The Influence of Drill Wear on Cutting Efficiency and Heat Production During Osteotomy Preparation for Dental Implants: A Study of Drill Durability

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Purpose: *The authors evaluated, under conditions simulating implant placement, the cutting efficiency, durability, heat production, and wear of implant drills.* ***Materials and Methods:*** *Osteotomies were performed on bovine ribs using a surgical unit mounted in a testing apparatus. A software program controlled the apparatus and recorded temperatures, depths, and drilling times. Seven brands of drills were tested (Nobel Biocare, 3i/Implant Innovations, Steri-Oss, Paragon, Implamed, Lifecore, and ITI). Spade, twist, tri-flute, and TiN-coated drill designs were evaluated and compared during 100 successive osteotomies. Scanning electron microscopic and energy-dispersive x-ray spectroscopic examinations were performed, and hardness was measured.* ***Results:*** *Two 2-mm drills (Nobel Biocare and 3i/Implant Innovations) had mean removal rates significantly greater than the others ($P < .05$). The 2-mm twist drill design with a low hardness (Implamed) exhibited plastic deformation at the cutting edge, loss of cutting efficiency, and drill fracture. The TiN-coated drills (Steri-Oss and Paragon) showed greater wear and significantly lower removal rates ($P < .05$) than noncoated drills. Temperature increases with different drills were not significantly different at depths of 5 or 15 mm or between 2-mm or 3-mm drills. With 1 exception (the 2.3-mm Paragon drill at a depth of 15 mm), the temperatures generated by the different types of drills were not significantly different. Clinically harmful temperatures were detected only at a depth of 15 mm during 5 osteotomies and coincided with a marked decrease in the rate of drill advancement with a resulting continuous drilling action.* ***Discussion:*** *Temperatures generated at depths of 5 and 15 mm by the different drill types and diameters were not significantly different and, with only 5 exceptions, were clinically safe. Several differences between brands were noted in regard to cutting efficiency and durability, underscoring the importance of material selection and quality on drill performance.* ***Conclusions:*** *Drill design, material, and mechanical properties significantly affect cutting efficiency and durability. Coolant availability and temperature were the predominant factors in determining bone temperatures. Implant drills can be used several times without resulting in bone temperatures that are potentially harmful. Continuous drilling in deep osteotomies can produce local temperatures that might be harmful to the bone.*

INT J ORAL MAXILLOFAC IMPLANTS 2004;19:335–349

Key words: *dental high-speed equipment, dental implants, equipment design, equipment safety, osteotomy*

Dental implant failures are most frequently detected at second-stage surgery and after initial loading.[1–9] Excessive trauma during surgery is considered an important cause of implant failure,[10,11] because thermal, vascular, and mechanical factors contribute to the formation of necrotic tissue, thereby affecting the maturation of tissue at the bone-to-implant interface. It has been reported that

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This study was presented in part at the annual meeting of the Academy of Osseointegration in 2000. It was also presented at the annual meeting of the Academy of Prosthodontics in 2004.

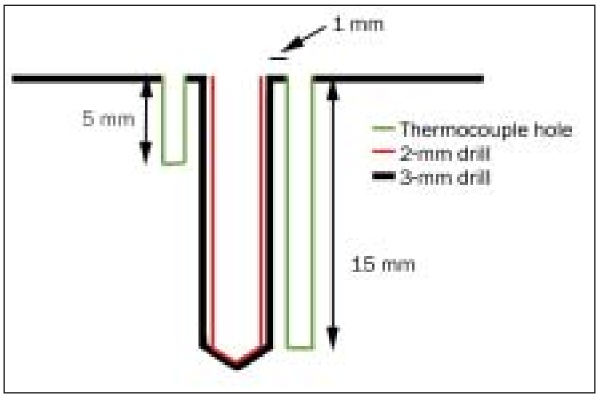


Fig 1 Cross-sectional schematic representation of drilling site and thermocouple position.

heat production leading temperature to rise above 47°C for 1 minute negatively affects living bone[12] and compromises its regeneration.[13–17]

During an osteotomy, most of the energy not used in the cutting process is transformed into heat. The amount of heat depends on the drill flute geometry,[18,19] the sharpness of the cutting tool,[8] the pressure applied,[8] the duration of the cutting action (ie, continuous versus intermittent),[11,20] whether graduated or 1-step drilling is used,[1] the cooling technique,[21,22] the speed of the rotary instrument,[20,23] and the bone density.[24] Repeated use of cutting tools progressively increases their wear and decreases their cutting efficiency, thus producing more frictional heat. It has also been proven that heat production, and with it the potential for damage, increases with the depth of the osteotomy.[25] Excessive heat production caused by worn drills can result in failure to achieve osseointegration.[9–12]

Published reports provide somewhat contradictory guidance in terms of both the occurrence of and the magnitude of the effects of drill wear, presumably because of differences in evaluation criteria and testing conditions. For example, while Brisman[26] and Cordioli and Majzoub[27] used a single drill to prepare multiple root-form implant sites (15 sites and 30 sites, respectively) without detecting a significant change in temperature, Matthews and Hirsch showed that worn drills caused greater temperature elevation and a longer duration of temperature increase than new drills.[28] Jochum and Reichart[29] examined the effects of different cleaning, disinfecting, and sterilizing treatments on drill cutting edge width using scanning electron microscopy (SEM) and concluded that autoclaving led to a loss of sharpness, but that this wear did not seem to significantly impact bone temperatures with drill reuse. Indeed, while they found that there was a greater incidence of higher bone temperatures when drills were used more than 40 times, these temperatures were well below the bone-injuring threshold. Harris and Kohles[30] examined the normal force and torque produced by 5 different types of dental drills while drilling a plastic material (Delrin Acetal; Commercial Plastics, West Palm Beach, FL) at a fixed rate of advancement. Although drill type was found to be the dominant factor affecting normal force and torque, indications of increased resistance to drilling with reuse were also observed.

The purpose of the present in vitro study was to assess the cutting efficiency of, durability of, and temperatures produced by a variety of commercially available drill designs with an in vitro testing apparatus that closely simulated the clinical setting.

MATERIALS AND METHODS

Bone Specimen Preparation and Temperature Reading System

Bovine ribs were used because bone density and the relationship between cortical and cancellous bone are similar in bovine bone and in human mandibular bone.[31,32] Transverse sections 8 to 10 cm long were obtained and stored at –20°C. The specimens were defrosted. When they reached room temperature, 2 canals for thermocouples, one 5 mm deep and the other 15 mm deep, were drilled into each specimen using a 1.5-mm twist drill and intermittent cutting (Fig 1) at a distance of 1 mm from the implant drilling site, as described by Matthews and Hirsch.[28] Precise parallelism and distance between the thermocouple canals and the implant drilling site were ensured using a drill press stand (Craftsman Model 572.530320; Sears, Chicago, IL) equipped with a micrometer-controlled bidirectional (x, y) positioning system (Model 4006 M; Parker Automation Positioning Systems, Daedal Division, Irwin, PA). The bovine rib was secured in a custom-made screw-assisted metal holder attached to the sliding device. Two positioning holes were made at one end of each rib parallel to the thermocouple canals and future implant osteotomy site. A silicone heat-transfer compound (Heat Sink Compound; GC Electronics, Rockford, IL) was injected into the thermocouple canals to facilitate heat transfer to the thermocouple. Two Teflon-insulated thermocouples (Model no. 5TC-TT-E-36-36, diameter 0.005 inches, length 36 inches, Chromega-Constantan; Omega Engineering, Stamford, CT) with a response time of 0.004 seconds in water were inserted into the bone blocks to the predetermined depths of 5 and 15 mm. These depths were selected to sample positions where high temperatures were

