doi:10.1111/j.1365-2591.2007.01244.x

Measurement of pressure and flow rates during irrigation of a root canal *ex vivo* with three endodontic needles

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Abstract

Boutsioukis C, Lambrianidis T, Kastrinakis E, Bekiaroglou P. Measurement of pressure and flow rates during irrigation of a root canal *ex vivo* with three endodontic needles. *International Endodontic Journal*, **40**, 504–513, 2007.

Aim To monitor *ex vivo* intra-canal irrigation with three endodontic needles (25, 27 and 30 gauge) and compare them in terms of irrigant flow rate, intra-barrel pressure, duration of irrigation and volume of irrigant delivered.

Methodology A testing system was constructed to allow measurement of selected variables with pressure and displacement transducers during *ex vivo* intra-canal irrigation with a syringe and three different needles (groups A, B, C) into a prepared root canal. Ten specialist endodontists performed the irrigation procedure. Each operator performed ten procedures with each needle. Data recorded by the transducers were analysed using Friedman's test, Wilcoxon Signed Rank test, Mann–Whitney *U*-test and Kendall's T_b test. The level of significance was set to 95%.

Results Significant differences were detected among the three needles for most variables. Duration of delivery and flow rates significantly decreased as the needle diameter increased, whilst pressure increased up to 400–550 kPa. Gender of the operator had a significant impact on the results. Experience of the operators (years) were negatively correlated to volume of irrigant (all groups), to the duration of delivery (groups A, B) and to the average flow rate (group A).

Conclusions Finer diameter needles require increased effort to deliver the irrigant and result in higher intra-barrel pressure. The syringe and needles used tolerated the pressure developed. Irrigant flow rate should be considered as a factor directly influencing flow beyond the needle. Wide variations of flow rate were observed among operators. Syringe irrigation appears difficult to standardize and control.

Keywords: irrigant flow rate, irrigation, needle, pressure.

Received 18 September 2006; accepted 4 December 2006

Introduction

Irrigation of the root canal with antibacterial solutions is considered an essential part of chemo-mechanical preparation (Haapasalo *et al.* 2005). Irrigation is complementary to instrumentation in facilitating removal of bacteria, debris and necrotic tissue (Lee *et al.* 2004), especially from areas of the root canal that remain unprepared by mechanical instruments (Gulabivala *et al.* 2005).

Although the effectiveness of irrigation relies on both the mechanical flushing action and the ability of irrigants to kill bacteria (Gulabivala *et al.* 2005) and dissolve tissue (Lee *et al.* 2004), it has been suggested that the flushing action may be the most important factor (Baker *et al.* 1975). Irrigation dynamics should then be considered when evaluating the effects of an irrigant on root canal contents (Gulabivala *et al.* 2005). The penetration of the irrigant and the flushing action created by irrigation are dependent not only on the anatomy of the root canal system, but also on the

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system of delivery, the depth of placement, and the volume and fluid properties of the irrigant (Kahn *et al.* 1995, Lee *et al.* 2004, Gulabivala *et al.* 2005).

Irrigant flow rate is rarely mentioned as a factor contributing to irrigation effectiveness (Williams *et al.* 1995) and standardized in research papers (Brown & Doran 1975, Ram 1977, Moser & Heuer 1982, Chow 1983, Meyer *et al.* 1991, Lee *et al.* 2004, Sedgley *et al.* 2005), although flow rate is considered a highly significant factor determining flow pattern in fluid dynamics (Tilton 1999) and has been shown to influence the replacement of the irrigant in certain parts of the root canal (Nanzer *et al.* 1989).

Conventional irrigation with syringes still remains widely accepted (Ingle *et al.* 2002, Peters 2004), and has also been advocated as an efficient method of irrigant delivery prior to passive ultrasonic activation (van der Sluis *et al.* 2006). Syringe delivery of the irrigant allows control of the depth of needle penetration in the canal and the volume of irrigant flushed through the canal (van der Sluis *et al.* 2006).

Increased pressure applied during irrigation has been associated with irrigant extrusion through the apex (Ram 1977, Druttman & Stock 1989, Gernhardt *et al.* 2004, Tinaz *et al.* 2005, Bowden *et al.* 2006), whilst others suggest that flow rate of irrigant is the factor influencing extrusion (Lambrianidis *et al.* 2001, Lambrianidis 2001). This apparent disagreement reflects some confusion regarding the difference between pressure and flow rate. In addition, the dental syringe plunger is relatively small in surface area, and this coupled with the strength of a clinician's thumb can develop unanticipated high pressures in the syringe barrel (Pashley *et al.* 1981, Whitworth *et al.* 2005). Such pressures could in fact lead to barrel failure or to sudden detachment of the needle hub from the syringe (Clarkson & Moule 1998, Lambrianidis 2001).

Classical endodontic handbooks refer to hand irrigation as a 'simple procedure' (Ingle *et al.* 2002) and provide general guidelines (Ruddle 2002, Wesselink & Bergenholtz 2004). These recommendations reflect a certain degree of empiricism regarding the irrigation procedure. Therefore, standardization of the procedure and recommendation of clear guidelines could prove quite useful for educational or research purposes.

The aim of this study is to monitor intra-canal irrigation *ex vivo* with three commonly used endodontic needles, in order to accurately describe the procedure and detect existing differences in irrigant flow rate, intra-barrel pressure, duration of irrigation and volume of irrigant delivered through various needles.

