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Analysis of forces developed during root canal preparation with the balanced force technique

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Summary

The aim of this study was to examine the forces and torque developed during root canal preparation with the balanced force technique using a recently described force-analyser device. A tooth was placed in a holder within the Endograph and forces and torques exerted were recorded. These parameters, which can be studied during preparation (on-line) or stored and examinated subsequently (off-line) generated endograms, which showed the forces generated with time. In addition, the endograms of preparations performed by students and endodontists, as well as deliberately induced failures in preparation technique (broken instruments), were compared. The values for the forces and torques depended on the size of the instruments and were related to the phase of the preparation. For the endodontists, the vertical and horizontal forces varied, respectively, from 0.08 ± 0.01 kg for a size 15 to 0.65 ± 0.10 kg for a size 45, and from 0.01 ± 0.005 kg for a size 15 to 0.4 ± 0.1 kg for a size 40. The torque varied from 0.08 ± 1 kg mm^{-1} for a size 15 to 1.6 ± 0.4 kg mm^{-1} for a size 45. With the Endograms used as a reference, the relation between the developed vertical forces and the torque became more similar between the groups of endodontists and students. The Endograph provides a new approach to the analysis of preparation technique because it depicts the relationships between the different parameters of the preparation.

***Keywords*: balanced force technique, force, torque, transducer.**

Introduction

The aim of root canal obturation is to achieve a fluid-tight seal of the root canal system in order to prevent periapical infection. The root canal system can be obturated with gutta percha but this material alone does not ensure a hermetic seal (Schilder 1974) and a sealer must also be used, combined with adequate preparation of the root canal system (Ingle 1961, Allison *et al.* 1979, Abou-Rass *et al.* 1980). Although each preparation method employs different techniques and instruments, the fundamental goals are the same: to clean the root canal system, to maintain original root canal anatomy and to provide a suitable shape for adequate obturation (Ingle 1961, Schilder 1974, Allison *et al.* 1979, Abou-Rass *et al.* 1980, Goerig *et al.* 1982).

Several hand preparation techniques provide adequate preparation of the root canal system. Ingle (1961) introduced the standardized technique and Schilder (1974), the serial preparation technique (1976). Marshall & Pappin (1980) described the crown-down pressureless techniques, which first addressed specifically the preparation of the coronal part of the root canal, with passive apical progression. For canals presenting specific difficulties, such as the mesial canals of mandibular molars, Abou-Rass *et al.* (1980) advocated the anticurvature filling method and Goerig *et al.* (1982) described the step-down technique, which divides the root canal instrumentation into coronal and radicular access.

The balanced force technique was described by Roane and colleagues (Roane & Sabala 1984, Roane *et al.* 1985, Sabala *et al.* 1988) and is derived from the physical law that states that for every action there is an equal and opposite reaction. Cutting is accomplished using a counter clockwise rotation and inward pressure adjusted to match the file's strength, that is, very light for small instruments and heavy for very large instruments (Roane & Sabala 1984, Roane *et al.* 1985).

Two recent publications described a new device, the Endograph, developed for the immediate subsequent study of forces exerted in root canal preparation (Blum *et al.* 1997a,b). The clinical sequences are plotted on graphs, or endograms, which depict the developed forces with time. When used in root canal preparation, the

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endograms not only detail the force variations, but are also able to show failures (revealed on the graphs by characteristic curves). To date, the Endograph has been used with a monoblock holder without transducers fixed on it, and thus only the vertical and horizontal forces for obturation have been analysed. In order to measure the torque induced during the different phases of the balanced force preparation, the design of the holder has been changed and a transducer added.

The aim of the present study was to analyse the forces and torques developed by the balanced force technique (BFT) as depicted by endograms.

Material and methods

The computerized recording system was developed in collaboration with INSERM (Unit 103, Montpellier, France) (Blum *et al.* 1997a,b). The main components were three transducers (Captels, St Mathieu de Treviers, France), electronic amplifiers, analogue–digital converters, a PC-compatible computer and data acquisition software (LAPS, INSERM, Unit 103, Montpellier, France). The force analyser device was composed of two perpendicularly linked transducers for the measurement of horizontal and vertical forces (Fig. 1, parts 1 and 2) (Blum *et al.* 1997a, 1997b). A new cupule (Fig. 1, part 4), equipped with two torque transducers (Fig. 1, part 3), was connected and fixed onto the bar arm holding the force transducers. The holder was machined from an aluminium cylinder so that its sensitive part, which will be deformed by torque action, had a thickness of 0.002 mm and a length of 13 mm (Fig. 2). A 45° Wheatstone bridge was then attached to it (Fig. 2). The steps for measuring were as follows: first, the electrical gain of amplification was set at 1000 in order to obtain a voltage range between a –2.5 V to +2.5 V. Signals were then digitized by an analogue–digital converter connected to the RS232 port of the PC. The sample frequency of the inputs was 800 Hz. The frequency acquisition varied from 10 Hz (low acquisition frequency) to 250 Hz (high acquisition frequency). Thus different aspects of preparation were studied. With low frequency the entire preparation was studied, while with high frequency only the work of one instrument was stored.

