Endod Dent Traumatol 2000; 16: 166–174
Printed in Denmark . All rights reserved

Endodontics &
Dental Traumatology
ISSN 0109-2502

The influence of interfacial forces and duration of filing on root canal shaping

Gulabivala K, Abdo S, Sherriff M, Regan JD. The influence of interfacial forces and duration of filing on root canal shaping. Endod Dent Traumatol 2000; 16: 166–174. © Munksgaard, 2000.

Abstract – The aim of this study was to investigate the possible relationship between interfacial forces, duration of instrumentation and effectiveness of root canal shaping by filing. All factors were standardised except the manner of manipulation of the files and the dependent variables (interfacial force and duration of filing). The outcome measured was the final prepared canal shape. The study tested the hypothesis that if interfacial forces and duration of filing had predictive value for effective canal shaping, a relationship between them should be apparent. If it was not, it could be inferred that the remaining uncontrollable variable, "manner of file manipulation" had a dominating influence. 18 operators used a standard filing technique to instrument a root canal each in single rooted teeth matched for anatomy. The teeth were mounted in a custom-made transducer designed to measure laterally applied interfacial forces between file and dentine. The length of time taken with each instrument in the series was measured giving a total duration of instrumentation. The final canal shape measured by standardised "before" and "after" radiographic images of the roots was judged against an "ideal" canal shape calculated from the size of instruments used and based on the preliminary canal shape. Although some trends were revealed, no obvious relationship was demonstrated between interfacial force, duration of filing and final canal shape. Operators clearly used a range of interfacial forces characteristic for each individual and for the different file sizes. Both light and heavy forces could produce a satisfactory canal shape. Use of light or heavy forces did not obviously affect speed of preparation. Tactile discrimination was not dependent on use of light or heavy forces. It was inferred that the "manner of file manipulation" remained undefined and was probably the dominant factor influencing outcome of canal shaping.

K. Gulabivala[1], S. Abdo[1], M. Sherriff[2], J. D. Regan[1]

[1]Department of Conservative Dentistry, Eastman Dental Institute for Oral Health Care Sciences, University College London, [2]United Medical and Dental School, Guy's Hospital, University of London, London, UK

Key words: canal shaping; duration of filing; interfacial forces

K. Gulabivala, Eastman Dental Institute for Oral Health Care Sciences, 256 Gray's Inn Road, London WC1X 8LD, UK
Tel: 0207 915 1033
Fax: 0207 915 1028
e-mail: K.Gulabivala@eastman.ucl.ac.uk

Accepted January 14, 2000

The aim of root canal preparation is to eliminate bacteria and organic debris as far as it is possible from the root canal system. Technically, the focus of this activity has been centered on the effectiveness of root canal shaping. The desired ideal is the classical tapering shape with minimal diameter at the apical constriction and maximal at the coronal orifice, whilst still maintaining the original canal curvature. Achievement of such an ideal requires practical skill of an order that has raised root canal treatment to a level regarded as one of the most skill-dependent surgical procedures. It is clear to clinical students, teachers and practitioners of root canal treatment that some individuals have an innate ability to prepare canals effectively, whereas others take longer to acquire this skill, regardless of use of rotational or filing techniques. Clinical studies have shown that the tooth-related factors which mainly appear to influence the results include canal curvature (1, 2) and the site in the mouth (2, 3). Technological advances in instrument design (rotary non-ISO tapered nickel-titanium instruments) appear to be levelling the playing field between the skilled and less technically able clinician (4). However, not all cases can be managed by these approaches. Ultimately, this intangible "skill factor" predominates in the management of the technically difficult cases.

In order to learn or teach these unique skills, it is essential to appreciate what actually constitutes such skill. Controlled shaping means controlled removal of dentine from within the root canal using tactile feedback alone. According to some, a mentally synthesised three-dimensional image of the root canal system aids the process (5, 6). It is acknowledged, albeit indirectly, that good tactile sense is a dominant requirement for root canal treatment in comparison with other dental procedures (7).

