turbulent flow (Holman 2002). Theoretically, laminar flow may be associated with a higher penetration depth of the irrigant, whilst turbulent flow may allow better removal of debris.

The factors affecting irrigant viscosity may influence its flow within the root canal in function of the Re value. For instance, viscosity could be expected to increase with the concentration of sodium hypochlorite and decrease with its temperature. Similarly, adding chemical products such as surfactants, often displaying viscous properties, may increase the viscosity. It would appear that no previous publication has studied the viscosity of endodontic irrigants. The purpose of the present work was thus to assess the influence of sodium hypochlorite concentration, temperature and addition of the surfactants benzalkonium chloride (BAK), Tween 80 (TW), Triton X-100 (TR) on the viscosity of sodium hypochlorite to determine the effect of these parameters on the Re value and therefore on flow properties. The Couette's method, which is known to be reliable and accurate to determine viscosity measurement (Couette 1890), has been used in the present work. The null hypothesis was that surfactant addition to NaOCl did not significantly influence the viscosity of irrigant and the Re value.

Materials and methods

Dynamic viscosity measurement

Dynamic viscosity (μ) was measured using a rotational viscometer (Elcometer 2300; Elcometer® inspection Equipment, Manchester, UK). According to the manufacturer's operating instructions, a constant temperature (37 or 22 °C) was maintained using a thermostat connected to a specific adaptor wrapped around the sample. The torque required to rotate the spindle in the fluid depended on fluid viscosity. Thus, the measurements corresponded to the torque necessary to rotate a cylinder plunged into a constant volume of liquid (18 mL) at a known constant speed (100 rpm). The validity of the protocol was verified recording the viscosity of pure water warmed at 22 and 37 °C as references.

To obtain accurate and precise data, an optional spindle dedicated to low viscosity fluids was used.

Stable flow conditions were reached quickly, and the dynamic viscosity (μ) readings on the screen were recorded after 30 s (in mPa s). The process was repeated 10 times per solution tested (n = 10 per group and per concentration). Between each measurement, the container, spindle and thermal adaptator were thoroughly cleaned with acetone then ethanol before flushing with ultrapure water (milli-Q; Millipore, Billerica, MA, USA) and dried.

The mean values and standard deviations were calculated from the 10 values obtained from each test parameter for further statistical analysis.

Factors affecting dynamic viscosity: concentration, temperature and surfactant addition

Effect of NaOCl concentration on dynamic viscosity
Different NaOCl solutions at various concentrations (C_{NaOCl}): 0.6%, 1.2%, 2.4%, 4.8% and 9.6% obtained from the dilution of 9.6% NaOCl with ultrapure water were stored at 37 °C prior to measurement (group 1).

Effect of NaOCl solution temperature on dynamic viscosity
The same experimental procedure was followed with NaOCl solutions at the same concentrations as group 1 but stored at 22 °C (group 2).

Effect of surfactant concentration on dynamic viscosity
A 2.4% NaOCl solution stored at 37 °C was mixed with one of the following surfactants:

- group 3: Benzalkonium Chloride (BAK) (Sigma-Aldrich B1383; Semisolid, St Louis, MI, USA), cationic surfactant at concentrations (C_{BAK}) from 0% to 12.5%.
- group 4: Tween 80 (TW) (Sigma-Aldrich P1754 viscous liquid), non-ionic surfactant at concentrations (C_{TW}) ranging from 0% to 25%.
- group 5: Triton X-100 (TR) (Sigma-Aldrich X100 laboratory grade), non-ionic surfactant at concentrations (C_{TR}) ranging from 0% to 25%.

All solutions were freshly prepared and energetically homogenized using a magnetic stirrer immediately before measurements. This was maintained through spindle rotation throughout the experimentation.

The 2.4% NaOCl solution without surfactant was used as the negative control (surfactant 0%). Extreme surfactant concentrations (inappropriate for clinical activity) were tested as positive controls (12.5% for C_{BAK} and 25% for C_{TW} and C_{TR}).

Reynolds number calculation

An irrigant flow rate of 0.14 mL s^{-1} previously used by Boutsioukis *et al.* (2009) was chosen for Reynolds number calculation. The needle tip must be placed about 3 mm short of the working length. Thus, for a given root canal preparation (6% taper with an apical diameter of 0.25 mm or 0.50 mm), the canal diameter at the needle tip level was of 0.45 or 0.70 mm. Then, the Reynolds number was calculated using these values according to the equation (1) given in the Introduction.