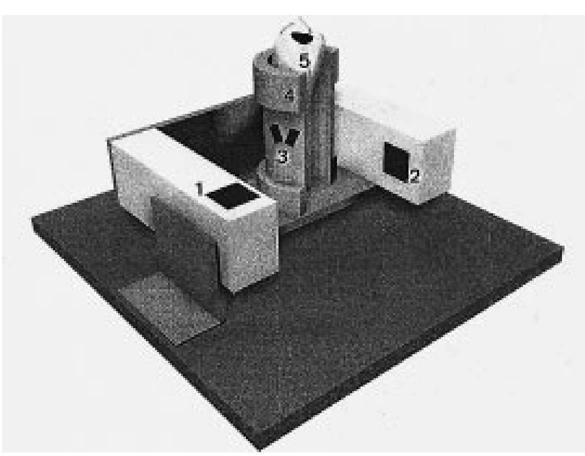

Fig. 1 Front view of the Endograph: (1) vertical transducer, (2) horizontal transducer, (3) torque tranducers, (4) holder in which the tooth (5) was embedded.

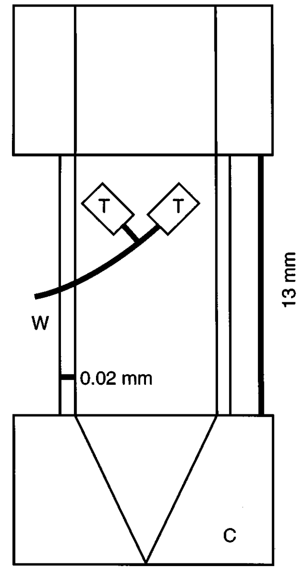

Fig. 2 Diagram of the specimen holder designed to store torque values. The low wall of the sensitive part of the holder is 0.02 mm thin (C). The two transducers (T) forming an angle of 45° to the vertical line to the Wheatstone bridge (W).

The main frame of the LAPS software provided access to the following principal functions.

- Configuration: selection of the port (COM 1 or COM 2) on the computer and the Baud rate transmission (9600 to 110 K Bauds).
- Identification: identification of the channels to be acquired: number, names, frequency of the sampling, duration of the acquisition.
- Acquisition: three modes possible: store and visualize, store without visualizing, and numerical storage.
- Disk access: for saving and loading data.
- Visualization: display of a graph as a function of time.
- Oscilloscope: on-line visualization of the data without storage.
- Transfer to Excel: for exportation of the LAPS files to a spreadsheet.

The preparation was considered to start at the first instrumental force impact on the Endograph, and to finish at the last. The difference between these time values, measured directly on the endograms, provided the duration of the entire preparation; it was also possible to record the duration of the individual instrument sequences, which were labelled elementary sequences. To measure the different values of force or torque for each preparation, the endogram (Fig. 3a) was generated initially. The start and finish times of each elementary sequence were noted from the low frequency acquisitions on the graph (Fig. 3a, b; sequences for sizes 15, 20, 25, 30). The transition phases during which no forces or torques were exerted, such as instrument change or cleaning, were then eliminated for the calculation of the mean values of force and torque. For the torque, the mean values of the clockwise and counterclockwise rotations were obtained separately. These calculations were performed for each elementary sequence of each preparation.

Nitiflex files (Maillefer, Ballaigues, Switzerland) with sizes ranging from size 15 to size 45 and K files (Maillefer, Ballaigues, Switzerland) with sizes 08 or 10, were used in this study. The use of each instrument followed the

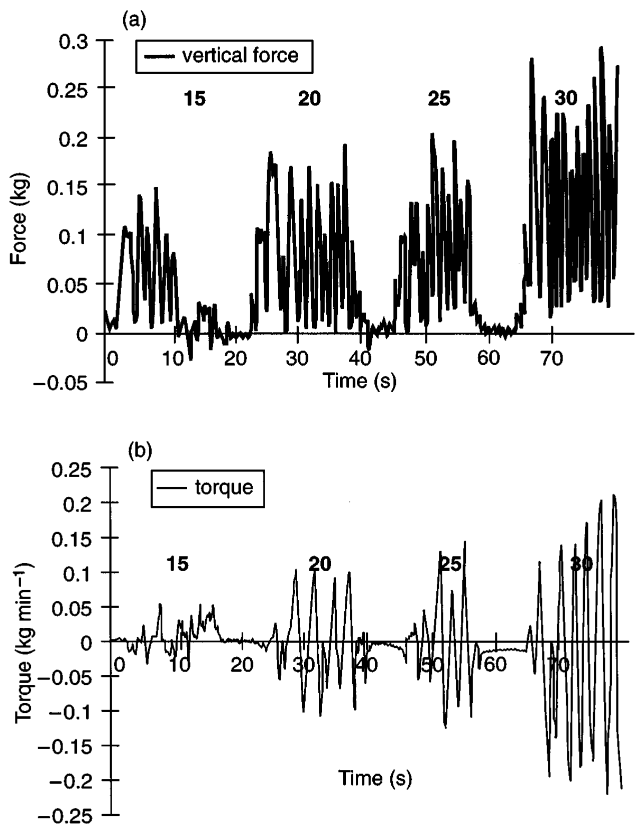

Fig. 3 Typical endograms generated by the BFT preparation performed by an endodontist. Line represents the gauge tracing over time (a) Vertical forces. (b) Torque. The numbers indicate the ISO sizes of the instruments. Frequency of recording was 10 Hz.

steps described by Roane *et al.* (1985). During all instrumentation the irrigant used was sterile water to avoid damage to the transducers and the specimen holder was protected by a rubber dam fixed onto the tooth.

