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ORIGINAL ARTICLE

Slow drilling speeds for single-drill implant bed preparation. Experimental in vitro study

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Abstract
Aims To evaluate the real-time bone temperature changes during the preparation of the implant bed with a single-drill protocol with different drill designs and different slow drilling speeds in artificial type IV bone.
Materials and methods For this experimental in vitro study, 600 implant bed preparations were performed in 10 bovine bone disks using three test slow drilling speeds (50/150/300 rpm) and a control drilling speed (1200 rpm). The temperature at crestal and apical areas and time variations produced during drilling with three different drill designs with similar diameter and length but different geometry were recorded with real-life thermographic analysis. Statistical analysis was performed by two-way analysis of variance. Multiple comparisons of temperatures and time with the different drill designs and speeds were performed with the Tukey's test.
Results T_{Max} values for the control drilling speed with all the drill designs (D1 + 1200; D2 + 1200; D3 + 1200) were higher compared to those for the controls for 11 ± 1.32 °C ($p < 0.05$). The comparison of T_{Max} within the test groups showed that drilling at 50 rpm resulted in the lowest temperature increment (22.11 ± 0.8 °C) compared to the other slow drilling speeds of 150 (24.752 ± 1.1 °C) and 300 rpm (25.977 ± 1.2 °C) ($p < 0.042$). Temperature behavior at crestal and apical areas was similar being lower for slow drilling speeds compared to that for the control drilling speed. Slow drilling speeds required significantly more time to finish the preparation of the implant bed shown as follows: 50 rpm > 150 rpm > 300 rpm > control ($p < 0.05$).
Conclusions A single-drill protocol with slow drilling speeds (50, 150, and 300 rpm) without irrigation in type IV bone increases the temperature at the coronal and apical levels but is below the critical threshold of 47 °C. The drill design in single-drill protocols using slow speeds (50, 150, and 300 rpm) does not have an influence on the thermal variations. The time to accomplish the implant bed preparation with a single-drill protocol in type IV bone is influenced by the drilling speed and not by the drill design. As the speed decreases, then more time is required.

Keywords Bone drilling · Thermal analysis · Single bur · Slow drilling speed

Clinical implications When using a single-bur protocol with tapered and multi-stepped twist drills, a slow drilling speed of 300 rpm in type IV bone density seems to be more efficient in terms of temperature increase and time reduction than using a single bur with a drilling speed of 50 rpm.

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Background

Bone drilling procedures are used in orthopedics and implant dentistry mainly for the insertion of fixation screws and the preparation of the dental implant bed [1]. During bone drilling, bone micro-fractures and bone temperature changes are induced [2]; if the temperature exceeds 47 °C for over 1 min, the bone can suffer thermal injury and bone necrosis [3, 4]. Factors like cortical and cancellous bone density [5], drill bit design [6, 7], surgical technique, and drilling speed [8] can influence the temperature of the bone during the implant bed preparation.

Regarding the drilling speed and its influence on temperature increments, the data are contradictory. Thompson suggested that low/slow drilling speeds (below 250 rpm) can increase the fragmentation of the osteotomy edge and the temperature [9]. Brisman used low drilling speeds with standardized vertical loads obtaining similar results [10]. Krause et al., Iyer et al., and Sharawy et al. suggested that higher drilling speeds might generate less heat increments than drilling with lower speeds [6, 11, 12].

On the other hand, it has been postulated that slow drilling speed reduces or limits the frictional heat [13], without substantial histological differences between the bone healing and bone repair in osteotomies produced with fast versus slow drilling speeds in dogs and rabbits [14]. Reingewirtz et al. found that drilling speeds of ≤400 rpm were correlated with lower temperatures [15].

Anitua et al. presented a slow drilling speed technique for the preparation of the implant bed, consisting in a pilot drill rotating at 800 rpm followed by drills of increasing diameters at 50 rpm without irrigation. This technique allowed the collection of vital bone and did not impaired the bone healing [16]. Kim et al. used a slow drilling speed of 50 rpm without irrigation and found out that the temperature increased from 1.57 to 1.79 °C for the 2-mm twist drill and increased from 1.72 to 2.46 °C for the 3-mm drill and concluded that "low-speed drilling at 50 rpm without irrigation may not significantly increase bone temperature, and that there may be a direct relationship between bur diameter and bone temperature" [17].

Gaspar et al. compared drilling at low speed (50 rpm) without irrigation versus high-speed drilling (800 rpm) with irrigation in rabbit tibias and concluded that the effects of low-speed drilling (50 rpm) without irrigation and conventional drilling (800 rpm) under abundant irrigation preserved the bone cell viability [18]. Sarendranath et al. studied the effects of slow drilling speed (drilling at 400 rpm) on osseointegration after simplified drilling protocols and reported that the bone-to-implant contact and bone area fraction occupancy were comparable to those obtained by conventional drilling protocols [19].

A simplified drilling protocol consists in the reduction on the number of drills for the preparation of the implant bed (only pilot and final drill). This technique reduces the surgery time and has shown similar bone formation compared to conventional drilling (sequence of drills with increments in the drill diameter) [20]. Guazzi et al. compared single bur versus multiple drilling steps for the preparation of the implant bed at higher speeds. After four months, they found that both techniques resulted in implant osseointegration, but the single-bur procedure required less surgical time and led to less postoperative morbidity [21]. Similar results were obtained by Abboud et al. using a single multi-stepped drill for the preparation of the implant bed [7].

Although drilling at slow speeds has some benefits, such as obtaining of vital bone for autografts, possibility of correction of the drill direction, and control of the temperature [16–18] and similar bone formation during healing compared to conventional drilling speeds [19–22], there is a lack of agreement about the drilling speed range that might be used during slow bone drilling with different drill designs when a single-bur protocol for the implant bed preparation is used.

Therefore, the purpose of the present experimental study was to evaluate in real-time the bone temperature changes during the preparation of the implant bed with a single-drill protocol with different drill designs and different slow drilling speeds in artificial type IV bone.

Materials and methods

Bovine bone disks

Ten bovine bone disks (BoneSim®, Newaygo, MI, USA) resembling type IV bone were used for this experiment. The disks have a thickness of 17 mm and a diameter of 3.5 cm. These bone samples have a conductivity of 0.3 to 0.4 W/m/K and have properties similar to human trabecular bone and serve as standardized bone model to perform osteotomies and evaluation of thermal changes during drilling for implant bed preparation [7, 23, 24].