Statistical analysis

First, after verifying the assumptions for analysis of variance (ANOVA), a two-way ANOVA, at 5% confidence level, was performed to determine the influence of concentration (way 1) and temperature (way 2) on the viscosity values. A Duncan multiple range test was carried out at the same confidence level to create groups which were not statistically different.

Second, after verifying the assumptions, an ANOVA, at the 5% confidence level, was performed for each surfactant, completed by a Duncan multiple range test to evaluate the influence of each surfactant concentration on NaOCl viscosity. It was not possible to compare the surfactants between each other because the surfactant concentrations were adapted to each surfactant and therefore varied from one group to another. The viscosity was plotted against the surfactant concentration to demonstrate the general feature of the relationship.

Results

Influence of NaOCl concentration and temperature on dynamic viscosity (Groups 1 & 2)

The two-way ANOVA test revealed a significant influence of C_{NaOCl} ($P < 0.001$) and temperature ($P < 0.001$) on μ: viscosity statistically increased with NaOCl concentration and decreased with increasing temperature (Table 1).

In group 1 tested at 37 °C, μ decreased from 1.31 ± 0.01 mPa s for C_{NaOCl} 9.6% (positive control) to 1.15 ± 0.009 mPa s for C_{NaOCl} 0.6% (negative control). The Duncan test could distinguish four different subgroups: 0.6% NaOCl and 1.2% NaOCl were similar, whilst the following concentrations – 2.4%, 4.8% and 9.6% – were each statistically different from each other. Re decreased, respectively, from 379 to

Table 1 Comparison of mean viscosity, μ ± standard deviation (mPa s) according to NaOCl concentration and temperature (22 or 37 °C), and corresponding mean Reynolds number ± standard deviation calculated for two values of the root canal diameter

C_{NaOCL}	μ (mPa s) 37 °C	Reynolds number for a root canal diameter of 0.45 mm	Reynolds number for a root canal diameter of 0.70 mm	μ (mPa s) 22 °C	Reynolds number for a root canal diameter of 0.45 mm	Reynolds number for a root canal diameter of 0.70 mm
0.6%	1.15 ± 0.009^{h}	379	244	1.202 ± 0.007^{d}	363	233
1.2%	1.152 ± 0.006^{h}	378	243	1.213 ± 0.006^{c}	359	231
2.4%	1.186 ± 0.008^{g}	368	236	1.224 ± 0.006^{c}	356	229
4.8%	1.245 ± 0.008^{f}	350	225	1.298 ± 0.007^{b}	336	216
9.6%	1.312 ± 0.01^{e}	332	214	1.772 ± 0.01^{a}	246	158

The superscript alphabets are the subgroups used in the statistical analysis.

332 and from 244 to 214 when sodium hypochlorite concentration increased from 0.6% to 9.6% for both the 0.45 mm canal diameter and the 0.70 mm canal diameter.

In group 2 tested at 22 °C, μ decreased from 1.77 ± 0.01 mPa s for C_{NaOCl} 9.6% (positive control) to 1.20 ± 0.007 mPa s for C_{NaOCl} 0.6% (negative control). The Duncan test distinguished four different subgroups: 0.6% NaOCl displayed the lowest value, 1.2% and 2.4% concentrations were statistically equivalent, 4.8% concentration was slightly higher and finally 9.6% concentration showed the highest viscosity. Re decreased, respectively, from 363 to 246 and from 233 to 158 when sodium hypochlorite concentration increased from 0.6% to 9.6% for a 0.45 mm canal diameter and 0.70 mm canal diameter.

Influence of surfactant concentration at 37 °C

Benzalkonium chloride: Group 3

The ANOVA test revealed a significant influence of C_{BAK} on μ ($P < 0.001$): μ increased with increasing C_{BAK}. Viscosity increased from 1.186 ± 0.008 mPa s for C_{BAK} 0% (negative control) to 2.081 ± 0.008 mPa s for C_{BAK} 12.5% (Table 2). The Duncan test distinguished three different subgroups with non-statistical different values of μ within each subgroup: the first from 0 to 3.125%, the second at 6.25% and the third at 12.5%. A clear increase in viscosity appeared from C_{BAK} of 6.25%. Re decreased with increasing C_{BAK}, respectively from 368 to 209 and from 236 to 135 for a 0.45 mm canal diameter and a 0.70 mm canal diameter.

