High and low torque handpieces: cutting dynamics, enamel cracking and tooth temperature

T. F. Watson,[1] D. Flanagan,[2] and D. G. Stone,[3]

Objective The aim of these experiments was to compare the cutting dynamics of high-speed high-torque (speed-increasing) and high-speed low-torque (air-turbine) handpieces and evaluate the effect of handpiece torque and bur type on sub-surface enamel cracking. Temperature changes were also recorded in teeth during cavity preparation with high and low torque handpieces with diamond and tungsten carbide (TC) burs. The null hypothesis of this study was that high torque handpieces cause more damage to tooth structure during cutting and lead to a rise in temperature within the pulp-chamber.

Materials and methods Images of the dynamic interactions between burs and enamel were recorded at video rate using a confocal microscope. Central incisors were mounted on a specially made servomotor driven stage for cutting with a type 57 TC bur. The two handpiece types were used with simultaneous recording of cutting load and rate. Sub-surface enamel cracking caused by the use of diamond and TC burs with high and low torque was also examined. Lower third molars were sectioned horizontally to remove the cusp tips and then the two remaining crowns cemented together with cyanoacrylate adhesive, by their flat surfaces. Axial surfaces of the crowns were then prepared with the burs and handpieces. The teeth were then separated and the original sectioned surface examined for any cracks using a confocal microscope. Heat generation was measured using thermocouples placed into the pulp chambers of extracted premolars, with diamond and TC burs /high-low torque handpiece variables, when cutting occlusal and cervical cavities.

Results When lightly loaded the two handpiece types performed similarly. However, marked differences in cutting mechanisms were noted when increased forces were applied to the handpieces with, generally, an increase in cutting rate. The air turbine could not cope with steady heavy loads, tending to stall. 'Rippling' was seen in the interface as this stall developed, coinciding with the bur 'clearing' itself. No differences were noted between different handpieces and burs, in terms of sub-surface enamel cracking. Similarly, no differences were recorded for temperature rise during cavity preparation.

Conclusions Differences in cutting mechanisms were seen between handpieces with high and low torque, especially when the loads and cutting rates were increased. The speed increasing handpiece was better able to cope with increased loading. Nevertheless, there was no evidence of increased tooth cracking or heating with this type handpiece, indicating that these do not have any deleterious effects on the tooth.

Even though new techniques such as lasers, airbrasion and chemical dissolution[1–3] are being advocated for the removal of dental hard tissue during cavity preparation, it seems probable that the use of rotary instruments will continue for some considerable time. Practising dentists routinely use rotary cutting instruments, but seldom question the mechanisms of cutting that are central to their use. Since the introduction of hand-driven rotary dental instruments in 1728 there has been a quest for ever greater cutting efficiency. This has usually been achieved by increasing rotational speeds, but at the cost of reduced torque. Air driven turbines will generally have less torque than available with slow speed, engine driven, handpieces: they thus require gentle handling and considerable skill in their use in order to achieve optimal performance. However, modern speed increasing handpieces, when coupled to high speed electric motors, produce ultra-high rotational speeds (200,000 rpm: 200 Krpm) while still retaining the flexibility of a high torque drive system. The operator is given more tactile feedback when cutting hard tissues with high torque handpieces than is felt with an air turbine. It might therefore be expected that there could be differences in their mechanisms of cutting.

Imaging of high speed cutting interactions between dental burs and enamel microstructure has become possible with the advent of video rate confocal microscopy and has been reported previously.[4–6] These previous studies did not record applied loads and displacements during the cutting process and did not compare the dynamics of the cutting interactions with high and low torque handpieces.

It might also be expected that sub-surface damage could be greater when higher torque is used and potentially higher loads are applied. The fact that cracking occurs in enamel as a result of cutting has been known for many years[6,7–10,11] but the effect of cutting torque on the generation of cracking has not been evaluated. Xu *et al.*[11] developed a technique for assessing the degree of enamel cracking when using different types of bur. A further effect of high torque could be the generation of increased heat within the tooth caused by the potential for greater loads to be applied during cutting.

The null hypothesis of this study was that high torque handpieces cause more damage to tooth structure during cutting and lead to a rise in temperature within the pulp-chamber.

The aims of this study were therefore to:

- Compare the cutting dynamics of high speed high torque and high speed low torque handpieces
- Evaluate the effect of handpiece torque on sub-surface enamel cracking
- Record temperature change in teeth during cavity preparation with high and low torque handpieces.

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[1]*Reader/Consultant, [2]Clinical Demonstrator, [3]Division of Conservative Dentistry, Guy's, King's & St Thomas' Dental Institute, KCL, Guy's Hospital, London Bridge SE1 9RT*
**Correspondence to: Dr T F Watson, Microscopy & Imaging, Floor 17 Guy's Tower, Guy's Hospital, London Bridge, SE1 9RT*
email: timothy.f.watson@kcl.ac.uk