It is not clear whether tactile discrimination is dependent on finely applied, light forces or equally effective at more heavily applied coarse forces. An analysis of the factors influencing dentine removal by filing indicates that the variables of probable importance are: type of instrument (file) and substrate (i.e. the nature of dentine), the nature of interaction between the two (including relative orientation, type of relative motion between the two, the angle of engagement of cutting edges, the interfacial forces, effectiveness of debris removal) and the duration of instrumentation. Of these factors, if it were possible to standardise the non-operator dependent factors, a study of the operator-dependent factors, such as interfacial force, orientation of file to substrate and duration of instrumentation, might provide a clue as to what factors predominantly dictate the apparently intangible quality called "tactile skill" (8). Interfacial forces (9) and duration of instrumentation are quantifiable, but orientation of file to substrate during clinical use would be difficult to measure. The purpose of this study was to standardise as many factors as possible and measure interfacial forces, duration of filing and achievement of a predetermined canal shape. Specifically, it was hypothesised, that good tactile discrimination would depend on small, finely controlled and applied forces and therefore a relationship should emerge between light forces and effective canal preparation. Furthermore, given a standard, predetermined target for canal preparation, an inverse relationship should emerge between duration of filing and interfacial forces. An absence of a clear relationship between the three may imply that the untested variables, namely, orientation and manipulation of the file have dominant influence on canal shaping.

Material and methods

Extracted, human teeth with pre-selected and standardised features of root canal anatomy were mounted in a specially constructed apparatus (9) to measure applied interfacial forces. Operators instructed in a standardised technique for canal preparation by filing using designated instruments were asked to prepare canals in this apparatus. The laterally applied interfacial forces, duration of instrumentation and achievement of the target canal shape were quantified.

Selection, preparation and standardisation of roots

Eighteen roots were selected after multiple view radiographic assessment from 350 extracted human maxillary and mandibular teeth (stored in 4% formal-saline) according to the following criteria:

- Canal curvature of between 40°–45°, determined using the Schneider technique (10)
- Canal curvature to be 5–7 mm from the apical foramen
- There should be no additional canal curvatures either in the selected or other planes
- The canal diameter should just permit its negotiation with a size 08 or 10 file (Kerr UK Ltd, Peterborough, UK).

The selected roots were separated using a diamond bur driven in an air turbine with copious water spray to preserve associated coronal tooth structure. To standardise working length, a size 10 file was placed until the tip was just visible at the apical foramen and 0.5 mm was subtracted from this length as the terminal apical position for preparation. The residual length of the file gave the length of the coronal portion of the tooth to be trimmed in order to standardise the working length to 17 mm.

Recording of canal shape before and after canal preparation

The canal shape was evaluated in the plane of the curve using a radiographic technique described by Tang & Stock (11). This required standardisation of the position of the tooth in relation to the X-ray beam and radiographic film, achieved by modifying a posterior Rinn film holder (Endo Ray Rinn, Claudius Ash, Potters Bar, UK) securely fixed to the radiographic tube head cone. The film holder retained the film in a standard position and the modified bite-block held a clear acrylic spectrophotometer cuvette (Lip Equipment, London, UK) firmly by friction. Each root was mounted in a cuvette using clear casting epoxy resin (Stycast 1266, Casting Resin, Emerson & Cuming, London, UK) so that the plane of curve was fixed and the root positioned centrally with the coronal long-axis aligned parallel to the cuvette. Evaluation of the canal shape was aided by a radio-paque solution (Isopaque 350 mg, Nycomed, London, UK) the insertion of which was facilitated by application of negative pressure to the apical foramen.

This required a channel to be built into the apical part of the cuvette in which the root was mounted.

High-resolution radiographic film (Q972, EM Film, Agar Scientific, Essex, UK) was used to obtain the radiographic images. The film, available in 6.5×9.0 cm was cut to 31×41 mm periapical film sizes under safety light (Safe light filter, Kodak, Herts., UK) and stored in conventional emptied periapical film packets, which were then sealed with black insulating tape. A standard exposure setting of 3.6 s gave the best image. The film processing was standardised. Once the un-instrumented canals were radiographed, the isopaque was removed by washing with water. Following instrumentation, the canals were similarly filled with isopaque and radiographed in a standard manner.

Root canal instrumentation, measurement of interfacial forces and duration of filing

18 operators each performed root canal instrumentation according to specific instructions using one root held in a cuvette which was in turn mounted in an apparatus to measure interfacial forces during instrumentation (9).

Apparatus for measurement of interfacial forces

The cuvette was mounted using plaster in a brass jig that was engineered to fit on top of a cantilevered aluminium beam. Two pairs of single element strain gauges were bonded at right angles to each other to this beam. These measured laterally applied forces in the X and Y direction (9). Calibration of the strain gauges was carried out by applying a series of known weights and was repeated before each operator prepared the canal. The strain gauges were connected to type 031 Sangamo-Schlumberger (Sangamo Transducers, Bognor Regis, UK) conditioning amplifiers with light-emitting diode digital displays whose output was in turn connected to an analogue-to-digital converter fitted in a microcomputer (PC-28, Amplicon Liveline, Brighton, East Sussex, UK). Using the PC-28 software, the information was recorded and stored prior to evaluation (9).

