Drilling- and Withdrawing-Related Thermal Changes during Implant Site Osteotomies

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ABSTRACT

Background: Intrabony temperature increase is not only dependent on shearing energy and mechanical friction between bone and surgical drill but is also related to heat capacity and thermal conductivity of the surrounding bone and the applied surgical instrument. Thus time of occurrence of the highest temperature rise can be expected after the shearing process of the osteotomy, potentially affecting the process of osseointegration.

Purpose: The aim of this study was to evaluate temperature changes during the shearing and withdrawing processes during osteotomies.

Materials and Methods: An overall 160 automated intermittent osteotomies (10/16 mm drilling depth) with 2 mm diameter twist drills and 3.5 mm diameter conical drills and different irrigation methods (without/external/internal/combined) were performed on standardized bone specimens. The drilling cycles were operated by a computer-controlled surgical system, while a linear motion potentiometer and multichannel temperature sensors in various intrabony levels ensured the real-time documentation of temperature changes during the shearing and withdrawing processes.

Results: The highest temperature changes were invariably recorded during the process of withdrawal. Significantly lower temperature changes ($p < .02$) could be recorded at maximum drilling depths during the shearing process regardless of drilling depth, diameter or irrigation method. During coolant supply, 2 mm diameter twist drills showed higher temperatures (10 mm, $p < .01$/16 mm, $p < .03$) compared with 3.5 mm diameter conical implant drills. Internal (10 mm, $p < .01$) or combined irrigation (16 mm, $p < .01$) was associated with significantly lower temperatures compared with external irrigation by the use of conical implant drills.

Conclusions: Considering that heat generation during osteotomies is a multifactorial scenario, this study could demonstrate that the highest temperature rise during implant osteotomies occurs during the withdrawing process and that the time of occurrence is influenced by predominant factors such as osteotomy depth and mode of irrigation.

KEY WORDS: heat generation, implant drill, implant osteotomy, irrigation, multiple temperature sensors, shearing process, withdrawing process

INTRODUCTION

For successful clinical treatment with dental implants, a gentle drilling technique and the preservation of healthy bone during preparation are essential prerequisites for the osseous integration of the implant. However, regardless of the smoothness of the drilling technique, an unavoidable necrotic border bone zone will develop primarily surrounding the inserted implant. The width of this necrotic border bone zone is mainly dependent on the degree of the surgical trauma and the frictional heat generated. Consequently, to avoid mechanical damage and high frictional forces during osteotomies,

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a minimally traumatic drilling procedure is required for implant site osteotomies.[1–5]

As the prevention of overheating during implant site osteotomies has drawn major attention from researchers over the years, Eriksson and Albrektsson determined the critical temperature threshold levels for bone survival during osteotomies in a histological study. Temperatures ranging from 44°C to 47°C during a drilling duration of over 1 minute were found to be the upper threshold for minimizing and avoiding thermal necrosis, while an inexistent regenerative capacity and resorption of adjacent bone of up to 30% can be observed after implant placement with temperatures over 50°C.[3,6] Further studies concerning temperature changes observed that even lower values of temperature increase (4.3°C) might reduce the rate and quality of the newly formed bone after implant preparation.[7] Other studies have shown that temperatures below the level of 56°C are associated with the denaturation of alkaline phosphate, the inactivation of enzymes and membrane proteins, cell dehydration and the reduction of blood flow, thus impacting the regenerative capacity of bone.[1,8–10] In addition, from a histological perspective, it can be observed that progressive temperature generation involves dislocations in the hydroxyapatite mineral lattice structure and thus leads to microscopic deformations and fractures of the compact bone. These effects affect primary stability of dental implants and reduce bone apposition during the early stages of osseointegration, potentially increasing the risk of an early implant failure.[4,8,11]

