Effects of Mechanical and Thermal Fatigue on Dental Drill Performance

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Osseous integration of dental implants depends on the use of proper surgical technique during site preparation, including the prevention of thermal injury to the surrounding bone. Heat generation during drilling has been reported to positively correlate with the production of forces at the surgical site. In this study, peak torque and axial load levels were measured during a drilling procedure into a polymeric material simulating the human mandible. Axial rotary milling was performed using 5 different twist drill designs (3i Irrigated Tri-Spade, 3i Disposable, Nobel-Biocare, Straumann, and Lifecore) of 15 to 20 mm in length and 2 to 2.3 mm in diameter, at a free-running rotational speed of 1,500 rpm and continuous feed rate of 3.5 mm/second, to a total depth of 10.5 mm. Ten drills representing each of the 5 types (n = 50) were subjected to 30 individual drill "pecks" and heat-sterilized every 3 "pecks" to determine the effects of cyclic mechanical and thermal loading on drill performance. Normal stress (σ) and shear stress (τ) were calculated from the kinetic data and drill geometries. A drill efficiency coefficient (μ) was also calculated as the ratio of torsional resistance to translational resistance. Overall, the hypotheses of drill performance dependency on drill type as well as mechanical and thermal accumulated loading were tested and confirmed ($P < .05$). The 5 drill types produced a range of normal stresses (2.54 to 5.00 MPa), shear stresses (9.69 to 29.71 MPa), and efficiency (1.16 to 3.16) during repeated testing. Scanning electron microscopic images revealed minor deformations in the cutting edges of the tri-spade drills following testing. (INT J ORAL MAXILLOFAC IMPLANTS 2001;16:819–826)

Key words: *dental instruments, mechanical stress, operative dentistry, torque*

Successful preparation of an implant cavity with minimal damage to the surrounding bone depends on the avoidance of excessive temperature generation during surgical drilling. Because of the low thermal conductivity of cortical bone, heat dissipation occurs slowly and temperature may remain elevated despite the use of external irrigation.[1] Research has demonstrated that thermal damage at the drilling site inhibits the regenerative response in bone healing, slowing the process of osseointegration and potentially resulting in implant mobility.[2–6] Eriksson and Albrektsson[2,7] have reported that bone is more susceptible to thermal injury than previously believed, and that temperatures in excess of 47°C can result in osseous necrosis. Thus, the production of heat during the osteotomy and the methods of heat reduction are major concerns in the dental community.

Numerous researchers have identified and evaluated many factors that affect heat generation at the implant site.[1,6,8–14] Most studies have focused on the relationship between either rotational speed, applied axial force, or drilling depth and the creation of elevated temperature levels. Cordioli and Majzoub[1] found a positive correlation between the maximum temperature generated and a drilling depth of 8 mm during the use of 2-mm twist drills at 1,500 rpm. This result encouraged the present authors to address the measurement of peak stress generation as a relative indicator of the peak elevation of temperature using similar test parameters.

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Table 1 Summary of Drills Used

Drill type	Dimensions (diameter/length)	Characteristics
3i Irrigated Tri-Spade twist	2.3 mm/15 mm	Three narrow cutting edges; internal irrigation cavity
3i disposable twist	2.0 mm/15 mm	Two cutting edges; single-use intent
Nobel Biocare twist	2.0 mm/15 mm	Two cutting edges; single-use intent
Straumann pilot	2.2 mm/17 mm	Two cutting edges
Lifecore twist	2.0 mm/20 mm	Two cutting edges; side grooves for irrigation

Two additional factors that may influence frictional heat and have so far received little attention in the dental literature are drill design and the loss of drill sharpness during repeated usage. In 1972, Matthews and Hirsch[8] measured the temperature elevation in human cortical bone when using a 3.2-mm spiral drill. They recorded significantly higher temperatures when drilling with an old drill (previously used) than with a new one (unused), and found that the application of less pressure resulted in greater heat. Other studies have shown that the loss of drill sharpness is related to the pressure applied during drilling, the number of times the drill has been used, and the methods of sterilization employed.[9,10] In a study on the reduction of bur temperature during irrigation, Yacker and Klein[9] asserted that the length of time that a bur stays sharp is related to the surface treatment and composition of the bur, suggesting that specific bur characteristics affect wear.