Root canal instrumentation

Each of the 18 operators was instructed to follow a specific sequence in order to prepare a pre-conceived taper using a serial filing technique that all operators were familiar with. They were provided with information about the root canal shape, the working length and reference points to use. Each operator was provided with a set of K-flex files (sizes 10–60, Kerr, Peterborough, UK) and 1% sodium hypochlorite together with a 27-gauge needle and syringe (Monoject endodontic locking syringes 3 cc, Sherwood Medical, St. Louis, MO, USA) to irrigate the root canals. The operators were given verbal and written instructions as follows:

1) Wear surgical hand gloves during instrumentation (Micro-Touch, Latex medical gloves, Johnson & Johnson, Berkshire, UK).
2) Use the provided files (appropriately precurved) in a reciprocal filing motion as opposed to rotational, so as to produce a flared canal with a minimal apical diameter at the working length and the maximum at the pulp chamber. They should not contact the transducer, during instrumentation which should be freely displaceable under applied loads.
3) Commence by filing with the size 10 file to the full working length until the file was loose and the canal was able to accept the size 15 passively to the full working length.
4) Thoroughly irrigate the canal and recapitulate with a smaller file to maintain patency and length.
5) Repeat steps 3 and 4 until the size 25 file was just loose at the working length.
6) Use a step-back sequence to flare the canal. Each larger file was to be used 1 mm shorter than the last until it was just loose. If the next precurved file was already loose at its correct length, then no filing was to be done with it. Irrigation and recapitulation to be performed as before. At the end of preparation wash the canals with water and dry with paper points.

The canals were once again filled with isopaque and radiographed in the standard manner described before.

Measurement of duration of filing and sampling of interfacial forces

The duration of filing with each instrument was measured with a stopwatch. This did not include the process of irrigation or recapitulation. Each operator was asked to signal verbally when instrumentation with a file was commenced and completed.

The interfacial forces were measured intermittently for each file. They were sampled for a specific length of time based on pilot studies that revealed that the smaller files in general were used longer than the larger sizes. The software was programmed to sample the vectorial components of the forces at 100 points during the recording period (100 values for the X direction and 100 values for the Y direction). The resultant force for the individual vectorial components was calculated by taking the square root of the sum of the squares of the individual vectorial components to give 100 values in all. The recording periods varied depending upon the file size and were 30 s for size 10–25, 20 s for size 30–45 and 10 s for size 50–60. This raw data was entered into a series of computer spreadsheets (Borland Quattro Pro, Borland International, Scotts Valley, CA, USA). There were 100 in-

Table 1. Univariate summary statistics for interfacial forces applied by all operators for each of the files

File size	Mean force/g	SD/g	Min. force/g	Max. force/g
10	49	26	9	115
15	68	30	30	133
20	62	27	29	122
25	74	44	25	226
30	91	46	42	231
35	79	38	42	190
40	87	44	43	218
45	104	59	35	269
50	95	50	32	192
55	90	49	26	224
60	92	47	21	166

terfacial force readings per file (11 files) used by each operator (18), a total of 19 800 readings.

Analysis of canal preparation

The pre- and post-operative canal shapes were compared by superimposing the radiographic images. This was achieved by projecting each film from a photographic enlarger (De Vere 504 photographic enlarger, Agar Scientific, Cambridge, UK) at a ×10 magnification onto graph paper. The outlines of the root and pre-operative root canal were traced onto the paper. The image of the post-operative canal shape was then separately projected onto the traced image of the root and also traced.

The canal preparation was assessed both quantitatively and qualitatively. An ideal canal preparation was calculated for each canal individually, based on the desired end-point the operators were asked to target. This was achieved as follows: The central axis of each pre-operative canal was determined by measuring the distance between the inner and outer canal wall at 1 mm intervals (1 cm on magnified image). These points were joined by a line to give the central axis of the canal. Perpendicular lines were drawn to this central axis at 1 cm intervals commencing at the working length which intersected the canal and root walls. The expected minimum dimensions of the ideal canal preparation were estimated from the respective file tip sizes and then plotted along each of these perpendiculars. This was possible because each of the perpendiculars corresponded to the terminal length of instrumentation of a file, the apical size of which was taken as the minimum dimension of the ideal preparation as each operator was advised to use each file only until it was just loose. Thus the dimension of the tip of a size 25 file was 2.5 mm on the magnified image (×10). Assuming a truly centered canal preparation, 1.25 mm was measured off in each direction along the perpendicular from the central axis of the canal. This was repeated for each larger file at 1 cm intervals. The joined points gave the calculated ideal canal preparation.

