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ORIGINAL RESEARCH

Determination of root canal curvatures before and after canal preparation (part II): A method based on numeric calculus

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Abstract

The aim of this paper is to present a new method based on numeric calculus to provide data on any type of root canal curvature at any point of the long axis of the canal. Twenty severely curved, simulated root canals were prepared with rotary FlexMaster® and Profile® instruments in the crown-down technique and manually in the step-back technique. The inner and outer curvatures were registered in a system of coordinates before and after preparation in increments of 0.5 mm. Using an equalising function, the curvatures were first represented in graphic and algebraic form. The maximum and the mean curvature as well as the length of the arc from the apical foramen to the point of maximum curvature were determined mathematically. An increase in maximum curvature was registered for all four shaping systems investigated. The radius of the inner curvature decreased by 0.5–1.2 mm in the manual systems as a result of the preparation. The Profile® system displayed the smallest changes in radius (–0.9 mm) even with the outer curvature, and manual preparation with stainless steel files the most pronounced change (–1.8 mm). The point of maximum curvature at the inner curvature was displaced by 1.6 mm to the apical foramen through manual preparation with Ni-Ti files. At the outer curvature, the maximum displacement (1.8 mm) recorded was also the result of preparation with Ni-Ti hand files, while a displacement of only 0.3 mm to the apical foramen was recorded with the other systems. The method offers a means of determining curvatures precisely without random specification of reference points. The method is also capable of registering only minor changes in curvature in the two-dimensional long axis of the canal.

Introduction

The objective of root canal preparation is to clean and shape the canal. The root canal should be conically prepared but changed as little as possible in its original shape. However, no rotary preparation technique available to date is fully capable of preventing modifications to canal morphology, such as zips, elbows, transportation or straightening.

Displacement of the canal axis or excessive removal of material at the inner curvature may result in stripping or perforation (1). The prognosis of teeth damaged in this way is dubious and surgical intervention is necessary in most cases (2).

For some decades, new files and techniques have been tested and evaluated with the aim of minimising these problems. The transportation of the long axis of the root canal has been investigated by numerous authors with reference to mechanical serial sections or virtual CT sections (3–5). Root canal curvature and curvature modification induced by rotary preparation of the root canal have also been evaluated with numerous methods (6–12).

Canal systems can be evaluated *in vitro* before and after preparation by means of micro-computed tomography (μCT) with a high spatial resolution of 33 μm (13). *In vivo*, less precise methods are generally applied, with the two-dimensional radiographic representation of a three-dimensional long axis of the canal being in any case inadequate. The accuracy could be enhanced here by taking recourse to and following up some precise mathematical methods already presented.

The aim of the present study was to present an optimised method providing data on root canal curvature at any point of a two-dimensional long axis. This method should permit even slight mechanically induced changes in the curvature of the long axis of the canal to be shown in clinical radiographs.

Materials and methods

Five dental students at Philipps-University, Marburg (Germany), with practical experience in manual and rotary root canal preparation, each prepared one root canal manually with stainless steel and Ni-Ti K-files (VDW, Munich, Germany) and one canal with the rotary Profile® (Maillefer Dentsply, Ballaigues, Switzerland) and FlexMaster® (VDW, Munich, Germany) systems. The 20 severely curved simulated root canals were industrially produced (VDW, Munich, Germany) and 19 mm long. The radius of the inner curvature (small curve) ranged from 5.0 to 6.5 mm, while the outer curvature (large curve) had radii of between 4.3 mm and 6.6 mm. The arc length (= canal length) from the apical foramen to the point of maximum curvature had a median value of 4.2 mm at the large curve and of 4.15 mm at the small curve.

Preparation for testing

Serial numbers from one to 20 were engraved into the acrylic blocks with the simulated root canals. A 0.1% aqueous methylene blue solution (Pharmacy of Philipps University) was injected into the canals to enhance the image contrast for the subsequent photographic documentation and to verify that the canals were suitable for instrumentation. If the solution failed to emerge through the apical foramen, the block was discarded and replaced with a new one. The blocks were photographed in a purpose-designed stand (Fig. 1; precision mechanics workshop, Philipps University, Marburg, Germany) in a reproducible position with a digital camera (Camedia C2500L, Olympus, Tokyo, Japan) against a plotting paper background and the image data were stored in a PC (Compaq Computer Corp., Houston, USA). The methylene blue solution was then flushed out of the canals with water to prevent any obliteration due to drying of the dye.