Drills

Three different drill designs with similar diameter and length were used for the implant bed preparation (Table 1):

– Tapered drill D1 (Nobel Biocare®, Yorba Linda-California, USA) (Ref. NP #29370) (3.4 mm diameter × 10 mm length) (Test 1). Tapered drill is made of surgical stainless steel with four blades and an amorphous diamond coating. The maximum number of uses recommended by the manufacturer is 20. This drill design allows internal and external irrigation but only the latter was used (Fig. 1).
– Tapered drill D2 (Galimplant®, Sarria-Lugo, Spain) (Ref. F #102936) (3.6 mm diameter × 10 mm length) (Test 2). Tapered drill is made of surgical stainless steel with four blades. The maximum number of uses is not disclosed by the manufacturer. This drill design only allows external irrigation (Fig. 2).
– Stepped drill D3 (Nobel Biocare®, Yorba Linda-California, USA) (Ref. # 35841) (3.6 mm maximum diameter × 10 mm length) (Test 3). Stepped twist drill

Table 1 Drill groups and characteristics. Different drill designs were selected; the diameter and length were similar for all the groups. One-stepped drill design and two tapered drill designs were used. The diameter of the Drill 3 group (stepped drill) shows two values: the first value of 3.2 mm is the diameter of the drill tip and the second value of 3.6 mm is the coronal diameter of the drill

Group	Drill bit wall geometry	Body clearance (diameter) (mm)	Point angle	Flutes	Material/surface
Test Drill 1	Tapered	3.5	107,86°	4	Stainless steel/amorphous diamond coating
Test Drill 2	Tapered	3.6	121,34°	4	Stainless steel/no coating
Test Drill 3	Twist-stepped	3.2/3.6	135,18°	2	Stainless steel/amorphous diamond coating

with parallel walls is made of surgical stainless steel with amorphous diamond coating. The maximum number of uses recommended by the manufacturer is 20. This drill design only allows external irrigation (Fig. 3).

Sample size

Sixty implant drills were used in this experimental study; twenty drills per each drill design (20D1, 20D2, and 20D3). Each drill was used 10 times to reduce the effect of the wear in the heat generation [7]. A total of 600 preparations were performed (10 per each experimental group).

Experimental groups

Four drilling speeds (50, 150, 300, and 1200 rpm) were used with each drill design (D1, D2, and D3). Test slow drilling speeds (50, 150, 300 rpm) and control conventional drilling speed (1200 rpm) were assigned to each experimental group D1, D2, and D3, as follows:

D1 (D1 + 50 rpm; D1 + 150 rpm; D1 + 300 rpm; D1 + 1200 rpm)

D2 (D2 + 50 rpm; D2 + 150 rpm; D2 + 300 rpm; D2 + 1200 rpm)

D3 (D3 + 50 rpm; D3 + 150 rpm; D3 + 300 rpm; D3 + 1200 rpm)

Experimental procedures

The artificial bone samples were stabilized in a metallic base. An aluminum template was used to mark the center of each implant bed and the center of the holes for the insertion of the thermocouples. Two small perforations of 0.5 mm diameter were prepared at a distance of 1 mm from the planned implant bed. Marks were performed with a graphite tip through the metal template to indicate the drilling zones for the implant and for the thermocouples. Then, the template was removed, and the perforations for the thermocouples were prepared with a fissure bur of 0.5 mm diameter at two different depths (3 and

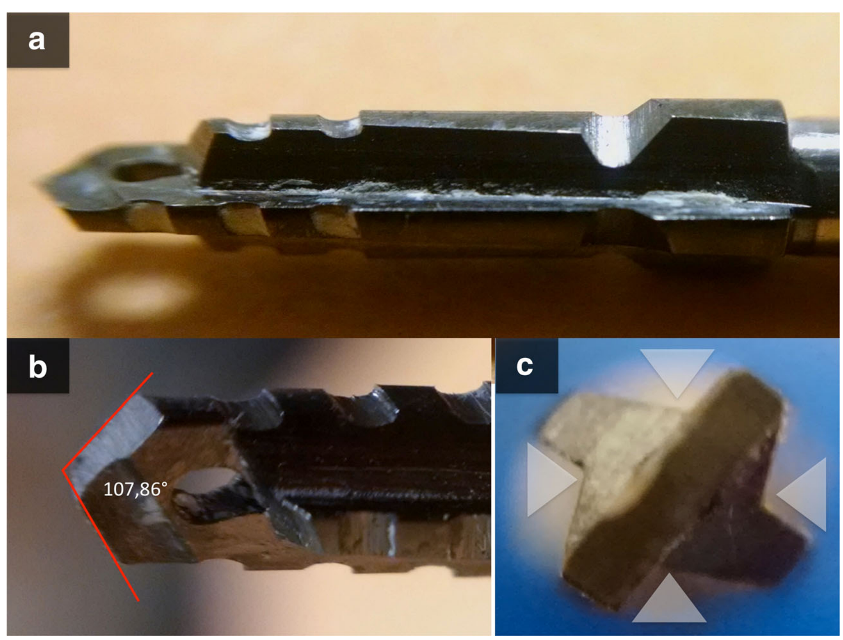

Fig. 1 Tapered drill D1 (Nobel Biocare®, Yorba Linda-California, USA). **a** The lateral view allows to observe a long flute and the areas for debris scape. **b** Shows the characteristic angle of the drill and a central hole which allows the reduction of the frictional heat. **c** The *white triangles* indicate that this drill design has four flutes

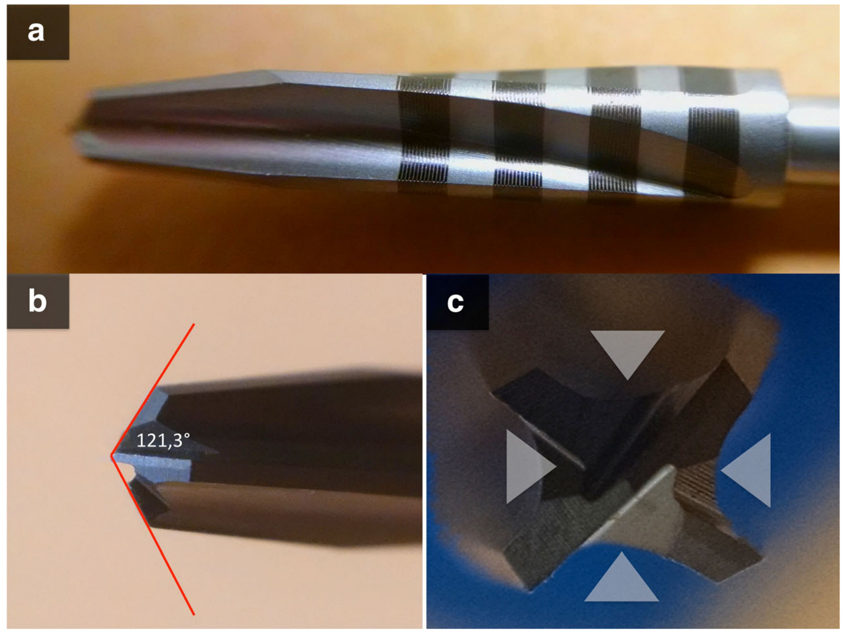

Fig. 2 Tapered drill D2 (Galimplant®, Sarria-Lugo, Spain). **a** The lateral view allows to observe a long flute with a smooth taper design. **b** Shows the characteristic angle of the drill. **c** The *white triangles* indicate that this drill design has four flutes and four cutting lips

10 mm) for the evaluation of the temperature variations at the crestal and the apical areas [7].

Next, the perforations were filled with a heat transfer gel (HTCP20S 20 mL, Electrolube®, Leicestershire, UK) [7, 25].