Miss-match between the ideal and actual canal preparation gave an indication of over- or under-preparation along the length of the canal. Measurements for miss-match were made along the perpendicular lines at which all determinations of canal dimensions were made. Three features of canal preparation were judged, over-/under-preparation, canal straightening and taper. The criteria for these were as follows:

Over/under preparation – if the measurements at 4 points or more differed by more than 1.5 mm (on the magnified image) then the canal was judged to be over-prepared (if larger) and under-prepared (if smaller). Otherwise the canal would by definition be judged ideal.

Canal straightening – if the measurements at 4 points or more were greater than the ideal on the inner aspect of the coronal curve and 4 or more were greater than the ideal on the outer aspect of the curve apically, then the canal would be judged straightened.

Canal taper – the canal taper was judged both visually and by measurement of the diameter of the post-preparation canal outline at each of the perpendicular lines. Each coronal measurement should be larger than the previous apical measurement. The proportion of increase should be dictated by the ideal preparation shape. Deviation from this would give a measure of over-tapering, under–tapering is theoretically impossible.

Statistical analysis

Differences in interfacial forces between files and operators were analysed using the Bonferroni (Dunn) *t*-test. An alpha value of 0.05, with 0.95 confidence level was used.

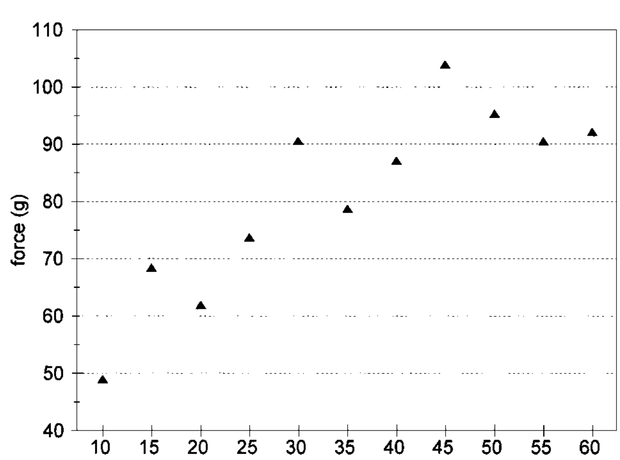

Fig. 1. Mean interfacial forces applied by all operators (n=18) for each of the file sizes.

Table 2. Univariate summary statistics for interfacial forces applied by individual operators

Operator no.	Mean force/g	SD/g	Min/g	Max/g
1	61	35	14	131
2	98	36	45	156
3	57	35	9	146
4	72	33	29	137
5	62	20	28	98
6	88	29	40	132
7	84	27	34	133
8	107	35	50	168
9	56	21	25	96
10	104	47	34	159
11	116	76	30	269
12	164	57	66	231
13	41	10	27	60
14	84	29	40	132
15	50	16	21	77
16	76	10	61	89
17	55	16	32	89
18	81	28	36	115

The correlation between interfacial forces, duration of instrumentation and effectiveness of canal shaping was assessed using three separate tests. A simple multiple linear regression analysis was carried out first. Next a stepwise multiple regression was used and finally a robust regression was used.

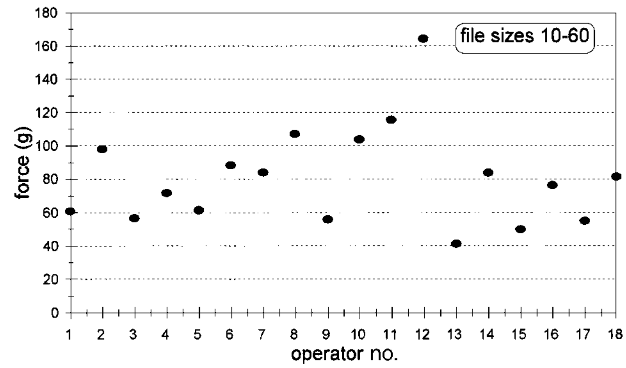

Fig. 2. Mean interfacial forces applied by individual operators, for all files (sizes 10–60).

Results

The results were analysed with respect to

1) Interfacial forces 2) Duration of instrumentation 3) Effectiveness of canal preparation and 4) Correlation between 1, 2 and 3.