Materials and methods

A freshly extracted human maxillary central incisor tooth was selected. Criteria for tooth selection included: a single root canal, no visible root caries, fractures or cracks on examination with a 4×-magnifying glass, no signs of internal or external resorption or calcification, a completely formed apex and curvature of ≤5° (Schneider 1971) with no lateral exit of the apical foramen. Preoperative mesiodistal and buccolingual radiographs were exposed to confirm the canal anatomy.

Following extraction the tooth was stored for 2 days in 3% NaOCl at room temperature to remove organic debris. Subsequently, it was scaled with ultrasonics, washed with distilled water for the removal of any calculus or soft tissue debris and then immersed in 10% formalin solution until use.

The tooth was handheld during instrumentation. After standard access cavity preparation, a size 10 K-file (Antaeos; Vereinigte Dentalwerke GmbH & Co, Munich, Germany) was introduced into the canal until it was visible at the apical foramen. Tooth length was standardized at 19.5 mm by removing excess crown structure perpendicularly to the tooth axis with a diamond disk. Working length was determined 0.5 mm short of this measurement, at 19 mm. This same file was used during preparation and it was introduced into the canal until it was visible at the apical foramen to maintain patency at all times. The first file that fitted at working length was size 30. Root canal preparation was performed using H-files (Antaeos; Vereinigte Dentalwerke GmbH & Co) with a step-back technique. Instrumentation was standardized with a size 45 H-file reaching full working length to a size 120 H-file 16 mm coronally. Finally, a rotary-driven Ni–Ti instrument size 45, 0.06 taper (K3; SybronEndo, Orange, CA, USA) was used at full working length.

A 17% EDTA gel (Nordent, Thessaloniki, Greece) was used as a chelating agent and was introduced in the canal on the tip of each successive instrument. The canal was irrigated between instruments with 5 mL of 1% NaOCl. Irrigation was performed using a 5 mL disposable plastic syringe (Ultradent Products Inc., South Jordan, UT, USA) with a 30-gauge needle (KerrHawe Irrigation Probe; KerrHawe SA, Biggio, Switzerland) placed passively into the canal, up to 3 mm from the apical foramen without binding. Finally, the root canal was irrigated with 5 mL of 1% NaOCl, followed by irrigation with 5 mL of 17% EDTA solution (Nordent) and a final rinse with 5 mL of 1%

NaOCl. Irrigation was performed under the same conditions as in the instrumentation phase. The root canal was dried with paper points.

The root of the tooth was wrapped in a single layer of aluminium foil (0.01 mm thickness) and the tooth was embedded in a resin block up to the cemento-enamel junction. Following setting of the resin, the tooth was detached from the block, the aluminium foil was removed and the tooth was reinserted in the block and stabilized with resin on the buccal and palatal surface.

A testing system was constructed to simulate the conditions of intra-canal irrigation. A 5 mL disposable syringe with Luer-Lock connector (Ultradent Products Inc.) was modified by the addition of a 21-G stainless steel needle (Penta; PentaFerte, Campi, TE, Italy), inserted and secured through the barrel. This needle was connected through thick-walled teflon tubing to a 0–344.7 kPa differential pressure transducer (TJE/0708-08TJG; RDP Electronics Ltd, Wolverhampton, UK), selected following preliminary tests to estimate the range of pressures that should be expected. When this pressure range was exceeded, a 0–689.5 kPa transducer (TJE/0708-10TJG; RDP Electronics Ltd) was used instead. The syringe was mounted on the testing bench in a vertical position. The exact position of all components was carefully checked with a plumb line. The tubing and pressure transducer were also mounted to the testing bench at a standard position. Furthermore, a linear potentiometer (0–10 kOhm) was fitted as parallel as possible to the syringe plunger and was mechanically connected to it, in order to be simultaneously displaced during the irrigation.

Both the pressure transducer and the potentiometer (displacement transducer) signals were amplified (611/600; RDP Electronics Ltd) and then interfaced to an analogue to digital (A/D) converter board (LAB PC1200; National Instruments Corp, Austin, TX, USA). Data were collected on a personal computer using LabView 5.0 software (National Instruments Corp), which allowed the simultaneous capture of pressure and displacement readings from the transducers (Fig. 1).

The tooth was fitted below the syringe, so that the test irrigation needle could be inserted in the root canal to the desired depth as close as possible to the longitudinal axis, and was secured in the same position for all measurements. A container was placed below the tooth to accumulate the out-flowing irrigant. The secondary needle tubing and transducer were carefully filled with distilled water prior to all tests to avoid measurement inaccuracy and delayed response of the transducer caused by residual air in the closed system. Sodium hypochlorite 1% at room temperature was used as an irrigant. The syringe was filled up to the same level prior to each experiment with the irrigant. Special care was taken to avoid insertion of air into the system.

The pressure transducer and operational amplifier were calibrated before each experiment according to the manufacturer's recommendations. The potentiometer (displacement transducer) was initially tested for accuracy and repeatability of readings with digital precision calipers (accuracy 0.05 mm). Furthermore, it was also calibrated before each experiment.