The numbered blocks were randomised to the individual groups and issued individually to the operators for preparation. The resulting assignments were entered in a coding list showing the operator and the preparation system of each root canal. The operator was also assigned a number to facilitate allocation in sequence of treatment (Table 1).

Following a theoretical refresher course on how to use the preparation systems, each student prepared one simulated root canal up to size ISO 35 with each of the four stated methods.

Root canal preparation

Prior to each preparation, pre-flaring was performed with Gates Glidden burs (Komet, Lemgo, Germany) in the crown-down technique in the upper-third of the canal.

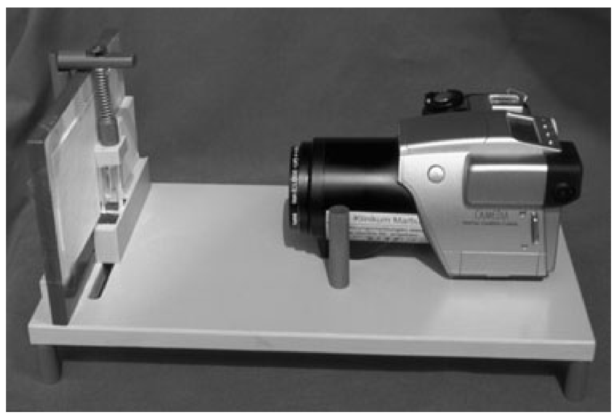

Figure 1 Purpose-designed stand for standardised photograph.

Table 1 Sequence in which the four systems were used by the operators

Operator No.	1st preparation	2nd preparation	3rd preparation	4th preparation
1	Hand Ni-Ti	FlexMaster®	Profile®	Hand SS
2	FlexMaster®	Hand Ni-Ti	Hand SS	Profile®
3	Profile®	Hand SS	Hand Ni-Ti	FlexMaster®
4	Hand SS	Profile®	FlexMaster®	Hand Ni-Ti
5	Profile®	FlexMaster®	Hand Ni-Ti	Hand SS

After each change of instrument the root canals were irrigated with water to remove debris.

The working length of the industrially produced blocks was set at 18 mm, corresponding to a distance of 1 mm from the apical foramen. The working length of each instrument was set by the students themselves with rubber stoppers prior to the start of treatment and was checked in the course of treatment. Preparations were performed with a new set of instruments for each preparation system. The conicity was 2% (taper 0.02) with manual preparation, and 4% (taper 0.04) with rotary preparation.

Manual preparation was performed with stainless steel or Ni-Ti K-files with a working length of 25 mm. For optimised canal preparation, the stainless steel instruments were pre-bent by the students and applied with slight apically directed pressure with a 1/8 turn clockwise and counterclockwise direction (14).

Rotary preparation was done with 25 mm long Ni-Ti FlexMaster® files and Profile® instruments, which were lightly coated with Glyde® (Dentsply De Trey, Konstanz, Germany) before being inserted into the canal. Both systems were driven at 250 rpm by a torque-controlled low-speed motor (Endo IT control; VDW, Munich, Germany) adapted to the individual instruments. Between each change of instruments the canals were irrigated with water. If necessary, the canals could be recapitulated with a previously used, smaller file.

The instrument application sequence is shown in Tables 2 and 3.

All prepared root canals were photographed once again with a digital camera in standardised position and the image data were stored in the PC. In contrast to the first photo, however, the canals were not dye-penetrated and the blocks were photographed against a black background.

Table 2 Instruments and working sequence in manual shaping technique

	Instrument	Sequence
Pre-flare	Gates Glidden burs	Sizes 110, 90, 70
Full working length (18 mm)	SS or Ni-Ti K-files	Sizes 15, 20, 25, 30, 35, all 0.02 taper
Step-back (17 mm)	SS or Ni-Ti K-file	Size 40, 0.02 taper

Geometrically based analytical method

Mathematical principles underlying the method

In mathematics, a curvature is described by means of hypothetical circles. The curvature at a specific point (x_0) is described by selecting a circle that is optimally adapted to the configuration of the curve at that point (x_0). The smaller the curvature, the larger the hypothetical circle. The curvature dimension at a point (x_0) is specified by the reciprocal value of the radius of the corresponding hypothetical circle:

$$k(x_0) = \frac{1}{r(x)}$$

$k(x_0)$ can be derived by means of differential calculus (15).

Using the curvature function $k(x) = \frac{\frac{d^2y(x)}{dx^2}}{\left[1+\left(\frac{d}{dx}y(x)\right)^2\right]^{\frac{3}{2}}}$ a specific curvature value $k(x)$ is assigned to each curve point P (x,y).