Interfacial forces

A mean value was calculated from each group of 100 values for each file. The overall data of mean interfacial forces applied by all of the 18 operators for each of the 11 files is shown in Table 1 and Figure 1. In

Table 3. Bonferroni multiple comparison of means of interfacial force (in grams) by file. The upper value of each pair is the difference between the mean values, and the lower value is the associated probability

File size	10	15	20	25	30	35	40	45	50	55
15	19 1.000									
20	13 1.000	−6 1.000								
25	25 1.000	5 1.000	12 1.000							
30	42 0.226	22 1.000	29 1.000	17 1.000						
35	30 1.000	11 1.000	17 1.000	51 1.000	−12 1.000					
40	38 0.464	19 1.000	25 1.000	13 1.000	−3 1.000	8 1.000				
45	55* 0.009	36 0.771	42 0.208	30 1.000	13 1.000	25 1.000	17 1.000			
50	46 0.093	30 1.000	33 1.000	22 1.000	5 1.000	17 1.000	8 1.000	−9 1.000		
55	42 0.262	22 1.000	29 1.000	17 1.000	0 1.000	12 1.000	3 1.000	−13 1.000	−5 1.000	
60	43 0.186	24 1.000	30 1.000	18 1.000	2 1.000	13 1.000	5 1.000	−12 1.000	−3 1.000	2 1.000

* indicate a significant difference, $\alpha=0.05$.

Table 4. Bonferroni multiple comparison of means of interfacial force (in grams) by operator. The upper value of each pair is the difference between the mean values, and the lower value is the associated probability

Operator no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
2	38 1.000																
3	−4 1.000	−41 1.000															
4	11 1.000	−26 1.000	15 1.000														
5	1 1.000	−36 1.000	5 1.000	−10 1.000													
6	28 1.000	−10 1.000	32 1.000	17 1.000	27 1.000												
7	24 1.000	−14 1.000	27 1.000	12 1.000	23 1.000	−4 1.000											
8	47 0.466	9 1.000	50 0.166	35 1.000	46 0.452	19 1.000	23 1.000										
9	−4 1.000	−42 0.956	−1 1.000	−16 1.000	−5 1.000	−32 1.000	−28 1.000	−51 0.140									
10	44 0.879	6 1.000	47 0.336	32 1.000	43 0.869	16 1.000	20 1.000	−3 1.000	48 0.286								
11	51 0.151	14 1.000	55* 0.047	40 1.000	50 0.141	23 1.000	27 1.000	4 1.000	56* 0.039	8 1.000							
12	104* 0.001	66* 0.003	108* 0.001	92* 0.001	103* 0.001	76* 0.001	80* 0.001	57* 0.035	108* 0.001	60* 0.016	53 0.075						
13	−19 1.000	−57* 0.038	-16 1.000	−31 1.000	−20 1.000	−47 0.336	−43 0.805	−66* 0.004	−15 1.000	−63* 0.009	−70* 0.001	−123* 0.001					
14	26 1.000	−14 1.000	27 1.000	12 1.000	23 1.000	−5 1.000	0 1.000	−23 1.000	28 1.000	−20 1.000	−28 1.000	−80* 0.001	43 0.836				
15	−10 1.000	−48 0.285	−7 1.000	−22 1.000	−11 1.000	−39 1.000	34 1.000	−57* 0.035	−6 1.000	−54 0.076	−61 0.008	−114* 0.001	9 1.000	−34 1.000			
16	16 1.000	−21 1.000	20 1.000	5 1.000	15 1.000	−12 1.000	−8 1.000	−31 1.000	21 1.000	−27 1.000	−35 1.000	−88* 0.001	35 1.000	−7 1.000	26 1.000		
17	−5 1.000	−43 0.795	−2 1.000	−17 1.000	−6 1.000	−33 1.000	−29 1.000	−52 0.113	−1 1.000	−49 0.233	-56* 0.031	−109* 0.001	14 1.000	−29 1.000	5 1.000	−21 1.000	
18	21 1.000	−16 1.000	25 1.000	10 1.000	20 1.000	−7 1.000	−3 1.000	−26 1.000	26 1.000	−22 1.000	−30 1.000	−83* 0.001	40 1.000	−2 1.000	32 1.000	5 1.000	27 1.000

* indicate a significant difference, α=0.05.

general terms, the interfacial forces used increased in magnitude up to file size 45 after which the mean forces decreased again.

Univariate summary statistics for the forces applied by each of the operators for the different files is shown in Table 2. The mean interfacial forces range from 41 g to 164 g. (Table 2 and Fig. 2). The raw data indicated a wide range of forces was used by each of the operators for each of the files. Bonferroni multiple comparisons of means for force by file and by operator are tabulated in Tables 3 and 4 respectively.

When the files were grouped into sizes 10–25 and 30–60 (Fig. 3), the operators used a characteristic range of forces, and the two groups followed a similar pattern. The difference between the two groups varied from operator to operator. Most used smaller forces for the smaller files although there were some exceptions (e.g. operators 7,15,17,18).