With regard to repeated usage, scanning electron microscopy (SEM) has revealed that as few as 12 drilling procedures can degrade the cutting surface of trephine bur drills.[11] Drill designs are classified as disposable when intended to serve in a single surgery, while drills classified as reusable are generally designed to serve for at least 10 surgical procedures. The Medical Data International report on the United States dental implant market indicates that the average implant-based restoration procedure involves the placement of 2.5 dental implants, meaning that a reusable drill should retain its cutting surface for the preparation of at least 25 implant cavities.[15] Loose guidelines for the number of uses per drill are given by manufacturers, but in clinical practice these guidelines are followed at the discretion of the surgeon. Clearly, a shortage of scientific data on the actual longevity of surgical drills still exists, and without this knowledge it remains difficult for a surgeon to assess the proper time to replace a used drill with a new, unused one.

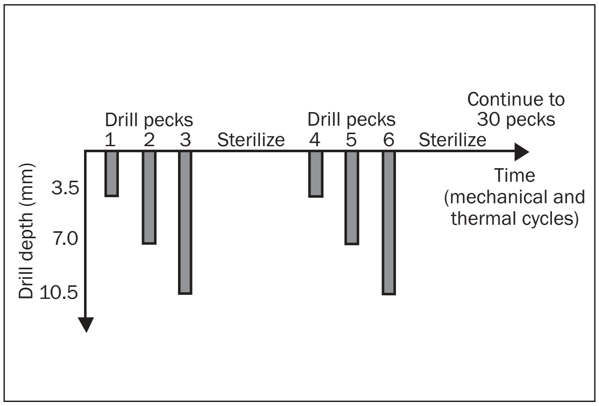
The overall objective of this study was to investigate the effects of repeated drilling and sterilization on drill performance. It was hypothesized that different commercial drill designs would respond uniquely to mechanical and thermal fatigue. The change in the mechanical stress state during cyclic procedures was determined and used to quantify dental drill cutting efficiency.

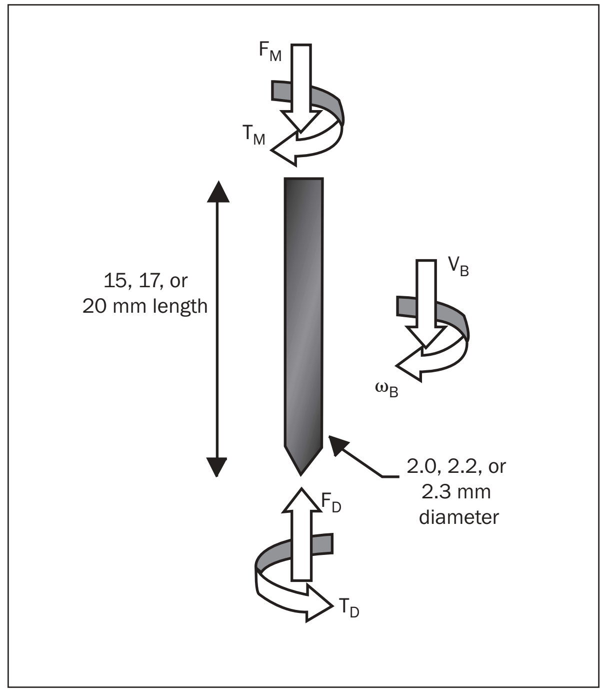
MATERIALS AND METHODS

Five typical dental drill types were evaluated in the following study. Ten drill bits of each type were submitted to cyclic mechanical and thermal loading (for a total of n = 50 individual drill bits). Commercially available, stainless steel (400 series), reusable and disposable drill types were compared. Reusable types included the Lifecore 2-mm twist drill (Lifecore Biomedical, Chaska, MN); the 3i 2.3-mm Irrigated Tri-Spade twist drill (Implant Innovations, Palm Beach Gardens, FL); and the Straumann 2.2-mm pilot drill (Straumann, Waltham, MA); while disposable types included the Nobel Biocare 2-mm twist drill (Nobel Biocare USA, Yorba Linda, CA) and the 3i 2-mm disposable twist drill (Table 1).