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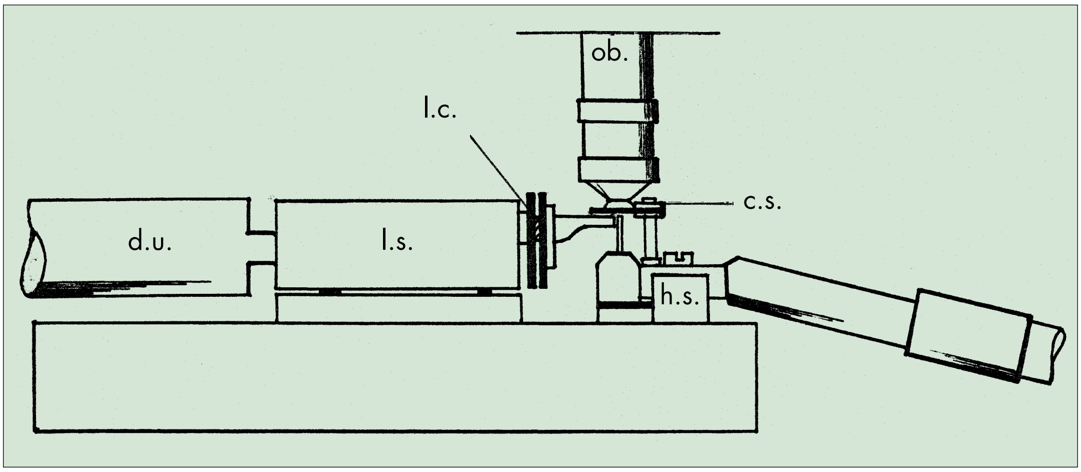

Fig. 1 Diagram of tooth-cutting apparatus (letters defined in text)

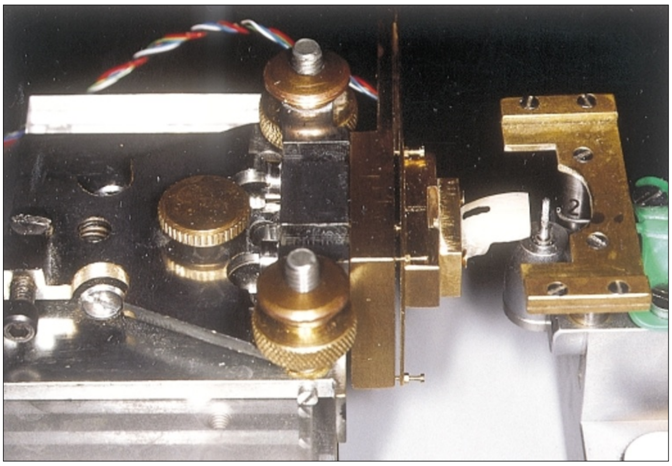

Fig. 2 Top view of the tooth-cutting apparatus. The tooth, in the centre, is advanced on to the bur held in a handpiece (right). The leads from the load cell can be seen exiting the stage at the backs

Materials and methods: dynamic cutting

In order to observe the cutting of teeth, in real-time on a confocal microscope, it was necessary to produce a stable, rigid platform which could be controlled precisely. The tooth being cut was advanced onto a safely-held rotating bur within the limited clearance of an objective lens, while the video image was recorded. The basis of the tooth cutting stage was originally described by Watson in 1990.[4] For the studies reported in this paper the apparatus was extensively re-engineered.

As can be seen in Figure 1, the base is mounted on the stage of a microscope and observed using a microscope objective lens, *ob.* The drive unit, *d.u.,* is fitted with an encoded micromotor comprising a 377:1 reduction ratio unit to move the linear stage, *l.s.* (PI Instrumente, Lambda Photometrics Ltd, Harpenden, Herts). This combination gave advance rates which could be adjusted between 0.01–14 mm/minute. In order to measure the forces applied to the tooth during cutting an ultra miniature low-compliance (2.5 µm at full deflection) 10 N load cell, *l.c.*, (Entran, Les Clayes, France) was sandwiched between the micromotor stage fixing and the mounting for the tooth. The high speed handpiece, *h.s.*, is fixed firmly to the base.

Twelve extracted human upper central incisor teeth were used, with the consent of the patients and according to the guidelines of the local ethical committee. The teeth were gently polished to provide a flat labial surface and a uniform labio-lingual thickness of 2 mm to be cut by the bur (Fig. 1). The experimental cavity was a slot cut from the incisal edge towards the cervical margin with a type 57 tungsten carbide fissure bur (ISO # 014). A tungsten carbide bur was preferred to a diamond bur as it resulted in a clearer image because of the irregular grit placement on the diamond bur producing variable chipping at the cavity margins. The tooth roots were removed at the amelo-cemental junction at 90° to the flat labial surface, the sectioned surface drilled, and a screw thread cut in the dentine to size 14 BA, using a tap. This coronal tooth portion was then mounted on a brass block with 14 BA screws (similar to dentine pins as used for plastic restorations). The tooth and block was then carefully levelled [6] and driven in a horizontal direction on the precision stage *l.s.* (Figs 1, 2).

Cutting was carried out under full water spray; a cover slip, *c.s.*, providing protection for the microscope objective lens, *ob.*, (Fig. 1). Viewing was via a tandem scanning confocal microscope (TSM) (Noran Instruments, Middleton, W1, USA), using a x20 oil immersion lens and either a x10 or x20 eyepiece. Images were captured by means of either a CCD (charge coupled device) (COHU, San Diego, USA) or SIT (silicon intensified target) (JAI, Copenhagen, Denmark) camera attached to the microscope. These images were recorded at 25 frames/second and transferred via a computer (486 66 Mhz, 64 Mb RAM) onto a random array of hard discs (RAID – 9x1 Mb) at a transfer rate of 14 Mb/second. Simultaneous recordings of load, position and time with respect to the digital images were possible by this means. The video signal was also recorded on a video cassette recorder. Ultimate computer image storage was onto CD-ROM. Micro-photographs were taken at the end of cutting runs, through the eyepiece using a 35 mm camera.