Two thermocouples (T Type MLT 1406, AD Instruments Inc., Colorado Springs, USA) were inserted at 3- and 10-mm depth and sealed with bone wax. The thermocouples were connected to two conditioners (ML312, T-Type Pod, AD Instruments Inc., Colorado Springs, USA) which in turn were connected to a bridge amplifier (FE221, AD Instruments Inc., Colorado Springs, USA). The signals were analyzed with the software LabChart® for Mac OS (AD Instruments Inc., Colorado Springs, USA) (Fig. 4).

Drilling speed

A single operator was calibrated by repeating 10 times each drilling protocol. Twelve additional drills were used for the calibration (4 drills per each drill design to be used with each drilling speed). The ICC (intraclass coefficient) obtained by the operator was of 0.86 (considered as reliable). Three different test slow drilling speeds (50, 150, and 300 rpm) and a

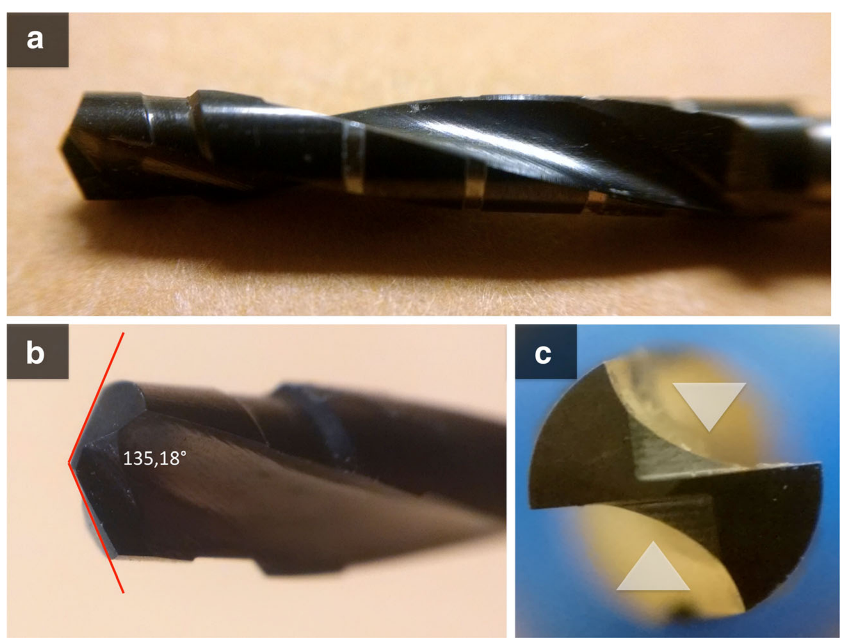

Fig. 3 Stepped drill D3 (Nobel Biocare®, Yorba Linda-California, USA). **a** The lateral view allows to observe the contour of the stepped twist drill with two steps. **b** Shows the characteristic angle of the drill tip. **c** The *white triangles* indicate that this drill design has two flutes and two cutting lips

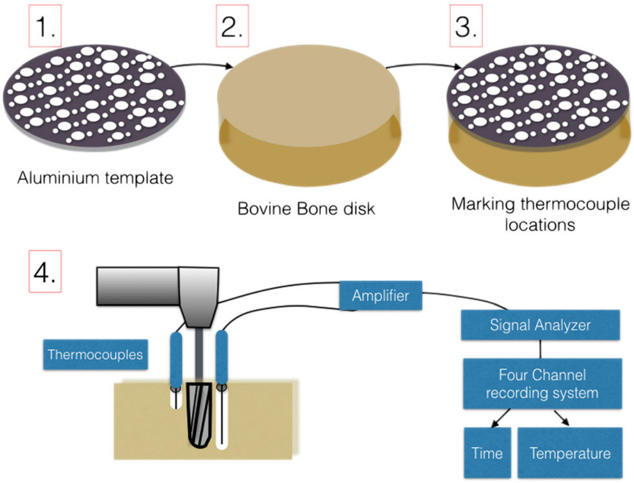

Fig. 4 Experimental set-up. **a** An aluminum template was used for the transference of standardized distances between the thermocouples and the planned implant bed. **b** The bovine bone disks had the same diameter with that of the aluminum template. **c** The aluminum template was superimposed to the bone disks, and marks were performed. **d** Two paired thermocouples were inserted in the small orifices which were located at a distance of 1 mm from the implant bed walls. The implant drilling was performed. Temperature and time were recorded in real-time, transferred to a signal amplifier then to a signal analyzer

control drilling speed of 1200 rpm were combined with the three drill designs (D1, D2, and D3), and using the website Randomization.com (http://www.randomization.com), the resulting randomization scheme with 600 implant bed preparation options was used for the preparation of the implant beds.

Measured variables

T_0: Base temperature recorded before drilling at the crestal and apical areas for each drill design and drilling speed. Values are expressed as degrees Celsius (°C).

T_{Max}: Maximum temperature recorded at the crestal and apical areas when the drill reached the 10-mm depth for each drill design and drilling speed. Values are expressed as degrees Celsius (°C).

ΔT: Differential temperature ($T_{Max} - T_0$) at the crestal and apical areas for each drill design and drilling speed. Values are expressed as degrees Celsius (°C).

Time: Total time used for the completion of the implant bed for each drill design and drilling speed. Values are expressed as seconds (s).

Statistical analysis

The normal distribution of the samples was confirmed with the Kolmogorov–Smirnov test. Statistical analysis was performed by two-way analysis of variance. Multiple comparisons of temperatures and time with the different drill designs were performed with the Tukey's test. Descriptive statistics

Table 2 T_{Max} different slow speeds with three drill designs at the crestal and apical areas. Forty drill bits of each design were used for simulated implant bed preparation at 50, 150, 300, and 1200 rpm in type IV bone. A total of 120 drills with similar dimensions but different geometries were used. D1 (Tapered drill Nobel Biocare®), D2 (Tapered drill Galimplant®), and D3 (Stepped drill Nobel Biocare®). Values expressed as °C. Median, upper quartile, lower quartile, and standard deviations are included. Significance was set as $p < 0.05$

Drilling speeds		Drill design 1		Drill design 2		Drill design 3	
		Crestal temperature (°C)	Apical temperature (°C)	Crestal temperature (°C)	Apical temperature (°C)	Crestal temperature (°C)	Apical temperature (°C)
50 rpm	Minimum	22.625	22.722	22.815	22.935	22.467	22.645
	Median	23.673	24.130	23.721	24.017	23.456	23.988
	Maximum	24.254	24.621	24.378	25.012	23.954	24.641
	SD	1.332 ± 0.487	1.215 ± 0.351	1.426 ± 0.446	1.320 ± 0.460	1.385 ± 0.510	1.263 ± 0.250
150 rpm	Minimum	23.342	23.681	23.814	23.935	23.467	23.645
	Median	24.673	25.454	24.721	25.017	24.456	24.288
	Maximum	25.171	25.897	25.184	25.945	25.563	25.375
	SD	1.483 ± 0.545	1.312 ± 0.267	1.510 ± 0.364	1.493 ± 0.312	1.490 ± 0.500	1.391 ± 0.360
300 rpm	Minimum	24.723	24.962	24.573	24.847	24.482	24.723
	Median	26.435	26.645	26.375	26.731	26.596	26.819
	Maximum	26.528	27.011	26.843	27.102	26.841	27.130
	SD	1.576 ± 0.598	1.469 ± 0.313	1.599 ± 0.488	1.549 ± 0.445	1.593 ± 0.566	1.489 ± 0.422
1200 rpm	Minimum	32.323	32.843	32.924	33.628	32.729	33.100
	Median	33.324	34.815	33.483	34.424	33.612	34.275
	Maximum	35.365	35.851	35.617	35.741	35.683	35.911
	SD	1.788 ± 0.659	1.573 ± 0.565	1.914 ± 0.351	1.895 ± 0.321	1.837 ± 0.601	1.732 ± 0.469