Three different stainless steel irrigation needles were sequentially attached to the modified syringe (Table 1). A rubber stop was applied to indicate the desired depth

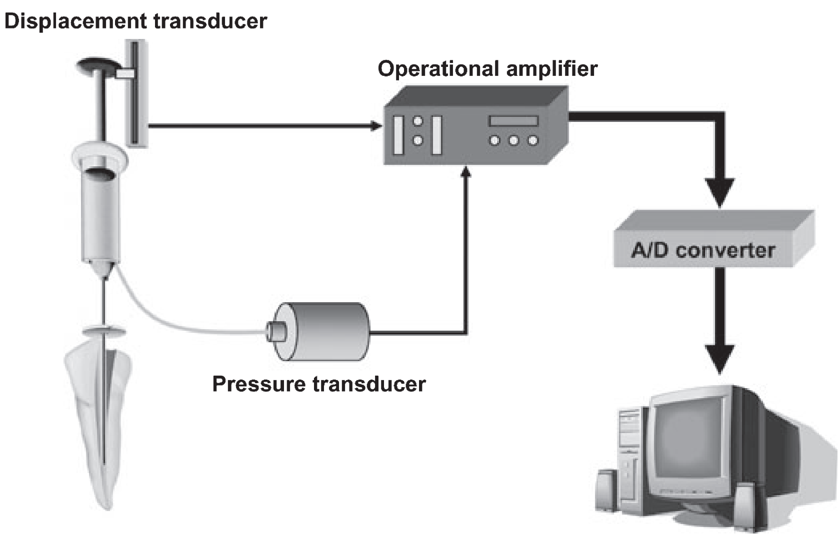

Figure 1 Schematic diagram of data-acquisition system.

Table 1 Characteristics of the needles used in the study

Group	Gauge	External diameter	Tip	Type	Lot. no.
A	25	0.5 mm	Side-vented	KerrHawe Irrigation Probe (KerrHawe SA, Bioggio, Switzerland)	70403645
B	27	0.4 mm	Monoject	Endo-Eze (Ultradent Products Inc., South Jordan, UT, USA)	2075Q1Q
C	30	0.3 mm	Side-vented	KerrHawe Irrigation Probe (KerrHawe SA, Bioggio, Switzerland)	70403645

of penetration, namely 3 mm from the apical foramen for all needles without binding. Ten specialized endodontists with at least 2 years of postgraduate clinical experience performed a series of irrigation procedures. All the operators were familiar with the type of syringe and needles used in the study. For every operator, time of postgraduate clinical endodontic experience, limitation of clinical practice to endodontics, and gender were recorded.

A series of ten irrigation procedures were conducted by each operator with each of the three needles (Groups A, B, C). Operators were instructed to conduct a typical clinical irrigation, just as they would do between successive instruments during an endodontic treatment, into the root canal of the prepared tooth. The pressure developed in the syringe barrel and the displacement of the plunger were recorded as a function of time at 0.005 s intervals (sampling frequency = 200 Hz). Between successive attempts, the syringe and probe were flushed with 5 mL of distilled water to prevent crystal accumulation in the probe. Moreover, successive attempts were spread over 3 days to minimize operator fatigue. A new set of needles was used for every operator. Operators were blinded to the size and type of needle used for each irrigation.

Based on previously determined calibration curves, displacement measurements were converted to volume. The duration of irrigation, total volume of irrigant delivered, mean flow rate, maximum pressure, and average pressure during each irrigation were calculated with Excel 2003 software (Microsoft Corp, Redmond, WA, USA). Mean irrigant flow rate was calculated by dividing the total volume of irrigant delivered with the duration of the irrigation. Curves of intra-barrel pressure development, irrigant flow rate and volume of irrigant as a function of time were plotted.

Nonparametric statistical tests were conducted because the data were not normally distributed (Williams *et al.* 2004). Groups A, B, C were compared with each other to detect significant differences regarding recorded variables, using Friedman's test followed by Wilcoxon Signed Rank test, as the three groups were considered related. The null hypothesis was that there is no significant difference between groups regarding the recorded variables. Within each group, comparisons regarding gender and practice limited to endodontics were conducted using Mann–Whitney *U*-test. The null hypothesis was that there is no difference between the sexes or between dedicated endodontists and endodontists practicing general dentistry, within each group. Correlation between recorded variables and time of clinical experience was examined by nonparametric Kendall's T_b test. The null hypothesis was that none of the recorded variables was correlated to the time of postgraduate clinical experience of the operators. The level of significance was set to $P < 0.05$. Bonferroni correction was applied to the level of significance when appropriate. Statistical analysis was performed using SPSS 14.0 for Windows (SPSS Inc., Chicago, IL, USA).

Results

The profile of the operators is presented in Table 2. Two measurements in group C were considered inconsistent due to a technical error discovered during examination of the pressure–time curves. These measurements were excluded from statistical analysis, resulting in a sample size $n = 98$ for group C, compared with size $n = 100$ for groups A and B.

Descriptive statistics for groups A, B and C is presented in Table 3. Friedman's test indicated signifi-

Table 2 Brief description of the operators' profile

Operator	Time of clinical experience (years)	Practice limited to endodontics	Gender
1	37	No	M
2	14	No	M
3	12	No	M
4	3	Yes	F
5	2	No	M
6	2	Yes	F
7	28	Yes	M
8	27	No	M
9	6	No	F
10	26	Yes	M

M, male; F, female.