Before analytical methods can be used to investigate root canal curvature, a mathematical model of the configuration of the curve has to be produced for the inner (small) curve and the outer (large) curve. The actual configuration of the canal wall is described by specifying x,y coordinates of selected measuring points. Using this point sequence, an equalising function describing the configuration in mathematical terms can be determined. The quality of the adaptation of the equalising function to the point sequence is described by the so-called degree of accuracy (correlation coefficient). The less this dimension deviates from 1, the better the adaptation.

Use of the equalising function adapted to the configuration of the long axis of the canal permits exact determination of the curvature for each point x and for the point of maximum curvature, as well as the mean curvature of the measured canal section. In the formula used, the configuration ascertained for the curve is designated $y(x)$, and the pertinent curvature function $k(x)$.

The distance of the point of maximum curvature from the apical foramen can also be calculated by means of the

Table 3 Instruments and working sequence in rotary shaping technique

	Instrument	Sequence
Pre-flare	Gates Glidden burs	Sizes 110; 90; 70
Crown-down (to working length)	FlexMaster® or Profile® Ni-Ti files	Sizes 30/0.06 taper; 25/0.06; 20/0.06; 30/0.04; 25/0.04; 20/0.04
Apical preparation (18 mm)	FlexMaster® Ni-Ti files	Sizes 20/0.02 taper; 25/0.02; 30/0.02; 30/0.04, 35/0.02; 35/0.04
Apical preparation (18 mm)	Profile® Ni-Ti files	Sizes 15/0.04 taper; 20/0.04; 30/0.04; 35/0.04

arc length $b = \int_{x_1}^{x_2} \sqrt{1 + \left(\frac{dy}{dx}\right)^2} dx$, with x_1 and x_2 signifying the x-coordinates of apex and maximum curvature.

The mean curvature over an interval $[x_1, x_2]$ is calculated with the formula

$$\frac{1}{x_2 - x_1} \int_{x_1}^{x_2} k(x)dx.$$

Image processing and evaluation

Using Photoshop 5.5 image processing software (Adobe Systems Inc. San Jose, USA), the images were calibrated by means of the plotting paper located in the background.

Using a purpose-developed program for digital image scanning, the coordinates of the canal wall configuration of the large and small curve were determined before and after preparation by registering points on the canal wall at intervals of approximately 0.5 mm. Each point marked in the image was stored automatically in a file with its coordinates. During the scanning of a simulated root canal, only the lower two-thirds of the canal, which had been prepared with files, (12.5 mm from the apical foramen upwards) were taken into account. The top third of the canal, which had been prepared with Gates Glidden drills, was not included.

Using EXCEL® software (Microsoft, Redmond, USA), the point sequence determined by the configuration of the canal wall was displayed in graphic form. An appropriate type of function for the trend line (equalising function) was selected using third-degree polynomial functions, as these offered the greatest reproducibility. The selected polynomial function was automatically displayed in graphic form, with the functional equation and the correlation coefficient being specified.

Further mathematical calculations were performed with a computer-algebra system (Derive®, TI Inc., Denver, USA). The curvature function $k(x)$ and the maximum and mean curvature of the selected curvature morphology were subsequently determined by this means and displayed in graphic form (Figs 2–4). To make the calculated curvature values comprehensible in clinical terms, the reciprocal value that expressed the radius in millimetres was formed. Changes in curvature are referred to below as changes in radius.

The length of the arc from the apex to the point of maximum curvature before and after preparation was calculated separately for each curve.

Statistical analysis

Statistical analysis of the collected data and production of the graphics were performed with SPSS 11.0 statistics software (SPSS, Inc., Chicago, USA). Statistical tests designed to reveal significant differences were renounced on account of the small number of cases. Median values and the 1st and 3rd quartile of the collected data were represented.

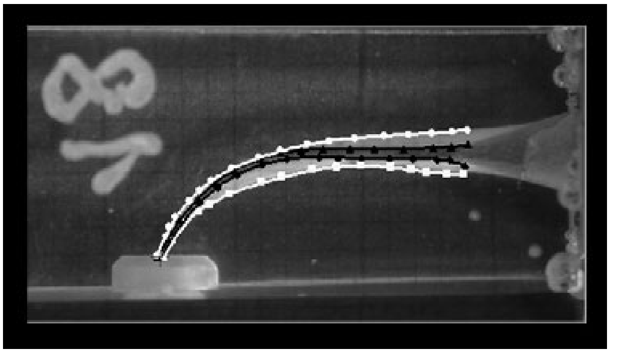

Figure 2 Superimposed images of a root canal before and after instrumentation with stainless steel files. Dark lines, canal prior to preparation; light lines, canal after preparation.

