Basic Science Research

Tooth Preparation: A Study on the Effect of Different Variables and a Comparison Between Conventional and Channeled Diamond Burs

Daniel F. Galindo, DDS,[1] Carlo Ercoli, DDS,[2] Paul D. Funkenbusch, PhD,[3] Thomas D. Greene, BSc,[4] Mark E. Moss, DDS, PhD,[5] Han-Joo Lee, DDS, PhD,[6] Uri Ben-Hanan, DSc,[7] Gerald N. Graser, DDS, MS,[8] and Izchak Barzilay, DDS, MS[9]

Purpose: The purpose of this study was to evaluate the different variables involved in tooth cutting to characterize intrapulpal temperature generation, cutting efficiency, and bur durability when using conventional and channeled diamond burs.

Materials and Methods: Forty premolars and 60 molars were selected for the study. Four diamond burs were paired according to grit size: 125-μm grit: Brasseler Coarse (Control 1) and TDA System (Test 1) burs; and 180-μm grit: Brasseler CRF (Control 2) and NTI Turbo Diamond (Test 2) burs. Each bur was used twice when cutting the premolar teeth, whereas it was used for 60 cuts when cutting the molar teeth. The data were analyzed to compare the correlation of bur design, grit and wear, amount of pressure, advancement rate, revolutions per minute, cutting time and rate, and proximity to the pulp chamber with intrapulpal temperature generation, cutting efficiency, and bur longevity. The mean values of test and control burs in each group were compared using an ANOVA ($p < 0.05$ for significant differences) for temperature generation and an ANOVA and the Tukey multiple range test ($p \leq 0.05$) for cutting efficiency and bur longevity.

Results: No significant difference was found in intrapulpal temperature generation while cutting premolar and molar teeth with conventional and channeled diamond burs. In both groups, the mean temperature recorded during and after the cutting procedure was lower than the baseline temperature. For premolar teeth, no significant difference was established for control and test burs for the load required to cut into the tooth and the cutting rate. However, both test burs showed significantly

From the Eastman Dental Center and College of Applied Sciences, Department of Mechanical Engineering, University of Rochester, Rochester, NY.

[1]Private Practice, Scottsdale, AZ; Former Postgraduate Prosthodontic Student, Division of Prosthodontics, University of Rochester Eastman Dental Center.

[2]Assistant Professor and Program Director, Division of Prosthodontics.

[3]Professor, Department of Mechanical Engineering, University of Rochester.

[4]Technical Associate, Department of Mechanical Engineering, University of Rochester.

[5]Assistant Professor, Division of Oral Sciences.

[6]Visiting Professor, Division of Prosthodontics.

[7]Visiting Professor, Department of Mechanical Engineering, University of Rochester.

[8]Professor and Chief, Division of Prosthodontics.

[9]Head, Division of Prosthodontics and Restorative Dentistry; Associate in Dentistry, Department of Prosthodontics, Faculty of Dentistry, University of Toronto.

Q1 *Accepted*

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Correspondence to: Daniel F. Galindo, D.D.S., 11139 E. Laurel Lane, Scottsdale, AZ 85259. E-mail: dr.galindo@cox.net

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fewer revolutions per minute when compared to their control counterparts. For the molar teeth, the Brasseler CRF bur required a significantly lower cutting load when compared to the NTI bur, whereas no difference was noted between the other pair of burs. The cutting rate was significantly higher for both control burs, whereas revolutions per minute (rpm) were greater for control coarser burs only. Overall, channeled burs showed a significantly lower cutting efficiency when compared to conventionally designed burs.

Conclusion: **Within the limitations of this study, channeled burs showed no significant advantage over conventional diamond burs when evaluating temperature generation and bur durability. Moreover, the cutting efficiency of conventional burs was greater than that of channeled burs.**

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INDEX WORDS: tooth preparation, intrapulpal temperature, diamond burs, bur design, diamond grit, handpiece cooling, cutting efficiency, handpiece speed, handpiece torque

THE GENERATION of heat during restorative procedures isa source of trauma for the dental pulp and has been suggested to lead to inflammation and necrosis.[1,2] Zach and Cohen[3,4] showed through in vivo studies that temperature increases cause intrapulpal tissue damage. In their studies, heat was applied with a hot soldering iron to the teeth of *Macaca rhesus* monkeys for periods of time ranging from 5 to 20 seconds, leading to increased intrapulpal temperatures. Reversible histological changes were noted with temperature increases of 3.3°C, whereas temperature increases of 5.6°C led to a loss of vitality in 15% of the teeth. Temperature increases beyond 5.6°C invariably led to pulpal necrosis. In a study by Bergenholtz and Nyman,[5] 15% of 255 originally vital teeth were necrotic 8–12 years after preparation for crown placement. Only 2.5% of control non-prepared teeth had lost vitality during the same observation period.

During tooth preparation, energy not used in the cutting process is mostly transformed into heat. The amount of heat transmitted to the tooth typically depends on the type of bur, pressure applied, cutting time and rate, cooling technique, and speed and torque of the rotary instrument.[2] Whereas the manufacturers can standardize the cooling technique and speed of the rotary instrument, the choice of bur, pressure, and cutting time varies from clinician to clinician.

Studies have shown that most dentists, when preparing teeth for fixed restorations with a high-speed handpiece, apply a force that varies from 50 to 150 g.[6] This is partially due to the design of current air-driven handpieces that provide high revolutions per minute (rpm), but poor torque regulation.[7] Hatton et al[8] determined that the pressure applied during tooth preparation and the duration of contact of the bur with the tooth have a direct influence on the temperature of the pulp. The authors established that doubling the rotating speed of the bur and/or the pressure applied on the handpiece produced a 50% temperature increase in the tooth. Furthermore, Sorenson et al[9] demonstrated that the rate of tooth-structure removal and the rate of heat transfer to the teeth are related in a parabolic form to the magnitude of the applied load. As such, the cutting loads under which the rate of heat transfer and the rate of tooth removal reach their maximum values are not the same. From a fundamental standpoint it is useful to consider the cutting process from an energy-based perspective. There are two important sources of energy in the cutting process: the clinician and the handpiece. The energy supplied by the clinician is proportional to the load being applied and the distance traveled by the bur. Assuming that the total distance is fixed, the clinician can decrease the total work (i.e., energy) he/she supplies by reducing the force applied to the handpiece. A practical limit is set, however, by the fact that the rate of advance also decreases as the load is decreased. Moreover, if the rate of advance is lowered, the contact time between the rotating bur and the tooth is increased, potentially increasing the energy input from the handpiece. Hence, from the perspective of the work supplied by the clinician, an effective bur should be able to produce a relatively high ratio between the rate of advance and the applied load.