Table 3 Descriptive statistics of recorded variables according to different groups

Group (needle) sample size	A (25 G), $n = 100$	B (27 G), $n = 100$	C (30 G), $n = 98$
Δt			
Mean (SD)	11.66 (12.35)	14.96 (15.30)	17.23 (17.37)
Range	0.88–48.27	1.49–59.39	1.85–68.31
Vol			
Mean (SD)	1.85 (0.65)	2.02 (0.61)	1.77 (0.62)
Range	0.61–4.91	0.46–3.00	0.71–3.09
Vol/Δt			
Mean (SD)	0.39 (0.33)	0.29 (0.24)	0.22 (0.19)
Range	0.03–1.25	0.01–1.01	0.02–0.80
MaxPres			
Mean (SD)	92.67 (63.36)	141.55 (99.97)	243.18 (154.51)
Range	10.34–273.52	9.38–409.89	30.41–546.27
AvPres			
Mean (SD)	54.47 (31.23)	87.29 (55.30)	153.62 (96.25)
Range	7.38–138.03	4.48–213.60	21.51–355.70

Δt (s), duration of irrigation; Vol (mL), volume of irrigant delivered; Vol/Δt (mL s^{-1}), average flow rate of irrigant, MaxPres (kPa), maximum pressure recorded per irrigation, AvPres (kPa), average pressure recorded per irrigation.

cant differences in all variables between the three groups. Wilcoxon Signed Rank test showed that duration of irrigation was significantly increased across the three groups (A, B, C) ($P < 0.001$). Volume of irrigant delivered was significantly different between groups A-B and B-C ($P < 0.001$), but not between groups A-C ($P = 0.182$). Flow rates significantly decreased across the three groups (A, B, C) ($P < 0.001$). On the contrary, both maximum pressures and average pressure recorded significantly increased across the three groups (A, B, C) ($P < 0.001$).

Furthermore analysis within each group using Mann–Whitney *U*-test revealed significant differences according to gender (Table 4). In general, male operators delivered less irrigant in less time than female operators, whilst the average flow rate was higher for males than females. Significant differences were also revealed in the average and maximum recorded pressures within group A.

No significant differences were detected using Mann–Whitney *U*-test between operators with practice limited to endodontics and operators practicing general dentistry, within each group.

Kendall's T_b test indicated that the time of postgraduate clinical experience was negatively correlated to the volume of irrigant delivered, regardless of group ($P < 0.001$). Moreover, within groups A and B, a significant negative correlation was detected between duration of irrigation and time of clinical experience ($P < 0.001$). Finally, in group A, a significant positive correlation was detected between average flow rate and time of clinical experience ($P = 0.004$) (Table 5).

Discussion

The purpose of this study was to monitor irrigations *ex vivo* with three commonly used endodontic needles and to detect differences in irrigant flow rate, intra-barrel pressure developed, duration of irrigation and volume of irrigant delivered among tested needles. Similar studies have been conducted in the field of neurosurgery to facilitate the design of improved injection equipment (Krebs *et al.* 2005) and in dental anaesthesia, to evaluate the risk of local tissue damage (Pashley *et al.* 1981, Maita & Horiuchi 1984, Shepherd *et al.* 2001), cartridge failure (Whitworth *et al.* 2005) and needle clogging (Rieu *et al.* 1989). Pressure developed during periodontal pocket irrigation has also been studied (Kelly *et al.* 1985).

Syringes of variable capacity, ranging from 1 mL (Senia *et al.* 1971), 3 mL (Abou-Rass & Piccinino 1982, Kahn *et al.* 1995, Sedgley *et al.* 2005), 5 mL (Ram 1977, Moser & Heuer 1982, Chow 1983, Tinaz *et al.* 2005) to 10 mL (Sabins *et al.* 2003, Lee *et al.* 2004), have been used for conventional hand irrigation in previous studies. A 5 mL syringe was selected in this study to combine adequate capacity with minimum difficulty in use. Larger capacity syringes require greater force to move the plunger and result in less control of the procedure, as a small movement of the plunger results in larger volume delivered. On the other hand, they also require less frequent refilling. According to the results, the selected 5 mL syringe would have to be refilled every two irrigations on the average.

Table 4 Comparison of sexes regarding the recorded variables within each group

Group (needle) sample size	A (25 G), $n_M = 70$, $n_F = 30$	B (27 G), $n_M = 70$, $n_F = 30$	C (30 G), $n_M = 68$, $n_F = 30$
Δt			
M	9.82 (12.48)	13.26 (16.47)	14.63 (17.94)
F	16.29 (10.88)	19.11 (11.15)	23.11 (14.63)
P-value	0.022*	0.001*	<0.001**
Vol			
M	1.73 (0.51)	1.85 (0.64)	1.69 (0.66)
F	2.15 (0.84)	2.42 (0.30)	1.95 (0.50)
P-value	0.006*	<0.001**	0.038*
Vol/Δt			
M	0.41 (0.33)	0.33 (0.27)	0.26 (0.20)
F	0.33 (0.35)	0.19 (0.13)	0.14 (0.11)
P-value	0.017*	0.019*	0.02*
MaxPres			
M	104.46 (66.47)	151.96 (104.11)	271.58 (155.89)
F	63.02 (43.16)	116.18 (85.56)	178.85 (132.45)
P-value	0.002*	0.135	0.064
AvPres			
M	60.12 (31.65)	91.22 (56.12)	169.13 (97.35)
F	40.20 (25.44)	77.57 (52.95)	118.38 (85.22)
P-value	0.002*	0.229	0.063

Values are given as Mean (SD).
M, male; F, female; Δt (s), duration of irrigation; Vol (mL), volume of irrigant delivered; Vol/Δt (mL sec^{-1}), average flow rate of irrigant; MaxPres (kPa), maximum pressure recorded per irrigation; AvPres (kPa), average pressure recorded per irrigation.
*Significant difference ($P < 0.05$).
**Highly significant difference ($P < 0.001$).