The handpieces used were:

- A W&H 999 LT200 1:5 speed increasing handpiece (Park St, St Albans, Herts) driven by a variable speed electric motor (Bien Air:MC 40 Isolite 300/100: Bienne, Switzerland). This gave a maximum load-free speed of 200 Krpm. Back emf circuitry allowed the motor speed to be maintained under normal loads.
- A W&H Toplight 898 air turbine handpiece with a free running speed of nominally 350 Krpm ± 20 Krpm.

Various advance rates (the rate at which the tooth was driven towards the bur) were used during the study, with rates of 1 mm/minute and 5 mm/minute providing the main results. In addition, the speed of the high torque handpiece was reduced to 20 Krpm with a subsequent reduction in available torque. This could not be done reliably with the air turbine handpiece. A total of forty eight cuts were made in the teeth. A new type 57 TC bur (ISO # 014) was used in the dynamic cutting experiments for each tooth.

Results: dynamic cutting experiments

Advance rate — 1 mm/minute

At a low advance rate of 1 mm/minute the results for both the air turbine and the speed increasing handpiece were comparable. Cutting was smooth and regular, with the load remaining fairly steady

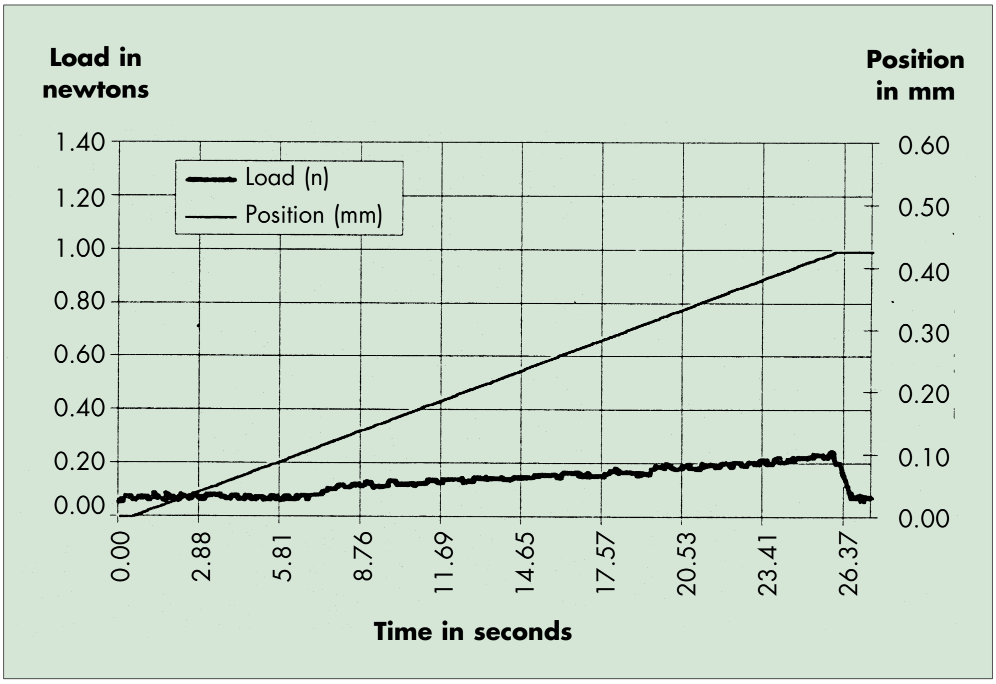

Fig. 3 Graph showing the progression of cutting (thin line) at a low advance rate (1 mm/minute) versus load (bold line). The progression and load are recorded simultaneously with the video images and all are stored in computer memory

at about 0.1–0.2 N (Fig. 3). Subsurface cracking could sometimes be seen (Fig. 4) but some of the cracking visible in the dynamic images was attributable to cracks and lamellae already present in the teeth.

Advance rate — 5 mm/minute

At the higher advance rate of 5 mm/minute the results for the two handpieces were dramatically different. With the air turbine handpiece, initially, the cutting progressed smoothly showing little variation in the measured load. Then the load started to rise quite dramatically without a corresponding increase in the advance rate. The load continued to rise to the point where cutting was erratic and very uneven. At this point, loads of 1.1 N were recorded (Fig. 5). The advance of the bur was stopped, or reduced, to prevent stalling of the handpiece, before progressing again. The images of the bur while cutting at a high rate showed a very noticeable wave-like rippling effect as the bur alternately slowed and 'cleared' itself in a cyclic manner (Fig. 6).

The 1:5 speed increasing handpiece showed a steady load of about 0.4 N, (Fig. 7) while cutting progressed smoothly and evenly in the same way as it did at the lower advance rate (Fig. 4). There was no need to adjust or vary the advance rate to prevent stalling of the handpiece. The images of the bur while cutting did not show the rippling that was evident with the air turbine.