The second important source of energy is the handpiece. In the current study, the handpiece is powered by a compressed air supply, which provides an approximately constant energy input per unit time (power) to drive bur rotation. When the bur is freely spinning (not in contact with the tooth), the resistance to rotation comes predominantly from internal resistance (friction) inside the handpiece. This condition produces the maximum rotation speed, with the energy supplied by the compressed air being dissipated by moving the bur very rapidly against the low internal resistance inside the handpiece. When the bur contacts the tooth, the resistance to bur rotation is increased and there is a distinct (and often audible) decrease in rotation rate. In this case, a portion of the energy supplied by the compressed air is being used to overcome the resistance caused by contacting the tooth. This energy appears at the interface between the bur and tooth (rather than inside the handpiece) and so is potentially available for material removal as well as acting as a heat source on the tooth. In general, the greater the resistance to rotation between the bur and tooth, the greater the energy consumed at the bur/tooth interface, and the lower the rotation speed. Hence, the decline in bur rotation rate upon contact with the tooth may be taken as a measure of the resistance between the bur and tooth and of the energy input along the bur/tooth interface by the handpiece system.

On the other end, bur wear and debris accumulation decrease the overall cutting efficiency of a bur, increasing the total cutting energy and time required to remove a certain volume of the tooth. It has been demonstrated that proper water-cooling decreases clogging of the bur, dissipates heat, and often leads to a decrease in the recorded pulpal temperature.[8-14] However, a recent survey indicates that less than 19% of North American dental schools make specific recommendations about coolant flow rates.[15] When specific recommendations are made, they range from an unspecified flow rate (including mist/light spray, moderate flow, and copious flow) to high spray flow rates (30–40 mL/min). Meanwhile, the International Organization for Standardization (ISO) recommends a handpiece coolant flow rate of 50 mL/min.[16]

New diamond bur designs have been introduced into the dental market [TDA (Turbo Double Action) system (North Bel, Milan, Italy) and NTI Supercoarse Turbo Diamond (Axis Dental Corp., Irving, TX)]. These burs have a single (NTI) and double (TDA) channel on their surfaces. The channels are arranged in a spiral-type configuration for the NTI bur and in a double-helix design for the TDA bur. The manufacturers of these products suggest that these burs have higher cutting efficiency than conventional diamond burs. It is also claimed that the presence of the channel(s) allows water to remain in contact with the tooth surface and re-circulate within the groove(s), providing continuous cleaning and rapid heat dissipation.[17] Few studies have been done to confirm this hypothesis[18-20] and these were not entirely conclusive due to inadequate control of some potentially important experimental variables. To our knowledge, no study has systematically evaluated all the variables related to high-speed tooth cutting.

The purpose of this study was to provide an in-depth description of the phenomenon of tooth cutting in a highly controlled in vitro environment. This environment allowed an evaluation of the different variables related to tooth cutting, such as bur design, grit and wear, amount of pressure, advancement rate, revolutions per minute, cutting time and rate, and proximity to the pulp chamber. Specifically, this study sought to characterize the correlation of the experimental variables with intrapulpal temperature generation, cutting efficiency, and durability (longevity) of channeled and conventional non-channeled diamond bur designs.

Materials and Methods

Tooth Selection

Forty single-root/single-canal premolars and 60 molars were selected. All teeth had been recently extracted and had intact enamel and dentin without carious lesions and/or restorations. After extraction, teeth were stored in an isotonic saline solution to prevent desiccation of the dental tissues.

Teeth were of approximately the same dimensions to minimize variability. The length, bucco-lingual and mesio-distal dimensions were measured with a Mitutoyo caliper (Mitutoyo Mfg. Co. Ltd., Kawasaki, Japan) (error $\leq$ 0.001 mm). Radiographs of all teeth were taken from the buccal and mesial aspects using standard intraoral films (Kodak Ektaspeed Plus, Rochester, NY). The radiographs were developed and then digitized with an IBM compatible computer (Adobe Photoshop 4.0, Adobe Systems, Inc.) and scanner (UMAX Astra 2400S, 600 × 1200 dpi, UMAX Technologies, Inc., Fremont, CA). The distance between the outer surface of the tooth and the pulp chamber was measured in the radiograph and in the digital images (Fig 1). These measurements were used to determine enamel and dentin thickness, and pulp chamber dimensions.

Tooth Preparation

The apexes of the teeth were sectioned with a serrated double-sided diamond disc (Brasseler USA, Savannah, GA) 6 mm below the cemento-enamel junction (CEJ).

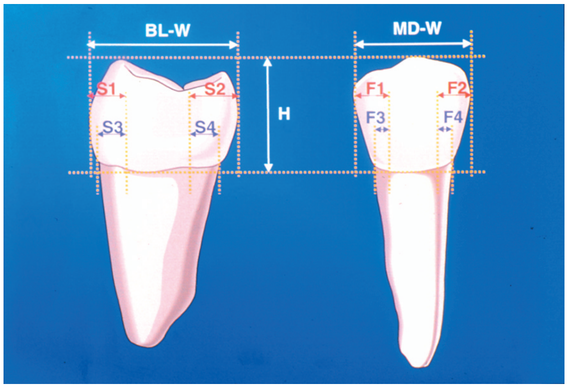

Figure 1. Schematic illustration of the procedure used to measure teeth and radiographs. The distance between the surface and pulp chamber was measured and recorded at different anatomic areas: BL-W: buccolingual width; MD-W: mesiodistal width; H: height from CEJ to cusp tip; S1: distance from most buccal aspect of clinical crown to pulp chamber; S2: distance from most lingual aspect of clinical crown to pulp chamber; S3: distance from most buccal aspect of CEJ crown to pulp chamber; S4: distance from most lingual aspect of CEJ to pulp chamber; F1: distance from most mesial aspect of clinical crown to pulp chamber; F2: distance from most distal aspect of clinical crown to pulp chamber; F3: distance from most mesial aspect of CEJ crown to pulp chamber; and F4: distance from most distal aspect of CEJ to pulp chamber.