Table 5 Correlation of the recorded variables to the time of clinical experience (Time) within each group

Group (needle) sample size	A (25 G), $n = 100$, Time (years)	B (27 G), $n = 100$, Time (years)	C (30 G), $n = 98$, Time (years)
Δt			
Correlation coefficient	–0.283	–0.241	–0.141
P-value	<0.001**	0.001*	0.051
Vol			
Correlation coefficient	–0.342	–0.481	–0.319
P-value	<0.001**	<0.001**	<0.001**
Vol/Δt			
Correlation coefficient	0.205	0.159	0.014
P-value	0.004*	0.026	0.843
MaxPres			
Correlation coefficient	0.182	0.048	–0.036
P-value	0.01	0.505	0.62
AvPres			
Correlation coefficient	0.145	0.008	–0.035
P-value	0.04	0.907	0.629

Δt, duration of irrigation; Vol, volume of irrigant delivered; Vol/Δt, average flow rate of irrigant; MaxPres, maximum pressure recorded per irrigation; AvPres, average pressure recorded per irrigation.
*Significant difference ($P < 0.05$) with Bonferroni correction.
**Highly significant difference ($P < 0.001$) with Bonferroni correction.

It has been argued that use of fine-diameter needles leads to more efficient irrigant replacement and debridement (Chow 1983, Sedgley *et al.* 2005). Three needles of the finer diameters commercially available were selected for this study. This was based mostly on clinical practice, as these needles are the most widely used.

Sodium hypochlorite at a concentration of 1% is widely recommended as an endodontic irrigant (Spangberg & Haapasalo 2002, Zehnder 2006). It has been advocated that root canals should be irrigated with copious amounts of the hypochlorite solution between successive instruments (Zehnder 2006). Regular replenishment of the irrigant is considered essential (Druttman & Stock 1989), as chlorine, the element responsible for tissue dissolution and antimicrobial action of the solution, is rapidly consumed (Moorer & Wesselink 1982). Volume of irrigant delivered has also been reported as a significant factor influencing irrigation efficacy (Kahn *et al.* 1995, Lee *et al.* 2004, Gulabivala *et al.* 2005), but the optimal volume has not been determined yet. Although significant differences in the amount of irrigant delivered were detected between groups A-B and B-C, a clear relationship between volume and needle size could not be verified. It is possible that differences in needle design contributed to the detected differences, since in both groups A and C a side-vented needle was used, in contrast to a monoject needle in group B.

The major variable directly controlled by operators during this study was the force of the clinician's thumb applied to the syringe plunger and being transmitted to the barrel. This force leads to the development of pressure within the syringe barrel, which is a direct short-term measure of the applied force [pressure (P) is defined as force (F) applied over a surface area (S), $P = F/S$] (Pashley *et al.* 1981). Pressure difference between the syringe barrel and the root canal is the cause of irrigant flow and determines the flow rate, but it does not directly affect flow pattern within the root canal. In addition, intra-barrel pressure is higher than the one developed beyond the tip of the needle, which is normally close to atmospheric, due to pressure drop occurring across the needle during the flow (Tilton 1999). The amount of pressure drop is influenced by the needle diameter (Tilton 1999). Thus, flow rate rather than intra-barrel pressure, should be regarded as the factor directly influencing flow beyond the needle, in the area of interest.

The intra-barrel pressure versus time for three representative irrigation procedures of the same operator, one of each group, is presented in Fig. 2. During the first few seconds of the irrigation, pressure increased rapidly, regardless of needle. This rapid increase may also be attributed to the delay of the clinician's regulation of applied force according to the resistance felt and the velocity of plunger movement. As the syringe and the tubing were plastic, it seems reasonable to assume a certain degree of elasticity, which may have acted as a regulator during rapid changes in pressure, normalizing these changes. A glass or metal syringe and tubing would lead to more acute changes in pressure, as they would be less distensible. Although not common, resting periods during the irrigation could be recognized, during which the irrigant flow rate and intra-barrel pressure decreased slightly (dashed arrows in Fig. 2). These periods were identified more frequently in group C (30 G needle). As soon as irrigation was completed (bold arrows in Fig. 2), the pressure in the barrel begun to decline exponentially, due to irrigant late escape through the needle and the root canal towards the