One hundred freshly extracted mandibulary incisors were used in this study. They were similar in length and not curved. Cusp tips were flattened to simplify measurement of root canal length, and standard root canal access preparation was undertaken on each tooth. A size 08 or 10 K-file was passed through the apical foramen to demonstrate canal patency. Orifice enlargement, with the use of Gates–Glidden drills (Maillefer, Ballaigues, Switzerland), improved access to the apical aspect of the canal as described by Roane *et al.* (1985).

Canal instrumentation was performed by10 operators (five endodontists, five students), using the BFT to each prepare 10 teeth. All files were used with clockwise rotation until slight torque was felt as the cutting edges engaged the canal wall. The file was then rotated anticlockwise for 180° while maintaining apical pressure. This combination of rotational file movement was continued until the working length, measured length of the tooth, was reached. Apical patency was maintained with a size 08 file. Canals were irrigated with 1 ml of sterile water after each file use. All the files were used at the working length. The choice of teeth to be used by a specific operator was made randomly.

For five other teeth, the size 35 NiTi was inserted, before canal enlargement, until it fractured, even if this fracture happened after the instrument was forced into the canal. The choice of tooth-practitioner was random.

All the results were analysed with ANOVAs. Significance was fixed at $P < 0.05$. When the ANOVA F was significant, a contrast method (Duncan's test) was applied. For the endodontists' preparations, a two way ANOVA was first perfomed using the successive preparations (at ten levels) and the resolution forces and torques (at three levels).

Results

The BFT-generated characteristic graphs or endograms are shown in Figs 3a,b, 4, 5, 6, 7 and 8. The differences in the forces or torque developed among the individual endodontists (practitioners) were not significant ($P > 0.05$). The vertical and horizontal forces varied from 0.08 ± 0.01 kg for a size 15 file to 0.65 ± 0.10 kg for a size 45 file and from 0.01 ±0.005 kg for a size 15 file to 0.4 ± 0.1kg for a size 45 file, respectively. The torque varied from 0.08 ± 0.02 kg mm for a size 15 file to 1.6 ± 0.4 kg mm^{-1} for a size 45 file (Figs 9, 10, 11).

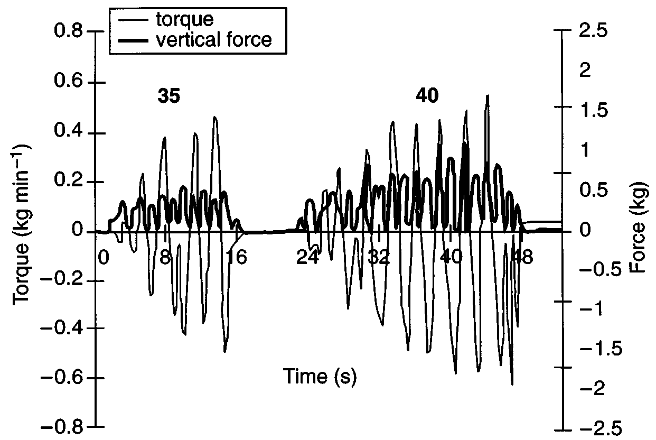

Fig. 4 Comparison using endograms generated by the BFT preparation performed by an endodontist. The graph compares the vertical forces and the torques over time. The numbers indicate the size of the instruments (35 and 40). Frequency of recording was 50 Hz.

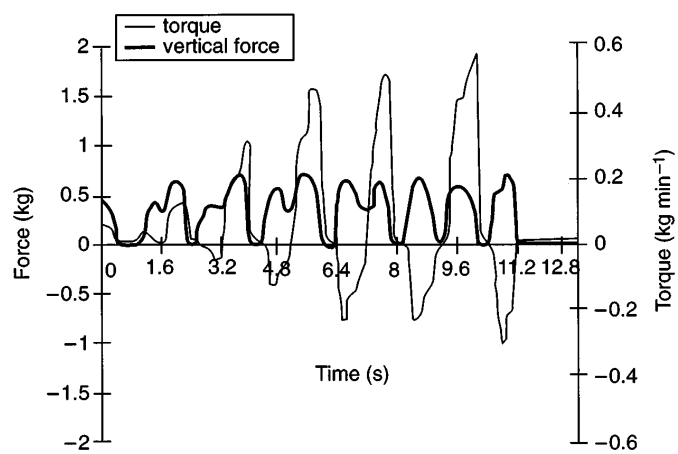

Fig. 5 Comparison using endograms generated by the BFT preparation performed by an endodontist. The graph compares the vertical forces and the torques over time. The size of the instrument was ISO size 30. Frequency of recording was 100 Hz.

Indeed, the forces and the torques induced by each instrument varied but remained within a similar range of values (Fig. 12). A twoway ANOVA using the successive preparations (at ten levels) and the resolution forces and torque (at three levels) was then performed for the students. For each instrument, except the size 15 file, the range of values different significantly among them for the first seven sessions ($F = 14.3$, $P < 0.05$) but was not significantly different for the last three ($P > 0.05$). Finally, a twoway ANOVA using the mean values of the endodontists' sessions, the mean values of the students' last three sessions (at two levels) and the resolution forces (at three levels) was performed. For each instrument except the size 20 file the differences between the two groups were significant ($F = 14.2$, $P < 0.05$) (Tables 1, 2 and 3). The overall appearance of the endograms of the endodontists (Figs 3a, b, 4 and 5) was more regular than that of the students' (Figs 7 and 8). At the beginning of the the experiment, the appearance of vertical forces in relation to the torque was very different between the student group (Fig. 7) and the endodontists (Figs 5 and 6). After repeated trials using the Endograph as an on-line and off-line reference, the visual appearance of the forces became more similar (Fig. 8). For the