Duration of instrumentation

The duration of use of each file by each operator is given in Table 5 together with subtotals for instrumentation from size 10–25 and from 30–60. The total time for instrumentation for each operator is also given. The total duration of filing ranged from 282–755 s. The mean for all the operators was 499 s. Some operators used the smaller files (sizes 10–25) longer while others used the larger files (sizes 30–60) longer.

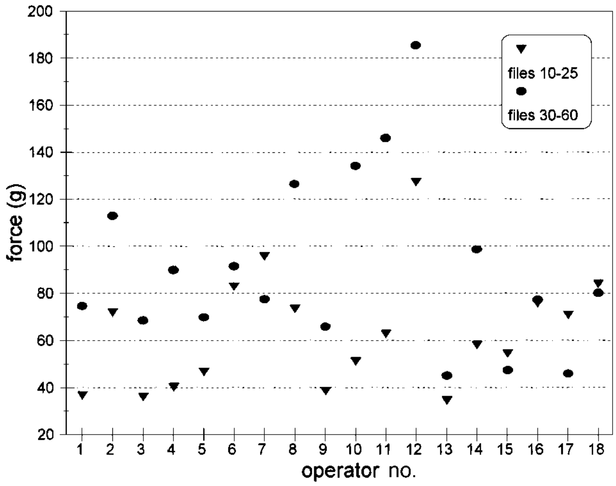

Fig. 3. Mean interfacial forces for files grouped into two (sizes 10–25 and sizes 30–60) for each operator.

Effectiveness of root canal instrumentation

The reproducibility of the tracings was determined by repeating the tracings of a selected canal five times at half hour intervals. One tracing was arbitrarily selected as a standard with which to compare the others. Linear measurements to the nearest mm were recorded at several predetermined points. This method of tracing was determined to be very accurate (90% reproducibility).

The results for each of the categories of canal preparation judged (over-prepared, good taper, tendency to straighten) were scored as "Yes" (Y) or "No" (N) and are presented in Table 6. Eleven of the 18 preparations were judged to be over-prepared in comparison to the ideal preparation. The degree of over-preparation beyond the arbitrarily chosen minimum was variable. In 8 preparations, the over-preparation was predominantly on the inner curve, in 2 it was predominantly on the outer curve and in 8 it was equal on the inner and outer walls.

Half of the 18 preparations were judged to be well tapered; in that, each coronal portion of the canal at 1 mm intervals was larger in diameter than the last apical segment. Six of these 9 well tapered canals were also over-prepared and 2 were also judged to be straightened.

Eight of the 18 prepared canals were judged to be straightened.

Correlation between interfacial forces, duration of instrumentation and Canal shaping

The results were analysed by examining the variables, i) interfacial force, ii) duration of instrumentation and iii) features of canal preparation (over-preparation, canal straightening and taper). Canal preparation variables were scored as '0' for no and '1' for yes. Due to the scatter in the data, the median of the force rather than the mean was used as a better measure of the central tendency. A simple multiple linear regression analysis was carried out, but the full model was found to have low predictive power due to the inadequate sample size. Next a stepwise multiple regression analysis was carried out, this tests the significance of a selected variable by excluding it and then re-including it to test the effect of another. On the basis of this analysis, the interfacial force was found to be a function of the tendency to straighten the canal and the duration of instrumentation. The final

Table 5. The duration of use of each file (sizes 10–60) for all 18 operators given in seconds

Operator no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
10	51	61	58	16	40	40	22	4	31	45	30	27	32	24	54	28	52	31
15	51	77	80	37	29	62	21	54	94	47	17	23	93	89	43	47	90	36
20	45	112	86	28	38	–	54	79	86	40	17	38	113	61	7	109	111	36
25	40	69	122	79	45	–	152	86	71	51	34	30	137	80	122	47	46	36
Total for file sizes 10–25	187	319	346	160	152	102	249	223	282	183	98	118	375	254	204	231	299	139
30	29	96	36	53	38	38	38	50	61	39	36	35	67	60	90	65	77	40
35	27	91	73	28	25	50	50	21	48	31	33	51	105	58	108	35	75	44
40	21	75	76	23	34	53	53	72	36	47	30	67	57	86	69	24	48	36
45	32	17	57	13	32	40	40	38	38	57	40	30	92	100	39	61	31	11
50	27	20	30	21	16	27	27	20	39	41	33	40	17	86	19	–	38	33
55	18	27	28	22	42	28	28	20	29	53	8	24	23	50	10	–	31	38
60	40	16	10	14	35	34	34	25	40	28	4	17	10	61	15	–	14	27
Total for file sizes 30–60	194	342	310	173	222	270	270	283	291	296	184	264	371	501	536	195	314	229
Total	381	611	656	333	374	374	372	506	573	479	282	382	746	755	640	426	613	368