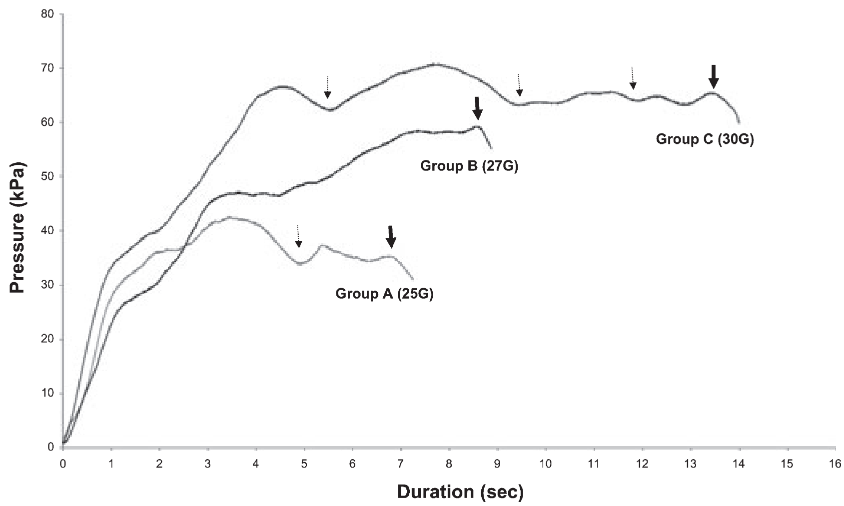

Figure 2 Intra-barrel pressure developed during three representative irrigations of the same operator, one of each group, versus time. The end of each irrigation is marked with a bold arrow. Note the resting periods (dashed arrows).

canal orifice. Rate of irrigant escape depends on residual pressure within the barrel, but pressure is also gradually reduced due to irrigant escape (Tilton 1999).

No previous data concerning intra-barrel pressure during root canal irrigation could be retrieved from the literature. However, Moser & Heuer (1982) investigated *ex vivo* the force required to depress syringe plungers during irrigation using several types of irrigation systems. Although their findings may vary from those observed under clinical conditions, as the syringe was driven by an Instron mechanical testing machine, their conclusion that smaller diameter needles required increased force is in agreement with the present findings. Increased force during irrigation is implied by the increased pressure recorded (Fig. 2). Average values of the force required to depress the syringe plunger can be calculated for the three groups [Group A: 6.36 Nt (1.43 lb), group B: 10.2 Nt (2.29 lb), group C: 17.96 Nt (4.04 lb)]. These values are generally in agreement with those reported previously for similar gauge needles. Observed deviations may be due to different needle designs, minor differences in needle diameter, a syringe of different capacity, the presence of the root canal surrounding the needle in the present study, or operator variability.

The use of a needle with a very fine lumen is considered impractical clinically, because of crystallization of the NaOCl solution in the lumen during the course of treatment (Senia *et al.* 1971, Moser & Heuer 1982), which would further increase the required effort. During the experiment, needles were flushed with distilled water following each irrigation, a condition that is not possible in the clinical situation. Therefore, although not supported by the findings of this study, the possibility that operator fatigue could lead to less that optimal irrigation duration and volume of irrigant delivered during repeated irrigations under clinical conditions cannot be overlooked.

Manufacturers of the irrigation systems have furnished needles and syringes with Luer-Lock connectors to prevent needle detachment during use, in contrast to simple friction fitting available in normal medical syringes (Moser & Heuer 1982). Syringes and needles with such connectors should be preferred (Clarkson & Moule 1998, Lambrianidis 2001). No detachment of needle hub or barrel failure occurred during the study. Thus, it can be assumed that peak intra-barrel pressures in the range of 400–550 kPa are well-tolerated by the syringe-needle systems used. Further studies are needed to determine the failure limit.

Duration of irrigation along with volume of irrigant delivered influenced the average flow rate. For a given volume, average flow rate is inversely proportional to the duration of delivery (average flow rate = volume/duration) (Tilton 1999). Despite the increased force required during irrigation with finer needles, increased duration was unexpectedly recorded, a highly significant difference for all groups. It may be argued that specialized operators involved in this study were strict during the delivery of a certain amount of irrigant simulating a clinical situation, according to the instructions they had been given, and were not distracted by fatigue or impatience.

Clinically realistic data concerning the average irrigant flow rate have been sought (Williams *et al.* 1995). Rough estimations have been attempted, ranging from 0.03–0.05 mL sec^{-1} (Moser & Heuer 1982), 0.12 mL sec^{-1} (Lee *et al.* 2004), 0.13 mL sec^{-1} (Brown & Doran 1975, Meyer *et al.* 1991), 0.2 mL sec^{-1} (Sedgley *et al.* 2005) to 0.31 mL sec^{-1} (Chow 1983). These estimations ignored the possible effect of different needle sizes and designs. In a recent study (Nguy & Sedgley 2006), the possible effect of needle size on the irrigant flow rate was mentioned. The range of values recorded in this study was 0.01–1.01 mL sec^{-1} (Table 3). Finer needles were significantly associated with lower mean flow rates. However, it seems reasonable to assume that values in the range of 0.05 mL sec^{-1} are not realistic approximations. The optimal irrigant flow rate has not been determined, future studies should test the effect of more realistic flow rates.