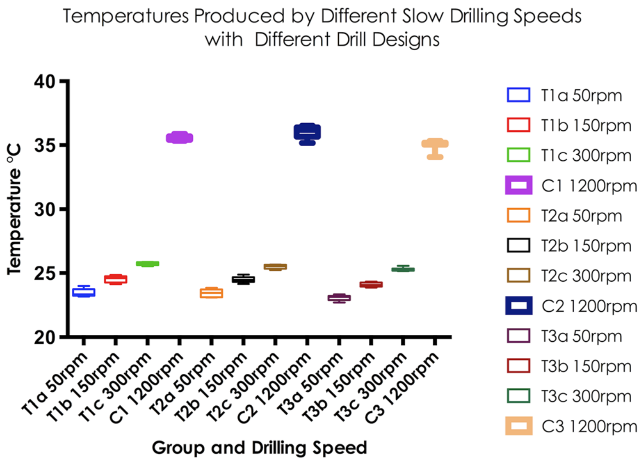

Fig. 5 Thermal variations for each drill design with each drill speed. *T1a* drill design 1 + 50 rpm, *T1b* drill design 1 + 150 rpm, *T1c* drill design 1 + 300 rpm. The same pattern is repeated with drill design 2 and drill design 3. *C1* control group for the drill 1, *C2* control group for the drill 2, *C3* control group for the drill 3. Higher temperatures were observed for the controls for each drill design (1200 rpm). At the test groups, drilling at 300 rpm resulted in higher temperatures compared to drilling at 50 rpm

mean, median, and standard deviation values were used. The level of significance was set as $p < 0.05$.

Results

Temperature changes at crestal level

T_{Max} values for the controls (D1 + 1200; D2 + 1200; D3 + 1200) ranged between 36.324 ± 2.76 °C without significant differences between groups ($p > 0.05$). The test groups (D1 + 50/150/300 rpm; D2 + 50/150/300 rpm; D3 + 50/150/300 rpm) showed a T_{Max} range between 23.121 and 29.76 °C. The T_{Max} was significantly higher for the control groups compared to that for the test groups ($p < 0.033$) (Table 2).

The comparison of T_{Max} within the test groups showed that drilling at 50 rpm resulted in the lowest temperature increment (2.11 ± 0.8 °C) compared to the other slow drilling speeds of

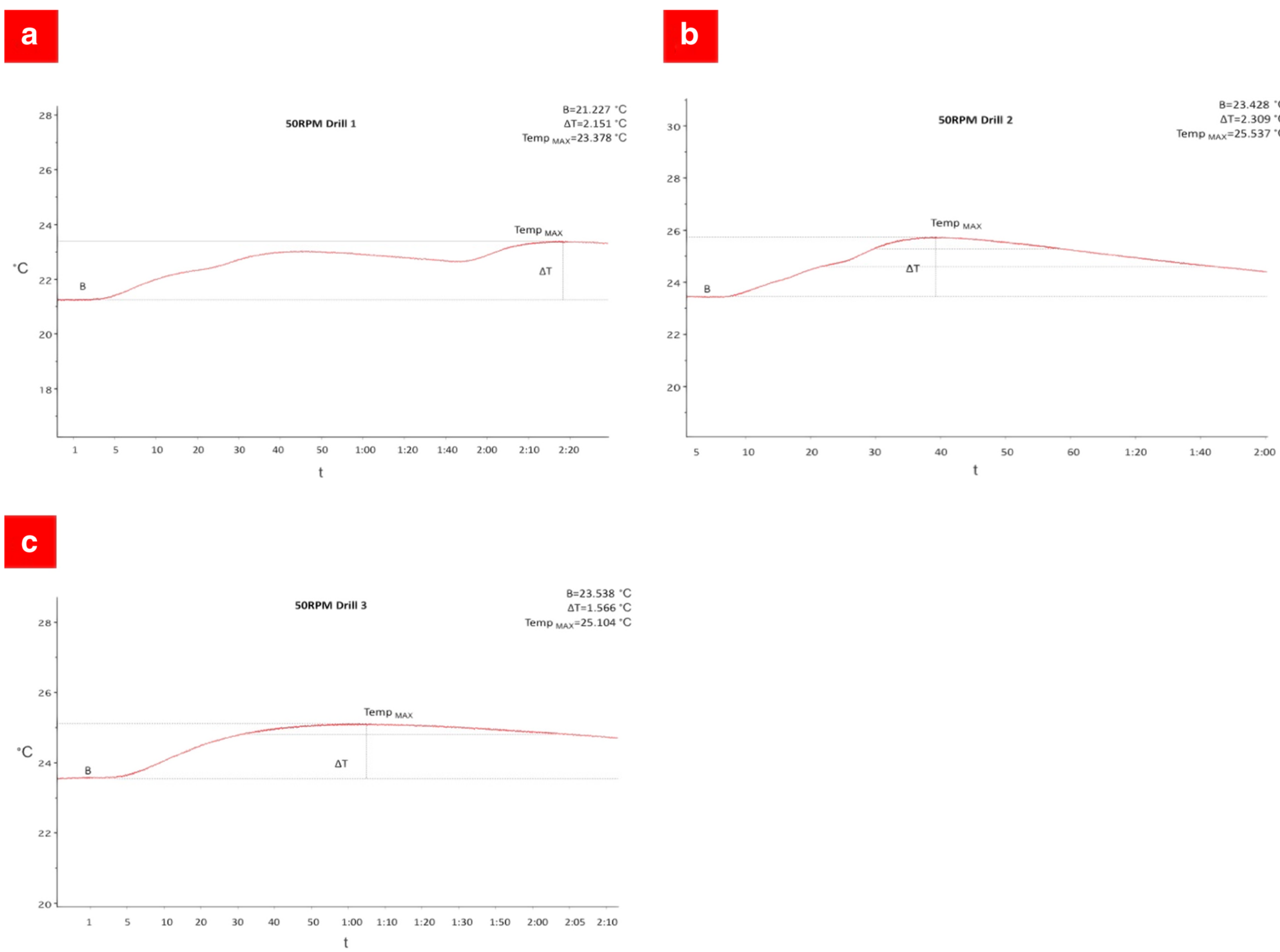

Fig. 6 Thermal curve for drilling at 50 rpm for all drill designs. Figure composition showing the thermal behavior for single-bur drilling protocols with three different drill designs. The curve is almost flat, and the temperature increment for all the groups was within 2.23 ± 0.48 °C. The time required to finish the implant bed when drilling at 50 rpm was 180 ± 15 s. (**a**) Drill 1, (**b**) Drill 2, and (**c**) Drill 3. *B* base temperature, ΔT differential temperature $T_{Max} - T_{base}$, T_{Max} maximum temperature recorded when the drill reached the drilling depth

150 (26.752 ± 1.1 °C) and 300 rpm (31.977 ± 1.0 °C) ($p < 0.042$) (Fig. 5).