The root canal of each tooth was enlarged to insert a thermocouple (Chromega-Constantan, Omega Engineering, Inc., Stamford, CT) (response time = 0.004 sec in water) without modifying the dimensions of the pulp chamber. A special silicone material (Heat Sink Compound, GC Electronics, Rockford, IL) was injected into the pulp chamber. This compound facilitates the heat transfer from the walls of the pulp chamber to the thermocouple. The position of the thermocouple was verified by taking a radiograph prior to the testing procedure. The thermocouple was secured to the tooth using composite resin applied to the apical opening (Fig 2). Time-temperature constants (heating and cooling) and time delay for each premolar tooth were calculated. The thermal heating and cooling time constants (τ) and the average time delay (t_d) were computed for the onset of the temperature change and for the condition when an external heat source or generator was applied to each tooth. Heating and cooling curves for the temperature range of 34–44°C (10°C above normal) were collected for each tooth. Heating curves were obtained by placing the tooth, with a teflon-insulated thermocouple inserted and sealed within the pulp chamber, into a water bath maintained at 44°C. Time and temperature data were recorded until equilibrium was attained. The tooth was then removed from the water bath, blotted dry, and

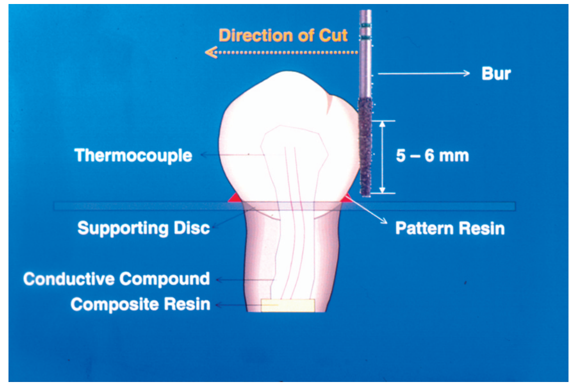

Figure 2. Schematic description of the position of the thermocouples and direction of cutting action.

the reverse cooling curve was measured until the tooth returned to room temperature. Thermal time constants (τ) and average time delays (t_d) for each tooth were determined by applying the following first-order heat transfer formulas[21] to the data:

$$\text{For heating: } \Delta T = \Delta T_i\,(1 - \exp[-(t - t_d)/\tau]),$$
$$\text{for } t > t_d\ \tau = t - t_d \text{ at } \Delta T = 0.63\Delta T_i.$$
$$\text{For cooling: } \Delta T = \Delta T_i \exp[-(t - t_d)/\tau],$$
$$\text{for } t > t_d\ \tau = t - t_d \text{ at } \Delta T = 0.37\Delta T_i,$$

where ΔT is the instantaneous temperature in the pulp chamber minus ambient (room) temperature, ΔT_i is the absolute value of the initial difference between the pulp chamber and external temperatures, t is elapsed time, t_d is the initial time delay, and τ is the heating or cooling time constant. (Note that when $\tau = t - t_d$, the exponential term becomes $\exp(-1) = 0.37$. This yields the corresponding values of $\Delta T = 0.63\Delta T_i$ and $\Delta T = 0.37\Delta T_i$ given for heating and cooling, respectively.)

A data sample is illustrated in Figure 3. The time constants describe the thermal behavior versus time of the

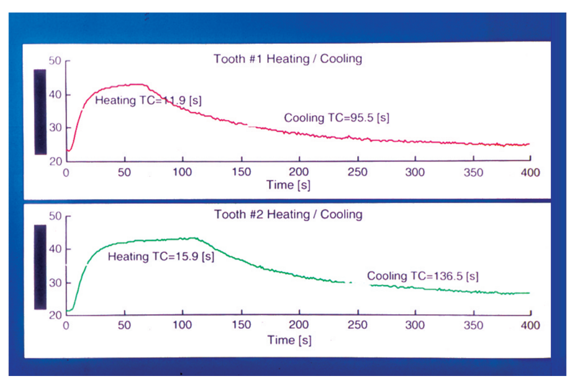

Figure 3. Heating and cooling time constants for two single-rooted premolar teeth. Teeth selected for the study exhibited a similar heating and cooling time constant.

Table 1. Diamond Burs Specifications Obtained from Manufacturers

	Code	Catalog Number	Grit (µm)	Head Diameter (mm)	Head Length (mm)	Tip Diameter (mm)
Brasseler Coarse	C1	6856L-31-018	125	1.8	9	1.2
TDA System	T1	M132	125	1.8	10	1.2*
Brasseler CRF	C2	2856L-31-018	180	1.8	9	1.2
NTI Turbo	T2	848T-018	180	1.8	10	1.2

*Value not provided by manufacturer, but measured by authors.

tooth. The time constant varies according to its volume, density, and composition. This parameter allows for an understanding of the individual performance of each tooth during high-speed cutting. The weight and volume of premolar teeth were also measured and the specific weight calculated. The tooth was then mounted on a stainless steel supporting plate with autopolymerizing resin (Pattern Resin, GC America, Inc., Alsip, IL) up to the CEJ level. The metal plate was then mounted on a custom-made water bath in which the level and temperature of the water were controlled with the use of a combined water bath/water pump system (Haake D3 and Haake L, Germany). This system allowed the baseline temperature of the pulp chamber to be set at 34°C. The thermocouple was connected to an electronic digital thermometer (Omega 2176A, Stamford, CT) allowing constant reading of the temperature within the pulp chamber. In order to test the sensitivity of the thermocouple system, a limited number of teeth were cut with no coolant. These pilot tests demonstrated that the thermocouple could detect temperature changes generated during tooth preparation.

Diamond Burs

Four types of diamond burs were selected and paired according to their grit size: Brasseler Coarse 125-μm grit (control bur 1 or C1) (Brasseler) and TDA system bur 125-μm grit (test bur 1 or T1) (North Bel); and Brasseler CRF 180-μm grit (control bur 2 or C2) (Brasseler), and NTI Supercoarse Turbo Diamond 180-μm grit (test bur 2 or T2) (Axis Dental Corp.). Burs were selected and standardized according to length and di-
Q2 ameter (Table 1). For premolar teeth, each bur was used for two cuts only. The same bur in each group was used for 60 cuts when cutting molar teeth.