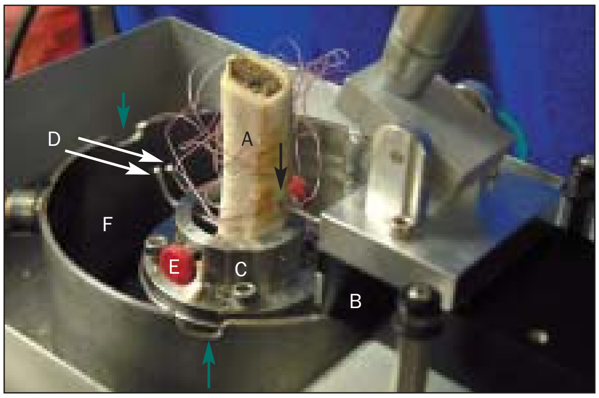


Fig 2a Bone *(a)* with the wire for the thermocouples secured to the drilling apparatus. Also shown are the sliding device *(b)*, the metal holder *(c)*, the metal positioning pins *(d)*, the lateral screws *(e)*, the water bath *(f)*, and the osteotomy site *(black arrow)*. Note that water is not present. During the experiment the water level was kept constant by allowing the water to flow out of the water bath at the level of the indentations in the bath wall *(green arrows)*.

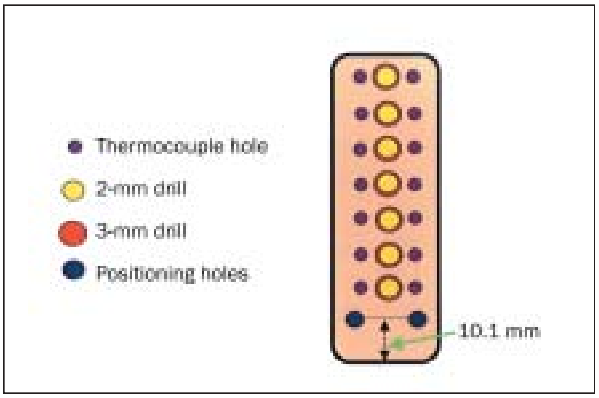


Fig 2b Schematic representation of the osteotomies, thermocouple positions, and positioning holes.

thought most likely to occur, ie, near the hard cortical bone where drill advancement is more difficult (5 mm) and deep within the osteotomy, where coolant penetration may be more difficult (15 mm).

Radiographs were taken to verify the position of the thermocouples. The thermocouples were secured to the bone block and insulated from the outer environment with sticky wax applied to the canal opening. They were connected to an electronic digital thermometer (2176A; Omega Engineering) that allowed constant reading of the temperatures within the bone block. If a significant temperature rise occurred during testing, outputs from both thermocouples could be used to define a temperature gradient. A pilot study, performed without coolant, showed that the thermocouples were able to detect changes in temperature at the drilling site. Each rib was positioned in the cutting apparatus by inserting 2 stainless steel pins in the positioning holes (Fig 2a). These pins also engaged 2 positioning holes in the holder. The pins, which had a diameter 0.1 mm smaller than the positioning holes of the bovine rib and holder, maintained the mediolateral and superior-inferior position of the rib. Two lateral screws were also manually tightened to block the rib from sliding along the pins anteroposteriorly. The positioning holes, pins, thermocouple canals, and implant osteotomy sites were all designed on parallel lines and at a constant transversal distance from each other (Fig 2b). The bone block was partially immersed in a custom-made water bath/water pump system (Haake D3; Thermo Electron, Karlsruhe, Germany). This system allowed control of the baseline bone temperature, which was set at 29°C ± 2°C.[31] The metal rib holder was equipped with a screw mechanism that allowed vertical movement of the bone specimen so that multiple osteotomies could be performed in the same bone specimen while maintaining parallelism and a constant distance between the thermocouple canals and the osteotomy site.

Drills and Handpieces

Table 1 lists the drills selected for the study. Initial cutting was performed with a 2-mm drill. The osteotomy was then enlarged with a 3-mm drill. In those cases in which these drill diameters were not available (Steri-Oss, Paragon, and ITI), the closest diameter was used. The same surgical unit (W&H Elcomed 100 Surgical Console System; Nobel Biocare, Yorba Linda, CA) was used for all osteotomies. The free-running rotational speed of the drills was set at 1,500 rpm; the torque was set at 37 N·cm. Room-temperature water (external irrigation) was automatically provided by the unit, directed to the drill, and maintained constant at 90 mL/min (40% of the unit setting).

Support Mechanism for the Handpiece

The handpiece was secured to a custom-made low-friction ball bearing sliding device (Parker Automation Positioning Systems, Daedal Division) to maintain the drill in a horizontal position (Fig 2a). This sliding device was equipped with a linear variable differential transducer (LVDT) (Fig 3) to control the depth of each osteotomy. The sliding device was connected to a pneumatic cylinder (Bimba, Monee, IL) that provided a force of 2,000 g at 60 psi of air

Table 1 Implant Drill Specifications and Irrigation Design

	Initial osteotomy			Sequential osteotomy		
Manufacturer	**Bit (w × l)**	**Design**	**Irrigation**	**Bit (w × l)**	**Design**	**Irrigation**
3i/Implant Innovations (Palm Beach Gardens, FL)	2 × 15 mm	Twist	External	3 × 15 mm	Twist	External
Straumann (ITI) (Waldenburg, Switzerland)	2.2 × 16 mm	Twist	External	2.8 × 16 mm	Tri-spade	External
Lifecore (Chaska, MN)	2 × 15 mm	Twist	External	3 × 15 mm	Twist	External
Nobel Biocare (Brånemark System) (Göteborg, Sweden)	2 × 15 mm	Twist	External	3 × 15 mm	Twist	External
Implamed (Attleboro, MA)	2 × 15 mm	Twist	External	3 × 15 mm	Twist	External
Paragon (Encino, CA)*	2.3 × 15 mm	Tri-spade	External/ internal	3.2 × 15 mm	Tri-spade	External/ internal
Nobel Biocare (Steri-Oss)*	2 × 15 mm	Spade	External/ internal	3.25 × 15 mm	Spade	External/ internal

Although some drills had both internal and external irrigation systems, only external irrigation was used during testing.
Drill specifications were obtained from the manufacturers.
*TiN coated.