Table 6. The results of analysis of prepared canal shape judged in terms of over-preparation, good taper and tendency to straighten

	Operator no.																	
Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Over-prepared	N	Y	N	Y	Y	Y	N	N	Y	N	N	Y	N	Y	Y	Y	Y	Y
Good taper	N	Y	N	N	Y	Y	N	N	Y	Y	Y	N	Y	N	N	N	Y	Y
Tendency to straighten	Y	Y	Y	N	N	Y	N	Y	N	N	N	Y	N	N	Y	Y	N	N

analysis was a Robust regression just using the interfacial forces and the tendency to straighten as the variables, but it revealed no significant differences.

Discussion

In order to define factors affecting an outcome all factors have to be identified and accounted for. In the present study many variables were difficult to control. Root and canal anatomy were standardised as far as they practically could be. In terms of standardisation of instruments, the choice was between a separate set of files for each operator, accepting their variability (12) or the same set of instruments for all operators, accepting their progressive blunting. In the final event, a compromise was achieved. The smaller instruments (sizes 10–20) were replaced, and the larger instruments (sizes 25–60), i.e. those used to gauge canal shape, were re-used for all operators to achieve consistency. Although the operators all came from a group who received standard instruction in root canal preparation technique and were given precise instructions for preparation, it was considered impossible to achieve absolute standardisation. For example, the degree of accuracy with which each operator may precurve a file or manipulate it is likely to remain variable. In fact, the manner of manipulation of the instruments remained the major uncontrolled and unquantified variable. It was accepted at the outset that this would be so. The dependent variables and those that were quantified were the interfacial forces and the duration of filing. The measured outcome was the efficacy of canal shaping. It would be unrealistic and irrelevant to try to control either of the dependent variables.

The method selected for evaluating canal shape and the qualitative nature of the subsequent assessment of shaping may be a matter of some debate. Clearly, a more accurate and quantitative means of determining canal shape before and after preparation is desirable, but no sophisticated method currently exists that could have evaluated the relevant parameters. Image analysis with a dedicated software may be a future solution. The use of a calculated "ideal canal shape" was a useful baseline from which to judge the final canal shape although it is recognised that it would not necessarily be perceived as the "ideal" by every operator. Nevertheless, the designated ideal shape and the qualitative criteria formed a useful arbiter of deviations from the stated pre-operative goals. The criteria were based on a pilot study in which two endodontists scored the canal shapes for over-/under-preparation, straightening and canal taper. It was found that the selected criteria most closely matched the subjective scores and were thus taken as reliable.

The interfacial forces were measured in two dimensions (lateral pressure) as opposed to three dimensions (apical pressure as well) that would have been desirable but difficult. As filing mainly involves lateral forces, those measured were considered most relevant. The method has been tested and found to be satisfactory (9). The results corroborated our previous findings that different operators use characteristically different forces (Table 2, Fig. 2 and Fig. 3). In general, the smaller files were used with smaller forces (Table 1, Fig. 3), but this was not always so. Some operators (7,15,17,18) applied higher forces when using smaller files (Fig. 3). The general trend may be explained by the greater flexibility of the smaller files that presumably allow more dissipation of some of the applied force. The implication seems to be that in order to generate higher measured forces, the applied forces on the files must be even greater. It is assumed that some operators prefer to feel the file cutting dentine and lean more heavily on the smaller instrument, whereas others do not. Conversely, the need to apply heavier forces is reduced with larger and rigid instruments, but transmission of applied force is greater.

Operators using heavy forces (e.g. 11,12) tend to do so for most files but not for all (Table 2, Fig. 3). Conversely, those tending to use light forces (e.g. 9,13) do so for most files but not all. There is no clear trend for file sizes that are exceptions. It is obvious that operators function within a range of interfacial forces and that this range is narrow for some and wide for others.

The anticipation that there may be an inverse relationship between interfacial forces and duration of filing was not obviously borne out. This was partly because of the variability of the final prepared canal and its departure from the targeted ideal. Considering those cases where the canals did meet the required ideal standard (Table 6 – operators 10,11,13) a vague inverse relationship did seem to exist. For example, operator 13, used the lowest forces and took the second longest to complete the preparation. Whereas operator 11 used the second highest forces and was the quickest. Operator 10, did not quite fit the pattern in that he/she used the fourth highest forces but took almost twice as long as operator 11 to complete the preparation. Taking all operators together, the statistical analysis indicated a relationship between interfacial forces and duration of instrumentation but it seemed to be masked by confounding factors from individual to individual. It can only be assumed that the confounding factor was related to the manner of manipulation of the file.