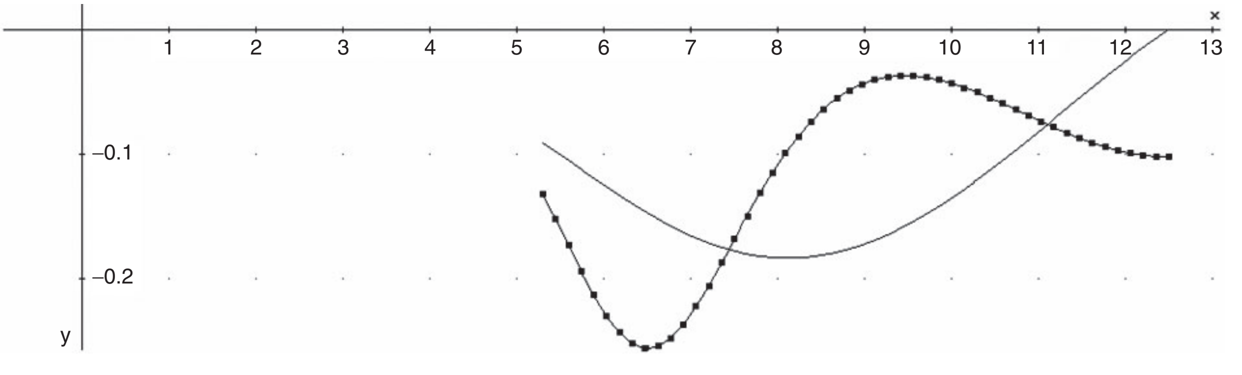

Figure 3 Curvature of the inner curve of the canal from Figure 2. Continuous line, curvature before preparation; dotted line, curvature after preparation. The point of maximum curvature was transported further around the apex through the instrumentation.

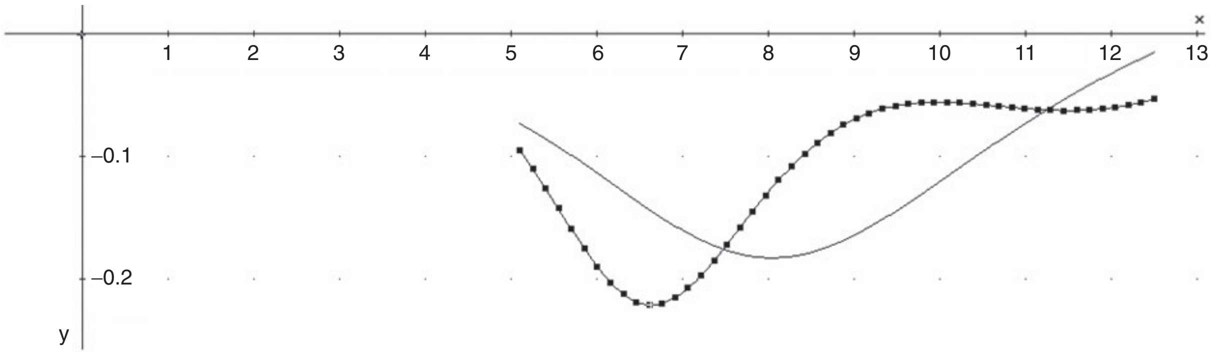

Figure 4 Curvature of the outer curve of the canal shown in Figure 2. Continuous line, curvature before preparation; dotted line, curvature after preparation. The increase in curvature is reflected in the greater distance of the point of maximum curvature from the X-axis.

Table 4 Accuracy (correlation coefficient) of the small and large curve before and after root canal instrumentation

	Median value	1st quartile	3rd quartile
Small curve before preparation	0.999808	0.999839	0.999693
Small curve after preparation	0.999730	0.999885	0.999520
Large curve before preparation	0.999803	0.999895	0.999760
Large curve after preparation	0.999038	0.999703	0.997229

Results

Correlation coefficient

The degree of accuracy (correlation coefficient) was calculated for each curve as a measure of the adaptation quality of the selected regression approach. The median value of all curves was 0.999767, with the lowest value found to be 0.995343 and the highest value 0.999970. The values for the individual curvatures before and after preparation are shown in Table 4.

Intra-examiner reliability

Intra-examiner reliability was verified by having the outer and the inner curve measured twice in the Profile® instrument group by one examiner at an interval of 14 days. The aim was to compare the reliability of the results measured for the radius of the maximum curvature. Comparison of the 20 individual values revealed an agreement rate of 90%. The kappa value was 0.849 (Table 5).