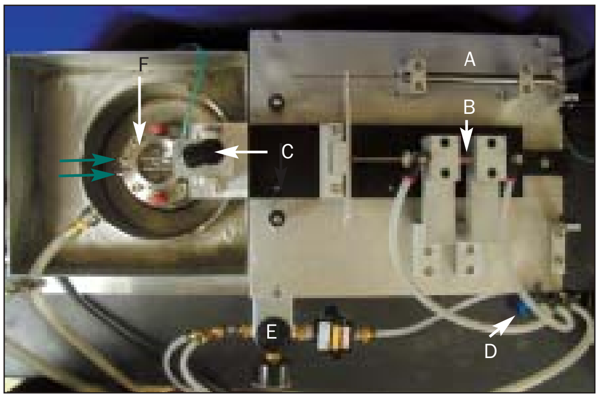


Fig 3 Top view of drilling apparatus, showing *(a)* the linear variable differential transformer (LVDT), *(b)* the pneumatic cylinder, *(c)* the handpiece (note that the handpiece is not connected to the surgical unit), *(d)* the electronic valve, *(e)* the air regulator, and *(f)* the bone holder inside the water bath. Note that the bone sample is not shown, so that the positioning pins can be seen *(green arrows)*.

pressure.[27,33] The pneumatic cylinder was equipped with 2 opposing air lines so that the handpiece could be driven back and forth. Each air line was equipped with an adjustable valve that allowed gradual force application to the handpiece during advancement or retraction. A computer-controlled, programmable, 2-way electronic switching valve controlled the back-and-forth motion of the sliding device/handpiece assembly (Fig 3).

Cutting Procedure

The bone specimen was secured to the holder with the positioning pins. Once the baseline temperature of 29°C ± 2°C was reached, the cutting action was initiated. A small depression was created on the bone surface with a no. 8 round bur (SS White, Lakewood, NJ) to better accommodate the tip of the 2-mm drill and guide it in the initial part of the osteotomy. The 2-mm drill was placed in contact with the bone block, and the LVDT was zeroed on the bone surface. The handpiece assembly was then retracted and the software program was initiated. The program instructed the operator to activate the handpiece, starting drill rotation and cooling action. After 3 seconds, the computer activated the electronic valve and initiated the movement of the handpiece toward the bone, thus starting the cutting action. The depth of each cut (15 mm measured from the zero position) was programmed into the computer. To simulate the back-and-forth pumping motion used during implant osteotomy in the clinical setting, the software program was designed to allow drilling to a depth of 2 mm, retract the handpiece to the starting position for 1 second, drill an additional 3 mm (5 mm total), retract to the starting position (1 second), drill an additional 5 mm (10 mm total), retract to the starting position (1 second), drill an additional 5 mm (15 mm total), and finally return to the starting position. The operator then deactivated the handpiece. The handpiece rotation and cooling were not interrupted during the drilling sequence. The bone piece was then moved down by the vertical screw mechanism and another osteotomy was performed following the same sequence.

Each bone sample was used for 7 osteotomies. Drills were randomly assigned to the osteotomy sites. Prior to the start of testing, a protocol for discarding and replacing drills was determined. A drill was discarded if

- It was fractured or otherwise visibly damaged as determined by the unaided eye
- It showed a low material removal rate (arbitrarily defined as the inability of the drill to complete the first drilling step [2 mm] in 5 minutes)

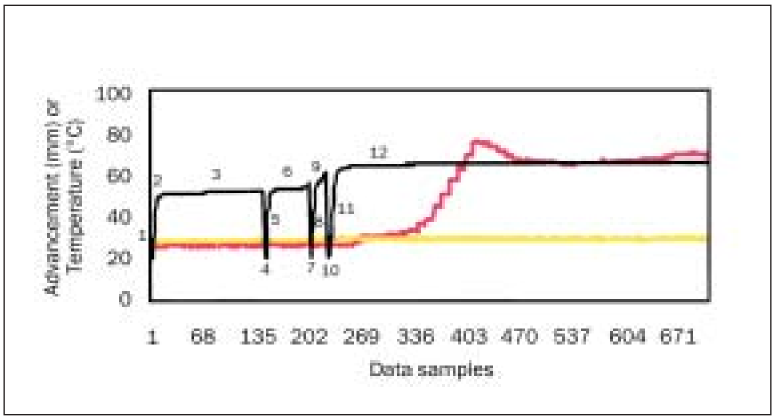


Fig 4 Data recorded by the computer. The drill advanced rapidly from the starting position (1) to contact the bone surface (changes in slope inclination [2]) and penetrate 2 mm (3). The drill was retracted to the starting position (4) for 1 second. It then traveled to the bone surface again (5) and advanced an additional 3 mm (6). This sequence was repeated at steps 7 to 9 and steps 10 to 12 for 2 additional advancements of 5 mm each. Note that in this specific test, the penetration rate decreased significantly during the last 5-mm advancement, and the temperatures recorded at 15 mm deep increased to almost 80°C. Black line: drill position; yellow line: thermocouple (5 mm); red line: thermocouple (15 mm).

- It caused a temperature greater than 47°C for 3 consecutive osteotomies

When a drill was discarded it was replaced with a new drill of the same specification. Testing continued for a sequence of 100 osteotomies using this procedure.

Ten drills (the 3i/Implant Innovations 3-mm, ITI 2.2- and 2.8-mm, Lifecore 2- and 3-mm, Nobel Biocare 2- and 3-mm, Implamed 3-mm, Paragon 3.2-mm, and Steri-Oss 2-mm drills) successfully completed the initial sequence of 100 osteotomies. Among these drills, the Steri-Oss 2-mm drill exhibited a rapid decline in material removal rate. Therefore, although the removal rate did not fall below the cutoff for replacement (less than 2 mm in 5 minutes), the authors decided to test a second drill of identical specification. This drill showed a similar rapid decline in the removal rate, and its testing was terminated after 50 osteotomies, when the drill removal rate dropped under the established threshold.

Four drills did not successfully complete the initial sequence of osteotomies—the 3i/Implant Innovations 2-mm and the Implamed 2-mm drills, which fractured; the Steri-Oss 3.25-mm drill, which sustained visible damage; and the Paragon 2.3 mm drill, which could not sustain an acceptable removal rate. Therefore, new same-specification drills from each of these manufacturers were tested.

SEM/Energy-Dispersive X-ray Spectroscopy and Hardness Testing

SEM (S/240, Leo Microscopy, Thornwood, NY) images of each drill were obtained, in secondary electron emission mode, before and after the 100-osteotomy series. Qualitative (QX 2000, Oxford Instruments, Concord, MA) and quantitative (DX-4; EDAX, Mahwah, NJ) energy dispersive x-ray spectroscopy analyses were performed to assess the chemical composition of each drill. The hardness of each drill was measured using a Vickers microhardness indenter with a 500-g load. For this purpose, the drills were embedded in acrylic resin, transversally sectioned, and polished. Hardness values were obtained by averaging the results of 6 microhardness indents at the center of each drill section.

Software, Data Recording, and Analysis

A computer recorded the time required to complete each osteotomy and the temperatures produced up to 30 seconds after the completion of the osteotomy. The outputs from the thermocouples and the LVDT were recorded and plotted with the total drilling time by a custom software program (Lab View MIO-16 Data Collection Card; National Instruments, Austin, TX) (sampling rate: 25 readings/s) operated by a personal computer (Fig 4).

A basic measure considered to demonstrate the efficiency of a drill is the drill's volumetric removal rate, calculated according to the following equation:

$$V = A\,dx/dt$$

where V is the volume removed per unit time, A is the cross-sectional area of the drilled hole, and dx/dt is the rate at which the drill advances into the bone. For this analysis, it has been assumed that the diameter of the osteotomy was approximately equal to the diameter of the drill. This allowed comparison of the results obtained for the slightly different sizes of the tested drills through a comparable scale. The rate of drill advancement during drilling was established by plotting the drill position as a function of the drilling time. A typical curve (Fig 4) shows 3 distinct regions. There is an initial range where the drill advances rapidly, which reflects travel of the drill to the bone and the initial seating of the drill into the cortical bone. This is followed by a leveling of the curve to an approximately constant slope (the linear region of the curve), which corresponds to advancement of the drill through the cortical bone. Finally, when the drill begins to enter the cancellous bone, the resistance to motion drops and the rate of advancement rapidly increases. Since the bulk of the drilling time typically takes place in the cortical bone, the rate of drill advancement in this region (ie, the slope of the curve for the first 2 mm of advancement) has been taken as a measure of the drilling efficiency.