Tween 80: Group 4

The ANOVA test revealed a significant influence of C_{TW} on μ ($P < 0.001$): μ increased with increasing C_{TW} (Table 3). Viscosities ranged from 1.186 ± 0.008 mPa s for C_{TW} 0% (negative control) to 4.943 ± 0.009 mPa s for C_{TW} 25%. The Duncan test distinguished four different subgroups with non-statistically different values of μ in each subgroup: from 0% to 6%, 15%, 20% and finally 25%. A significant increase in viscosity occurred from C_{TW} of 15% and above. Re decreased from 368 to 88 and from 236 to 57 with increasing C_{TW} for a 0.45 mm canal diameter and a 0.70 mm canal diameter, respectively.

Table 2 Comparison of mean viscosity, μ ± standard deviation (mPa s) according to benzalkonium chloride concentrations (C_{BAK}) mixed with 2.4% NaOCl at 37 °C and corresponding mean Reynolds number ± standard deviation calculated for two values of the root canal diameter

C_{BAK}	μ (mPa s)	Reynolds number for a root canal diameter of 0.45 mm	Reynolds number for a root canal diameter of 0.70 mm
0% control	1.186 ± 0.008^{a}	368	236
0.004%	1.179 ± 0.005^{a}	370	238
0.008%	1.18 ± 0.009^{a}	369	237
0.5%	1.18 ± 0.006^{a}	369	237
1%	1.18 ± 0.008^{a}	369	237
3.125%	1.203 ± 0.004^{a}	362	233
6.25%	1.38 ± 0.004^{b}	316	203
12.5%	2.081 ± 0.008^{c}	209	135

The superscript alphabets are the subgroups used in the statistical analysis.

Triton X-100: Group 5

The ANOVA test revealed a significant influence of C_{TR} on μ ($P < 0.001$): μ increased with increasing C_{TR} (Table 4). Viscosity increased from 1.186 ±

Table 3 Mean viscosity, $\mu \pm$ standard deviation (mPa s) according to Tween 80 concentrations (C_{TW}) mixed with 2.4% NaOCl at 37 °C and corresponding mean Reynolds number ± standard deviation calculated for two values of the root canal diameter

C_{TW}	μ (mPa s)	Reynolds number for a root canal diameter of 0.45 mm	Reynolds number for a root canal diameter of 0.70 mm
0% control	1.186 ± 0.008^{a}	368	236
0.0015%	1.184 ± 0.005^{a}	368	237
0.003%	1.172 ± 0.01^{a}	372	239
0.006%	1.157 ± 0.004^{a}	377	242
0.02%	1.123 ± 0.004^{a}	388	250
0.04%	1.130 ± 0.009^{a}	386	248
0.0625%	1.135 ± 0.005^{a}	384	247
0.12%	1.151 ± 0.007^{a}	379	243
0.24%	1.153 ± 0.006^{a}	378	243
0.45%	1.172 ± 0.004^{a}	372	239
0.9%	1.173 ± 0.001^{a}	372	239
1%	1.182 ± 0.007^{a}	369	237
1.2%	1.191 ± 0.005^{a}	366	235
6%	1.196 ± 0.005^{a}	365	234
15%	2.529 ± 0.008^{b}	172	111
20%	3.983 ± 0.009^{c}	109	70
25%	4.943 ± 0.009^{d}	88	57

The superscript alphabets are the subgroups used in the statistical analysis.

Table 4 Mean viscosity, $\mu \pm$ standard deviation (mPa s) according to Triton X-100 concentrations (C_{TR}) mixed with 2.4% NaOCl at 37 °C and corresponding mean Reynolds number ± standard deviation calculated for two values of the root canal diameter

C_{TR}	μ (mPa s)	Reynolds number for a root canal diameter of 0.45 mm	Reynolds number for a root canal diameter of 0.70 mm
0% control	1.186 ± 0.008^{a}	368	236
0.000035%	1.176 ± 0.006^{a}	371	238
0.00007%	1.173 ± 0.009^{a}	372	239
0.0001428%	1.144 ± 0.005^{b}	381	245
0.00386%	1.146 ± 0.009^{b}	380	245
0.125%	1.147 ± 0.012^{b}	380	244
0.25%	1.156 ± 0.005^{b}	377	242
0.5%	1.161 ± 0.005^{a}	375	241
0.8%	1.168 ± 0.004^{a}	373	240
1%	1.181 ± 0.007^{a}	369	237
3.12%	1.181 ± 0.008^{a}	369	237
6.25%	2.375 ± 0.008^{c}	184	118
15%	6.012 ± 0.02^{d}	73	47
20%	18.426 ± 0.06^{e}	24	15
25%	24.218 ± 0.06^{f}	18	12

The superscript alphabets are the subgroups used in the statistical analysis.