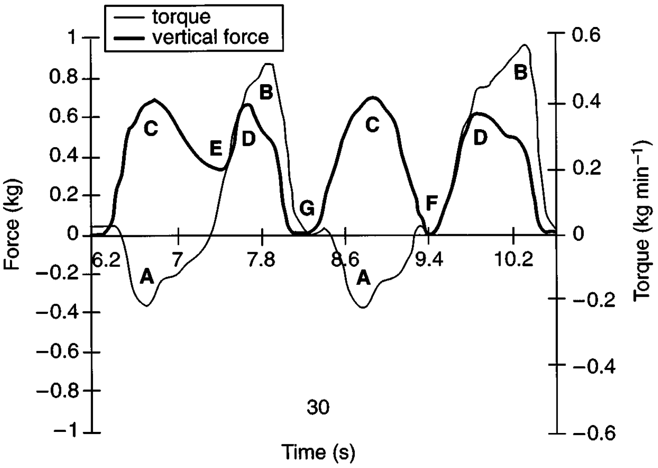

Fig. 6 Detail of endograms in Fig. 5. The graph compares the vertical forces and the torque with time. The instrument was ISO size 30. Frequency of recording was 100 Hz. (a) Clockwise torque, (b) anticlockwise torque, (c) clockwise screwing vertical force, (d) anticlockwise screwing vertical force, (e) transition between clockwise and anticlockwise torque without lack of vertical forces, (f) transition between clockwise and anticlockwise torque with lack of vertical forces, (g) transition between anticlockwise and clockwise torque with lack of vertical forces.

induced failures, with deliberate breaking of an instrument, the Endograph generated characteristic endograms (Fig. 13).

Discussion

The Endograph allowed the storage of forces and torque developed during preparation with the balanced force technique. Graphs, or endograms, were then generated, which permitted the analysis of the vertical and horizontal forces and the torque developed by this technique (Figs 3–8).

The Endograph is based on Newton's third law of action–reaction. The developed forces, as with all

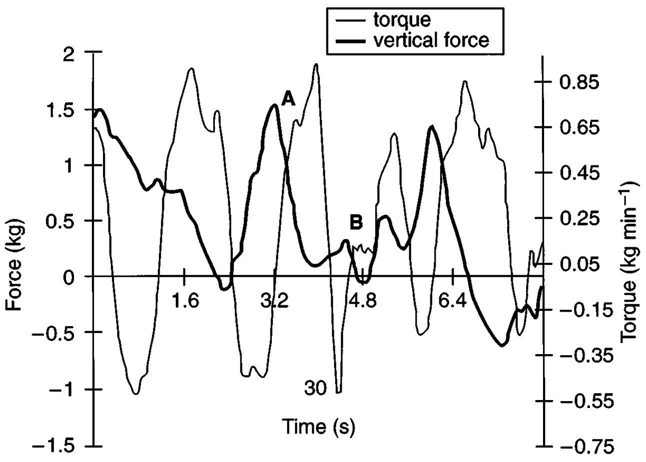

Fig. 7 Detail of endograms generated by the first BFT preparation performed by a student. The graph compares the vertical forces and the torque with time. The instrument size was ISO size 30. The forces are not applied synchronously. (a) The vertical force was applied before anticlockwise torque. (b) The anticlockwise torque was applied without developed vertical force. Frequency of recording was 100 Hz.

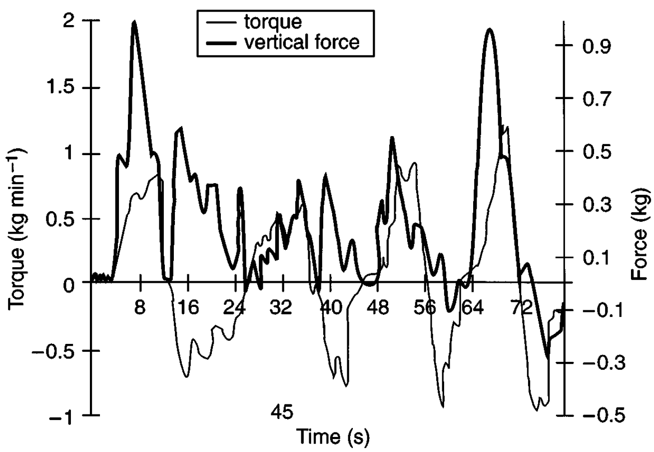

Fig. 8 Typical comparison of endograms generated by the BFT preparation performed by a student, after five attemps with the Endograph. The graph compares the vertical forces and the torque with time. The instrument size was ISO size 45. The forces are applied synchronously in relation to the torque. Frequency of recording was 100 Hz.

physical forces, may be represented by vectors. If the action of the force being applied is the only action, acceleration occurs and the object is moved (Fig. 14). A force applied to an object will deform it only if a reaction force, with the same intensity and duration (same start and finish time) but applied in the opposite direction, is applied simultaneously to the same point (Fig. 14). In the case of the Endograph, the tooth was fixed (no movement) and, in accordance with the physical principles of the action–reaction law, the transducers stored the developed forces. An earlier publication has described the limitation of the endograph in measuring horizontal forces applied simultaneously in opposite directions (Blum *et al.* 1997a,b). Indeed, although the Endograph stores all the vertical forces, it is only able to store the external horizontal force or the imbalance of intracanal horizontal forces applied simultaneously in opposite directions. In similar fashion, the torque may be represented by a vector that is perpendicular to the plane in which the torsional movement is developed (Figs 15 and 16). The position of the transducers is such that if the torque (T) was developed in a horizontal plane, the Endograph stored the entire developed torque by measuring its vertical vector (V) (Fig. 15). If the torque (T) was not developed in the horizontal plane, because of the canal anatomy, the Endograph stored only the pro-