Cutting System and Set Up

For all cutting procedures, test or control diamond burs were mounted on a new single nozzle Midwest Quiet-Air high-speed handpiece (Midwest Dental Products Corp., Des Plaines, IL). The handpiece was connected to a compressed air tank with a regulator, set to provide airflow at a constant pressure of 32 pounds per square inch (psi). Maximum bur rotation rate (400,000 ± 2,000 rpm) occurred when the burs were freely spinning. In the current experimental set up, the revolutions per minute were monitored with an optical tachometer (Model no. 9732 MEX, Monarch Instruments, Amherst, NH) mounted on the handpiece head. In order to facilitate the tachometer reading, the posterior part of the head of the handpiece was modified and the turbine rotor painted half black and half white (Fig 4).

The amount of room temperature cooling water was regulated with a valve and maintained constant at 25 mL/min. This coolant flow was established by having two investigators calibrate the flow of water in their handpieces according to their clinical preferences. For this purpose, the handpieces were run for 1 minute, water collected in a calibrated pipette, and measured. This procedure was repeated three times and a mean water volume of 25 mL/min established.

The handpiece was mounted on a low-friction ball bearing slider (Parker Automation Positioning Systems, Daedal Division, Irwin, PA) that was maintained radial to the tooth surface (Fig 5). Therefore, the coolant spray was always directed to the bur without interference with the tooth, as may happen in the clinical setting.

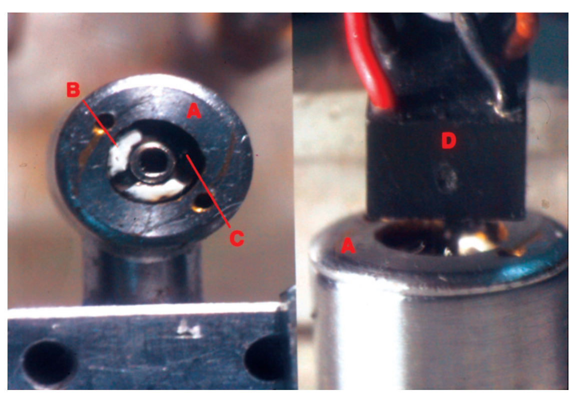

Figure 4. Composite view of the posterior aspect of the head of the handpiece and the optical tachometer. Turbine motor was painted half white and half black to facilitate tachometer reading. Posterior aspect of the handpiece (a); white half of turbine rotor (b); black half of turbine rotor (c); and optical tachometer (d).

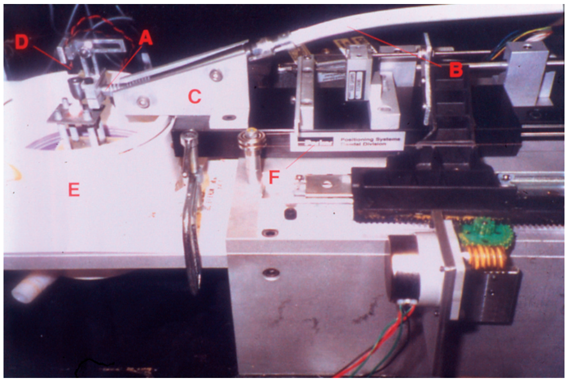

Figure 5. General view of system set up. High-speed handpiece (a); handpiece tubing (b); handpiece mount (c); optical tachometer (d); custom-made water bath (e); and low-friction ball bearing slider (f).

Position (displacement) of the handpiece was measured with a linear variable differential transformer (LVDT), calibrated with its zero reference position on the tool surface. The contact force between the bur and the tooth was measured with a strain-gauge load cell (500 g maximum load, Transducer Techniques Co., Temecula, CA).

A computer system was set to turn on the handpiece, activate the movement of the sliding device, and start the cutting action. An electronically controlled stepper motor was used to move the sliding device-handpiece assembly at a rate set by the computer. The crown of the tooth was cut with the bur parallel to the long axis of the tooth in a horizontal plane (Fig 6). A summary of the system set up is presented in Table 2.

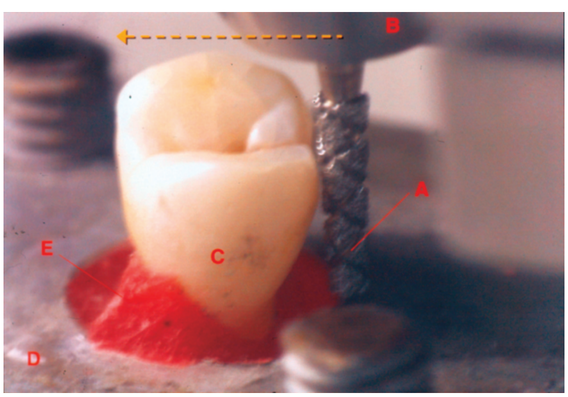

Figure 6. Close-up view of cutting action. Coolant spray was always directed to the bur without interference. TDA bur (a); handpiece head (b); premolar tooth (c); stainless steel supporting plate (d); and autopolymerizing pattern resins (e). Arrow indicates direction of cutting action.

Load and rate of advancement are directly related (i.e., a higher load produces a faster rate of advancement), and so it is not possible to set both independently. In clinical practice, the clinician is aware, in a general sense, of the amount of force he/she is applying, the rate of bur advancement (tooth removal), and the relation between them. In particular, if the rate of bur advancement becomes too rapid, he/she can reduce the applied load. To simulate this in our experimental apparatus, the control system (load cell-software stepper motor) was designed to apply a constant nominal load of 125 g, but to reduce this load if the rate of advancement exceeded an arbitrarily set limit (0.15 mm/sec). This protocol was implemented as follows. The computer monitored both load and rate of advancement. If the load was more than the nominal value, the rate of advancement was decreased, until the load was below the limit. If, on the other hand, the load was less than the nominal value, the rate of advancement was increased to increase the load, provided the rate limit was not exceeded. When the rate limit was reached, bur advancement was continued at the limiting rate (Table 2).