It is evident that each implant bed preparation causes mechanical damage to the bone and that the shearing energy and mechanical friction required for achieving this preparation procedure is subsequently converted into heat at 98%.[12–14] The shearing energy released in the form of heat during the drilling process is produced by the cutting edges of the surgical drill by breaking intermolecular bonds of the bone tissue. The amount of bone chips produced during this osteotomy procedure determines the frictional forces induced in the specimen. Moreover, the noncutting surface of the surgical device, including the flank, flutes, and shaft of the drill, are responsible for the mechanical friction, which is also converted into heat. The ultimate temperature rise during the osteotomy procedure is also dependent on the heat capacity and thermal conductivity of the bone specimen and the material of the applied surgical instrument.[1,15] Heat capacity and thermal conductivity are two important factors that should not be disregarded and should be taken into consideration. These factors can delay heat expansion and therefore influence the temporal and local occurrence of maximum temperature increase during a drilling procedure. Based on this fact, it can be hypothesized that the time of occurrence of the highest temperature rise can be expected with a certain time lag to the shearing process of the osteotomy and consequently after ending the cutting process and during the withdrawal of the surgical instrument.

As heat generation during implant osteotomies can be detected in different locations of the investigated specimen, two different measurement methods, the thermocouple and infrared thermography, have been established in dental research.[1,8] However, it should be considered that these investigations recorded temperature changes during the shearing process of bone without observing the temperature distribution throughout the whole drilling procedure including shearing and withdrawal of the surgical drill. As yet, no data have been analyzed with respect to the topographic and real-time temperature expansion during the entire implant osteotomy procedure.

The aim of the study was to investigate the temperature changes during the whole drilling procedure including shearing and withdrawing and to record the influence of drilling depth, drill diameter, and different irrigation methods with regard to the time and location of maximum temperature increase.

MATERIALS AND METHODS

Experimental Setup

Bone Specimen. The temperature measurements during drilling osteotomies were evaluated in vitro using artificially manufactured bovine bone specimens (BoneSim™, 1800.35/1300.14 Composite, BoneSim™, Newaygo, MI, USA). This bovine bone specimen represents a recently introduced study model with a bone density of type 2, according to the Lekholm and Zarb classification, with predefined vertical (3 mm cortical and 15 mm cancellous bone) and horizontal parameters (58 mm diameter).[16,17] With density and relationship between bone areas similar to human bone, this bone specimen ensures analogous thermal conductivity (0.3–0.4 W/m/K) for comparable results of temperature changes in this study.[14,17–19] Each testing specimen was bonded with auto-polymerizing acrylic resin (SR Ivolen®, Ivoclar Vivadent, Schaan, Liechtenstein) in a rectangular test box (No. 34160-0101, Bock, Lauterbach, Germany) to secure its stable position throughout the drilling procedure.[20,21]

Surgical Drilling Simulator. In this study, the implant osteotomies were performed using a custom-made surgical system (SH-Surgical Drilling-Sequence-Simulator System, Center for Medical Physics and Biomedical Engineering, Medical University of Vienna, Vienna, Austria) to simulate a clinical atraumatic intermittent osteotomy procedure. A surgical handpiece (WS-75 E/KM 20:1, W&H, Bürmoos, Austria), mounted in a CNC-produced clamp to ensure its vertical position, was moved along a guidance rail with a stepper motor by the aid of a software program (SSH-Surgical Drilling-Sequence-Software 1.0, Center for Medical Physics and Biomedical Engineering). The motion program generated a predefined vertical moving sequence to ensure drilling depths of 10 mm (drilling duration 17.3 seconds, withdrawal duration 10.3 seconds, total osteotomy procedure 27.6 seconds) and 16 mm (drilling duration 27.1 seconds, withdrawal duration 16.4 seconds, total osteotomy procedure 43.5 seconds) with constant processing durations, including drilling and withdrawing, for both investigated drilling depths. To ensure an automated, reproducible intermittent drilling procedure, the software program also simulated the clinical back-and-forth pumping movement of the drills at predetermined positions of 2 mm, 4 mm, 8 mm, and 10 mm for 10 mm osteotomies and also 13 mm and 16 mm for 16-mm osteotomies, each with a retraction movement of 1 mm, closing the drilling cycle with a final retraction to the starting baseline position of 0 mm.[9,20,22]

The sliding device of the surgical system was additionally equipped with a linear motion potentiometer (No. 9615R5.1KL2.0, BEI Sensors, Goleta, CA, USA) for controlling the predefined depth (10 mm/16 mm) of each osteotomy and for documenting the advancement of the surgical drill, permitting the real-time recording of temperature changes during the whole drilling procedure, including shearing and withdrawal of the surgical drill.