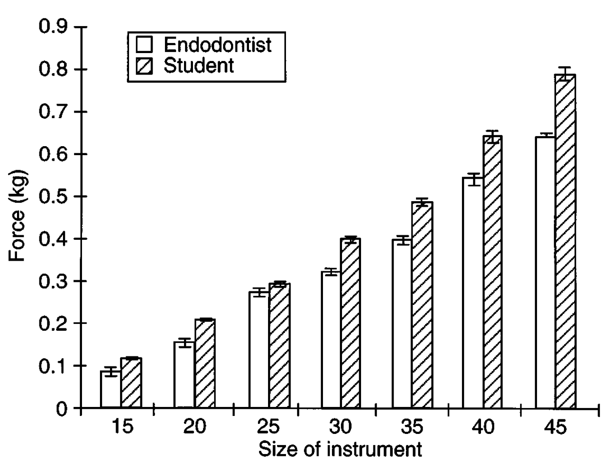

Fig. 9 Mean values (with standard errors) or vertical forces exerted by students and endodontists for the BFT.

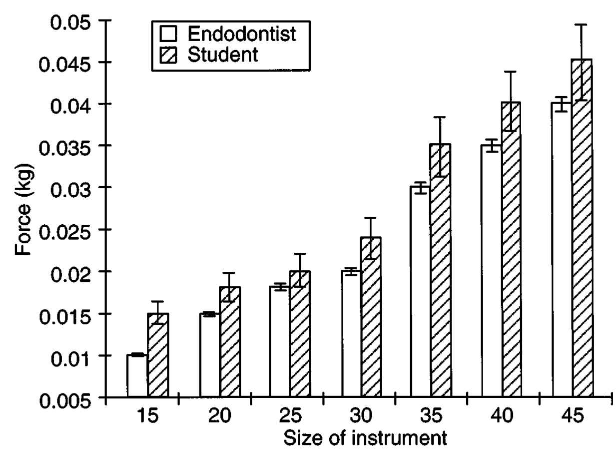

Fig. 10 Mean values (with standard errors) or horizontal forces exerted by students and endodontists for the BFT.

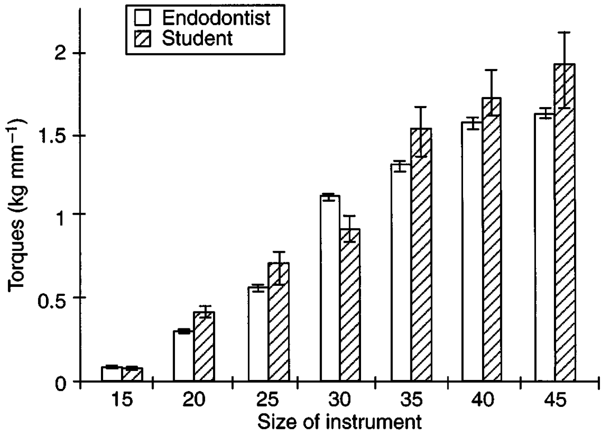

Fig. 11 Mean values (with standard errors) of torque exerted by students and endodontists for the BFT.

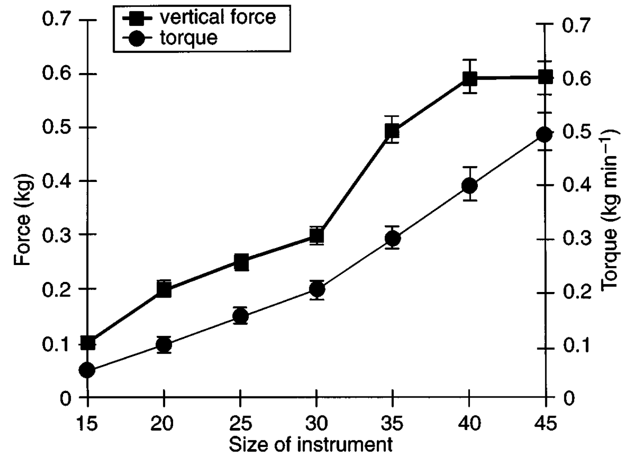

Fig. 12 Relation between the vertical forces and torque induced by each instrument used by the endodontists.

jection(V′) of the torque vector (V) on the vertical axis (Fig. 16). Thus a part of the torque value may have been lost. To minimize this limitation, teeth were chosen for the experiments with the straightest canals possible and were fixed with special care to be as vertical as possible.

The BFT is performed with the use of successive instruments to enlarge the canal. Each instrument is first screwed into the canal with a clockwise movement. Then, under apical-directed pressure, a counterclockwise movement at the same length cuts the dentine (Figs 3 a,b and 4). The efficiency and efficacy of the technique appears to be related to a nonstandardizable variable, the amount of apical loading applied to the file by each individual clinician (Kyomen *et al.* 1994). This nonstandardizable variable is precisely what the Endograph measures, in addition to horizontal forces and torque (Figs 3, 4 and 5). Moreover, as the analysis can be dissociated from the actual preparation, and thus is independent of time, the device can be used to study the preparation process: (i) with low storage frequency, so that the progression of instrument use and the entire preparation may be analysed (Fig. 3a,b); (ii) with medium storage frequency, in which case the Endograph can make precise comparisons among instruments (Fig. 4); and (iii) with high storage frequency, to analyse precisely the work of one instrument, termed the elementary sequence (Figs 5 and 6). In this study, the endograms were used primarily to analyse and then describe and analyse the insertion and cutting action of the instruments as handled by experienced endodontists and students.