An acetal homopolymer (Delrin Acetal, Commercial Plastics, West Palm Beach, FL) was used to simulate living maxillofacial bone as the drilled substance. Delrin rods of uniform density (1.41 g/cm^3) were prepared into cylindric blocks of 30.53 mm length and 7.97 mm diameter. The use of a homogeneous, isotropic material minimized the variability that cortical/cancellous bone samples would have incorporated into the results. The implications of this choice in a drilling substance are further elucidated in the Discussion.

An experimental setup was designed to subject each drill bit to mechanical and thermal loading (Fig 1a). Load and torque were measured while applying a constant feed rate and rotation to each





Figs 1a and 1b Schematic description of experimental protocol and mechanical test environment. *(Left)* Experimental sequence of alternating mechanical and thermal loading applied to each drill bit. Three successive 3.5-mm pecks into the polymeric material (Delrin) were alternated with high-temperature sterilization. *(Right)* Free-body diagram identifying the kinetic and kinematic components of the cyclic mechanical loading environment. Force (F_M) and torque (T_M) were applied by the mill machine; reaction force (F_D) and torque (T_D) were measured in the Delrin block; and the drill bit was advanced with a feed rate (v_B) and rotational speed (ω_B).

drill bit for a total of 1,500 individual drilling procedures (Fig 1b). A Delrin cylinder was placed in a torque measuring unit (Mark 10 Series STJ12 Torque Sensor, Cole Parmer Instruments, Niles, IL), which was mounted on an axial load cell (Mark 10 Series SS500 Load Cell, Cole Parmer Instruments). Digital gauges (Mark 10 Series BGI Gauge, Cole Parmer Instruments) were connected to the torque sensor and load cell and set to record the peak values of torque (in Ncm) and load (in N), respectively, during each procedure. Accuracy of the torque and load cells was confirmed at ± 0.5% and ± 0.1% of known values, respectively. Precision of the torque and load cells was measured with coefficients of variation of 0.16 and 0.17, respectively. The combined instruments were affixed to a mill machine (MSV-21 Vertical Mill, Miyano Machinery USA, Wood Dale, IL), which provided a continuous feed rate of 3.5 mm/second and free-running rotational speed of 1,500 rpm (9,000°/second).[1] A total of 30 drilling cycles were applied to each drill at room temperature (25°C) in sets of 3 pecks of increasing depth, with the final peck per set creating a drill hole of depth 10.5 mm. After each set of 3 pecks was completed, the drill bits were subjected to a thermal cycle via autoclave sterilization (Model 2340M, Tuttnauer USA, Ronkonkoma, NY) to simulate repeated surgical usage. Each sterilization cycle consisted of a 25-minute steam application at 114°C and a 25-minute drying period at room temperature. The drills were then removed from the autoclave for the next series of 3 drilling procedures. This procedure was repeated up to the total of 30 drilling cycles; thus each drill was submitted to 9 total thermal cycles. Following mechanical and thermal loading, SEM images of the drill cutting tips were taken of 2 representative drill types to visually demonstrate any qualitative fatigue effects at a magnification of ×60.

To normalize the kinetic data by drill geometry, normal (σ) and shear (τ) stresses were calculated from the resistance peak load (F_D) and torque (T_D) values, respectively, where:

$$\sigma = \frac{F_D}{A} \qquad \text{and} \qquad \tau = \frac{T_D r}{J}$$

for drill cross-sectional area (A), radius (r), and polar moment of inertia ($J = \frac{1}{2}\pi r^4$). In addition, an efficiency parameter was defined in a manner similar to that of a coefficient of friction (μ), as a ratio of torsional resistance to translational resistance[16]:

$$\mu = \frac{f_T}{F_D}$$

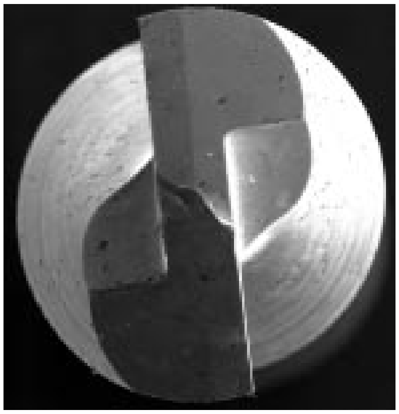
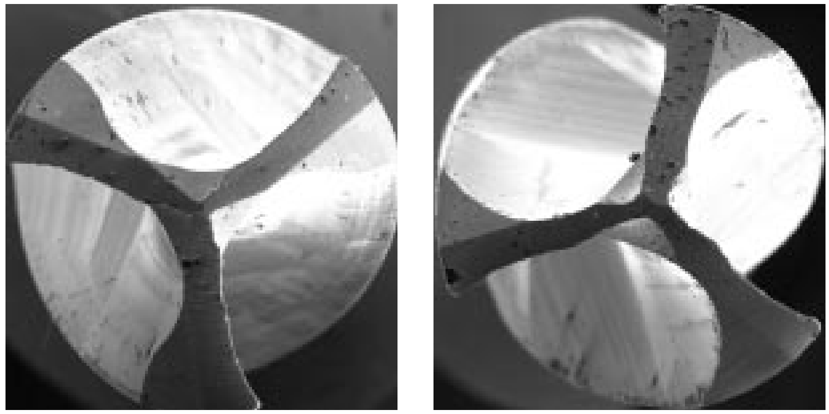


Fig 2 Representative SEM image of an axial view of the cutting tip on a Lifecore drill after 30 drilling procedures (magnification ×60).



Figs 3a and 3b Representative SEM images of axial views of a cutting tip on a 3i Irrigated drill (reusable), *(left)* before and *(right)* after 30 drilling procedures. Note the slightly warped cutting edges on the used drill (magnification ×60).

Table 2 Summary of Drill Performance

Drill type	Normal stress (MPa) (SD)	Shear stress (MPa) (SD)	Efficiency coefficient (SD)
3i Irrigated Tri-Spade twist	4.11 (1.36)	9.69 (2.44)	1.29 (0.63)
3i disposable twist	5.00 (0.46)	11.50 (3.34)	1.16 (0.39)
Nobel Biocare twist	3.16 (0.58)	18.83 (2.60)	3.10 (0.84)
Straumann pilot	2.54 (0.33)	15.80 (1.68)	3.16 (0.49)
Lifecore twist	4.96 (0.68)	29.71 (2.12)	3.05 (0.45)

Aggregate means and standard deviations listed for each drill type were calculated from 30 loading cycles of the 10 representative drill bits of each type (300 samples/drill type).

where f_T is the force-couple associated with the maximum torque ($T_D = f_T r$).

Descriptive data analysis was applied to demonstrate the changes in mean drill performance (± standard deviation) during cyclic mechanical and thermal loading. Statistical analyses were completed to quantify the effects of drill type, mechanical cycles, and thermal cycles as predictors of normal stress, shear stress, and the drill efficiency coefficient. A 1-factor analysis of variance (ANOVA) was used to address the isolated effects of the predictors, while a 2-factor ANOVA clarified any interactive effects. Additionally, cyclic normal stress, shear stress, and the drill efficiency coefficient values were organized as compact variables to examine their time-based changes via a repeated-measures ANOVA. For statistically significant dependencies ($P < .05$), the Fisher protected least significant difference (PLSD) post hoc test was applied. All statistical analysis was undertaken using a commercial software package (Statview v5.0, SAS Institute, Cary, NC).

RESULTS

Normal stress, shear stress, and a coefficient of efficiency confirmed the hypotheses of drill performance dependency ($P < .05$) on both drill type and on mechanical and thermal accumulated loading.

Although drill corrosion is frequently cited as a consequence of the autoclaving procedure, none of the drills tested showed visible signs of surface corrosion during testing. Representative SEM images of a Lifecore drill revealed no corrosion characteristics after 30 drilling procedures were completed (Fig 2). A qualitative assessment of the initial and final states of a representative 3i drill demonstrated slightly warped cutting edges after cyclic use (Figs 3a and 3b). A more thorough examination of the surfaces and cutting edges would be needed to fully characterize the morphologic effects of fatigue loading on the tested drills.

The translational resistance of the advancing drills during each procedure demonstrated clear differences between drill types (Table 2, Fig 4a). Mean

Figs 4a to 4c Plots of translational resistance, rotational resistance, and coefficient of drill efficiency during accumulative mechanical and thermal loading. Each data point represents the mean calculated from 10 representative drill bits of each drill type at that particular load level.