Inter-examiner reliability

Inter-examiner reliability was verified by having the outer and the inner curve measured in the Profile® instrument group by two different examiners. To allow the kappa test to be performed, categories of 0.5 mm each, into which the measured results were classified, were formed for the radius. Comparison of the 20 individual values revealed an agreement rate of 85%. The kappa value was 0.755 (Table 6). The presented method is thus capable of reproducibly determining the radius of the maximum curvature of a root canal to the nearest 0.5 mm.

Change in maximum curvature

Examination of the results of preparation revealed that the radius of the small curve increased most markedly, from 5.8 to 4.8 mm, when preparation was performed by hand with stainless steel files. The least change in curvature was registered when the FlexMaster® system was used (radius –0.3 mm).

The outer canal wall underwent the least preparation-induced increase in curvature when instrumentation was performed with the Profile® system (radius –0.9 mm). The most pronounced increase in curvature was recorded when preparation was done by hand with Ni-Ti files (radius –2.0 mm) (Tables 7,8; Figs 5,6).

Arc length to point of maximum curvature

The point of maximum curvature of both the small and the large curve was found to be transported from coronal to apical as a result of the root canal preparation. In each case, the distance from the apical foramen to the point of maximum curvature was calculated in millimetres. In the small curve, the point was transported most markedly in canals prepared with manual stainless steel files (1.5 mm) and least markedly in canals prepared with manual Ni-Ti files and with Profile® instruments (0.3 mm).

In the large curve, the point was transported most markedly through manual preparation with Ni-Ti files

Table 5 Intra-examiner agreement for the radius of the maximum root curvature (mm) in the Profile® instrument group (% agreement: 90; kappa: 0.849)

	2nd Examination				
1st Examination	4.0–4.49 mm	4.5–4.99 mm	5.0–5.49 mm	5.5–5.99 mm	Totals
4.0–4.49 mm	0	1	0	0	1
4.5–4.99 mm	0	5	1	0	6
5.0–5.49 mm	0	0	8	0	8
5.5–5.99 mm	0	0	0	5	5
Totals	0	6	9	5	20

Table 6 Inter-examiner agreement for the radius of the maximum root curvature (mm) in the Profile® Instrument group (% agreement: 85; kappa: 0.755)

	2nd Examiner				
1st examiner	4.0–4.49 mm	4.5–4.99 mm	5.0–5.49 mm	5.5–5.99 mm	Totals
4.0–4.49 mm	0	0	0	0	0
4.5–4.99 mm	1	4	0	0	5
5.0–5.49 mm	0	0	10	0	10
5.5–5.99 mm	0	0	2	3	5
Totals	1	4	12	3	20

Table 7 Curvature radii of both curves (mm) before and after manual preparation; arc lengths (mm) to point of maximum curvature before and after manual preparation

	Hand Ni-Ti before preparation	Hand Ni-Ti after preparation	Hand SS before preparation	Hand SS after preparation
Max. curvature, small curve	5.8	4.8	5.5	4.4
Max. curvature, large curve	5.8	3.8	5.6	4.0
Mean curvature, small curve	8.3	8.7	8.1	8.5
Mean curvature, large curve	8.7	8.5	8.5	9.0
Arc length, small curve	4.2	3.9	4.1	2.6
Arc length, large curve	4.4	3.4	4.1	3.3

Table 8 Curvature radii of both curves (mm) before and after rotary preparation; arc lengths (mm) to point of maximum curvature before and after rotary preparation

	FlexMaster® before preparation	FlexMaster® after preparation	Profile® before preparation	Profile® after preparation
Max curvature, small curve	5.4	5.1	5.5	5.0
Max. curvature, large curve	5.5	4.5	5.8	4.9
Mean curvature, small curve	8.0	8.1	8.2	8.3
Mean curvature, large curve	8.1	9.0	8.4	8.5
Arc length, small curve	4.0	2.8	4.2	3.9
Arc length, large curve	3.6	3.3	4.2	3.9

(1.0 mm), and least through rotary preparation (0.3 mm in each case) (Tables 7,8; Figs 7,8).

Change in mean curvature

At the small curve, a preparation-induced decrease in mean curvature was recorded with all systems. Preparation with rotary instruments resulted in a smaller decrease in curvature (radius +0.1 mm) than with hand instruments (radius +0.4 mm).