The main aim of the study was to determine the degree of influence of interfacial forces and duration of filing on canal shaping. The latter, judged using 3 separate criteria gave a matrix of canal characteristics for each operator (Table 6). The optimal canal preparation meeting target requirements would achieve the responses, "No" for over-preparation, "Yes" for good taper and "No" for tendency to straighten. Only 3 out of 18 operators achieved this score (operators 10,11,13), although by clinical standards many with a score of Yes for over-preparation would also have been acceptable (operators 5,9,17,18). An operator-by-operator analysis of interfacial forces and duration of filing revealed no clear trends. It was just as possible for an operator to use heavy forces and take a long time (operator 10) or a short time (operator 11). Conversely, some operators used light forces and took a long time (operator 13) or a relatively short time (operator 5).

Even though one of the statistical tests showed interfacial forces to be a function of tendency to straighten, further tests revealed no significance, and case-by-case analysis of operators showed no obvious trends. For example, some operators using heavy forces showed no canal straightening (operators 10 & 11), whereas, those using light forces (operators 1,3,15) did.

The general impression created was that tactile discrimination was not affected by the level of interfacial force used. Operators functioned at a characteristic range of interfacial forces. The duration of filing could have a bearing on final outcome of preparation, but it seemed that the unmeasured quantities, the manner of manipulation of the instruments (i.e., how they were precurved and handled in relation to the dentine) were the dominating factors. Future studies on factors affecting effective achievement of target canal shape should focus on these factors. It may be valuable to divide the operators into the technically good and poor and to characterise their mental, psychological, behavioural and neuro-motor qualities, in order to gain further insight into what influences learning and teaching of endodontic skills (8).

Within the limitations of this study it was concluded that, no clear relationship could be demonstrated between interfacial forces, duration of filing and effectiveness of canal shaping. Operators functioned at a range of interfacial forces characteristic to them. The weight of interfacial forces used did not relate to presence or absence of tactile discrimination. The duration of instrumentation did not obviously relate to the effectiveness of preparation. It was inferred that the major unaccounted variable, the manner of instrument manipulation had a dominant effect on canal shaping.

Acknowledgment – The authors would like to express their gratitude to all who participated in this study and specifically to Mr. K. Elias and Dr. N. Meredith for their help with the equipment used for measuring interfacial forces.

References

1. Stadler LE, Wennberg A, Olgart L. Instrumentation of curved root canal using filing or reaming technique – a clinical study of technical complications. Swed Dent J 1986;10:37–43
2. Greene KJ, Krell KV. Clinical factors associated with ledged canals in maxillary and mandibular molars. Oral Surg Oral Med Oral Path 1990;70:490–7.
3. Smith CS, Setchell DJ, Harty FJ. Factors influencing the success of conventional root canal therapy – a five-year retrospective study. Int Endod J 1993;26:321–33.
4. Pettiette MT, Metzger Z, Phillips C, Trope M. Endodontic complications of root canal therapy performed by dental students with stainless-steel K-files and nickel-titanium hand files. J Endod 1999;25:330–4.
5. Gulabivala K. Preparation of the root canal. In: Stock CJR, Gulabivala K, Walker RT, Goodman JR, editors. Color Atlas and Text of Endodontics. 2nd ed. St. Louis: Mosby-Wolfe; 1995. p. 110.
6. Buchanan S. Cleaning and shaping the root canal system. In: Cohen S, Burns RC, editors. Pathways of the pulp. 5th ed. St. Louis: Mosby; 1996. p. 172–177.
7. Rustage KJ, Rothwell PS, Brook IM. Evaluation of a dedicated dental procedure glove for clinical dentistry. Brit Dent J 1987;163:193–5.
8. Graham KS and Deary IJ. A role for aptitude testing in surgery? J Royal Coll Surg Edinb 1991;36:70–4.
9. Regan JD, Sherrif M, Meredith N, Gulabivala K. A survey of interfacial forces used during filing of root canals. Endod Dent Traumatol In press, 2000.
10. Schneider SW. A comparison of canal preparation in straight and curved root canals. Oral Surg Oral Med Oral Path 1971;32:271–5.
11. Tang MPF, Stock CJR. An *in vitro* method for comparing the effects of different root canal preparation techniques on the shape of curved root canals. Int Endod J 1989;22:49–54.
12. Stenman E, Spangberg LSW. Root canal instruments are poorly standardised. J Endod 1993;19:327–34.