Temperature Measurement. For measurement of intrabony temperature changes, a custom-built multichannel

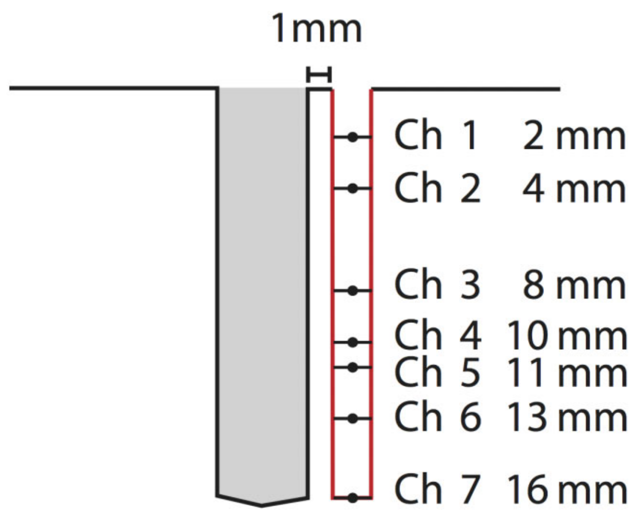

Figure 1 Schematic representation of osteotomy site and temperature recording by thermoprobe with multiple sensors (Ch 1–4 for 10-mm drilling depth and Ch 1–7 for 16-mm drilling depth).

thermoprobe (SHT-Thermoprobe, Center for Medical Physics and Biomedical Engineering; 1.5 mm diameter and 18 mm length) with seven temperature sensors (Miniature Axial Glass Thermistor, No. GA10KM3499J15, Measurement Specialties™, Hampton, VA, USA; diameter 0.4 mm, temperature range −40°C to +250°C, response time <0.2 seconds) was inserted into the testing specimen to record temperature changes.

The seven temperature sensors, located in the custom-built thermoprobe at predefined measurement depths (Channel (Ch); Ch 1 = 2 mm, Ch 2 = 4 mm, Ch 3 = 8 mm, and Ch 4 = 10 mm for 10-mm drilling depths, additionally Ch 5 = 11 mm, Ch 6 = 13 mm, and Ch 7 = 16 mm for 16-mm drilling osteotomies), were calibrated (range from 5°C to 100°C) prior to drilling procedures (Figure 1). Real-time measurements were carried out by a temperature measurement system (SHTM-Temperature Measurement System, Center for Medical Physics and Biomedical Engineering) and a signal capture program (DASYLab® Software 5.0, Measurement Computing Corporation, Norton, MA, USA).[20]

Operational Protocol

The drilling osteotomies were performed in a total of 40 bone specimens at constant room temperature (21 ± 1°C) using different irrigation methods. For every irrigation method (without/external/internal/combined), each bovine specimen was randomly divided and perforated four times to ensure equal conditions for comparable results and to reduce any bias due to potentially varying bone densities.[4,9,11,20]