Cutting Procedure for Premolar Teeth

Two cuts were done on the mesial and distal surfaces of each premolar tooth, respectively, for a total of 20 cutting actions per group. Control and test burs were used on the same tooth with an alternated sequence (i.e., C1 and then T1; C2 and then T2; and vice versa). Before performing the second cut, the first one was sealed with composite resin to avoid false temperature readings due to dentin exposure. The depth of each cut was variable and was input in the computer based on the dentin-enamel thickness recorded in the preliminary radiograph. The maximum height of each cut (length of bur engaging tooth structure) was the same for control and test burs used on the same tooth (to ensure uniform bur–tooth contact) and varied in the premolar and molar testing between 5 and 6 mm (Fig 2). The cutting action was automatically stopped by the computer 0.5 mm short of the pulp chamber. This allowed a comparison of the temperature generated by each bur at a predetermined distance from the pulp chamber. Temperature changes in the pulp chamber were recorded from the beginning of the cutting action up to 4 min after the end of the cutting procedure. The computer also recorded the time required to complete the cut.

Cutting Procedure for Molar Teeth

Four cuts (one for each bur) were made on each molar tooth, respectively, on the buccal, mesial, lingual, and distal surfaces. After the completion of each cut, the

Table 2. Summary of the System Set Up for Both Premolar and Molar Cutting Tests

	Value	*Monitoring System*
Free bur rotation	400,000 ± 2,000 rpm	Optical tachometer
Cooling water flow and temperature	25 mL/min at room temperature	Valve
Baseline tooth temperature	34°C	Thermocouple and digital thermometer
Maximum load	125 g	Strain-gauge system and software
Maximum advancement rate	0.15 mm/sec	LVDT and software
Software control mechanism	Advancement rate ↓: load ↑ up to 125 g	Custom LabView Program
Software control mechanism	Load ↓: advancement rate ↑ up to 0.15 mm/sec	Custom LabView Program

area was sealed with composite resin to avoid false temperature readings, as described previously. Each bur was used for a total of 60 cuts in a random order. Possible differences due to the anatomical characteristics of each tooth surface were normalized by cutting an equal number of buccal, lingual, mesial, and distal surfaces (15 in each group). In contrast to the cuts done on premolars, for the molars each cut was only 2 mm in depth. Intrapulpal temperature and the time required to complete the cut were recorded, as with the premolar teeth.

A sample of each type of bur was examined under scanning electron microscopy (LEO 982 Field Emission, Thornwood, NY) before and after cutting to determine diamond configuration and accumulation of dental debris. X-ray energy-dispersive spectroscopy (EDS) was used to qualitatively check the elements present on the bur-cutting surface before and after cutting procedures.

Data Recording and Analysis

The outputs from the thermocouples, tachometer, LVDT, and load cell were recorded and plotted with the total duration of cutting by a software program (Lab View MIO-16 Data Collection Card, National Instruments, Austin, TX) (sampling rate: 25 readings/sec) operated by a personal computer (Apple Macintosh 266 MHz Power PC, Cupertino, CA). For temperature generation, these values were then compared using ANOVA (statistical significance at $p \leq 0.05$). The comparisons of primary interest were C1 versus T1 and C2 versus T2 to evaluate bur design (conventional or channeled), and C1 versus C2 and T1 versus T2 to evaluate bur grit size (125 μm diamond grit or 180 μm diamond grit). Also, the data for the molars were averaged over 60 cuts to evaluate temperature generation as a function of continued use. The average slopes of the plots of the temperatures as a function of time (in linear coordinates) were compared to assess the pattern of temperature change.

The data files for the cutting rate (the slope of the displacement vs. time curve) showed an initial transition area upon bur contact with the tooth, followed by a steady state area once the bur was fully engaged. In the steady state area, values of load, rpm, and cutting rate were approximately constant. Data in the steady state condition were used to represent the bur performance obtained in each experiment. A plot of the displacement versus time values was examined and the starting point for the steady state range was identified, based on the point at which the relationship became essentially linear. The cutting rate was then determined by the slope of the least-squares best-fit straight line to the data in the steady state region. Values for the load and rpm were then calculated by averaging the data over this range. These values were then compared using ANOVA (statistical significance set at $p \leq 0.05$) and the Tukey multiple range test. The comparisons of primary interest were: C1 vs. T1 and C2 vs. T2 to evaluate for bur design (conventional or channeled), and C1 vs. C2 and T1 vs. T2 to evaluate for bur grit size (125 μm diamond grit or 180 μm diamond grit). Part of the data for the molars was also combined (rate/load) to characterize the overall ease of bur advancement.

Results

Temperature—Premolar Teeth

For the premolar teeth group, the mean temperatures recorded with each of the different burs were 2–3°C below the baseline intrapulpal temperature of 34°C (Table 3). In this part of the study, the

Table 3. Means and Standard Deviations* for Recorded Intrapulpal Temperature on Premolar Teeth

	C1	*T1*	*C2*	*T2*
Temperature (°C)	30.8937	32.0748	31.3228	31.5894
Standard deviation	(2.3593)	(3.6016)	(2.2839)	(1.8747)

*Means and standard deviations computed to 4 decimal places for consistency in the statistical analysis.

Table 4. Means and Standard Deviations* (in Parenthesis) for Heating Time Constant, Cooling Time Constant, and Delay Time in Premolar Teeth

	C1 and T1	*C2 and T2*	*p Values*
Heating time constant (sec)	13.3525 (2.6246)	13.8825 (2.82909)	0.5427
Cooling time constant (sec)	65.885 (7.05218)	66.2225 (5.4842)	0.8667
Delay time (sec)	1.625 (0.83721)	1.49 (0.62568)	0.5669

All values expressed in seconds.
*Means and standard deviations computed to 4 decimal places for consistency in the statistical analysis.

cutting procedure stopped 0.5 mm short of the pulp chamber, leaving a thin layer of dentin from the pulp chamber. No significant differences were noticed with either bur design or either diamond grit.

Time/temperature constants recorded for premolar teeth are illustrated in Table 4. No significant difference was seen between the time/temperature constants and delay times of the premolar teeth cut with finer or coarser burs.

Temperature—Molar Teeth

Preparation on the molar teeth varied from that on the premolar teeth as a 2-mm cut was performed on each surface of each tooth. A variable amount of dentin was left surrounding the pulpal chamber, depending on the anatomy of the tooth. The same bur was used for all 60 cuts, allowing the evaluation of the bur performance during an extended period of use. The resultant mean temperatures recorded with the different burs ranged between 0.2°C and 0.9°C below the established baseline intrapulpal temperature, and no statistical difference was found in terms of bur design and diamond grit (Table 5). During the 60-cut usage period, the greatest temperature increase was seen with the finer 125-μm-grit burs, although the difference was not statistically significant in spite of significant changes in the surface of all burs that were evident when comparing SEM microphotographs before and after extended use. Comparison of the slopes of the generated curves throughout the 60 cuts showed no difference between groups.