Differential temperature (ΔT) was higher for the control groups (ranging from 12.3 to 13.2 °C) compared to that for the test groups (ranging from 1.2 to 5.8 °C) ($p < 0.021$).

The comparison of ΔT within the controls did not show differences between groups ($p > 0.05$). The comparison of ΔT within the tests showed higher values for drilling at 300 rpm (5.21 ± 0.7 °C) compared to drilling at 50 rpm (1.3 ± 0.68 °C) ($p < 0.046$).

Temperature changes at apical level

The temperatures showed a similar behavior compared to those in the coronal area.

T_{Max} values for the controls (D1 + 1200; D2 + 1200; D3 + 1200) ranged between 37.741 and 40.911 °C without significant differences between control groups ($p > 0.05$).

Meanwhile, the test groups (D1 + 50/150/300 rpm; D2 + 50/150/300 rpm; D3 + 50/150/300 rpm) showed a T_{Max} range between 26.621 and 31.130 °C. The T_{Max} was significantly higher for the control groups compared to that for the test groups ($p < 0.036$) (Table 2; Figs. 5, 6, 7, and 8).

Within the test groups, drilling at 300 rpm produced a temperature increment of 5.390 ± 1.18 °C which was higher compared to drilling at 50 rpm (1.78 ± 1.32) ($p < 0.048$) (Fig. 5).

Time required to complete the implant bed preparation with a single bur with different slow drilling speeds

The time required for the preparation of the implant bed with a single bur was inversely proportional to the rpm; thus, at a higher rpm, less time was utilized. Low drilling speeds required more time to finish the preparation of the implant bed shown as follows: 50 rpm > 150 rpm > 300 rpm. The drill design did not affect the time required to finish the preparation ($p > 0.05$) (Table 3; Figs. 6, 7, 8, and 9).

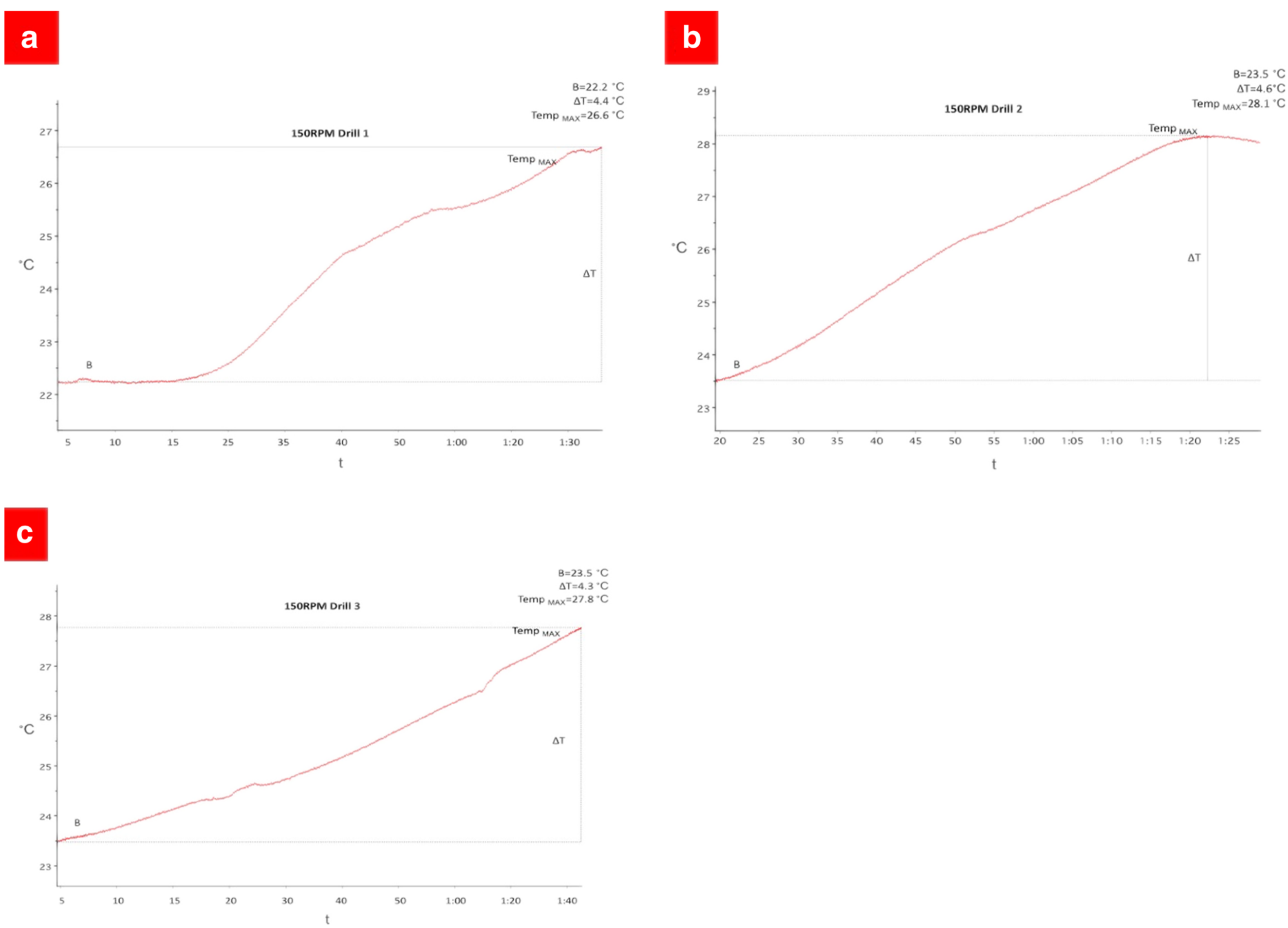

Fig. 7 Thermal curve for drilling at 150 rpm for all drill designs. Figure composition showing the thermal behavior for single-bur drilling protocols with three different drill designs. The curve slope is higher, and the temperature increment for all the groups was almost 2.12 °C higher compared to 50-rpm drilling speed, with a range within 4.23 ± 0.28 °C. The time required to finish the implant bed when drilling at 150 rpm was shorter (100 ± 10 s) compared to drilling at 50 rpm. (**a**) Drill 1, (**b**) Drill 2, and (**c**) Drill 3. B base temperature, ΔT differential temperature $T_{Max} - T_{base}$, T_{Max} maximum temperature recorded when the drill reached the drilling depth