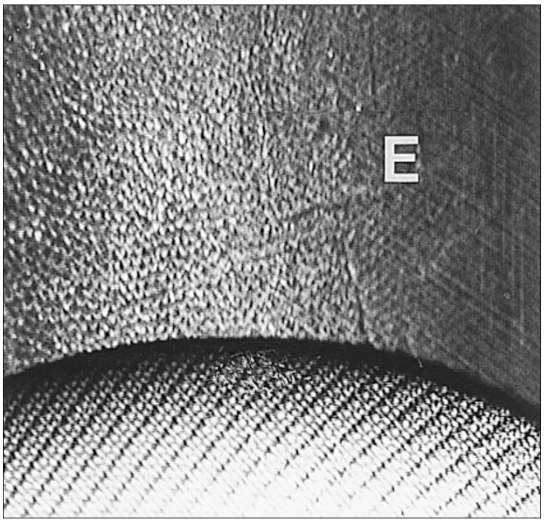

Fig. 4 Single video frame showing steady cutting through enamel. Horseshoe shaped enamel prisms (E) can be seen at the top of the frame. The dots at the bottom are an interference pattern set up between the rotating bur and the rotary scanning system of the microscope. Fieldwidth 300 µm

1:5 speed increasing handpiece running at reduced speed

With the speed of the handpiece reduced to 10 Krpm and cutting at an advance rate of 1 mm/minute, there was a noticeable difference from when the handpiece was running at full speed. The load rose to about 0.2 N, but there were noticeable fluctuations in the load as the cutting progressed, which were not present when running at full speed (Fig. 8). There was no pronounced rippling effect, as appeared with the air turbine at 5 mm/minute, although a slight effect was just discernible. At the end of each cutting experiment, the samples were inspected for evidence of cracking. This was noted in many instances and images recorded using a 35 mm camera, with cracking following the 'classical' plains of weakness (Fig. 9).

Materials and methods: sub-surface cracking

In order to study the effect of cutting on subsurface enamel it is clearly necessary to view beneath the cut surface of the tooth. Teeth were prepared in the same way as reported by Xu *et al.*[11] although in our study the cracks were imaged using confocal microscopy rather than Normarski contrast imaging.

Eight pairs of matching third molar teeth were sectioned across their occlusal surfaces and again 5 mm more cervically. After careful polishing, the matched surfaces were bonded together using cyanoacrylate adhesive (Loctite Corp, Newinton, CT, USA) to providing a very thin interface. Bonding also provided support to the edges of the teeth during the cutting experiment.

The paired teeth were hand held and cut using full water spray in a way which closely resembled clinical conditions. One group of teeth (four pairs) were cut with a tungsten carbide bur (No 57. plain cut fissure) using both handpieces, the other group were cut in the same manner using a diamond bur (type 541, fissure). A mark allowed areas cut by the different handpieces to be identified. Uncut areas of paired teeth acted as controls for both handpieces.

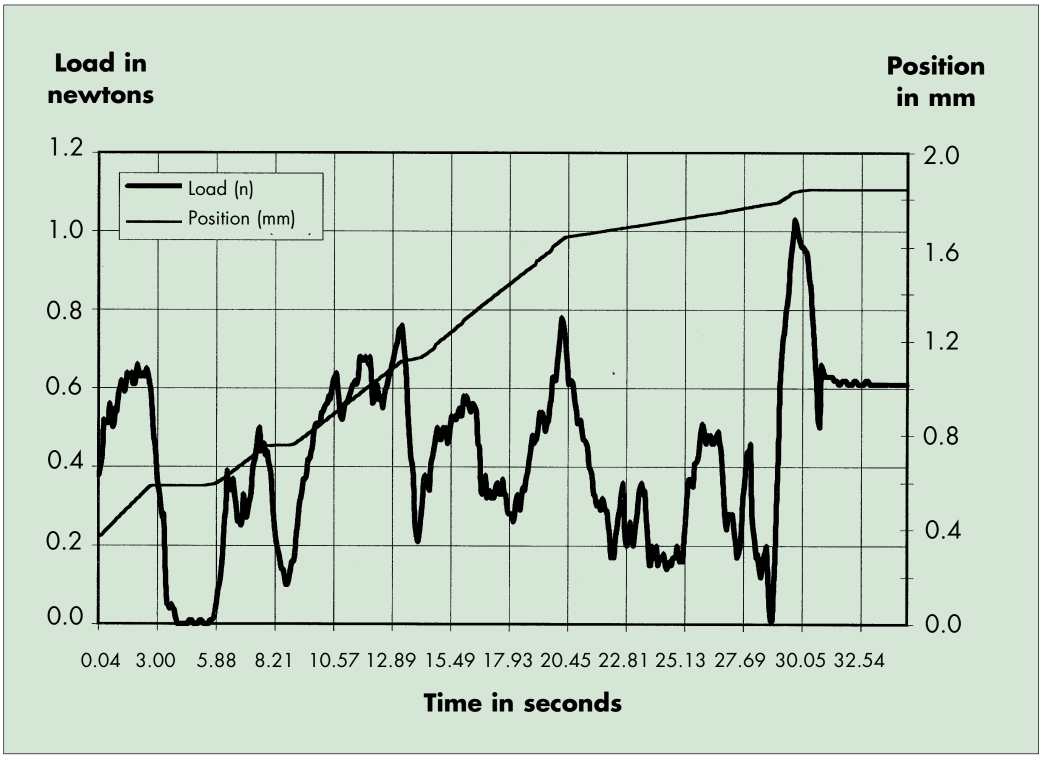

Fig. 5 Graph showing the faltering progression of cutting (thin line) at a high advance rate (5 mm/ minute) versus load (bold line). The air turbine is overloaded. The load is fluctuating widely and the progression is erratic in order that the cutting could continue

The teeth were separated by soaking them in acetone and were then kept fully hydrated until required. Once separated, enamel under the cut surface could be observed directly.