Table 5. Means and Standard Deviations for Recorded Intrapulpal Temperature on Molar Teeth

	C1	*T1*	*C2*	*T2*
Temperature (°C)	33.8112	33.6974	33.1138	33.4125
Standard deviation*	(3.1241)	(4.9063)	(2.6846)	(2.4994)

*Means and standard deviations computed up to 4 decimal places for consistency in the statistical analysis.

SEM examination revealed noticeable wear on the bur surface in contact with the tooth as well as the accumulation of debris. Blunting of the diamond-cutting surface was also observed for the tested burs. EDS analyses identified calcium and phosphorus on the surface of the bur after use, consistent with accumulation of debris from teeth. A number of possible quantitative measures of bur wear were examined, including topographical measurement of grit sharpness and changes in overall bur size and shape. Unfortunately, the relatively large size of the grits compared to the bur diameter produced unacceptably large variability in the preliminary measurements. Therefore, whereas SEM observations provided a descriptive evaluation of test and control burs for the current study, additional work will be necessary to develop an accurate quantitative measurement. At least two approaches seem possible. The number of burs tested could be significantly increased, making it possible to deal with the variability statistically. Alternatively, initial examination of burs could be used to identify specific grits on each bur, which would then be tracked by periodically examining the bur during use.

Cooling, using room temperature water at a flow rate of 25 mL/min, was evidently sufficient with the current apparatus so that any difference in bur performance, as well as any difference in the ability of the burs to pump coolant, was insufficient to overcome its effects.

Cutting Efficiency and Bur Longevity—Premolar Teeth

The means and standard deviations for the recorded values of load, cutting rate and rpm for the premolar teeth series are presented in Table 6. No significant difference was found between paired test and control burs for the cutting load and rate required to cut into the tooth, in spite of the variations in bur design. Examining the load and cutting rate data together, however, a non-significant trend was found for test burs in

Table 6. Means and Standard Deviations (in Parenthesis) for Testing of Load, Cutting Rate, and Revolutions Per Minute in Premolar Teeth

	C1	*T1*	*C2*	*T2*
Load	107.0917 (23.5253)*	113.4294 (9.3121)	113.3553 (10.4947)	120.7239 (10.9500)
Rate (mm/min)	0.0930 (0.0409)	0.0809 (0.0170)	0.0854 (0.0233)	0.0830 (0.0280)
RPM	259,058.9474§ (44,091.6142)	236,100.5556§ (26,141.1183)	254,647.3333§ (20,492.6044)	224,235.6250§ (60,123.0160)

*Means and standard deviations computed up to 4 decimal places for consistency in the statistical analysis.
§Variable with significant difference.

which the advancement through tooth structure was more difficult (higher load and/or lower rate) than for their control counterparts. A significant difference was noted in the revolutions per minute at which test and control burs worked. Both test burs (T1 and T2) rotated with fewer revolutions per minute compared to their controls. This indicates greater resistance to bur rotation during the use of the test burs. The origin of this effect is still uncertain, but it may reflect increased resistance to rotation caused by motion of water along the channels or differences in the cutting efficiency of the diamond abrasives.

Cutting Efficiency and Bur Longevity—Molar Teeth

Data from the molar testing were analyzed in three distinct ways: (1) to examine the effects of bur design, burs of identical grit size were paired and the data averaged over the 60 cuts; (2) to examine the effects of grit size, burs of similar design (channeled and conventional) were paired and the data again averaged over 60 cuts; and (3) the performance of each bur as a function of continued use (cut number) was examined.

(1) *Effects of bur design*. The means and standard deviations for the recorded values of load, cutting rate, and rpm for molar teeth are presented in Table 7. Note that in comparison to the results in the premolar series, these data show the averages obtained for burs used for an extended series of cuts (60). The recorded values indicate that the Brasseler CRF bur (C2) required a significantly lower load when compared to the NTI bur (T2). Data for the other pair of burs (C1 and T1) in this test, as well as for both sets of burs in the premolar tests, appeared to show the same trend. However, the differences observed were not large enough to be statistically significant ($p > 0.05$).

The average rate at which each bur was cutting into the sample teeth was significantly higher for both control burs compared to the test burs. This is paralleled by differences observed in the premolar study, however, at a level below the established statistical threshold.

As discussed before, load and cutting rate are interrelated; both were subject to some control (limitation) in this study. Examining the load and cutting rate data together, a consistent pattern is found: advancement of the bur is more difficult (higher load and/or lower rate) for the test burs compared to the paired control burs. This may also be seen by combining the data into a single parameter (rate of advancement/load), which captures the overall ease of bur advancement. As shown in Table 8, the two test burs had lower values of this combined parameter than the paired control burs, indicating more difficult bur advancement.

Table 7. Means and Standard Deviations (in Parenthesis) for Testing of Load, Cutting Rate, and Revolutions Per Minute on Molar Teeth

	C1	*T1*	*C2*	*T2*
Load	96.7013 (15.7293)*	104.4417 (11.4266)	81.8910§ (19.9029)	98.5694§ (13.9067)
Rate (mm/min)	0.1087§ (0.0226)	0.0816§ (0.0197)	0.1107§ (0.0204)	0.0994§ (0.0274)
RPM	261,120.0000 (34,042.9569)	269,440.0000 (29,778.9131)	278,017.6829§ (32,101.2707)	258,847.1607§ (42,786.4881)

*Means and standard deviations computed up to 4 decimal places for consistency in the statistical analysis.
§Variable with significant difference.

Table 8. Means for Cutting Rate, Testing of Load, and Cutting Rate/Load on Molar Teeth

	C1	*T1*	*C2*	*T2*
Rate (mm/min)	0.1087	0.0816	0.1107	0.0994
Load	96.7013	104.4417	81.8910	98.5694
Rate/Load	0.0011	0.0008	0.0014	0.0010

Means computed up to four decimal places for consistency in the statistical analysis.

The rpm recorded during cutting for the Brasseler CRF bur (C2) was statistically higher than that for its test counterpart (NTI bur), indicating a higher resistance to rotation of the test bur. This is the same pattern observed in the premolar tests. The difference in values for the other pair of burs [Brasseler Coarse (C1) vs. TDA (T1)] was very small and not significantly different.