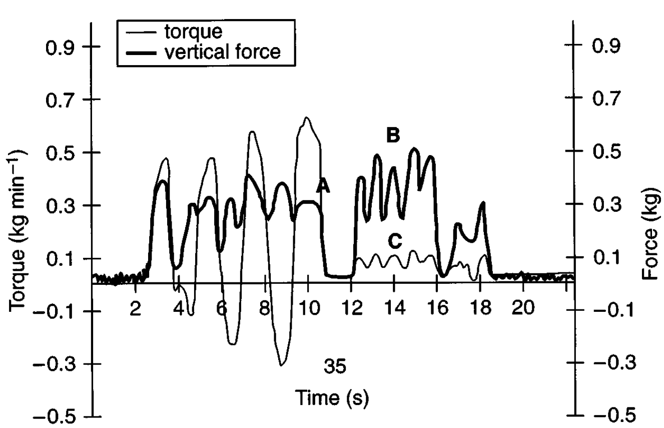

Fig. 13 Comparison of endograms generated by the BFT preparation during instrument fracture. The graph compares the vertical forces and torque with time. The instrument was ISO size 35. Frequency of recording was 20 Hz. (a) Fracture, (b) increase in the vertical forces after fracture, (c) lack of increase in torque after fracture.

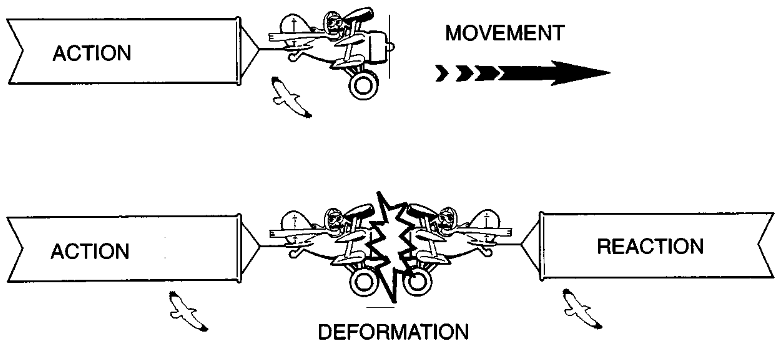

Fig. 14 Diagram demonstrating the physical law of action–reaction. (a) A single force induces movement. (b) If a reaction-force in the opposite direction is applied simultaneously, no movement takes place and deformation occurs.

By successive clockwise and anticlockwise movements, the BFT induces forces and torque. For the endodontists, the endograms were specific. The first impression is of the uniformity of the action; that is, uniformity in the work duration of each instrument (elementary sequences) and in the time needed for a change of instrument (Fig. 3a, b). The endograms also showed regularity in the increase in the forces and torques, and in the relationships between them (Figs 4, 5, and 6). The different values increased in parallel with an increase in instrument size (Figs 10 and 11). The vertical forces showed a variation from 0.08 kg (size 15) to 0.65 kg (size 45), the latter being in close agreement with the findings of Kyomen *et al.* (1994), who showed that the overall mean of clinically applied forces apically was 0.75 kg for a size 45 file. During the endodontists' experiments, the mean values of the vertical forces and of the exerted torque were related to the size of the instruments (Figs 9, 10 and 11). This may imply an optimal application range for each instrument. For a

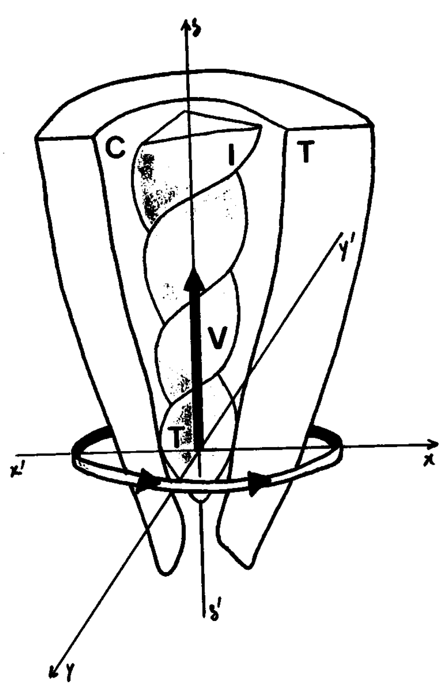

Fig. 15 Diagram of the vector representing torque. If the torque (T) is performed in the horizontal plane, with a straight canal, the representing vector (V) is vertical and the Endograph stores the entire value of it. C, Canal, I, instrument.