Cracking was highlighted by immersing the sectioned teeth in rhodamine B solution, and subsequently viewing them using the TSM which allows cracks under the surface enamel to be studied. A mercury arc light source and green filter of wavelength 546 nm caused the rhodamine B to fluoresce. A x50 / 1.2 NA water immersion lens in conjunction with a x10 eyepiece were used for observing the cracking. The image combined fluorescence and reflection and was captured using the video cameras described for the dynamic cutting experiments. Measurements were made of the image on a calibrated TV monitor; only cracking which reached the surface of the tooth was included.

Forty eight measurements were made for each of the handpiece/bur type combinations, giving a total of 192 crack depth

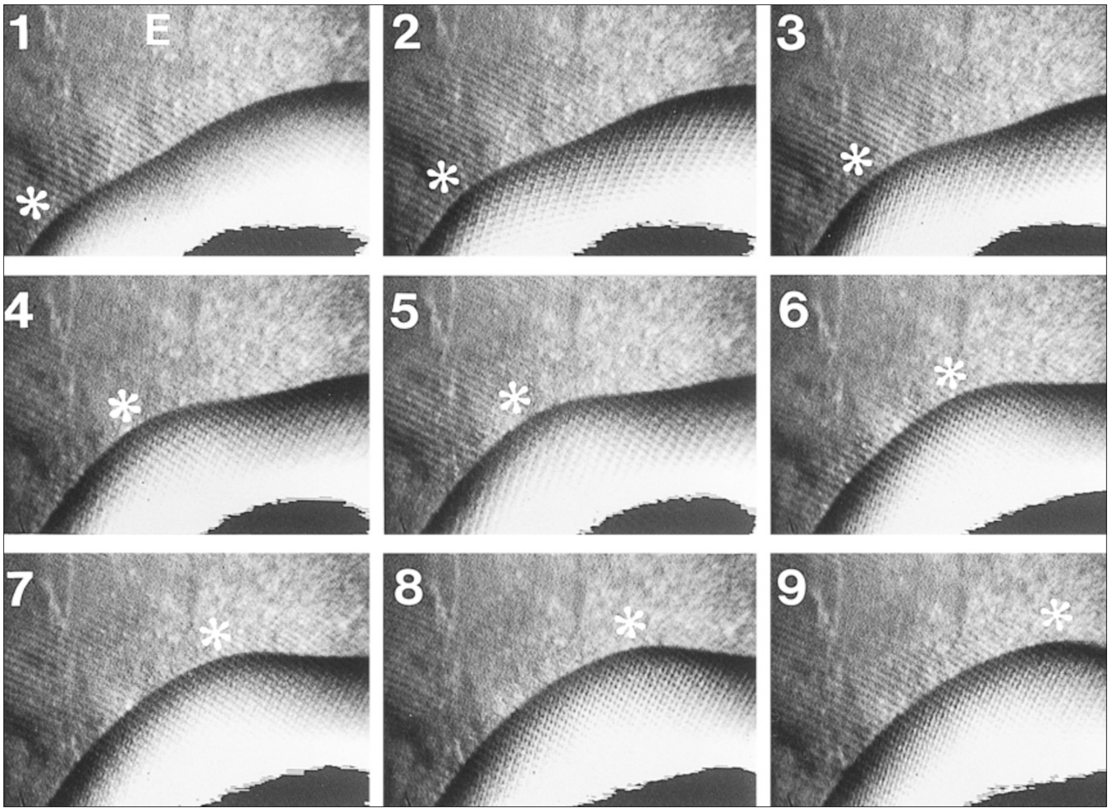

Fig. 6 Nine video image frames taken from the above experiment showing 'rippling' at the interface between the bur and the tooth (E). The steady progression of a ripple along the interface is indicated by the ✱. The calculated speed of this ripple is 35 rpm. Each frame is 300 μm across

measurements. Forty eight control measurements were made for the two different bur types (the control acting for both handpieces). Data was analysed using two-way analysis of variance (ANOVA) for investigation of the effect of torque. The bur type was investigated separately using one-way analysis of variance and the Scheffe test for post-ANOVA contrasts.

Results: subsurface cracking

The results of this study showed that there was no statistical difference in the amount of subsurface cracking between high and low torque handpieces, regardless of the bur type. Equally there was no statistical difference between the bur type used regardless of whether they were used with high or low torque handpieces. There was a significant increase in the amount of subsurface cracking when comparing the cut and control areas ($P < 0.001$), see Table 1.

Materials and methods: recording of temperature changes within teeth

The air turbine selected was a KAVO handpiece with 3 jet water spray running freely at a nominal 450 Krpm, while the speed increasing handpiece was the same as for the dynamic cutting experiments. This 1:5 speed increasing handpiece also had a 3 jet water spray and was operated at 3 speeds on the motor controller, at 4–20–40 Krpm, giving a total range of 20–100–200 Krpm.