At the large curve, the mean curvature increased through instrumentation with Ni-Ti hand files (radius –0.2 mm) but decreased through instrumentation with the other systems (Tables 7,8; Figs 9,10).

Discussion

In the present investigation, the inner and outer canal curvature was measured in a system of coordinates before and after root canal preparation. The curves were mea-

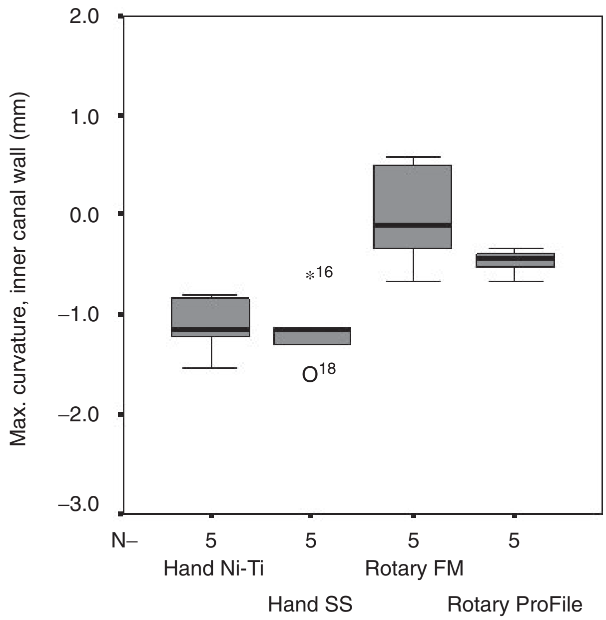

Figure 5 Preparation-induced change in the radius of the maximum curvature of the inner curve.

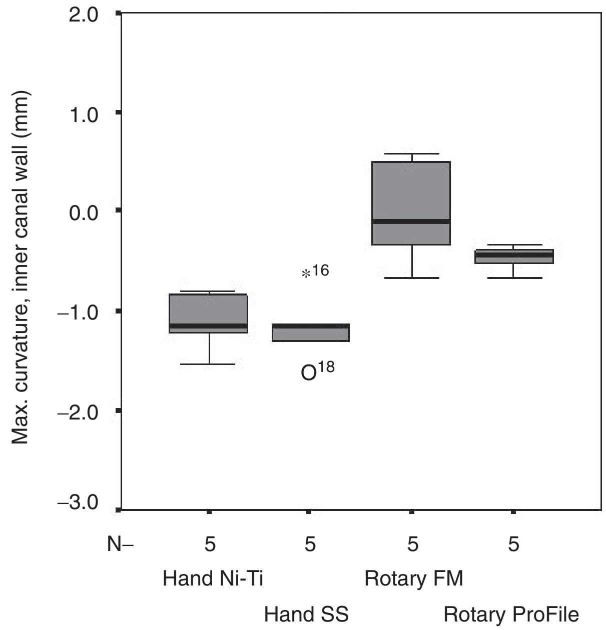

Figure 7 Change in arc length from the apical foramen to the point of maximum curvature of the inner curve in millimetres.

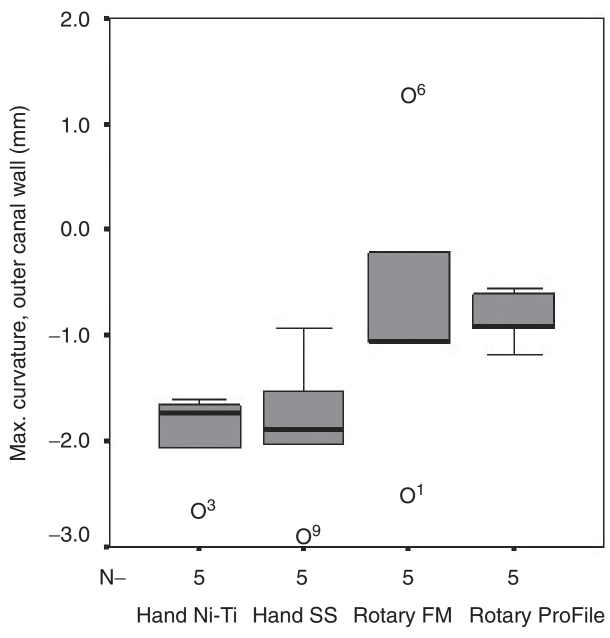

Figure 6 Preparation-induced change in the radius of the maximum curvature of the outer curve.