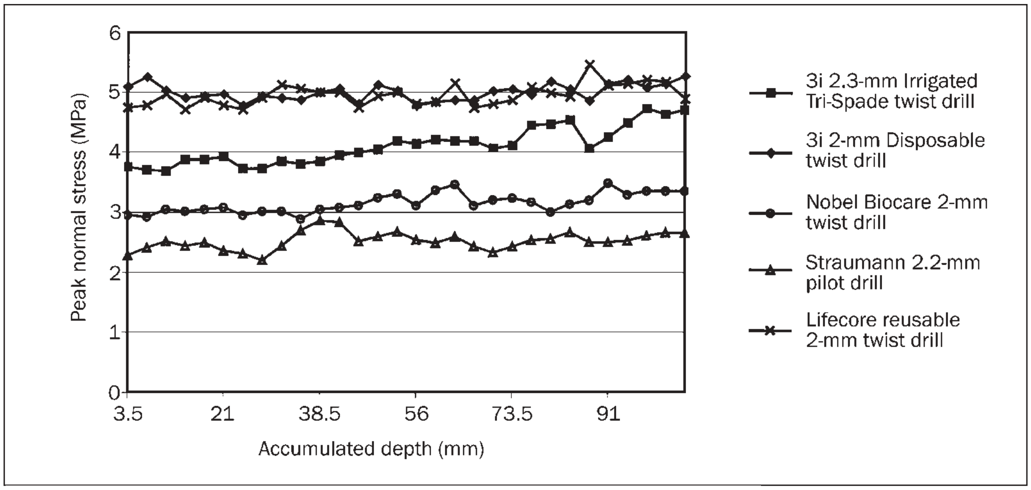


Fig 4a Translational resistance.

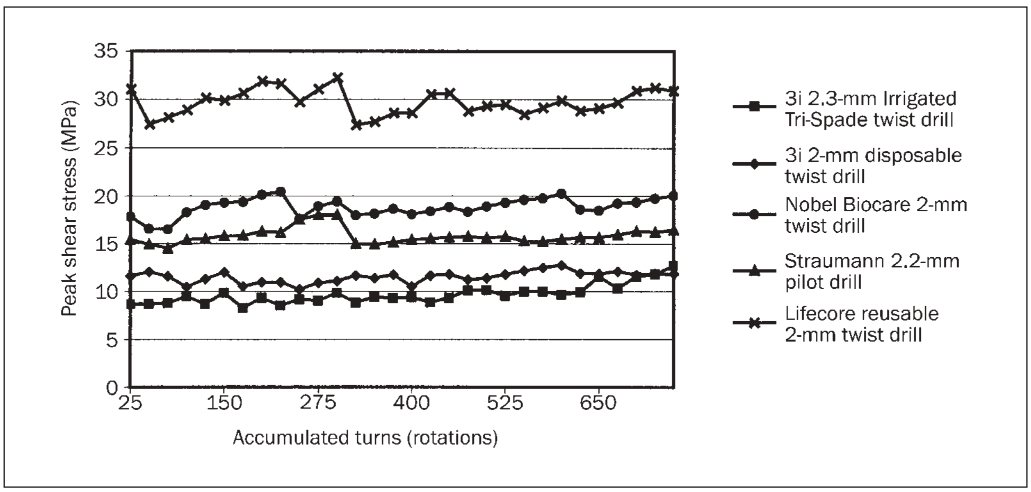


Fig 4b Rotational resistance.