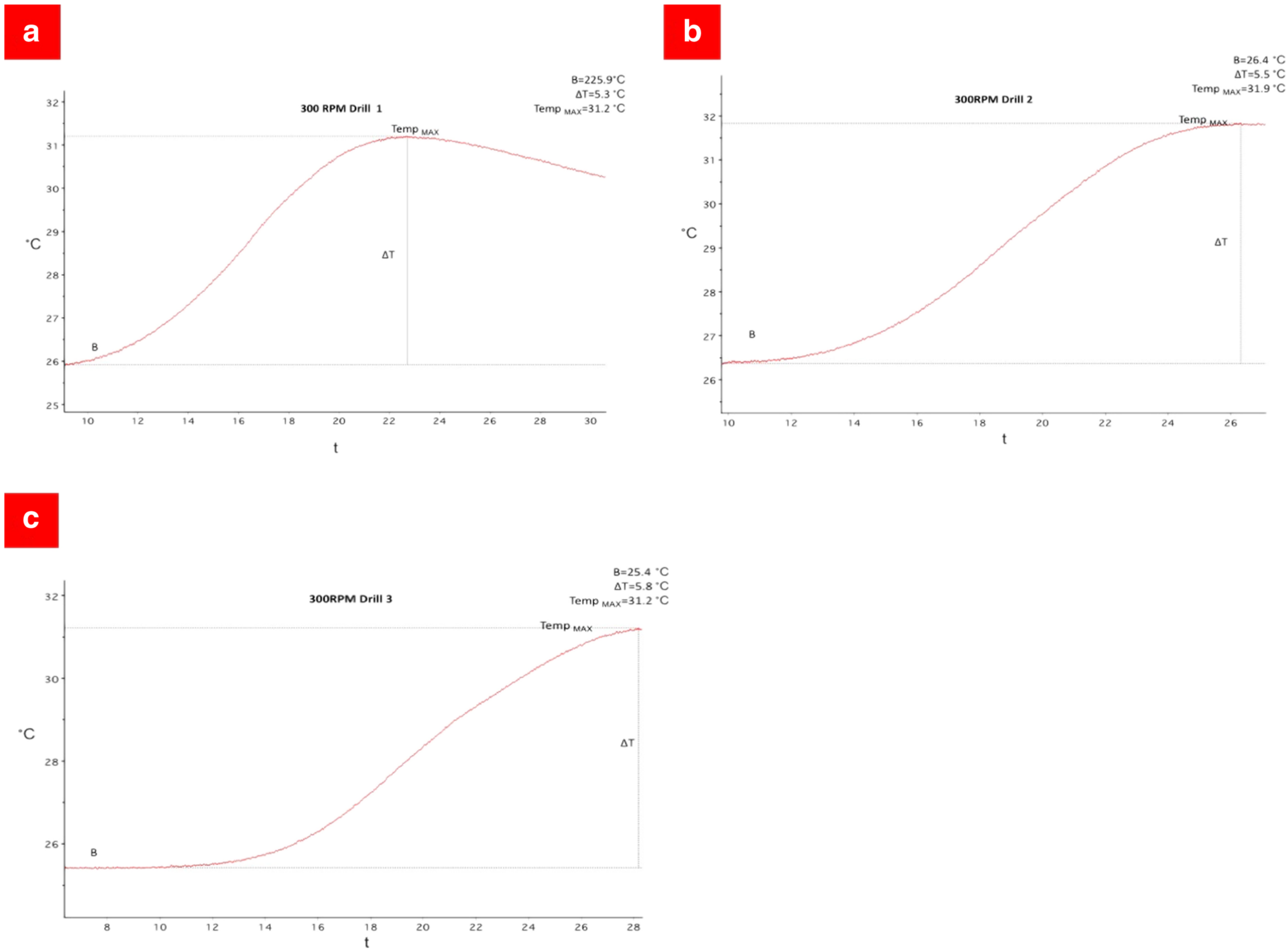

Fig. 8 Thermal curve for drilling at 300 rpm for all drill designs. Figure composition showing the thermal behavior for single-bur drilling protocols with three different drill designs. The curve slope is higher, and the temperature increment for all the groups was almost 3.52 °C higher compared to 50-rpm drilling speed, with a range within 5.43 ± 0.22 °C. The time required to finish the implant bed when drilling at 300 rpm was shorter (30 ± 3 s) compared to drilling at 50 rpm. (**a**) Drill 1, (**b**) Drill 2, and (**c**) Drill 3. *B* base temperature, ΔT differential temperature $T_{\mathrm{Max}} - T_{\mathrm{base}}$, T_{Max} maximum temperature recorded when the drill reached the drilling depth

The analysis of the thermal curves in the graphics for the apical area showed that drilling at 50 rpm resulted in a slight slope that is maintained during the whole drilling process; when the drilling speed is increased to 150 and 300 rpm, the slope is higher, and when drilling at 1200 rpm, the curve is more pronounced with significantly shorter time (Figs. 6, 7, 8, and 9).

Discussion

The purpose of this work was to evaluate the thermal changes in real-time during the preparation of the implant bed with a single-drill protocol with three drill designs and different slow drilling speeds in artificial type IV bone.

To minimize confounding factors, the drilling was performed without irrigation to eliminate the influence of the coolant in the temperature. Therefore, only the drill design and the speed could have influenced the thermal variations.

Type IV bone was chosen because it is more feasible to perform the single-bur drilling technique with slow speeds with less thermal increment at areas with higher trabecular patterns and low bone density, i.e., maxillary bone and areas of the maxillary tuberosity. This is supported by the findings from Möhlhenrich SC et al. in 2016 who showed that higher bone densities, drill diameter, and a single bur resulted in higher temperature increments compared to drilling in lower bone densities [26].

The results of the present work showed that although slow drilling speeds (50, 150, 300 rpm) with a single-drill protocol increased the temperature at the coronal and apical areas, the temperature was below the critical threshold of 47 °C [3, 4]; and compared to the temperature changes induced by 1200-rpm drilling speed, the temperature was significantly lower.

Table 3 Drilling time obtained with different slow drilling speeds and different drill designs. The real-time used for drilling an implant bed of 10-mm depth in artificial soft bone was recorded using a thermocouple system. Three drill designs were used, namely tapered drill 3.5 mm diameter (T1), tapered drill 3.6 mm diameter (T2), and stepped drill 3.6 mm diameter (T3). Three slow drilling speeds were used, namely 50 (a), 150 (b), 300 (c), and 1200 rpm (control). The 50-rpm drilling speed required 10× more time to finish the preparation compared to the control drilling speed. Values expressed as seconds (s). Median, upper quartile, lower quartile, and standard deviations are included

Drilling speed		Drill design 1 (s)	Drill design 2 (s)	Drill design 3 (s)
50 rpm	Minimum	125.834	125.167	125.923
	Median	126.876	127.163	127.411
	Maximum	127.564	128.641	128.835
	SD	5.24 ± 1.462	5.11 ± 1.993	5.86 ± 1.9
150 rpm	Minimum	88.834	89.246	88.738
	Median	89.600	90.100	89.112
	Maximum	91.463	91.350	90.994
	SD	6.14 ± 0.93	6.52 ± 0.76	6.01 ± 0.67
300 rpm	Minimum	46.732	46.926	47.124
	Median	47.438	48.100	48.690
	Maximum	48.984	49.016	49.384
	SD	7.42 ± 0.83	7.28 ± 0.69	7.34 ± 0.72
1200 rpm	Minimum	9.460	9.943	10.104
	Median	11.325	11.576	11.833
	Maximum	12.567	12.654	12.589
	SD	7.88 ± 0.35	8.15 ± 0.74	8.23 ± 0.68

This is in agreement with previous studies which found that slow drilling speeds of different values, such as 50 [16, 18], 317 [27], 400 [19], 100 and 500 [22], and 230 to 570 rpm [1], resulted in minimal variations of the temperature.