Caries-free extracted teeth, permanent premolars and molars, which had been stored in a dilute solution of sodium hypochlorite (Milton's solution) had the apical portion of the root cut off, and the contents of the pulp chamber removed. A thermocouple was inserted into the pulp chamber from the apex, held firmly in place with a pledget of cotton wool, and the tooth kept in a water bath at 37 °C.

The output from the thermocouple was amplified and connected to a pen recorder giving a graphic indication of time/temperature and peak temperature was recorded. A series of up to four cavities were cut with the air turbine, while the speed increasing handpiece was used to produce similar cavities but at three different speeds. One occlusal cavity (Size 4x2 mm), and two or three cervical cavities (Size 3x2 mm) were cut through enamel into dentine to a total depth of 1.5 mm. Recordings were made with cavities cut with both type 57 TC (ISO # 014) and FF Diamond (Medium grit ISO # 109/014) burs, both with and without water spray cooling. All cavities were prepared in 20–30 seconds, except when cutting at the lowest speed of 20 Krpm, which then took 45 seconds. The teeth were removed from the water bath and hand held while each cavity was cut, and replaced in the water bath to return to 37 °C between cavity preparations.

Three to four measurements were made for each operating condition and consisted of the peak temperature during cutting. Data was analysed using factorial analysis of variance (ANOVA) to investigate the effect of handpiece and bur and the use of water spray. Differences between cutting speeds using the speed increasing handpiece were assessed using one-way analysis of variance and the Scheffe test for post-ANOVA contrasts.

Results: temperature changes

No significant differences in temperature were found between cutting occlusal and cervical cavities, so these have been grouped together, and the results are shown in Table 2. These showed that in every instance the temperature within the tooth fell below the starting temperature of 37 °C.

The overall mean peak temperature using the air turbine handpiece was 26 ° C (standard deviation = 3.5) and 26.8 °C (3.6) for the speed increasing handpiece. The mean temperatures for the 57 TC and diamond burs were 26.1 °C (3.6) and 27.1 °C (3.6) respectively. A mean temperature of 24.0 °C (2.5) was achieved using water spray and 29.3 °C (2.5) without water spray. Factorial analysis of variance indicated that the major effect on temperature was caused by the use of the water spray ($P < 0.001$), but a marginally significant effect was also observed because of the difference between burs ($P = 0.043$). No statistically significant effect caused by different handpieces was observed.

One way analysis of variance indicated that there were differences between between operating speeds using the speed increasing handpiece. The mean peak temperatures were 24.9 °C (2.6), 28.0 °C (3.3) and 27.7 °C (4.2) for 20, 100, and 200 Krpm respectively. Post-ANOVA analysis indicated that peak temperature was

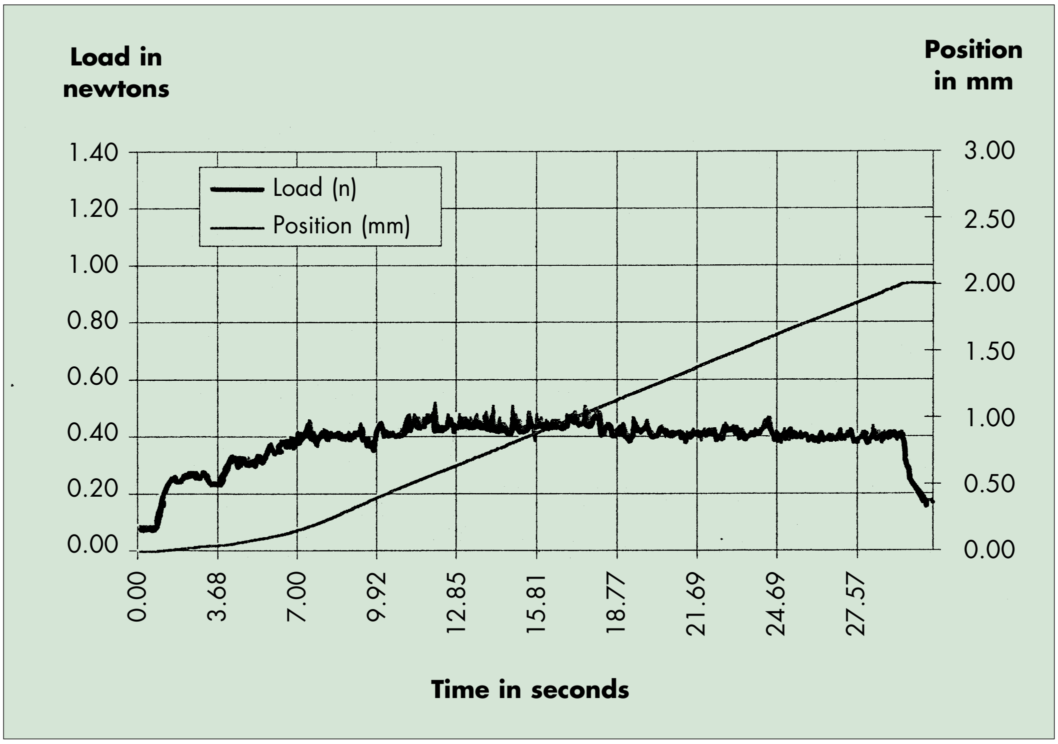

Fig. 7 High torque cutting with a 1: 5 speed increasing handpiece. Graph shows the progression of cutting (thin line) at a high advance rate (5 mm /minute) versus load (bold line). Load is increased compared with Fig. 3