The use of the volumetric removal rate as a measure of the efficiency with which the drill penetrates the bone is consistent with the principles of material removal. For most material removal operations, such as grinding, polishing, and sawing, the rate of material removal is found to increase with increased force and surface speed (ie, speed of the cutting tool parallel to the material surface). This relationship is most commonly expressed either in terms of specific grinding energy or, in the case of glass polishing, as Preston's coefficient.[34] In this study, both the applied normal load and the rotational speed of the drill were fixed during testing of the different drill types, so the volumetric removal rate can be used as a measure of the ease of material removal. In terms of application, if the removal rate is high under the current fixed conditions, it is an indication that in practice the drill could be used either for a shorter time period or with a lower load, reducing the potential for thermal effects on the bone tissue.

Durability can then be defined as the ability of the drill to retain its cutting efficiency during successive osteotomies. During successive osteotomies, this is best described by the changes in removal rate (grinding energy). If the removal rate decreases during subsequent osteotomies, increased drilling time and energy will be input to the system. Some of this energy may be removed harmlessly, for example by the coolant, but the remainder of the energy has the potential to cause a rise in the temperature or other undesirable effects (eg, vibration). Therefore, both removal rate and temperature changes were used as parameters to characterize drill durability. Specifically, a drill was discarded if it repeatedly produced temperatures greater than 47°C for 1 minute (ie, in at least 3 consecutive osteotomies) or failed to complete the first 2-mm advancement in 5 minutes.

After the removal of outliers (defined as values that were 3 standard deviations away from the mean) an analysis of variance (ANOVA) and Tukey's studentized range test were used to compare mean removal rates among groups and for each successive group of 10 osteotomies. Eight values were identified as outliers in the entire data. The same tests were also used to compare mean baseline temperatures, maximum temperatures, and temperature increases among groups at the 2 different depths (5 and 15 mm). A *t* test was used to compare temperatures at the 2 depths in each group. Statistical significance was set for all tests at $P < .05$.

RESULTS

Removal Rate

Removal rate data for the 2-mm and 3-mm drills, averaged over groups of 10 cuts, are presented in Figs 5a and 5b, respectively. Most of the 2-mm drills exhibited high variability from test to test, but distinct patterns can be distinguished in a few cases, principally those involving premature test termination (drill failure). To make quantitative comparisons of the performance of different drills, statistical data are presented in Tables 2 and 3. Table 2 gives the removal rate and standard deviation for each drill averaged over all cuts, along with information on how many cuts were successfully completed. Also shown are the groupings of the results from the Tukey test. To make initial performance comparisons, Table 3 provides similar information, but averaged only over the first 10 cuts for each drill. The 3-mm drills also showed variability, but definitive patterns could be seen as for the 2-mm data. The first 3-mm Steri-Oss drill showed a distinct decline in removal rate, which led to drill failure due to visible damage. The second Steri-Oss drill exhibited a high removal rate for the first 10 cuts, but the removal rate rapidly declined and seemed to follow the same pattern observed for the first 3-mm drill. The testing of the second Steri-Oss 3-mm drill was interrupted in conjunction with the failure (due to low removal rate) of the second 2-mm drill. All the other 3-mm drills completed the 100 osteotomies. The removal rates of the 3-mm drills are compared in Tables 4 and 5.

Temperature

Mean baseline temperatures for the 2 thermocouple locations in all groups were 28.4°C (15 mm) and 30.4°C (5 mm), and mean maximum temperatures were 30.9°C (15 mm) and 31.9°C (5 mm).

Mean increases in temperature (2.5°C at 15mm, 1.4°C at 5 mm) between the 2 locations were not statistically different when drilling with 2-mm or

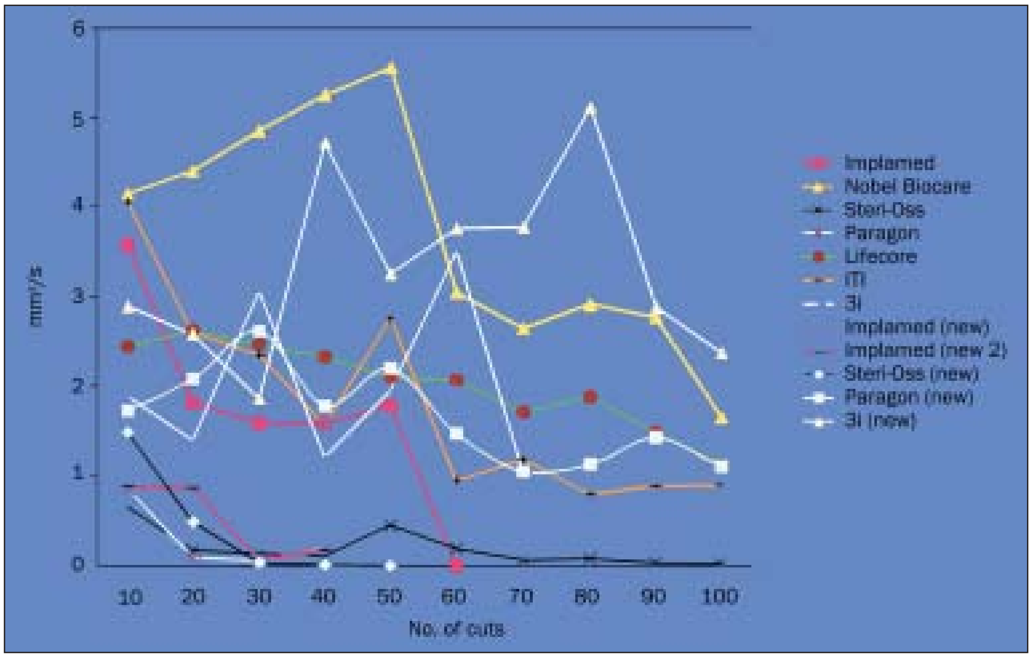


Fig 5a Removal rates for 2-mm drills. The word "new" or "new2" following a drill type indicates a new drill of the same specifications.