At the present work, the temperature was slightly higher at the apical zone for all the groups. This can be attributed to the prolonged contact of the drill tip with the apical bone and to the presence of bone fragments/debris which increase the friction with the bone walls [28]. Another possible explanation was provided by Scarano et al. who found that differences in the apical shape of the drill might be correlated with the temperature of the apical bone [29].

The results of the present work showed that two tapered drill designs (Nobel® and Galimplant®) and one-stepped twist drill design (Nobel®) with similar diameter and length produced similar increments of temperature when drilling at different slow drilling speeds.

Although the drill design is one of the factors which might influence the temperature variations during drilling at higher speeds (>1200 rpm) [5, 30], the results of the present work suggest that this factor does not induce significant temperature changes when performing slow drilling protocols (50, 150, 300 rpm) with a single bur. In addition, according to Augustin et al., factors like the rotational speed and the feed rate have more influence in the temperature variations than the drill design [31].

At the present work, the time necessary to perform the implant bed preparation was inversely proportional to the rpm; at higher speeds (1200 rpm), less time was used, and at lower speeds (30, 150, and 300 rpm), more time was required.

Considering the small difference in the temperature increments at different slow drilling speeds, it might be suggested that a slow drilling speed of 300 rpm is more efficient than 50 rpm in terms of the relation temperature/time.

The present work has some drawbacks which are as follows: first, a clear definition of what is a slow drilling speed does not exist, therefore the range selected for evaluation from 50 to 300 rpm may have excluded other valid slow drilling ranges; second, we used only bone type IV which excluded the analysis of the single-drill protocol with different slow speeds in other bone qualities; and third, the results of an in vitro experiment cannot be extrapolated to the clinical setting.

The strengths of this investigation are as follows: lie in the strict control of the experimental variables, which allows the reduction of confounding factors; the previous calibration of the operator for each drill speed and for each drill design, which reduced the error and variability of the drilling procedure; the effects of the drill wear were limited by the replacement of each drill after 5 uses; and as per our knowledge, this is the first study that analyzed the thermal effects of different slow drilling speeds and different drill designs during single-drill protocols.

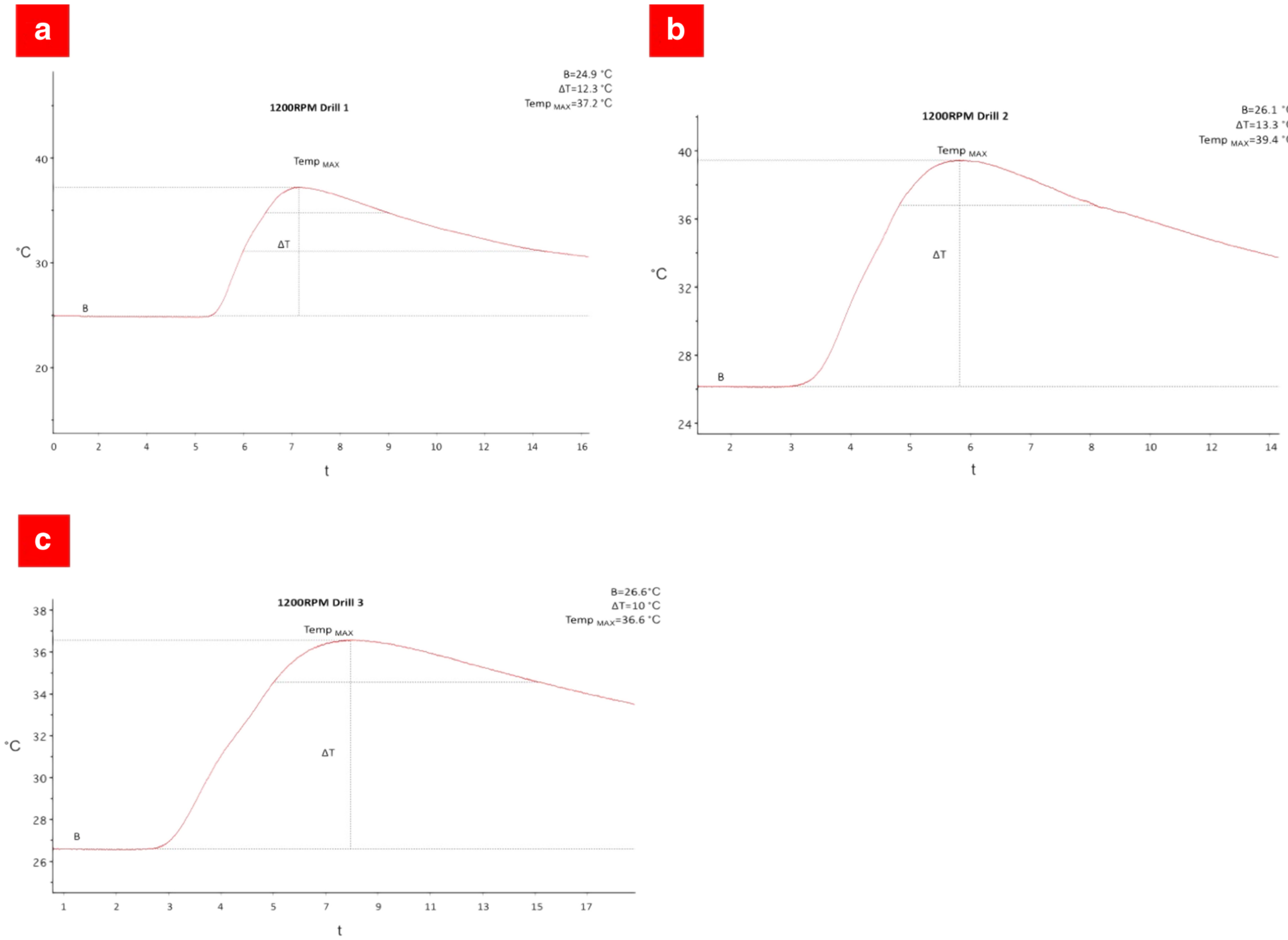

Fig. 9 Thermal curve for drilling at 1200 rpm for all drill designs. Figure composition showing the thermal behavior for single-bur drilling protocols with three different drill designs. The curve slope is the highest, and the temperature increment for all the groups was almost 12.78 °C higher compared to 50-rpm drilling speed, with a range within 12.16 ± 2.31 °C. The time required to finish the implant bed when drilling at 1200 rpm was shorter (14 ± 2.5 s) compared to drilling at 50 rpm. (**a**) Drill 1, (**b**) Drill 2, and (**c**) Drill 3. *B* base temperature, ΔT differential temperature $T_{\text{Max}} - T_{\text{base}}$, T_{Max} maximum temperature recorded when the drill reached the drilling depth

Conclusions

Within the limitations of this experimental study, the following might be concluded:

A single-drill protocol with slow drilling speeds (50, 150, and 300 rpm) without irrigation in type IV bone increases the temperature at the coronal and apical levels but is below the critical threshold of 47 °C.