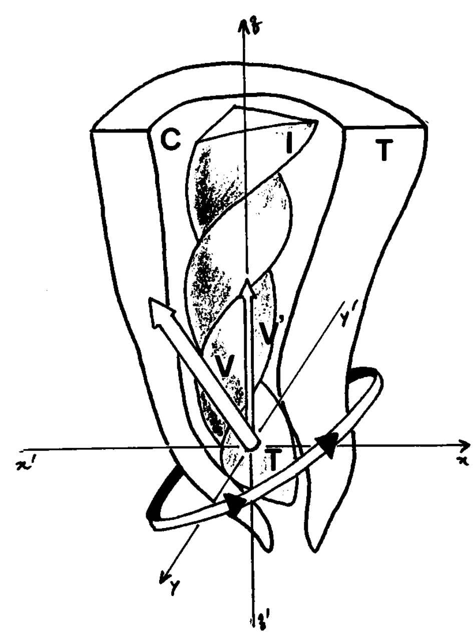

Fig. 16 Diagram of the vector representing torque. The developed torque (T) is performed on an inclined plane in relation to the horizontal plane because of the curved canal. The representing vector (V) is inclined and only the vector projection (V′) is measured by the endograph. C, Canal, I, instrument.

given size, the forces and torque varied between minimal and maximal values that were constant (Fig. 12). Below the minimal value for the vertical forces, the instrument had no effect and revealed no cutting torque; this confirms the findings of Krupp *et al.* (1984). Above the maximum value of torque, the instrument risked breakage under the vertical forces. It thus seems that skill is developed only by a long period of trial and error, as these limit values, which have never been described objectively, were respected by the endodontists but not by the students.

During the preparations performed by students, the endograms showed striking differences from those of the endodontists. The students were not practiced in the BFT and, indeed, the experiment was their first contact with this technique. On the other hand, they were familiar with the Endograph (Blum *et al.* 1997a,b). Their endograms revealed that: (i) the instrumental work had no rational line (Fig. 7), with a complete lack of the linear progression observed for the endodontists' work in terms of phase duration and instrumental change time (Fig. 3a, b); and (ii) the forces used to place the instrument and the clockwise torque were not synchronous, with the values of the vertical forces higher compared with the values produced by the endodontists (Figs 5 and 6). Two events were observed;

1 the students first introduced the instrument with vertical force, and then performed a rotational movement. This action induced a torque that was too intense (Fig. 7a);
2 the students first performed rotational counterclockwise movements and then introduced the instrument apically into the canal. This action induced no torque, because the blade of the instrument was not engaged into the dentine (Fig. 7b).

The progress of the student work movements was interesting. With the endograms used as objective references for analysing the preparation technique, the students were able to adapt and correct their movements by trying to reproduce the movements of the endodontists. This explains why there was a significant difference in the force and torque values among students at the beginning of the experiment (Fig. 7) but not during the last three sessions (Fig. 8). The relation between the developed vertical forces and the torque also became more similar between the two groups (Figs 6 and 8). Although the relation between the quality of the preparation and method of instrumentation was not examined in this study, it can be speculated that the movements of the endodontists were efficient and resulted in correct instrumentation because of their long experience with the technique. Studies are currently being conducted to analyse the relationship between the endograms and the quality of a preparation or obturation.

The central aim of this study was to analyse the BFT of experienced endodontists. Thus, with the high storage frequency, the details of the endodontists' preparation technique were analysed. The torques generated during the clockwise movement (insertion phase) (Fig. 6a) were lower in intensity than the torque during the anticlockwise movement (Fig. 6b). Indeed, during insertion, the instrument is screwed into the root canal and the torque is induced by frictional forces between the instrument and the wall of the root canal. The edge of the instrument blade is at 45° to the direction of the movement, and thus no cutting action is made with a screwing movement of the instrument. The vertical forces necessary to introduce the instrument were moderate (Fig. 6c, d). Generally the endograms showed an increase in the vertical forces between the clockwise and the anticlockwise movements (Figs 3 and 4). When the instrument was at its working length, the anticlockwise movement began and the torque increased (Fig. 6b). The mean values of the anticlockwise torque were double the mean values of the clockwise torque (Fig. 6a, b). Indeed, the anticlockwise torque was induced by frictional forces in addition to the cutting action of the instrument. The cutting torque is directly related to the developed vertical forces (Roane & Sabala 1984, Roane *et al.* 1985). The endograms showed this relationship (Fig. 4). The more the instrument is blocked into the canal by clockwise rotation and not by vertical forces, the higher the cutting torque will be (Roane *et al.* 1985). As shown by endograms and previous authors, this cutting action is directly related to the size of the instrument (Figs 3 and 4) (Krupp *et al.* 1984, Roane & Sabala 1984, Kyomen *et al.* 1994).

The precise mechanism of dentine removal has not yet been elucidated. It must be very complex, however, considering the multiple microscopic fractures and stresses that occur on the dentine surface during the clockwise rotational phase (Roane & Sabala 1984, Roane *et al.* 1985), the irregular contours of the canal, the complex structure of dentine, and the fact that the shear strength of dentine is very high, at about 20 000 PSI. When an instrument cuts material, which can be compared to a deformation in terms of physical development, the cutting torques must be constant or decrease. In fact, the endograms showed that, at the beginning of the anticlockwise movement, the torque increased (Fig. 6b) up to a maximum value. The explanation is physical: all movements of the tip of the instrument were the repercussions of movements of the handle. At the beginning of the anticlockwise movement, the torque was created at the handle (hand of the practitioner). The rigidity of the instrument was not sufficient, or the elasticity was too great, to cut the dentine immediately in the working area (tip of the instrument). The instrument, whose tip was blocked into the dentine by the screwing movement, was thus deformed initially. Thus the tip did not move so the blades did not cut the dentine. The hand continued to move in an anticlockwise direction and the torque increased, as did the vertical forces (to avoid withdrawal of the instrument) (Fig. 6b, d). When the anticlockwise torque was greater than the forces that blocked the tip of the instrument, the cutting action began, and the torque decreased (Fig. 6b). Thus the tip-to-handle distance induced a time lag between the cutting movement of the handle and the movement of the tip. When the tip moved, the torque and the vertical forces decreased, as observed previously (Roane & Sabala 1984, Roane *et al.* 1985), indicating the cutting action of the active part of the tip of the instrument.