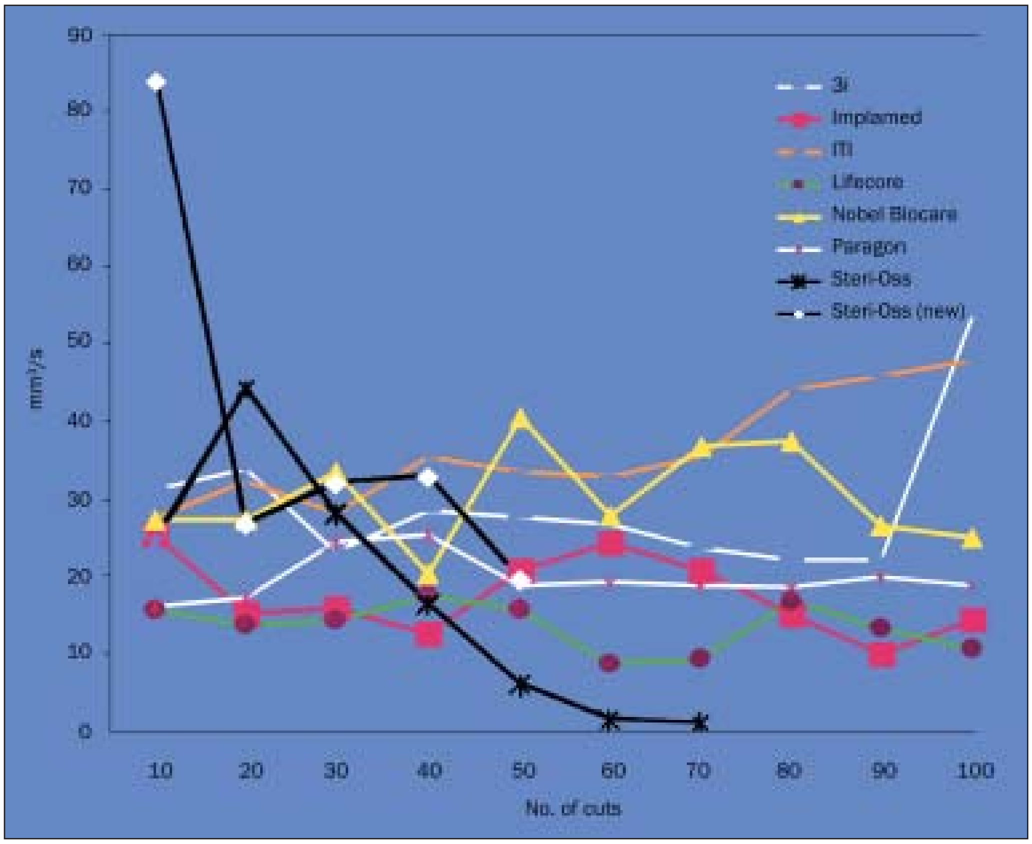


Fig 5b Removal rates for 3-mm drills. The word "new" following a drill type indicates a new drill of the same specifications.

Table 2 Measured Removal Rate and Final Test Results for 2-mm Drills

Drill type	Removal rate (mm^3/s)	SD (mm^3/s)	Tukey grouping*	Test termination
3i/Implant Innovations				
First drill	2.1	3.3	B	61 cuts (fracture)
Second drill	3.3	1.9	A	100 cuts (normal)
Straumann ITI	1.8	1.7	B	100 cuts (normal)
Lifecore	2.0	0.7	B	100 cuts (normal)
Nobel Biocare Brånemark System	3.6	1.9	A	100 cuts (normal)
Implamed				
First drill	2.0	1.4	B	52 cuts (fracture)
Second drill	0.9	1.2	B,C,D	11 cuts (fracture)
Third drill	0.5	0.9	C,D	41 cuts (fracture)
Paragon				
First drill	0.3	0.5	C,D	33 cuts (low rate)
Second drill	1.4	0.9	B,C	100 cuts (normal)
Nobel Biocare Steri-Oss				
First drill	0.2	0.4	D	100 cuts (normal)
Second drill	0.4	0.8	C,D	50 cuts (low rate)

*Drills with identical letter designations could not be distinguished from each other with the specified confidence ($P < .05$), but were judged significantly different from those without a matching designation.

Table 3 Initial Measured Removal Rate (First 10 Cuts) and Final Test Results for 2-mm Drills

Drill type	Initial removal rate first 10 cuts (mm^3/s)	SD (mm^3/s)	Tukey grouping*	Test termination
3i/Implant Innovations				
First drill	1.8	0.8	C,D,E	61 cuts (fracture)
Second drill	2.9	0.7	A,B,C,D	100 cuts (normal)
Straumann ITI	4.0	2.0	A,B	100 cuts (normal)
Lifecore	2.4	0.3	A,B,C,D,E	100 cuts (normal)
Nobel Biocare Brånemark System	4.1	1.2	A	100 cuts (normal)
Implamed				
First drill	3.5	1.8	A,B,C	52 cuts (fracture)
Second drill	0.9	1.2	E	11 cuts (fracture)
Third drill	0.8	0.7	E	41 cuts (fracture)
Paragon				
First drill	0.8	0.6	E	33 cuts (low rate)
Second drill	1.4	1.5	B,C,D,E	100 cuts (normal)
Nobel Biocare Steri-Oss				
First drill	0.6	0.7	E	100 cuts (normal)
Second drill	2.2	1.6	D,E	50 cuts (low rate)

*Drills with identical letter designations could not be distinguished from each other with the specified confidence ($P < .05$), but were judged significantly different from those without a matching designation.

3-mm drills. No significant differences were noted in the temperatures produced by the 2- and 3-mm drills at the 2 locations.

Comparing temperature data among different groups, only the mean temperature increase for the 2.3-mm Paragon drills at 15 mm deep was significantly higher than that of the other groups; this increase (4.5°C), however, was not clinically significant. The temperature increases at 5 mm deep for the 2-mm drills and during drilling with 3-mm drills for both 5- and 15-mm depths did not show statistically significant differences among the groups.

While mean temperature changes were not clinically significant when averaged over multiple osteotomies, on 5 nonconsecutive occasions (3 with 2.3 mm Paragon drills and 2 with the 2-mm Steri-Oss drill), the temperature recorded was above 47°C at the 15-mm location (up to 60 to 90°C).

Table 4 Measured Removal Rate and Final Test Results for 3-mm Drills

Drill type	Removal rate (mm^3/s)	SD (mm^3/s)	Tukey grouping*	Test termination
3i/Implant Innovations	29.4	14.9	A	100 cuts (normal
Straumann ITI	36.5	12.3	A	100 cuts (normal)
Nobel Biocare Brånemark System	30.0	11.9	A	100 cuts (normal)
Lifecore	13.6	6.8	B	100 cuts (normal)
Implamed	17.6	11.6	B	100 cuts (normal)
Paragon	19.7	9.8	B	100 cuts (normal)
Nobel Biocare Steri-Oss				
First drill	18.0	27.2	B	69 cuts (visible damage)
Second drill	33.3	28.1	A	50 cuts[†]

*Drills with identical letter designations could not be distinguished from each other with the specified confidence ($P < .05$), but were judged significantly different from those without a matching designation.

[†] Test terminated in conjunction with low removal rate of the second 2-mm Steri-Oss drill.

Table 5 Initial Measured Removal Rate (First 10 Cuts) and Final Test Results for 3-mm Drills

Drill type	Initial removal rate first 10 cuts (mm^3/s)	SD (mm^3/s)	Tukey grouping*	Test termination
3i/Implant Innovations	31.4	12.6	A	100 cuts (normal
Straumann ITI	27.5	2.5	A	100 cuts (normal)
Nobel Biocare Brånemark System	27.4	3.9	A	100 cuts (normal)
Lifecore	15.7	4.8	A	100 cuts (normal)
Implamed	25.4	8.3	A	100 cuts (normal)
Paragon	16.1	10.2	A	100 cuts (normal)
Nobel Biocare Steri-Oss				
First drill	24.6	24.5	A	69 cuts (visible damage)
Second drill	84.0	29.3	B	50 cuts[†]

*Drills with identical letter designations could not be distinguished from each other with the specified confidence ($P < .05$), but were judged significantly different from those without a matching designation.