The drill design in single-drill protocols using slow speeds (50, 150, and 300 rpm) does not have influence on the thermal variations.

The time to accomplish the implant bed preparation with a single-drill protocol in type IV bone is influenced by the drilling speed and not by the drill design. As the speed decreases, then, more time is required.

Clinical implications

When using a single-bur protocol with tapered and multi-stepped twist drills, a slow drilling speed of 300 rpm in type IV bone density seems to be more efficient in terms of temperature increase and time reduction than using a single bur with a drilling speed of 50 rpm.

Compliance with ethical standards

Conflict of interest Rafael Delgado-Ruiz declares that he has no conflict of interest.

Eugenio Velasco Ortega declares that he has no conflict of interest.

Georgios Romanos declares that he has no conflict of interest.

Sergio Gerhke declares that he has no conflict of interest.

Ivana Newen declares that she has no conflict of interest.
Jose Luis Calvo-Guirado declares that he has no conflict of interest.

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Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent For this type of study, formal consent is not required.

References

1. Karaca F, Aksakal B (2013) Effects of various drilling parameters on bone during implantology: an in vitro experimental study. Acta Bioeng Biomech 15:25–32
2. Wawrzinek C, Sommer T, Fischer-Brandies H (2008) Microdamage in cortical bone due to the overtightening of orthodontic microscrews. J Orofac Orthop 69:121–134
3. Eriksson A, Albrektsson T, Grane B et al (1982) Thermal injury to bone: a vital-microscopic description of heat effects. Int J Oral Surg 11:115–121
4. Eriksson A, Albrektsson T (1984) The effect of heat on bone regeneration: an experimental study in the rabbit using the bone growth chamber. J Oral Maxillofac Surg 42:705–711
5. Chacon G, Bower D, Larsen P et al (2006) Heat production by 3 implant drill systems after repeated drilling and sterilization. J Oral Maxillofac Surg 64:265–269
6. Krause W, Bradbury D, Kelly J et al (1982) Temperature elevations during orthopaedic cutting operations. J Biomech 15:267–275
7. Abboud M, Delgado-Ruiz R, Kucine A et al (2015) Multistepped drill design for single-stage implant site preparation: experimental study in type 2 bone. Clin Implant Dent Relat Res Suppl 2:e472–e485
8. Abouzgia M, Smyngton J (1996) Effect of drill speed on bone temperature. Int J Oral Maxillofac Surg 25:394–399
9. Thompson H (1958) Effect of drilling into bone. J Oral Surg 16:22–30
10. Brisman D (1996) The effect of speed, pressure, and time on bone temperature during the drilling of implant sites. Int J Oral Maxillofac Implants 11:35–37
11. Iyer S, Weiss C, Mehta A (1997) Effects of drill speed on heat production and the rate and quality of bone formation in dental implant osteotomies, part I: relationship between drill speed and heat production. Int J Prosthodont 10:411–414
12. Sharawy M, Misch C, Weller N et al (2003) Heat generation during implant drilling: the significance of motor speed. J Oral Maxillofac Surg 60:1160–1169
13. Watcher R, Stoll P (1991) Increase of temperature during osteotomy. In vitro and in vivo investigations. Int J Oral Maxillofac Surg 20:245–249
14. Tehemar S (1999) Factors affecting heat generation during implant site preparation: a review of biologic observations and future considerations. Int J Oral Maxillofac Implants 14:127–136
15. Reingewirtz Y, Szmukler-Moncler S, Senger B (1997) Influence of different parameters on bone heating and drilling in implantology. Clin Oral Implants Res 8:189
16. Anitua E, Carda C, Andia I (2007) A novel drilling procedure and subsequent bone autograft preparation: a technical note. Int J Oral Maxillofac Implants 22:138–145
17. Kim S, Yoo J, Kim Y et al (2010) Temperature change in pig rib bone during implant site preparation by low-speed drilling. J Appl Oral Sci 18:522–527
18. Gaspar J, Borrecho G, Oliveira P et al (2013) Osteotomy at low-speed drilling without irrigation versus high-speed drilling with irrigation: an experimental study. Acta Medica Port 26:231–236
19. Sarendranath A, Khan R, Tovar N et al (2015) Effect of low speed drilling on osseointegration using simplified drilling procedures. Br J Oral Maxillofac Surg 53:550–556
20. Jimbo R, Giro G, Marin C et al (2013) Simplified drilling technique does not decrease dental implant osseointegration: a preliminary report. J Periodontol 84:1599–1605
21. Guazzi P, Grandi T, Grandi G (2015) Implant site preparation using a single bur versus multiple drilling steps: 4-month post-loading results of a multicenter randomised controlled trial. Eur J Oral Implantol 8:283–290
22. Yeniyol S, Jimbo R, Marin C et al (2013) The effect of drilling speed on early bone healing to oral implants. Oral Surg Oral Med Oral Pathol Oral Radiol 116:550–555
23. Sener B, Dergin G, Gursoy B et al (2009) Effects of irrigation temperature on heat control in vitro at different drilling depths. Clin Oral Implants Res 20:294–298
24. Strbac G, Giannis K, Unger E et al (2014) A novel standardized bone model for thermal evaluation of bone osteotomies with various irrigation methods. Clin Oral Implants Res 25:622–631
25. Rashad A, Kaiser A, Prochnow N et al (2011) Heat production during different ultrasonic and conventional osteotomy preparations for dental implants. Clin Oral Implants Res 22:1361–1365
26. Möhlhenrich SC, Abouridouane M, Heussen N et al (2016) Thermal evaluation by infrared measurement of implant site preparation between single and gradual drilling in artificial bone blocks of different densities. Int J Oral Maxillofac Surg 45:1478–1484
27. Toews A, Bailey J, Townsend H et al (1999) Effect of feed rate and drill speed on temperatures in equine cortical bone. Am J Vet Res 60:942–944
28. Gabrić Pandurić D, Bago I, Katanec D et al (2012) Comparison of Er:YAG laser and surgical drill for osteotomy in oral surgery: an experimental study. J Oral Maxillofac Surg 70:2515–2521
29. Scarano A, Piattelli A, Assenza B et al (2011) Infrared thermographic evaluation of temperature modifications induced during implant site preparation with cylindrical versus conical drills. Clin Implant Dent Relat Res 13:319–323
30. Coelho P, Suzuki M, Guimaraes M (2010) Early bone healing around different implant bulk designs and surgical techniques: a study in dogs. Clin Implant Dent Relat Res 12:202–208
31. Augustin G, Davila S, Mihoci K et al (2008) Thermal osteonecrosis and bone drilling parameters revisited. Arch Orthop Trauma Surg 128:71–77