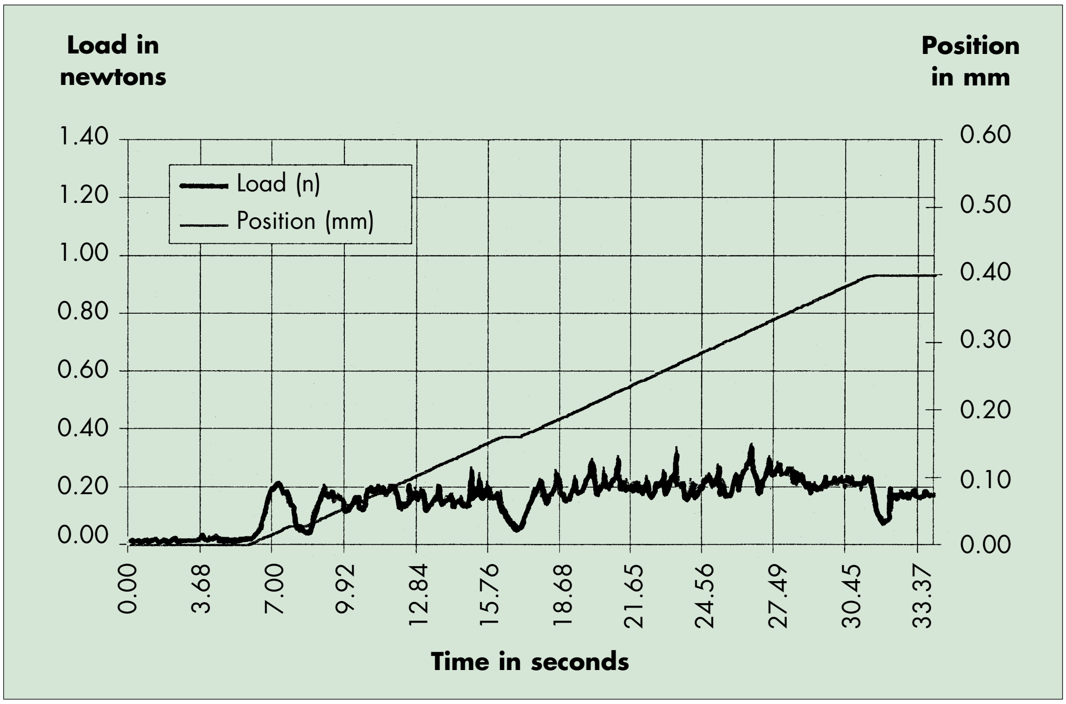

Fig. 8 Cutting (thin line) at a low advance rate (1 mm /minute) versus load (bold line). In this experiment the 1:5 speed increasing handpiece has been slowed down to 10 Krpm with reduced power from the motor. There is a wide fluctuation in load, which correlated with a tendency to 'ripple' in the video images

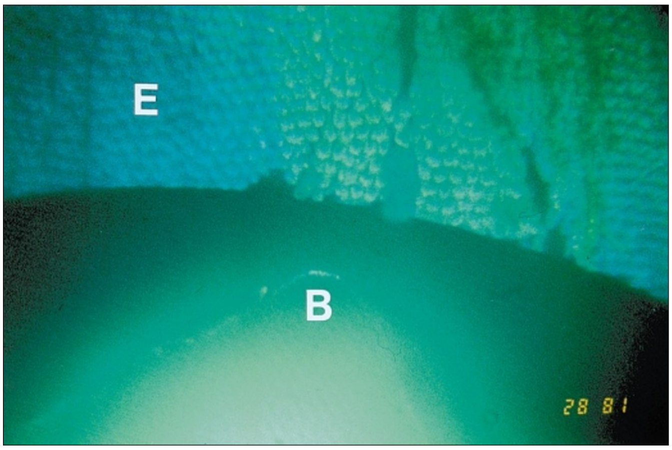

Fig. 9 Microphotograph recorded after a cutting experiment showing sub-surface cracking along the enamel prism boundaries (E). One blade (B) of a TC bur is visible close to, but not touching, the cavity surface. Cracking follows the 'classical' plains of weakness as described by Boyde.[15] Fieldwidth 200 µm. x50/1.0 numerical aperture, water immersion lens

significantly lower at 10 Krpm than at both 100 ($P = 0.009$) and 200 Krpm ($P = 0.035$).

Using a handpiece and rubber wheels at 20 Krpm to smooth and polish occlusal and axial surfaces invariably produced a rise in temperature in the pulp chamber ranging from 50–90 °C, indicating that the thermocouple was capable of recording temperatures above 37 °C during procedures which could be duplicated clinically.

Discussion

A number of experiments aimed at elucidating the cutting mechanisms caused by high torque, high speed and different bur types, formed the basis of this study. The fact that no difference was seen between the two handpieces at gentle cutting rates (advance rate of 1 mm/minute) is what might be expected, as at this rate both should be working well within their working limitations.