As stated above, the instrument response, that is, the time lag in the movement of the handle and the tip of the instrument, is related to the instrument design. As the slopes of endograms for torque are different, this time lag depended on the different characteristics of the instrument: (i) the design, (ii) the diameter, and (iii) the metal. Indeed, a triangular file has a cross-sectional area or mass that is 37.5% less than that of a square file of the same standardized size (Roane & Sabala 1984, Roane *et al.* 1985). The results of Roane indicated that when the cutting radius is 0.4 mm (i.e. a size 40 file), a triangle has a cross-sectional area of 0.05 mm^2, whereas a square has an area of 0.08 mm^2. By recognizing that geometry has an influence upon the structural properties of materials, a relationship between the developed forces and torque and the cross-sectional geometry was established.

During each elementary sequence, the endodontists' endograms showed that the vertical forces were constant or increased (Figs 4 and 5) when the instrument was cutting. Two explanations should be considered. The first concerns tactile sensation. Unconsciously, the clinician endodontists may have protected the instrument and avoided the application of too strong a force during anticlockwise movement. By constant vertical forces, the instrument is pushed out of the canal slightly and the cutting power is decreased. With this action the cutting efficiency is lowered, but excessive stresses are avoided. This clinical sensation was very difficult for the students to understand initially. It became demonstrably more understandable with the endograms. The second explanation is more rational. The cutting action of the instrument eliminates dentine at the tip of the instrument and thus improves the instrument penetration. This action equals the vertical forces required to maintain the instrument at the same length. With the clockwise movement, higher forces allowed the instrument to penetrate deeper into the root canal (Figs 3 and 4).

When the instrument was used until fracture, the endograms showed a sudden lack of torque, which was induced directly by the fracture of the instrument (Fig. 13a). Moreover, after instrument fracture, the operator was able to produce vertical forces (Fig. 13b) but not torque (Fig. 13c). With nickel-titanium instruments, the clinician is unable to recognize that the instrument is approaching failure point (Massa *et al.* 1992). During the experiments under discussion, the fractures appeared during both the clockwise and anticlockwise movements, and at the beginning, middle and end of the torque movements. These results showed that the fracture conditions are unknown and that prediction of a fracture is impossible.

During this study, preparations were analysed by visualization of vertical and horizontal forces and by torque sequences. The endograms can be used for both on-line monitoring (during preparation) and off-line analysis (after preparation). With the separation between time and action, the analysis of movement may be performed with different storage frequencies and thus with different views of the preparation. Other preparation techniques will be studied and this device will be of use in the ongoing research to improve preparation techniques.

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References

Abou-Rass M, Frank AL, Glick DH (1980) The anticurvature filing method to prepare the curved root canal. *Journal of American Dental Association* **101**,792–4.

Allison DA, Weber CR, Walton RE (1979) The influence of the method of canal preparation on the quality of apical and coronal obturation. *Journal of Endodontics* **5**, 298–304.

Blum JY, Parahy E, Micallef JP (1997a) Analysis of forces developed during obturations: warm vertical compaction. *Journal of Endodontics* **2**, 91–5.

BLUM JY, ESBER S, MICALLEF JP (1997b) Analysis of forces developed during obturations: Comparison of three techniques. *Journal of Endodontics* **5**, 340–5.

GOERIG AC, MICHELICH RJ, SCHULTZ HH (1982) Instrumentation of root canals in molar using the step-down technique. *Journal of Endodontics* **12**, 550–4.

INGLE JI (1961) A standardized endodontic technique utilizing newly designed instruments and filling materials. *Oral Surgery, Oral Medicine, Oral Pathology* **14**, 83–91.

KRUPP JD, BRABTLEY WA, GERSTEIN H (1984) A. Investigation of the torsional and bending properties of several brands of endodontic files. *Journal of Endodontics* **10**, 372–80.

KYOMEN SM, CAPUTO AA, WHITE SN (1994) Critical analysis of the balanced force technique in endodontics. *Journal of Endodontics* **20**, 332–7.

MARSHALL FJ, PAPPIN J (1980) *A Crown-down Pressureless Preparation Root Canal Enlargement Technique*. Technique manual Portland, Oregon 1980, Oregon Health Sciences University.

MASSA GR, NICHOLLS JI, HARRINGTON GW (1992) Torsional properties of the canal master instrument. *Journal of Endodontics* **18**, 222–7.

ROANE JB, SABALA CL (1984) Clockwise or counterclockwise. *Journal of Endodontics* **10**, 349–53.

ROANE JB, SABALA CL, DUNCANSON MG (1985) The balanced force concept for instrumentation of curved canals. *Journal of Endodontics* **11**, 203–11.

SABALA CL, ROANE JB, SOUTHARD LZ (1988) Instrumentation of curved canals using a modified tipped instrument: a comparison study. *Journal of Endodontics* **14**, 59–64.

SCHILDER H (1974) Cleaning and shaping the root canal. *Dental Clinic of North America* **18**, 269–96.