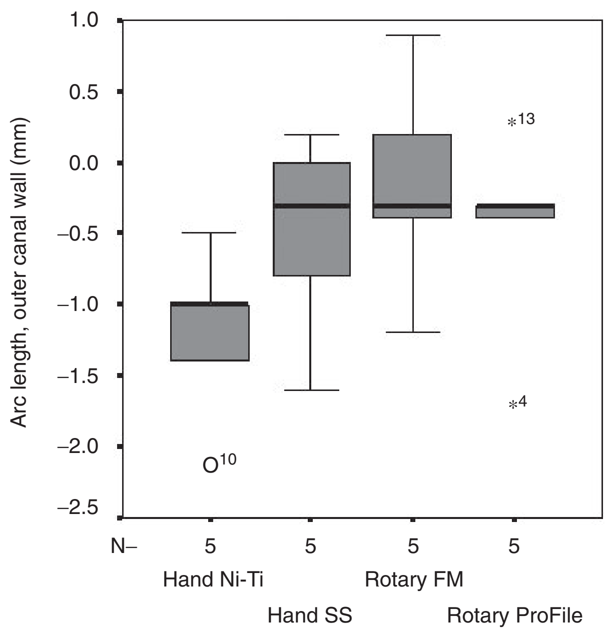

Figure 8 Change in arc length from the apical foramen to the point of maximum curvature of the outer curve in millimetres.

sured separately, as the amount of material removed from the inner and outer curve during preparation is known to differ (1,16).

The change in curvature was determined and the point of maximum curvature in the long axis of the canal was calculated. The preparation-induced change in curvature of the imaginary midline of the canal has been investigated by numerous authors. As the methods used for measuring changes in curvature vary substantially, comparison is problematic. The frequently quoted degree

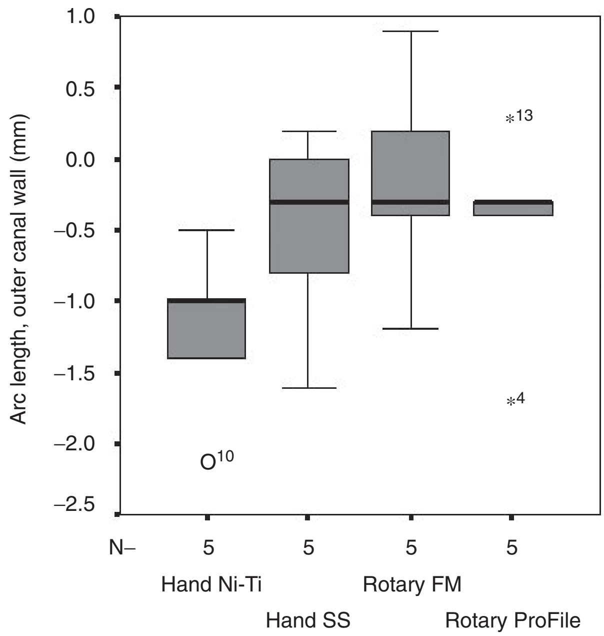

Figure 9 Preparation-induced change in the radius of the mean curvature of the inner curve in millimetres.

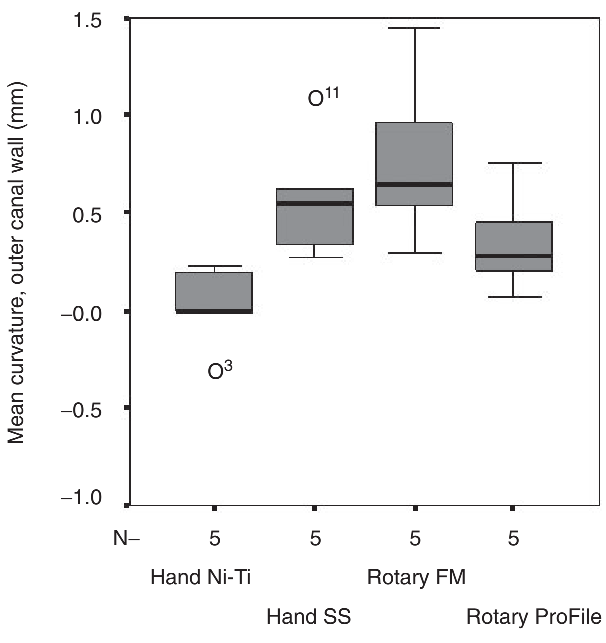

Figure 10 Preparation-induced change in the radius of the mean curvature of the outer curve in millimetres.