0.008 mPa s for C_{TR} 0% (negative control) to 24.218 ± 0.06 mPa s for C_{TR} 25%. The Duncan test distinguished six different subgroups: 0.000035%, 0.00007%, 0.50%, 0.80%, 1% and 3.12% none of which were statistically different from the negative control. The viscosities recorded with concentrations from 0.0001428% to 0.25% were significantly lower. Finally, the viscosity shown by the following concentrations – 6.25%, 15%, 20% and 25% – were much higher and significantly different from each other. Re decreased from 368 to 18 with increasing C_{TR} for a 0.45 mm canal diameter and from 236 to 12 for a 0.70 mm canal diameter, respectively.

Plotting of μ versus C_{BAK}, C_{Tw} and C_{TR} showed that μ generally increased with the concentration of surfactants. However, when examining low range surfactant concentration, an initial decrease of μ was observed for all of the surfactants before μ increased with concentration (Fig. 1). This minimum value of μ was reached for different concentrations according to the surfactant: 0.004% for C_{BAK}, 0.02% for C_{TW} and 0.0001428% for C_{TR}. These concentrations are twice the critical micellar concentration (CMC) of each surfactant.

Discussion

The purpose of the present study was to assess the impact of NaOCl concentration, temperature and surfactant addition on the dynamic viscosity of the irrigant to calculate the corresponding Reynolds number. It can be concluded that dynamic viscosity statistically increased with NaOCl concentration and with surfactant concentration beyond the CMC but decreased with temperature. The Reynolds number values calculated from the data corresponded to laminar flow and were a long way from the threshold for a turbulent flow (Guyon *et al.* 2001).

Calculation of the Reynolds number (Re) was carried out by applying the equation (1) under 'typical' endodontic conditions: an irrigant flow rate of 0.14 mL s^{-1} and mean root canal diameter of 0.45 mm (Boutsioukis *et al.* 2009). The 2.4% NaOCl viscosity at 37 °C was 1.186 mPa s, leading to a Reynolds number of 277 which means a laminar flow. According to equation (1), this flow could be switched to turbulent by increasing the flow rate or decreasing the root canal diameter. When working with μ = 1.186 mPa s, the calculations showed that Re could be increased beyond 4000, either using a flow rate larger than 1.6 mL s^{-1} or when working

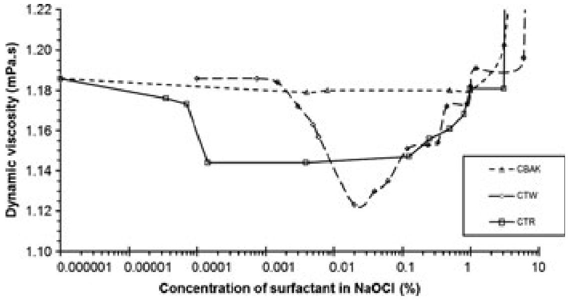

Figure 1 Relationship between dynamic viscosity μ (mPa s) and concentrations of surfactants benzalkonium chloride (C_{BAK}), Tween 80 (C_{TW}) and Triton X-100 (C_{TR}) for low concentrations (from 0% to 10%) mixed with 2.4% NaOCl at 37 °C.

on root canals with a diameter smaller than 0.04 mm. Unfortunately, a flow rate of 1.6 mL s^{-1} is inappropriate for clinical activity due to the risk of NaOCl extrusion, which has been observed for flow rates higher than 0.3 mL s^{-1} (Chow 1983). Concerning the canal diameter, only lateral canals and ramifications have diameters smaller than 0.04 mm. Therefore, neither the irrigant flow nor the canal diameters are sufficient to switch from a laminar to a turbulent flow. A substantial decrease in viscosity combined with these parameters may be required to change the flow regimen. With this aim in mind, the present work focused on the effects of temperature, NaOCl concentration and surfactant concentration on irrigant viscosity.

Root canal irrigant temperature can be heated before using (Sirtes *et al.* 2005). In the present study, when temperature increased from 22 to 37 °C, NaOCl viscosity decreased. This well-known phenomenon may be explained by thermal agitation of the molecules which move more easily at 37 °C than at 22 °C (Guyon *et al.* 2001). This result must be related to those of other studies, which have evaluated the influence of NaOCl temperature on its protein dissolving ability (Sirtes *et al.* 2005, Stojicic *et al.* 2010) and its antibacterial efficiency (Sirtes *et al.* 2005). Irrigant flow remains laminar because temperature only has a limited effect on NaOCl viscosity. The low viscosities (near 0.2 mPa s for μ) required to switch from laminar to turbulent flow correspond to higher temperatures not compatible with clinical applications.