Prior to the investigated drilling procedures the embedded specimens were fixed to a computer-milled table of the surgical unit, which allowed a precise movement of the bone models for further preparation and an accurate placement of the thermoprobe. The preparation for the insertion of the thermoprobe, at a predetermined distance of 1 mm parallel to the final drill osteotomy, was done using a twist drill (2 mm diameter, 18 mm drilling depth, 210 L20.205.020, Komet®, Gebr. Brasseler, Lemgo, Germany).[22–25] Before the thermoprobe was inserted, a heat-transfer compound (HTCP20S 20 ml, Electrolube®, Leicestershire, UK) was infilled into the prepared canal to permit a continuous heat transfer from the bone to each temperature sensor during the entire drilling.[9,20,22,25–27] The investigated osteotomies of 10-mm and 16-mm depth were carried out by surgical twist drills of 2 mm diameter, while the graduated osteotomies were performed with conical implant drills of 3.5 mm diameter after predrilling with pilot twist drills of 2 mm diameter (NobelReplace™ Tapered Drills, Nobel Biocare®, Göteborg, Sweden). Temperature changes were recorded during the entire drilling and withdrawing process of the 2 mm diameter twist drills and the final implant drills of 3.5 mm diameter, excluding the predrilling procedure with the pilot twist drills during graduated implant osteotomies. To avoid any influence of drill wear concerning temperature changes, new, out-of-the-box drills were used for each perforation.[24] As regards coolants during osteotomies, an isotonic saline solution (Viaflo, 0.9% NaCl, 1000 ml, Baxter Healthcare, Vienna, Austria) with a constant perfusion of 50 ml/min at room temperature (21 ± 1°C) was supplied by an irrigation tubing set (Hose set for machinery, 80 mm, Omnia®, Fidenza, Italy), which was connected to the surgical handpiece and to a surgical motor unit (Implantmed SI-923, Surgical Control S-N1, W&H), which additionally ensured a constant drilling speed of 800 rpm.[9,20,25] Every osteotomy was conducted with 10 repetitions, totaling 160 drilling procedures with 80 for each diameter (2 mm diameter twist drill/3.5 mm diameter conical implant drill) and 80 for each implant drilling depth (10 mm/16 mm drilling depth), including in each group osteotomies with different irrigation methods (without/external/internal/combined).

Statistical Analysis

The variation of temperature was calculated and compared by subtracting the recorded temperature T_x with the bone specimen baseline temperature T_0 before each osteotomy ($\Delta T[°C] = T_x - T_0$).[9,20,27] A custom analysis software program (Temperature-Analysis, Department of Radiology, Medical University of Vienna, Austria), built on a computing software program (MATLAB®, R2011a, MathWorks®, Natick, MA, USA), was used to process the data.

Continuous data were described as medians. Implant depths of 10-mm and 16-mm were analyzed separately with four (Ch 1–4 for 10-mm osteotomies) and seven (Ch 1–7 for 16-mm osteotomies) measurement sensor locations, respectively. Linear mixed models were estimated, including three main factors (drilling diameter, irrigation method, and osteotomy depth) and their interactions. The four drill holes per bovine specimen and four/seven measurement sensor locations were included as repeated-measurements factors, assuming an unstructured and a first-order autoregressive covariance between repeated measures, respectively. Heterogeneous variance estimations in subgroups were allowed to account for severe heterogeneity, and a Kenward-Roger adjustment to the degrees of freedom was applied. Normal distributions of standardized residuals were checked graphically. As the three-way interactions were highly significant, subgroup analyses were performed by comparison of least-square means within the linear mixed model. Measurement values were log-transformed in case of right skew data. Statistical calculations were performed with the statistical software SAS® (Version 9.3; SAS Institute Inc., Cary, NC, USA). All p values are two-sided and considered significant at $p \leq .05$.

RESULTS

For the evaluation of temperature changes, 160 drilling osteotomies were performed to investigate the entire drilling procedure, including the shearing and withdrawing processes.

The mean baseline temperature T_0 of the bone specimens ($n = 40$) was 21.80 ± 1.67°C prior to each drilling osteotomy. The intrabony temperature rise ΔT, recorded in real time by the multichannel thermoprobe, always revealed significantly higher temperature changes ($p < .01$) compared with the specimen baseline temperature values T_0.