of curvature according to Schneider (6) describes an angle (that is, a change of direction) but not a curvature in the mathematical sense. Luiten *et al.* (17) recorded canal curvature straightening by 8° to 13°, depending on the instrumentation method, in measurements from the canal orifice to the apex, using a modification of the method presented by Schneider (6). Using a comparable measuring method, Pettiette *et al.* (18) recorded instrumentation-induced straightening of 14° by stainless steel files and of 5° by Ni-Ti hand files. Cunningham and Senia (7) registered a mean straightening by between 5° and 9° in the curvature of root canals prepared with rotary files. Here too, graphic evaluation was performed with reference to Schneider. The fact that Schneider's measuring method is unsuitable for the differentiated assessment of changes in curvature is demonstrated in particular in the publication by Southard *et al.* (19). When using Schneider's method to measure the change in curvature induced by rotary instrumentation, a difference of up to 5° between the measurements recorded by the two investigators was still referred to as tolerable (19).

Using a method taking into account the curvature angle and the curvature radius, Schafer and Lohmann (12) reported straightening by 2° in root canal curvature for instrumentation with rotary Ni-Ti files, and by 7° with stainless steel hand files.

The first authors to describe root curvature in mathematically correct terms were Nagy *et al.* (8), who used a fourth-degree polynomial function. Fourth-degree function approximation as a method for describing the shape of root canal curvatures seems to be exact and reliably repeatable. However, this method has so far failed to assert itself as a means of determining either root curvatures or changes in root curvature. The method selected by us focuses on the canal walls instead of the centre of the long axis of the canal. In our method, third-degree polynomial functions were used. The lower the polynomial degree, the fewer curvature points the function has. A third-degree function has no more than two extremes, whereas a sixth-degree function may have up to five extremes. In addition, higher-degree polynomial functions respond far more sensitively to minimal deviations during determination of the coordinates of the curvature configuration. The exponent, x^6, with a sixth-degree function, is raised even if deviations between the coordinates are given between two measuring sessions.

Subject to an adequate degree of accuracy, polynomial functions of the lowest degree possible should be selected for curvature determination in order to ensure good reproducibility. The high degree of accuracy recorded by us shows that a root canal curvature can be described with adequate precision by a third-degree function.

In this process, we found that the different instrumentation systems led to different rates of material removal at the two curves. Our results indicate that the change in curvature at the small curve does not correlate with that at the large curve. This suggests that it is advisable to assess the two curves separately in a two-dimensional image.

In investigations of root canal preparation with four different instrumentation systems, Peters *et al.* (11) recorded a mean canal straightening of 4.68% ± 18.22%. Evaluation by means of micro-computed tomography revealed a partial increase in canal curvature as a result of the instrumentation. In that study, root canals were prepared with Ni-Ti K-files, Lightspeed instruments, and Profile 0.04 and GT rotary instruments by two experienced operators.

In our study involving relatively inexperienced operators, the maximum curvature of both canal walls underwent an instrumentation-induced increase with all four systems investigated. With all instrumentation systems, the curvature of the outer curve increased more than that of the inner curve. The least change in maximum curvature was recorded when using the Profile® system. Various studies by other authors confirm that this passive root canal preparation system ensures good centreing in the long axis of the canal on account of its cutting geometry (20,21). In addition to the increase in maximum curvature, the point of maximum curvature was transported apically as a result of the preparation. While the transportation of this point measured only 0.2 to 0.4 mm with rotary instrumentation, it was more marked at up to 1.8 mm after manual preparation.

The mean curvature underwent an instrumentation-induced decrease at both curves with almost all systems investigated. The only exception was the large curve after preparation with Ni-Ti hand files.

The increase in maximum curvature recorded in our study is due in part to the lack of experience on the part of the operators. With rotary instrumentation, for example, an increase at individual points in the long axis of the root canal is readily produced through frequent recapitulation or through a long rotation time in the canal. In the case of manual preparation with stainless steel files, inadequate pre-bending or inexpert file movement is likely.

The recorded results also indicate changed conditions for the root filling. An increase in maximum curvature and transportation of the point of maximum curvature to apical may impede three-dimensional obturation of the canal system. A less efficient seal was shown to be provided by the cold condensation technique compared with the warm gutta-percha techniques with Schneider angles of more than 25° or 20° respectively (22,23).

Conclusions

The presented method enables instrumentation-induced changes in the curvature of the small and large curve to be precisely described. In view of the good reproducibility of the measurements, the method can provide more valid results than can be obtained with data expressed in angles. The method is thus a suitable means of verifying canal curvature retention after root canal instrumentation.

Further radiographic investigations are needed to confirm the applicability of this method to clinical investigations.

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