[†] Test terminated in conjunction with low removal rate of the second 2-mm Steri-Oss drill.

These events occurred during the last 5 mm of penetration (from 10 to 15 mm) and coincided with a marked decrease in the rate of drill advancement with a resulting continuous and prolonged drilling action (Fig 4).

SEM and Hardness

According to the manufacturers' specifications, the drill materials were made from various stainless steel alloys. Consistent with this, energy-dispersive x-ray spectroscopy analysis identified iron and chromium as major constituents in all of the drills. A strong titanium peak from the coating was also identified for the 2 titanium nitride (TiN)–coated drills (Paragon and Steri-Oss). SEM before and after cutting revealed 3 basic patterns of wear. Four of the drill types (Implant Innovations, ITI, Lifecore, and Nobel Biocare) exhibited small amounts of abrasive wear along the cutting edges, as illustrated in Fig 6a. In contrast, all of the Implamed drills tested, while performing fewer osteotomies (because of fracture), showed significant plastic deformation of the cutting edge, resulting in "curling" of the edges (Fig 6b). Finally, examination of the 2 TiN-coated drill types showed varying degrees of blunting of the cutting edges, coating damage, and coating loss along the cutting edges (Fig 6c). Coating loss was confirmed by EDAX testing of the surfaces. The periphery of the worn cutting edges showed a high titanium peak, while the central areas showed peaks typical of a stainless steel alloy (Fig 7).

Vickers microhardness values recorded for each drill type are shown in Table 6 along with the groupings of the results from the Tukey test. Note that the hardness was measured on the base metal for all drills and thus does not include the coating hardness for the 2 coated drill types.

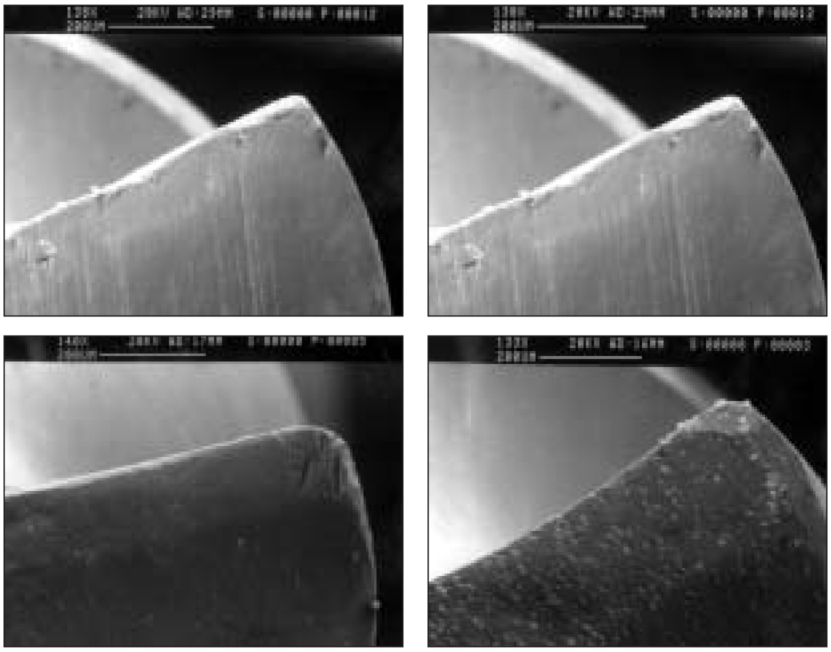


Fig 6a SEM of the cutting edges of drills following test completion illustrating cases of low or moderate wear. *(Above left)* 3i/Implant Innovations 2-mm drill; *(above right)* Nobel Biocare 2-mm drill; *(below left)* Lifecore 2-mm drill; *(below right)* ITI 2-mm drill.

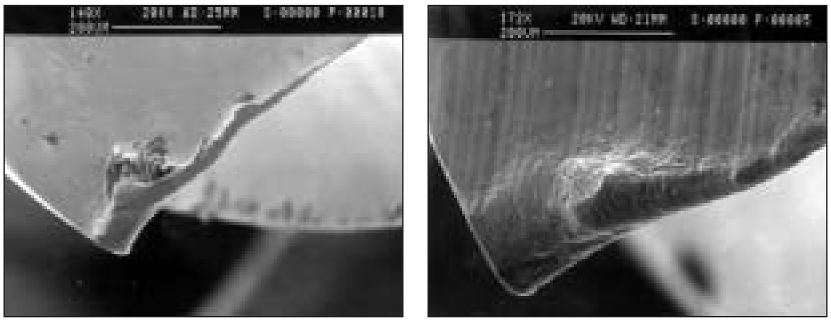


Fig 6b SEM of the cutting edges of drills following test completion illustrating plastic deformation and curling of the cutting edge. *(Left)* Implamed 2-mm drill; *(right)* Implamed 3-mm drill.

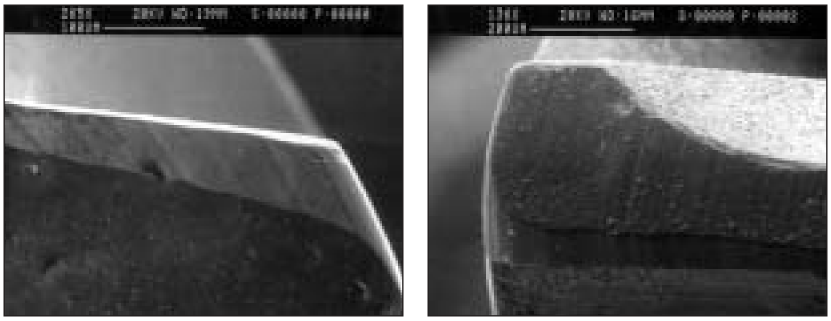
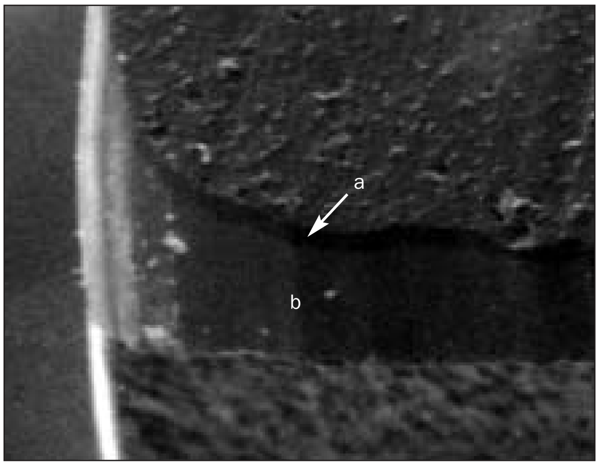


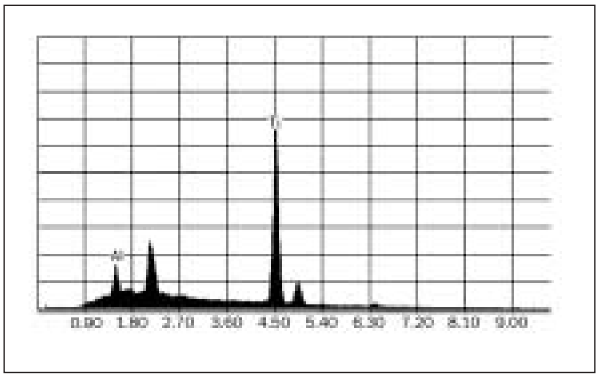
Fig 6c SEM of the cutting edges of drills following test completion illustrating the blunting of cutting edges. *(Left)* Paragon 2-mm drill; *(right)* Steri-Oss 2-mm drill. Note that magnifications are different.