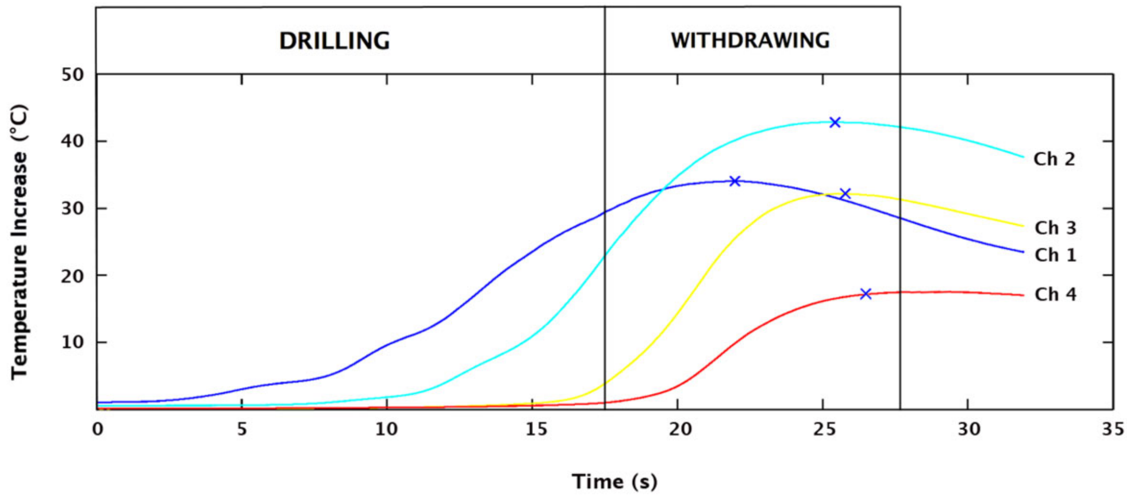

Figure 2 Illustration of temperature changes during 10-mm osteotomies: recorded in real time by four temperature sensors at predefined measuring depths; after 17.3 seconds reaching drilling depth of 10 mm (ΔT°C at Peak); highest temperature increase (Max ΔT°C) during the withdrawing procedure; x indicating highest temperature increase during the entire drilling procedure.

Temperature Changes during Drilling and Withdrawing

Maximum temperature changes were invariably observed during the process of withdrawing (Figures 2 and 3). These revealed significantly higher values ($p < .02$) compared with the temperature rise recorded at maximum drilling depths, no matter what drilling depth, implant drill, or irrigation method was deployed (Tables 1 and 2).

10-mm Drilling Osteotomies. The highest temperature changes during drilling osteotomies of 10 mm were always recorded at 4 mm sensor depth (Ch 2) (Table 1). Twist drills. The highest temperature increase of 40.16°C was observed with combined saline irrigation at 4 mm sensor depth (Ch 2), 6.05 seconds after reaching the maximum drilling depth with the surgical drill located at 4.28 mm during withdrawal.

The lowest temperature change of 9.03°C could be recorded with external saline irrigation at 2 mm sensor depth (Ch 1), 7.44 seconds after reaching 10 mm drilling depth with the twist drill located at 2.76 mm (Table 1).

Comparing the efficiency of various irrigation methods, external irrigation showed the lowest maximum temperature change (20.45°C) compared