Previous studies had reported that the irrigant viscosity statistically increased with C_{NaOCl} (Guerisoli *et al.* 1998). The result of the present study confirmed those given by another methodology (Guerisoli *et al.* 1998). Despite the significant differences between the concentrations, viscosity only varied from 1.20 ± 0.007 mPa s for 0.6% NaOCl to 1.77 ± 0.01 mPa s for 9.6% NaOCl. Thus, the choice of C_{NaOCl} influences the proteolytic and antibacterial activities more than the flow properties. Consequently, a 2.4% concentration within the recommended range between 1% and 5.25% can be used as irrigant without modifying irrigant flow properties.

The addition of a surfactant to NaOCl or EDTA to enhance wetting properties has already been evaluated with encouraging results (Abou-Rass & Patonai 1982, Berutti *et al.* 1997, Pecora *et al.* 1998, Gambarini 1999, Giardino *et al.* 2006, Merivale *et al.* 2009, Stojicic *et al.* 2010, Bukiet *et al.* 2012, Palazzi *et al.* 2012). However, no data are available concerning the modification of irrigant viscosity through surfactant addition, despite the potential impact that viscosity may have on irrigant flow. In this study, three surfactants with a wide range of concentrations were studied. BAK is a cationic detergent which has already been used in dentine bonding agents (Pashley *et al.* 2011), orthodontic resin (Othman *et al.* 2002) and in a commercial EDTA solution (Salvizol; Pierre Rolland, Merignac, France). Moreover, a recent study showed that BAK is an antiseptic which decreases bacterial adherence and biofilm growth (Jaramillo *et al.* 2012). TW and TR are both non-ionic surfactants with a syrupy appearance. They have also been included in root canal irrigant products like Biopure™ MTAD (for TW) and Chlor-Xtra™ (for TR) but with undisclosed concentrations. Although Gulabivala *et al.* (2010) asserted that the effect of additives would be to increase its viscosity and reduce its Reynolds number, it has never been proven or invalidated before the present work.

The study demonstrated that for low surfactant concentrations, viscosity first decreased until a minimum value (Fig. 1). This decrease is likely related to the neutralization of surfactant charges by the sodium cations present in NaOCl solutions. As a result, the conformation of surfactants is more compact and viscosity decreases (Onesippe & Lagerge 2009). The minimum μ value occurred for each surfactant at different concentrations. It is interesting to note that these concentrations are twice the CMC in 2.4% NaOCl solutions: 0.0076% for CMC_{BAK} (Bukiet *et al.* 2012), 0.01% for CMC_{TW} and 0.00035% for CMC_{TR}.

This relation between viscosity and CMC has already been used to determine CMC through viscosity measurements (Tyuzyo 1960). So, whilst viscosity decreases due to neutralization of surfactant charges, it then increases after formation of micelles. Thus, it has been logically shown that the initial decrease in viscosity was more efficient for TW which has the highest CMC. Consequently, adding a surfactant at concentration near the CMC reduces irrigant viscosity and increases Re. On the contrary, adding a surfactant at high concentration larger than CMC increases irrigant viscosity and decreases Re.

In the present work, the increase in viscosity beyond CMC is more noticeable at very high concentrations of surfactants not used in endodontics: 6.25% for BAK, 15% for TW and 6.25% for TR. However, regardless of the surfactant and the concentration, viscosity was high enough to give Reynolds numbers lower than 250 corresponding to a laminar flow (Re < 2500).

The clinical significance of irrigant flow regimen is still undetermined. Laminar flow is due to friction forces and likely more appropriate for allowing the irrigant to flow into the unshaped areas and ramifications due to its regularity. However, a previous work clearly highlighted a stagnation of the irrigant beyond the needle tip (1.5 mm), whatever the flow rate (Boutsioukis *et al.* 2009). This contradiction is due to gas bubble formation in the apical area, acting as a vapour lock when the irrigation needle is placed deeply (Tay *et al.* 2010). Theoretically, turbulent flow may improve root canal cleaning efficiency by breaking the biofilm, like the cavitation phenomenon reported with ultrasounds, but likely to a lesser extent. In practice, factors such as dentine irregularities, canal ramifications and agitation technique may also contribute to turbulent flow.

Conclusion

Calculations from the results of this laboratory study, using clinically relevant parameters, such as canal diameter and irrigant flow rate, showed that all of the viscosities would likely lead to laminar flow. The transition between laminar and turbulent flow may be reached by modifying different parameters simultaneously: (i) increase in irrigant flow rate, (ii) increase in temperature and (iii) decrease in irrigant viscosity by adding surfactants with a concentration close to their CMC.

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