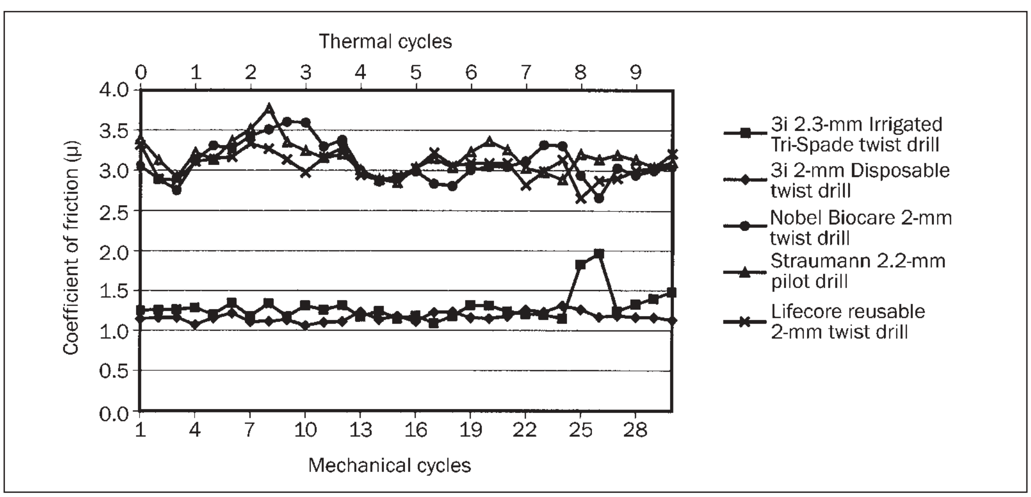


Fig 4c Coefficient of drilling efficiency.

Table 3 Comparative Statistical Results

Test	Normal stress	Shear stress	Efficiency coefficient
One-factor ANOVA*			
Drill type	$P = .0001$	$P = .0001$	$P = .0001$
Mechanical cycles	$P = .9318$	$P = .9995$	$P = .9991$
Thermal cycles	$P = .0635$	$P = .5894$	$P = .4970$
Two-factor ANOVA†			
Mechanical cycles	$P = .0202$	$P = .0001$	$P = .1242$
Thermal cycles	$P = .0001$	$P = .0001$	$P = .0004$
Repeated-measures ANOVA‡			
Within factor alone	$P = .0001$	$P = .0001$	$P = .0011$
Interaction with drill type	$P = .3681$	$P = .0001$	$P = .0126$

*Examined statistical strength of each independent variable alone as a predictor of each dependent variable.
†Examined statistical strength of independent variables as one predictor of drill performance while accounting for the effects of drill type as a second factor.
‡Considered 30 drilling cycles as repeated measurements of drill performance (within factors).
$P < .05$ = statistically significant.

peak normal stress was determined to be statistically dependent upon overall drill type ($P = .0001$). However, the Lifecore (4.96 ± 0.68 MPa) and 3i disposable (5.00 ± 0.46 MPa) drills performed with statistical similarity ($P = .4379$) and with the largest magnitudes in normal stress. Since the variance related to drill type was much larger than the variance related to loading cycles, this effect obscured the single-factor response (Table 3) of mechanical and thermal fatigue ($P > .05$). When the interaction with drill type was accounted for (Table 3), mechanical and thermal loading were identified as significant factors in translational drilling function ($P < .05$). Cyclic loading as a time-based factor strengthened the significance of fatigue due to normal stress (Table 3), although this was not enough to completely overcome the effect of drill type ($P = .3681$).

Rotational resistance during drill usage also identified clear differences between drill types (Table 2, Fig 4b). Overall, mean peak shear stress was statistically affected by drill type ($P = .0001$). This was true for all individual drill comparisons, with the Lifecore drill producing the highest magnitude in shear stress (29.71 ± 2.12 MPa during use). Again, the variance related to drill type was much larger than the variance related to cyclic loading. The drill type effect obscured the single-factor response (Table 3) of mechanical and thermal fatigue ($P > .05$). When the interaction with drill type was accounted for (Table 3), mechanical and thermal loading were identified as significant factors in rotational drilling function ($P < .05$). Cyclic loading as a time-based factor strengthened the significance of fatigue related to shear stress, even to the extent of overcoming the effect of drill type (Table 3).

In an effort to reduce drill translational and rotational performance to a single parameter, the coefficient of efficiency (similar to friction) identified clear differences between groups of drills (Table 2, Fig 4c). In this analysis, both 3i drills appeared to offer less torsional resistance per applied load than the remaining drill types ($P < .05$). The effect of mechanical loading on efficiency had less impact ($P > .05$) than thermal loading (Table 3). The time-based cycling strengthened the significance of efficiency, even to the extent of overcoming the effect of drill type (Table 3).

DISCUSSION

The overall objective of this study was to investigate the effects of repeated drilling and sterilization on the mechanical function of representative dental drills. It was hypothesized that different commercial drill designs would respond uniquely to mechanical and thermal fatigue. The change in the normal and shear stresses during cyclic procedures was determined and used to quantify dental drill cutting efficiency.