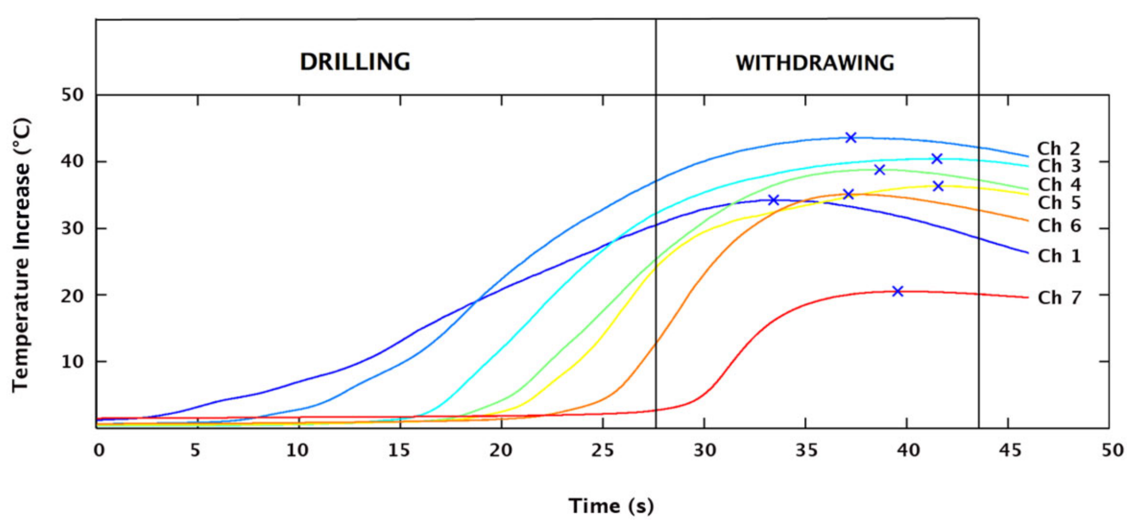

Figure 3 Illustration of temperature changes during 16-mm osteotomies: recorded in real time by seven temperature sensors at predefined measuring depths; after 27.1 seconds reaching drilling depth of 16 mm (ΔT°C at Peak); highest temperature increase (Max ΔT°C) during the withdrawing procedure; x indicates highest temperature increase during the entire drilling procedure.

TABLE 1 Median Values of Temperature Changes (10-mm Drilling Depth)

Drill Diameter	Irrigation	Channel	Max. ΔT (°C)#	Time of Max. (seconds)†	Depth of Max. (mm)‡	ΔT at Peak (°C)§	Diff. Max. vs. Peak (°C)¶
2 mm	Without	1	27.77	9.94	0.41	10.04**	15.83
		2	29.79	8.63	1.74	14.18**	15.66
		3	18.86	8.38	1.91	6.17**	13.59
		4	12.90	10.27	0.14	1.82**	11.35
	External	1	9.03	7.44	2.76	3.03**	6.43
		2	20.45	7.71	2.46	7.23**	11.39
		3	19.57	7.02	3.21	5.68**	12.99
		4	13.02	8.24	2.12	1.52**	11.56
	Internal	1	16.55	6.69	3.55	5.40**	11.13
		2	28.30	6.89	3.36	13.67**	11.20
		3	24.12	6.78	3.47	10.71**	13.22
		4	16.01	7.70	2.54	2.84**	13.12
	Combined	1	18.13	5.96	4.30	7.05**	12.14
		2	40.16	6.05	4.28	23.23**	14.22
		3	33.19	5.04	5.21	20.08**	14.42
		4	19.13	7.16	3.12	4.31**	13.29
3.5 mm	Without	1	31.40*	4.87	5.31	25.76**	5.90
		2	42.40*	4.95	5.16	32.49**	9.65
		3	32.22*	5.79	4.41	13.02**	18.72
		4	17.77*	9.35	0.96	3.17**	14.54
	External	1	3.16*	1.16	8.83	2.90	0.24
		2	5.79*	2.54	7.65	4.66**	1.46
		3	3.32*	2.55	7.62	1.37**	1.84
		4	1.37*	3.21	7.00	0.32**	1.08
	Internal	1	2.43*	1.40	8.57	1.83**	0.53
		2	2.50*	2.31	7.80	2.25**	0.38
		3	1.39*	2.41	7.78	0.35**	0.76
		4	0.35*	2.77	7.38	0.04	0.35
	Combined	1	2.73*	1.23	8.80	2.39	0.34
		2	4.22*	2.51	7.64	3.51**	0.96
		3	2.28*	2.90	7.26	1.21**	1.25
		4	0.68*	3.59	6.63	0.23**	0.51