It has been previously reported that differences between sexes exist in the pressure applied during dental anaesthesia (Maita & Horiuchi 1984, Whitworth *et al.* 2005). Although the present study was not designed to test a similar hypothesis during irrigation, significant differences between sexes for most recorded variables were detected in all groups, except for average and maximum pressure in groups B and C. In general, female operators tended to deliver greater amounts of irrigant under lower pressure, for a longer time, resulting in lower flow rates. The small sample size of the females ($n = 3$) could have been a reasonable cause for the absence of significance in groups B and C. Furthermore, the fact that all operators were specialized endodontists aware of the danger of periapical extrusion could have prevented male operators from applying excessive force on the syringe plunger.

The time of postgraduate clinical endodontic experience was considered as a covariate in the analysis of the recorded data. Kendall's T_b test showed a significant negative correlation between clinical experience and volume of irrigant delivered, regardless of needle used. It can be hypothesized that lack of clinical experience could lead to less self-confidence in the decision about the amount of irrigant necessary for each irrigation. Clinical experience was also negatively correlated to duration of irrigation in groups A and B, a finding also explicable by self-confidence levels. Thus, it can be speculated that the more experienced a clinician was, the more rapidly was the procedure carried out, a hypothesis supported in group A by the significant positive correlation between clinical experience and average flow rate.

Nonparametric tests were used for the statistical analysis, as most of the data were not distributed normally and a transformation to the normal distribution was considered unfeasible. These tests are less sensitive in detecting small differences between samples, thus requiring larger sample sizes (Jones *et al.* 2003). Consequently, although many significant differences were detected, it is possible that true differences escaped detection in some cases (Type II error).

Despite considerable effort to standardize irrigations, some degree of operator variability was inevitable, which is confirmed by the large standard deviation in most measured variables. However, the irrigations were clinically realistic, within the limitations of the current study design.

Conclusions

The results of this study indicate that finer diameter needles require increased effort to deliver the irrigant and resulted in higher intra-barrel pressures in the range of 400–550 kPa. Such pressures were tolerated by endodontic equipment used. Irrigant flow rate rather than intra-barrel pressure should be considered as the factor directly influencing flow beyond the needle. Wide variation of irrigant flow rate was observed among the operators. Syringe irrigation appears to be very difficult to standardize and control.

Acknowledgements

The authors wish to thank Dr A. Boutsioukis, Mr C. Dandakis, Dr C. Gogos, Ms M. Kalyva, Ms F. Mahaira, Dr I. Molyvdas, Ms C. Romania, Mr C. Soros and Dr L. Vasiliadis for participation in the lengthy procedure of measurements. Furthermore, they are grateful to Dr E. Kotsiomiti, Ass. Professor of Rem. Prosthodontics for her invaluable assistance with the statistical analysis.

References

Abou-Rass M, Piccinino MV (1982) The effectiveness of four clinical irrigation methods on the removal of root canal debris. *Oral Surgery, Oral Medicine, and Oral Pathology* **54**, 323–8.

Baker NA, Eleazer PD, Averbach RE, Seltzer S (1975) Scanning electron microscopic study of the efficacy of various irrigating solutions. *Journal of Endodontics* **1**, 127–35.

Bowden JR, Ethunandan M, Brennan PA (2006) Life-threatening airway obstruction secondary to hypochlorite extrusion during root canal treatment. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontics* **101**, 402–4.

Brown JI, Doran JE (1975) An in vitro evaluation of the particle flotation capability of various irrigating solutions. *Journal of the California Dental Association* **3**, 60–3.

Chow TW (1983) Mechanical effectiveness of root canal irrigation. *Journal of Endodontics* **9**, 475–9.

Clarkson RM, Moule AJ (1998) Sodium hypochlorite and its use as an endodontic irrigant. *Australian Dental Journal* **43**, 250–6.

Druttman ACS, Stock CJR (1989) An in vitro comparison of ultrasonic and conventional methods of irrigant replacement. *International Endodontic Journal* **22**, 174–8.

Gernhardt CR, Eppendorf K, Kozlowski A, Brandt M (2004) Toxicity of concentrated sodium hypochlorite used as an endodontic irrigant. *International Endodontic Journal* **37**, 272–80.

Gulabivala K, Patel B, Evans G, Ng YL (2005) Effects of mechanical and chemical procedures on root canal surfaces. *Endodontic Topics* **10**, 103–22.

Haapasalo M, Endal U, Zandi H, Coil JM (2005) Eradication of endodontic infection by instrumentation and irrigation solutions. *Endodontic Topics* **10**, 77–102.

Ingle JI, Himel VT, Hawrish CE et al. (2002) Endodontic cavity preparation. In: Ingle JI, Bakland LK, eds. *Endodontics*, 5th edn. Ontario, Canada: BC Decker, pp. 502.

Jones SR, Carley S, Harrison M (2003) An introduction to power and sample size estimation. *Emergency Medicine Journal* **20**, 453–8.

Kahn FH, Rosenberg PA, Gliksberg J (1995) An in vitro evaluation of the irrigating characteristics of ultrasonic and subsonic handpieces and irrigating needles and probes. *Journal of Endodontics* **21**, 277–80.

Kelly A, Resteghini R, Williams B, Dolby AE (1985) Pressures recorded during periodontal pocket irrigation. *Journal of Periodontology* **56**, 297–9.

Krebs J, Ferguson SJ, Bohner M, Baroud G, Steffen T, Heini PF (2005) Clinical measurements of cement injection pressure during vertebroplasty. *Spine* **30**, 118–22.