The results of this repeated-measures study were sufficient to highlight the effects of dental drill fatigue. Twist drill sizes of 2.0 to 2.3 mm in diameter and 15 to 20 mm in length were chosen for testing, since these are commonly used sizes in oral surgery. Additionally, it has been shown that twist drills of about 2 mm diameter generate a larger rise in the interface temperature than 3-mm twist drills or 3.3- and 4-mm triflute burs.[1] The data presented here support the primary research question that individual drill design strongly affects drilling performance. However, specific design characteristics were not parametrically included in the analysis. Thus, suggestions cannot be made regarding improvements in design-based function. The accumulation of mechanical and thermal cycles also indicated that multiple usages compromise drill function. Although each drill successfully removed material from the drilled substance throughout testing, the reaction stresses were altered with accumulated loadings. This increase in the stress state described by the upward (positive) slopes of Figs 4a and 4b may be an indicator of fatigue damage and degradation of the cutting edges. This response does not suggest that the drills will eventually fail—only that there is an increase in the mechanical resistance with each subsequent use while the same amount of material is removed.

This study offers new insight into dental drill mechanics, as few previous studies report the peak biaxial stress state during drilling. The maximum levels of normal stress shown here correspond with the levels of force observed by Hobkirk and Rusiniak[17] in their 1977 study. In that study, the maximum forces exerted by 20 dental surgeons during drilling in bovine mandibular bone were determined to be between 6 and 24 N. Those forces equate to a stress range of 1.9 to 7.6 MPa in a 2-mm-diameter drill bit, which is similar to the drill performance determined here. In more recent studies using bone,[1,14] constant loads of 19.62 N and 11.8 or 23.5 N were applied to the tested drills, respectively. These loads calculate as 2.8 MPa (3-mm drills) and 6.2 MPa (2-mm drills) stresses[1] versus a 3.8 or 7.5 MPa (2-mm drills) stress state.[14] Again, these axial stress states were similar to those reported here. As no prior studies were found in which the peak levels of torque generation were stated explicitly, there were no torque generation levels or shear stresses available for comparison with the present study. Finally, drilling efficiency was noted only generally in the literature as a positive relationship between average operating speed and the applied force.[18]

The strength of the present study lies in the focus on precision (repeatability) within the experimental design. Multiple representatives of each drill type combined with a homogeneous polymer as a drilling substance minimized the influence of local variances. Of course, the use of Delrin (polyoxymethylene) as a bone analog also represents a significant limitation. This material has been validated in its elastic similarity to bone via previous ultrasonic measurements of its longitudinal (8.99 GPa) and shear (1.76 GPa) stiffnesses.[19] Although the elastic properties are very similar, a heat transfer comparison of the 2 materials' ability to resist heat flow (thermal conductivity, k) indicates that bone would be a better promoter of heat conduction (k = 2.0 N/[°C/sec]) than the Delrin (k = 0.30 N/[°C/sec]).[20] However, the material property that relates the physical implications of the local temperature states during a drilling procedure is the difference in the coefficient of thermal expansion (α_T) between the stainless steel drills (α_T = 17.3 µm/m/°C) and the Delrin (α_T = 80 µm/m/°C) compared to that of bone (α_T = 5.5 µm/m/°C).[21,22] Since the Delrin would actually experience greater radial expansion during a specific temperature differential in comparison to bone, the stresses measured in this study may actually have been lower than if the experimental setup had utilized bone samples. Another possible influence by Delrin on the results was the upward evacuation of cut material along the grooves of the drill in comparison to how morselized human bone would efflux. Overall, because of the cyclic nature of fatigue experiments, it was felt that a polymeric replacement for tissue provided a better functional isolation of the surgical device.[23]

SUMMARY

The present study provides some clear distinctions in the performance of multiple drill types during repeated usage. The results suggest that drill function is dependent upon the specific drill design and that excessive repeated drilling and sterilization will alter the cutting ability of all drill types. A drill efficiency parameter is also proposed as a means to assess the biaxial nature of the drilling stress state. Further investigations are needed to highlight the exact characteristics of drill design that may actually degrade with repeated use. Incorporating the variances (elastic and anatomic) of cortical and cancellous bone would ultimately provide the final clinical assessment of drill fatigue life.

ACKNOWLEDGMENTS

Funding for this project was provided through an internship (BHH) from Implant Innovations (3i), West Palm Beach, FL. Technical assistance was provided by Chip Jones.

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