When cutting at the higher advance rate of 5 mm/minute there was a marked difference between the handpieces. As cutting progressed with the air turbine, the dynamic rippling effect seen in the video images seemed to be as a result of slowing of the bur and hence cutting. As a bur begins to slow down, the torque actually increases; the maximum torque being available at the point of stalling.[12,13] The extra torque maintains the cutting and 'clears' the bur of substrate. As the bur speed increases so the torque decreases. A cyclic cutting action develops which is characterised by the rippling that is seen. The rate of the 'ripple' was approximately 35 rpm; considerably slower than the rotation of the bur (Fig. 6). Had the advance rate not been reduced, the handpiece would certainly have stalled. Such a situation might arise as a result of heavy handedness on the part of the operator, or when using a handpiece that has a worn bearing.

When cutting with the speed increasing handpiece at the higher advance rate, however, the extra torque that was available meant that cutting could continue at the higher advance rate without the cutting dynamics being affected. This is undoubtedly helped by the back-emf load feedback system that maintains the speed of the electric motor. By reducing the speed of the electric motor to 10 Krpm, the available torque is also reduced. When cutting at an advance rate of 1 mm/minute, the handpiece was still able to cope with the situation although the slight ripple that was seen indicates that the handpiece was working towards its limits.

Clear advantages in the use of the high torque handpiece were therefore illustrated by these differences in cutting pattern, but it remained to be seen whether or not sub-surface cracking and heat generation would be unacceptable consequences of their use. The second and third parts of this study were therefore implemented.

The cracking found in the subsurface enamel confirms previous work.[4,11,14] This is particularly important for the integrity of the interface when adhesive materials are bonded to the cavity surface.

Table 1 Mean (standard deviation) crack length (mm) by bur type and torque

	High torque	Low torque	Control
Tungsten Carbide	41.5 (18.9)	39.0 (20.7)	9.6 (5.4)
Diamond	42.5 (24.2)	40.4 (20.7)	4.5 (6.2)

High torque: speed increasing handpiece; low torque: air turbine

Table 2

Air turbine

Speed	Bur	No. of cavities	Water spray	Range (°C)	Mean (°C)
450 Krpm	TC	4	Y	20–25	22.5
	TC	4	N	25–30	27.5
	Diamond	4	Y	24–26	25
	Diamond	4	N	29–30	30

1:5 Speed increasing handpiece

Speed	Bur	No. of cavities	Water spray	Range (°C)	Mean (°C)
20 Krpm	TC	4	Y	25–26	25
	TC	3	N	26–28	27
	Diamond	4	Y	20–22	21
	Diamond	3	N	27–27	27
100 Krpm	TC	4	Y	21–26	24
	TC	4	N	28–33	30
	Diamond	3	Y	25–30	27
	Diamond	3	N	30–32	31
200 Krpm	TC	4	Y	23	23
	TC	4	N	28–35	30
	Diamond	3	Y	25–28	26
	Diamond	3	N	30–34	32

Temperature rise recorded by thermocouples placed within the pulp chamber

Shrinkage or movement of the bonded restoration could cause fracture of the weakened enamel substrate.[15] The fact that there was found to be no statistical difference in the extent of the cracking for either of the handpieces of the bur types is important. Had this not been the case, there would be far reaching implications for both bur and handpiece manufacturers alike. Whether there was any increased subsurface cracking when using the handpieces at or near the limits of their capabilities was not examined in the second part of this study. However, there were no differences in the extent of the cracking as recorded in the dynamic images of the tooth cutting interactions.

The final component of the study aimed to assess the effects on pulpal temperature of the different handpiece types. The recording of 'pulpal' temperatures using a thermocouple does not register the actual temperature generated by the bur at the cutting interface, but does give an indication of gross differences. Experiments conducted in the past, where temperature rises may have been noted, may have used handpieces with a single or double water spray rather than a multiple air-water mist. Clearly, the air-water spray of the three jet handpieces had a profound effect, causing a net cooling of the teeth

All cavities cut under water spray, irrespective of handpiece, speed or bur, decreased the mean temperature in the pulp chamber from 37 °C. When cavities were cut dry the mean pulpal temperatures were 5 °C higher than with a water spray, but there was still a net drop in tooth temperature. Although not a major component of the study, it is interesting to note the slight relative increase in temperature when using diamond burs as compared with a fluted tungsten carbide bur. The mechanism for this may be attributable to the greater contact between the diamond grit and the enamel, so raising frictional heat, compared with the blades of the tungsten bur. In this situation the flutes may allow a slight cooling action. A corollary of this is that the thickness of the smeared layer has been reported to be greater when diamond burs are used.[14]

Clinically, one would expect cavities to be cut through enamel into dentine under water spray, with dry cutting perhaps limited to low speed removal of carious dentine, using a light pressure. Occlusion of the water spray by neighbouring tooth tissue should be a rarity when using a modern handpiece with a triple spray. In this experiment several cavities were prepared using far greater pressure than would be (clinically) recommended in a deliberate attempt to provoke stalling. This is fairly easy to achieve with the air turbine, but the torque of the speed increasing handpiece virtually precluded it, allowing one to maintain considerable pressure while the bur was still rotating. It was anticipated that this might well lead to a pronounced rise in temperature in the pulp chamber, but in no instance did this occur, no temperature above 35 °C being recorded.

Conclusion

This study reports no adverse effects related to the use of high torque/high speed handpieces when compared with air turbine handpieces. The added benefit of improved operator tactile feedback with a 1:5 speed increasing handpiece is not compromised by increased tooth damage.

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