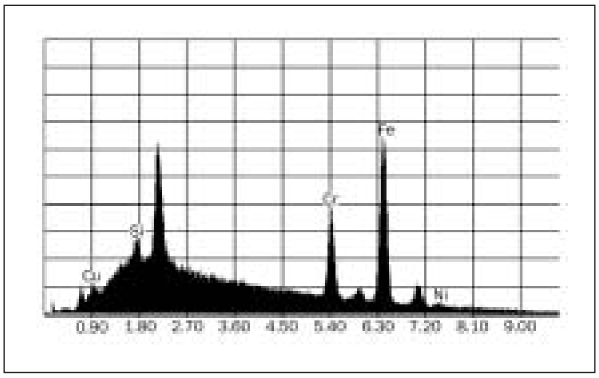
DISCUSSION

In considering the results of this study it is necessary to begin by recognizing 2 limitations of the study. First, in assessing the wear of the drills and the effect on cutting efficiency, durability, and temperature generation, focus has been on the effects occurring as a direct result of drilling. No attempt was made to simulate sterilization during the experiments (drills were only cleaned with water), so that the results do not reflect any potential impact (positive or negative) of sterilization on long-term drill performance. In this regard, Jochum and Reichart[29] have shown that, while 2 different disinfectants coupled with autoclaving led to a slightly greater amount of blunting of the cutting edges of titanium cannon drills after 51 osteotomies (a 1.34- to 1.36-µm increase in the width of the cutting edges every 10 osteotomies), the temperatures generated by drills that were disinfected and sterilized were well

Fig 7 *(Right)* SEM of a 2-mm Steri-Oss drill following test completion; *(below left)* EDAX at the periphery of the cutting edge *(a)*; *(below right)* EDAX at the center of cutting edge *(b).* The darker horizontal line at *a* is the TiN coating. At *b,* the center of the worn cutting edge, the underlying steel composition is evident.







below the threshold of 47°C and not significantly different than drills that were only cleaned with distilled water. Moreover, Harris and Kohles[30] have shown that, while autoclaving can affect the rotational and translational behaviors (resistance to rotation and penetration) of several drill types and decrease their cutting efficiency over time, these effects are generally obscured by those related to the design of the drill.

Secondly, only a limited sample of drills was tested. In some cases, only 1 drill of a particular specification was tested. The results obtained should not be assumed to be necessarily characteristic of the average performance of a particular drill. Nevertheless, by appropriate grouping of the results, it was possible to identify some of the features important in determining drill performance.

With these 2 caveats in mind, the first important conclusion that can be reached by examining the results is that these drills performed well overall and generally exhibited good durability. Of the 20 individual drills tested, most showed quite consistent performance during extended use, with 12 successfully completing all 100 simulated cuts. For all of the drills, the average temperature rise at both thermocouple sites was well below values of clinical concern. Considering that, on average, an implant-based restoration involves the use of 2.5 implants,[35] most drills can therefore be safely used for multiple surgeries. Clinically significant temperature increases occurred only sporadically and appeared to be connected with details peculiar to the specific test rather than with either drill type or wear.

The second important overall trend observed in the data is the much higher efficiencies observed for the second (larger-diameter) drill in each sequence compared to the first. The 2 drills in each sequence actually removed comparable volumes of material; the 2-mm drill removed approximately 47 mm^3 while the 3-mm one removed approximately 59 mm^3. Hence the large performance difference reflects the relative difficulty of cutting a new osteotomy versus that of widening an existing one. With the initial drill, the trade-off between load applied and bone removed is less efficient.

Efficiency and Durability

To observe overall patterns and identify possible causes, it is convenient to consider the 7 drill types in terms of 3 distinct groupings. The drills in the first grouping (the 3i/Implant Innovations, ITI, Lifecore, and Nobel Biocare drills) had similar

Table 6 Vickers Microhardness of Different Drill Types

Drill type	Vickers microhardness	SD	Tukey grouping*
3i/Implant Innovations	623	12	A
Straumann ITI	574	10	B
Nobel Biocare Brånemark System	560	4	B
Lifecore	570	9	B
Implamed	426	11	D
Paragon	391	5	E
Nobel Biocare Steri-Oss	452	7	C

*Drills with identical letter designations could not be distinguished from each other with the specified confidence ($P < .05$), but were judged significantly different from those without a matching designation.

designs; they were twist drills with external cooling (except the 2.8-mm ITI drill, which had a tri-spade design). In addition, the hardness of all 4 of these drills was significantly higher than that of the other drills tested (Table 6). From a performance standpoint, 4 of the five 2-mm drills in the first grouping (note that two 3i/Implant Innovations drills were used) and all of the 3-mm drills successfully completed 100 cuts. Their efficiencies generally were higher than the other drills tested (Tables 2 to 5). Microstructurally, they exhibited relatively little damage along their cutting edges (Fig 6a).

Like the drills in the first grouping, the drills in the second grouping (the Implamed drills) were twist drills designed for external irrigation. However, the hardness of the drill material was significantly lower for the second grouping than for the first grouping (Table 6). In terms of performance, the average efficiencies exhibited a wide range (Tables 2 to 5), but generally were lower than the drills in the first grouping. Moreover, all 3 of the 2-mm drills fractured during testing. Microstructurally, all of these drills exhibited extensive yielding of the material along the cutting edge (Fig 6b). From these observations, it seems clear that the hardness of the drill material was insufficient to retain its shape under the testing conditions, resulting in reduced efficiency and, ultimately, drill fracture.

The third grouping (the Paragon and Steri-Oss drills) differs from the other groupings in several ways. In particular, the drills in this grouping had distinctly different designs (tri-spade and spade, respectively, both with provision for internal irrigation). Both used a TiN coating. From a performance standpoint, 3 of the four 2-mm drills tested (2 Steri-Oss and 1 Paragon) showed a large decrease in performance with use (Fig 5a). Compare the initial efficiencies in Table 3 with the overall efficiency averages in Table 2. A similar pattern was observed for the first 3-mm Steri-Oss drill and the last part of the testing of the second 3-mm Steri-Oss drill. The SEM and EDAX (Figs 6c and 7) strongly suggest coating damage and loss coupled with blunting of the cutting edges as important contributors to the performance loss in these drills. Moreover, the second 2-mm Paragon drill and the 3-mm drill, which had the best performance in terms of both efficiency and durability among the coated drills (Tables 2 to 5; Figs 5a and 5b) exhibited relatively little blunting of the cutting edges and coating loss (Fig 8). Interestingly, both Steri-Oss and Paragon have discontinued the use of TiN coating.