(2) *Effects of grit size*. Burs were paired by surface design and compared. Group A consisted of the conventional burs (Brasseler Coarse and Brasseler CRF) and Group B consisted of the channeled burs (TDA and NTI). Thus each group had a 125-μm grit and a 180 μm grit bur (Table 9).

For the control Group A, statistically significant differences were found for the load (lower for the coarser grit) and value of rpm (higher for the coarser grit). The difference in the cutting rate was not judged significant. For Group B, the difference in the cutting rate (higher for the coarser grit) was judged significantly different, but not the differences in the load and rpm. In terms of the combined (rate/load) parameter, as would be expected, the coarser burs were found to produce easier advancement (Table 8). Overall, these results indicate that cutting is generally easier (lower load, higher rate, and higher rpm) when using burs with coarser grits.

(3) *Effects of continued use*. Changes in bur performance with use (cut number) exhibited a complicated pattern. The two coarser burs (C2 and T2) showed a decrease in the required load and in the rpm with increasing cut number. In addition, the T2 bur showed an increase in cutting rate (other effects were not judged significant). These results indicate that the ability of the coarser burs to advance actually increased with use, but that resistance to their rotation also increased. This emphasizes the importance of examining both the load (and/or rate) and the rpm when assessing bur performance. For the coarse burs, the load data seem to indicate an improvement in performance with bur use, but the rpm data make it clear that, at best, what has happened is a shifting of the "burden" of material removal from the applied load (normally supplied by the clinician) to bur rotation (supplied by the handpiece). It can be speculated that this reflects a gradual shift in the removal mechanism from that produced by the applied normal force to that produced by friction parallel to the bur/tooth contact. In contrast, the finer burs (C1 and T1) showed a decrease in the cutting rate with cut number, and split results for the rpm (increased with use for C1, but decreased for T1). No significant changes were found in the load required to complete the cutting actions.

These differences between burs must relate to the specific way in which the bur surfaces are altered during wear and to the extent of surface clogging. SEM examination of used burs showed noticeable wear of the surfaces in contact with the tooth and a build up of debris. EDS analyses identified calcium and phosphorous on the worn surfaces, consistent with accumulation of tooth debris. Blunting of the cutting surface/diamonds is presumably responsible for the decrease in rpm (increase in resistance to bur rotation) observed in most of the burs. However, it was not possible in this to quantify the wear or the extent of clogging in a fashion that would allow us to make definitive comparisons between different burs.

Table 9. Comparison of Means and Standard Deviations (in Parenthesis) for Load, Cutting Rate, and RPM for Burs with Similar Surface Configuration and Different Grit on Molar Teeth

	C1	*C2*	*T1*	*T2*
Load	96.7013§ (15.7293)*	81.8910§ (19.9029)	104.4417 (11.4266)	98.5694 (13.9067)
Rate (mm/min)	0.1087 (0.0226)	0.1107 (0.0204)	0.0816§ (0.0197)	0.0994§ (0.0274)
RPM	261,120.0000§ (34,042.9569)	278,017.6829§ (32,101.2707)	269,440.0000 (29,778.9131)	258,847.1607 (42,786.4881)

*Means and standard deviations computed up to 4 decimal places for consistency in the statistical analysis.
§Variable with significant difference.

Consistent with the previous results, when the data were combined in the form of rate/load, coarse burs seemed to cut faster into tooth structure as each successive cut was performed. Specifically, the values of rate/load increased with successive cuts for coarser burs, whereas it showed no significant difference in finer burs.

The slopes of the data curves for the experimental variables were also compared with linear regression analysis (C1 vs. T1 and C2 vs. T2), but no significant differences were found.

Discussion

Research published in the area of dental burs and tooth cutting is inconsistent. Studies published three and four decades ago report on the effects of tooth cutting using dental high-speed handpieces available at the time,[10,11,22] which differ significantly from today's technology.

The dental industry has developed ultra-high speed handpieces and continues to work on the development of new bur designs that enhance the cutting procedure while minimizing trauma to the tooth. Claims of rapid heat dissipation due to design modifications, specifically the incorporation of channels in the bur surface, are now common and endorsed by practitioners.[17] However, studies done to confirm the superior performance of these designs have not been conclusive due to inadequate control of the experimental variables. Moreschi and Gorni reported the absence of evident pulpal damage on clinically prepared teeth, even though they acknowledged "getting close to the pulp."[18] However, in their clinical study, variables such as cutting load and coolant flow rate were not standardized and pulpal damage was evaluated subjectively by means of radiographs. Laforgia et al reported a lower temperature increase in the pulp chamber of extracted teeth prepared with TDA burs when compared to conventional diamond burs.[20] However, a small sample size consisting of anatomically different teeth cut with undefined hand-pressure and no statistical analysis make the conclusions uncertain.

The results of this study demonstrated that preparation of teeth with cooling water at room temperature did not produce a significant change in temperature in the pulp chamber with either bur design, with either grit size, and during extended use. Temperatures did not vary significantly between different burs during premolar and molar testing.

For the premolar teeth, tooth preparation was completed with a new bur (each bur used only twice) and terminated at 0.5 mm from the pulp chamber regardless of the thickness of dentin and enamel. This deep preparation, uncommon in the clinical setting, was adopted to test the bur designs in an extreme condition. It allowed a comparison of the temperature generated by each new bur at a close and constant distance from the pulp chamber. Even with this limited residual dentin thickness between the bur and the pulp chamber, no clinically harmful temperature changes were recorded and no significant differences were noted among the groups. The mean temperatures recorded with each of the different burs were 2–3°C below the baseline intrapulpal temperature of 34°C. This decrease in recorded temperature is most likely a result of the availability and temperature of the coolant rather than an effect of the bur design or the diamond grit. This suggests that, from a thermal standpoint, tooth preparation with new burs at a distance of 0.5 mm or greater from the pulp chamber is a safe clinical procedure, provided that sufficient coolant is available with any of the bur designs used in this study.

Data from the tests on molar teeth were analyzed in three distinct ways: (1) to examine the effects of bur design, burs of identical grit size were paired and the data averaged over the 60 cuts; (2) to examine the effects of grit size, burs of similar design (grooved and conventional) were paired and the data again averaged over 60 cuts; and (3) the performance of each bur as a function of continued use (cut number) was examined. The cuts on the molars were 2 mm deep, stopped at a variable distance from the pulp chamber, and varied according to tooth surface and between teeth.