Lambrianidis TP (2001) *Risk management in root canal treatment*, 1st edn. Thessaloniki, Greece: University Studio Press, pp. 163–73.

Lambrianidis T, Tosounidou E, Tzoanopoulou M (2001) The effect of maintaining apical patency on periapical extrusion. *Journal of Endodontics* **27**, 696–8.

Lee SJ, Wu MK, Wesselink PR (2004) The effectiveness of syringe irrigation and ultrasonics to remove debris from simulated irregularities within prepared root canal walls. *International Endodontic Journal* **37**, 672–8.

Maita E, Horiuchi H (1984) Measurements of pressures developed in the syringe during dental infiltration anaesthesia. *British Dental Journal* **156**, 399–400.

Meyer G, Heinzel H, Hülsmann M (1991) Die effizienz von maschinell gestützter und manueller wurzelkanal-spülung im in-vitro-vergleich. *Deutsche Zahnärztliche Zeitschrift* **46**, 558–60.

Moorer WR, Wesselink PR (1982) Factors promoting the tissue dissolving capability of sodium hypochlorite. *International Endodontic Journal* **15**, 187–96.

Moser JB, Heuer MA (1982) Forces and efficacy in endodontic irrigation systems. *Oral Surgery, Oral Medicine, and Oral Pathology* **53**, 425–8.

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

Nguy D, Sedgley C (2006) The influence of canal curvature in the mechanical efficacy of root canal irrigation in vitro using real-time imaging of bioluminescent bacteria. *Journal of Endodontics* **32**, 1077–80.

Pashley EL, Nelson R, Pashley DH (1981) Pressures created by dental injections. *Journal of Dental Research* **60**, 1742–8.

Peters OA (2004) Current challenges and concepts in the preparation of root canal systems: a review. *Journal of Endodontics* **30**, 559–67.

Ram Z (1977) Effectiveness of root canal irrigation. *Oral Surgery, Oral Medicine, and Oral Pathology* **44**, 306–12.

Rieu R, Bouvier C, Fuseri J, Proust JP (1989) Injection pressure of anesthetics using 30-gauge needles with or without side perforation. *Journal of Endodontics* **15**, 453–6.

Ruddle CJ (2002) Cleaning and shaping the root canal. In: Cohen S, Burns RC, eds. *Pathways of the Pulp*, 8th edn. St Louis, USA: Mosby, pp. 258–62.

Sabins RA, Johnson JD, Hellstein JW (2003) A comparison of the cleaning efficacy of short term sonic and ultrasonic passive irrigation after hand instrumentation in molar root canals. *Journal of Endodontics* **29**, 674–8.

Schneider SW (1971) A comparison of canal preparation in straight and curved root canals. *Oral Surgery, Oral Medicine, and Oral Pathology* **32**, 271–5.

Sedgley CM, Nagel AC, Hall D, Applegate B (2005) Influence of irrigant needle depth in removing bacteria inoculated into instrumented root canals using real-time imaging in vitro. *International Endodontic Journal* **38**, 97–104.

Senia ES, Marshall JF, Rosen S (1971) The solvent action of sodium hypochlorite on pulp tissue of extracted teeth. *Oral Surgery, Oral Medicine, and Oral Pathology* **31**, 96–103.

Shepherd PA, Eleazer PD, Clark SJ, Scheetz JP (2001) Measurement of intraosseous pressures generated by the Wand, High-Pressure Periodontal Ligament Syringe, and the Stabident System. *Journal of Endodontics* **27**, 381–4.

van der Sluis LWM, Gambarini G, Wu MK, Wesselink PR (2006) The influence of volume, type of irrigant and flushing method on removing artificially placed dentine debris from the apical root canal during passive ultrasonic irrigation. *International Endodontic Journal* **39**, 472–6.

Spangberg LSW, Haapasalo M (2002) Rationale and efficacy of root canal medicaments and root filling materials with emphasis on treatment outcome. *Endodontic Topics* **2**, 35–8.

Tilton JN (1999) Fluid and particle dynamics. In: Perry RH, Green DW, Maloney JO, eds. *Perry's Chemical Engineer's Handbook*, 7th edn. New York, USA: McGraw-Hill, pp. 6.1–50.

Tinaz AC, Alacam T, Uzun O, Maden M, Kayaoglu G (2005) The effect of disruption of apical constriction on periapical extrusion. *Journal of Endodontics* **31**, 533–5.

Wesselink P, Bergenholtz G (2004) Treatment of the necrotic pulp. In: Bergenholtz G, Horsted-Bindslev P, Reit C, eds. *Textbook of Endodontology*, 1st edn. Oxford, UK: Blackwell Munksgaard, pp. 163–4.

Whitworth JM, Ramlee RAM, Meechan JG (2005) Pressures generated in vitro during Stabident intraosseous injections. *International Endodontic Journal* **38**, 291–6.

Williams CECS, Reid JS, Sharkey SW, Saunders WP (1995) In-vitro measurement of apically extruded irrigant in primary molars. *International Endodontic Journal* **28**, 221–5.

Williams AC, Bower EJ, Newton JT (2004) Research in primary dental care. Part 6. Data Analysis. *British Dental Journal* **197**, 67–73.

Zehnder M (2006) Root canal irrigants. *Journal of Endodontics* **32**, 389–98.