Nobel Biocare 2-mm drills showed a mean removal rate that was significantly greater than that of the other drills, with the exception of the 3i/Implant Innovations drills. This is especially interesting because the Nobel Biocare drills were specifically identified as "to be used for a single surgery only" by the manufacturer. Despite this single-use-only designation, neither their composition (characteristic of a stainless steel alloy; German standard DIN 1.4197) nor their mechanical properties (eg, hardness) distinguish them from several of the other drills. The 3-mm Nobel Biocare drills exhibited removal rates that were similar to those of drills intended for use in multiple surgeries. The hardness data and the elemental composition (according to the manufacturer, 0.2% sulfur, 0.2% carbon, 0.6% silicon, 0.8% nickel, 1.2% molybdenum, 1.6% manganese, 13% chromium, 22% carbon, balance iron) are characteristic of a stainless steel alloy (German standard DIN 1.4197) with properties and characteristics similar to the other drill materials. The manufacturer may have decided to recommend limiting its use to a single surgery for reasons other than its cutting efficiency, durability, and temperature generation. The authors suggest that these drills can be used for multiple osteotomies, since their cutting efficiency and durability are comparable to other drills.

In the present study, the rotational speed of the drill was controlled by the surgical unit and corresponded to the drill free-running speed. While it has

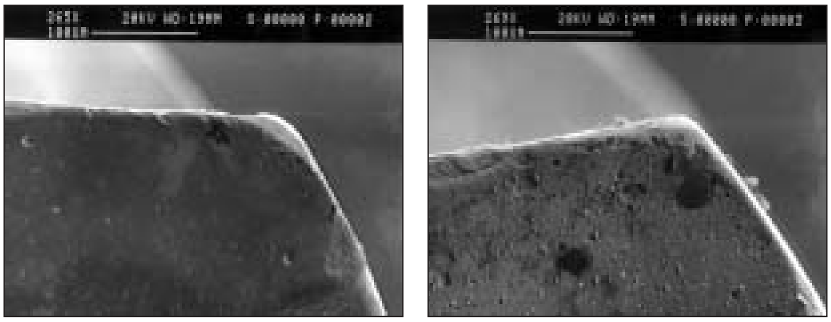


Fig 8 SEM of Paragon drills following test completion. *(Left)* Second 2-mm drill; *(right)* a 3-mm drill. Cutting edges do not show blunting as in Fig 7.

been shown that contact with the workpiece (bone in this study) decreases the rotational speed of a drill,[36] no differences are expected in the results, as all the drills were used with the same force and the same number of revolutions per minute.

Temperature

In this study, the mean temperatures recorded during drilling at the 2 locations increased only slightly above the baseline temperature and were never above the 47°C threshold. Also the mean temperatures recorded superficially (5 mm) and deep (15 mm) into the osteotomy were not significantly different and are similar to those recorded by other investigators.[26,27,29,31] Moreover, although significant surface wear was noted for most drills when comparing SEM photographs before and after use, these changes did not produce large variations in the recorded bone temperatures. This is in spite of the fact that different drill designs, materials, and amount of use did have significant difference in the measured cutting performance (removal rate), as previously discussed. This shows that the external irrigation and drilling methods employed in this protocol (ie, reproduction of pumping motion) were sufficiently effective, in most instances, to suppress excessive heating of the bone for any of the drills tested.

On 5 separate nonconsecutive occasions temperatures recorded at the 15-mm location reached 60 to 90°C—3 times with Paragon 2-mm drills and 2 times with Steri-Oss 2-mm drills. These occurrences were always correlated with a marked decrease in the penetration rate of the drill. It was speculated that these drills engaged the deep or remote cortical bone plate while trying to complete the last 5-mm advancement into the bone. Continuous drilling in a deep osteotomy, coupled with the relative lack of coolant availability, increases the likelihood of drill clogging and therefore requires a greater torque and cutting energy to complete the osteotomy.[19] Thus, it is important to follow a proper surgical protocol (including the use of a pumping motion) when drilling deep osteotomies, especially when faced with a decreased drill penetration. This finding agrees with those of Eriksson and Albrektsson, who recorded greater temperature elevation in the medial cortex of canine femora while continuously drilling from the lateral cortex.[21]

The absence of large increases in bone temperature under the controlled conditions of this study is consistent with the fact that drilling with a pumping motion is generally clinically successful in spite of the inherent variability in conditions.[31] The present results show that specific drill designs (twist, tri-spade, spade), materials (type of steel and presence of coating), hardness, and number of uses[29] do not have a significant influence on the recorded temperatures. These results demonstrate that bone temperatures during drilling are influenced more by the availability and temperature of coolant than by drill design or diameter.[37,38]

The experimental protocol employed external irrigation only for all drill types, in spite of the fact that 2 drill types (Paragon and Steri-Oss) were designed for use with external and internal irrigation. While external irrigation was sufficient to avoid any clinically significant increases in temperature, it is possible that the concomitant use of internal irrigation with these drills might have helped in decreasing the high temperature sometimes recorded at the 15-mm location.[22] Sutter and associates[37] found no difference in the recorded temperatures when drilling with internally or externally cooled twist drills. However, the Steri-Oss and Paragon drills had spade and tri-spade designs, respectively.

Unlike previous studies,[29,31] which used an approximate distance of 0.5 mm between thermocouple and osteotomy, in the present study the thermocouple was positioned 1 mm from the osteotomy. The studies that used a distance of 0.5 mm between the thermocouples and the osteotomy were performed in cortical bone[21,26–28,31,36]; because cancellous bone was used in the present study, a distance of 1 mm was felt necessary to ensure that the drill could not engage the thermocouple and destroy it. Although it would be ideal to record the temperatures right at the drilling site, Jochum and Reichart[29] have shown that changing the position of the thermocouple from 0.3 to 0.7 mm from the osteotomy causes a decrease in the recorded temperature of only 2°C. They also noted that thermocouples positioned 0.55 to 0.7 mm from the osteotomy record essentially the same temperatures.

From the standpoint of the workpiece material, studies that evaluate drill performance by using bone substitutes must be taken with caution when extrapolated to clinical conditions.[30] The current study was performed on bovine bone because of the similarities between bovine bone and human mandibular bone in terms of density and relationship between cortical and cancellous bone.[31,32] Since, in general, the cutting efficiency of a particular tool design will be affected by the substrate geometry and structure, as well as the material properties,[34] measurement of drill performance against bone tissue rather than artificial substitutes in an environment that strictly simulates clinical surgery may be especially significant. This allows for a more realistic simulation of the clinical conditions, including the effects of the natural variability of bone on drill performance.

CONCLUSIONS

An in vitro experimental protocol and testing apparatus that reproduced the clinical setting was developed to evaluate cutting efficiency, durability, and temperatures during dental implant drilling. Within the limits of this study it is concluded that:

1. Drill design, material, and mechanical properties significantly affect cutting efficiency and durability. These factors should be considered during implant drill design and their combined effect assessed during testing on bone tissue.
2. Coolant availability and temperature were the predominant factors in determining bone temperatures.
3. Implant drills can be used several times without causing bone temperatures that are potentially harmful to the bone tissue.
4. Mean temperatures produced by different drills were not clinically different and, with one exception, they were not significantly different.
5. Mean temperatures recorded at different depths were not significantly different.
6. Continuous drilling in deep osteotomies can produce local temperatures that might be harmful to the bone.

ACKNOWLEDGMENTS

Funded in part by a 1998 Osseointegration Foundation Implant Research Grant from the Research Committee of the Academy of Osseointegration, Board of Directors of the Academy of Osseointegration, and Osseointegration Foundation. The authors would like to acknowledge the late Thomas D. Greene for his invaluable help during the experimental setup. Our gratitude also goes to Dr Uri Ben-Hanan, Dr Daniel Galindo, and Dr Ross H. Tallents for their assistance and feedback. We would like to thank Ivoclar NA for their assistance with the SEM images.

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