The resultant mean temperatures recorded with the different burs ranged between 0.2°C and 0.9°C below the established baseline intrapulpal temperature, and no significant difference was found in terms of bur design and diamond grit size. A comparison with the data obtained in the premolar series indicated a smaller mean intrapulpal temperature reduction, 1–2°C, which can be explained by the greater thickness of residual dentin remaining. In the premolar teeth, the cuts were generally deeper, leaving a thinner layer of dentin between the pulp chamber and the coolant.

For the molar experiment, data were analyzed as a function of continued use; the greatest temperature increase was seen with the 125 μm grit burs, although the difference was not statistically significant, and was 4°C below the critical limit of 42.5°C described by Zach and Cohen.[3,4] Moreover, although significant changes to the bur surface were noted for all burs in the form of wear and clogging when comparing SEM microphotographs before and after extended use, these changes also did not produce large variations in pulp chamber temperature. This suggests that there are no significant intrapulpal temperature changes as a function of repeated use, in spite of the fact that different burs and different amounts of use do have significant effects on cutting efficiency.

The findings in the premolar and molar tests of this study are an indication that the cooling method employed was sufficient to suppress excessive heating of the pulp chamber under any of the conditions tested. The use of a moderate water flow of 25 mL/min counteracts the possible heating of the tooth and damage to the pulp is not expected to occur at the temperatures recorded in this study. Since test and control burs were paired on each premolar tooth, no difference was expected due to the specific thermal behavior of each tooth between conventional and channeled burs. Also, the values of the time/temperature constants, delay times, and corresponding standard deviations of the premolar teeth used for the coarser or finer burs were very similar, therefore indicating a relatively homogenous sample.

The absence of large pulp chamber temperature increases under these controlled conditions is consistent with the fact that cutting is generally clinically successful in spite of the inherent variability in conditions. Failure (damage to the pulp) is a relatively rare occurrence, presumably a consequence of an unusual condition or set of conditions, for example, full or partial loss of coolant flow. We speculate that it is under such circumstances that performance differences between burs, such as those examined in this study, could become critical in terms of the occurrence of thermal damage. Our results, in contrast to some previous studies,[18-20] did not indicate that the presence of one or two grooves on the bur surface significantly affected the recorded temperature in the pulp chamber of natural teeth during tooth preparation when compared to conventional diamond burs. Moreover, both bur designs and both diamond grits led to a decrease in the recorded intrapulpal temperature. One could speculate that the experimental cutting sequence only produced a single cut on the tooth surface and that this study design does not reproduce the more extensive tooth preparation that is generally required for partial and complete coverage crowns. Whereas a complete tooth preparation (extended to all tooth surfaces) was not attempted in this study, we believe that in such cases the availability of coolant to the tooth structure could actually be greater due to an increased surface area of dentinal exposure to it, thus avoiding excessive temperature increases. Therefore, claims by manufacturers of less tooth trauma due to the presence of channels on a diamond bur surface were not confirmed in this research, even in cases of long-term bur use. Temperature generation appears to be related directly, dominated by to, and the coolant temperature and flow rate rather than to specific modifications on instrument design.

Recent studies have addressed the effects of variables such as handpiece cooling rates,[14] diamond bur cutting efficiency,[23,24] and cutting load[25] under controlled laboratory conditions using a standardized protocol and current instrumentation. Such studies have provided a clear insight on the effect of the different variables involved in cutting. However, these studies were performed on a machinable glass-ceramic substrate and results must be taken with caution when extrapolated to clinical conditions. Although Macor, the substrate used in these studies, has many properties (hardness, elastic modulus, and thermal properties) that are comparable to those of dental enamel,[26] the thickness of enamel varies in different areas of each tooth and in different teeth.[27] Also, most dental restorative procedures involve preparation into the dentin, which has microstructure and properties that significantly differ from those described for the enamel.[28-30] In addition, teeth show significant variability in both material properties and geometry.[30-34] Since, in general, the cutting Q3
efficiency of a particular tool design will be affected by the substrate geometry and structure, as well as the material properties, measurement of bur performance against natural teeth, in an environment that simulates clinical practice, is especially significant. The use of recently extracted natural teeth also allows for a more realistic simulation of the clinical conditions as well as capturing the effects of the natural variability among teeth on

bur performance. In this way, a clearer understanding of the effect of different variables during the cutting procedure can be provided.

Claims of higher cutting efficiency related to the incorporation of channels in the bur surface are now common and endorsed by practitioners.[17] In this study, data for load, cutting rate, and rpm suggest that channeled burs do not show higher cutting efficiency than conventional diamond burs. Moreover, the experimental channeled burs required a higher load and exhibited a lower rate of cutting, suggesting that their advancement through tooth structure is apparently more difficult. Their lower rpm values seem to confirm this behavior, possibly suggesting an increased coefficient of friction for the test burs. The causes for this lower rpm are uncertain but it is speculated that it could be the result of increased resistance to rotation caused by motion of water along the channels and different configurations and cutting efficiency of the diamond abrasives.

The combined data for the molar testing seem to confirm this tendency. Control burs require less time (higher rate of advancement) to remove a certain amount of tooth structure, therefore showing a greater cutting efficiency.

Conclusion

In this study, a description of the phenomenon of tooth cutting in a highly controlled in vitro environment was provided, characterizing intrapulpal temperature generation, bur cutting efficiency, and durability when using channeled and conventional non-channeled diamond bur designs.

Within the limitations of this study, it was determined that tooth preparation with room temperature cooling water did not lead to a significant temperature increase in the pulp chamber of extracted teeth with either bur design (conventional or channeled diamond surface) or either diamond grit size (125 μm or 180 μm), nor during extended use. Furthermore, the mean temperature recorded during and after the cutting procedure was lower than the baseline intrapulpal temperature. Temperature generation appeared to be dominated by coolant temperature and flow rate rather than by specific features of the bur design. In addition, it was also established that different bur designs (conventional or channeled), diamond grit size (125 μm and 180 μm), and extended use have significant effects on the measured cutting performance. Specifically, conventional non-channeled and coarser burs showed greater cutting efficiency than channeled and finer burs, respectively.

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