Recorded by a thermoprobe with four sensors located at predefined measurement depths (channels [Ch] 1, 2, 3, and 4; Ch 1 at 2 mm, Ch 2 at 4 mm, Ch 3 at 8 mm, Ch 4 at 10 mm). Shading indicates channel with highest temperature increase.
#Highest temperature increase during drilling and withdrawing.
†Time after reaching 10 mm drilling depth when Max. ΔT was measured.
‡Location of surgical drill when Max. ΔT was measured.
§Temperature increase measured on reaching 10 mm drilling depth.
¶Difference between Max. ΔT and ΔT at Peak.
*Statistically significant difference Max ΔT of 2 mm diameter compared to 3.5 mm diameter ($P \leq 0.05$).
**Statistically significant difference Max ΔT compared to ΔT at Peak ($P \leq 0.05$).

with internal (28.30°C, $p < .01$) and then combined saline irrigation (40.16°C, $p < .01$).

Conical implant drills. During the drilling process the maximum temperature rise of 42.40°C was recorded without any saline irrigation method, 4.95 seconds after reaching the final depth of 10 mm at 4 mm sensor depth (Ch 2), with the drill situated at a depth of 5.16 mm from the starting position during the process of withdrawing.

The lowest temperature rise of 0.35°C could be obtained at 10 mm sensor depth (Ch 4) with internal

TABLE 2 Median Values of Temperature Changes (16-mm Drilling Depth)

Drill Diameter	Irrigation	Channel	Max. ΔT (°C)#	Time of Max. (seconds)†	Depth of Max. (mm)‡	ΔT at Peak (°C)§	Diff. Max. vs. Peak (°C)¶
2 mm	Without	1	38.39	11.65	4.49	28.87**	8.75
		2	45.46	10.13	5.87	42.53**	3.51
		3	43.67	9.28	6.83	41.66**	2.25
		4	42.82	7.60	8.52	34.96**	6.84
		5	40.45	7.20	8.85	31.54**	8.73
		6	35.80	6.73	9.30	19.04**	11.76
		7	17.34	8.05	7.95	4.18**	12.83
	External	1	21.75	8.27	7.89	15.77**	6.46
		2	45.46	9.20	6.94	38.83**	6.17
		3	45.95	8.01	8.12	44.78**	1.45
		4	42.72	7.25	8.86	34.64**	7.88
		5	41.74	7.39	8.57	31.68**	9.58
		6	34.92	6.70	9.29	19.97**	14.20
		7	18.54	10.42	5.70	4.87**	14.39
	Internal	1	21.47	12.24	3.89	14.47**	7.50
		2	40.51	12.26	4.01	35.98**	5.06
		3	44.43	9.59	6.50	40.53**	3.23
		4	40.67	8.12	8.04	30.94**	9.29
		5	40.82	8.03	8.10	28.06**	10.68
		6	32.64	7.80	8.38	18.29**	15.30
		7	14.41	13.47	2.62	1.82**	12.45
	Combined	1	19.32	11.44	4.68	13.74**	6.46
		2	39.59	11.36	4.82	34.96**	4.48
		3	42.01	8.93	7.15	39.86**	1.85
		4	39.69	8.07	8.11	31.04**	8.64
		5	38.70	7.22	8.86	28.21**	10.37
		6	32.69	7.78	8.38	17.04**	14.21
		7	14.25	15.49	0.85	2.00**	11.51
3.5 mm	Without	1	34.37	6.24	9.70	30.19**	4.94
		2	44.48	5.83	10.23	42.50**	2.30
		3	41.98	8.90	7.20	39.70**	2.65
		4	40.63	7.68	8.40	31.74**	8.24
		5	39.31	11.65	4.54	31.83**	6.96
		6	37.33	7.41	8.60	22.31**	13.04
		7	18.91	10.74	5.39	2.46**	16.45
	External	1	8.07*	7.79	8.33	4.49**	2.83
		2	19.48*	8.07	8.09	12.00**	8.46
		3	28.49*	7.42	8.76	17.11**	12.07
		4	24.41*	8.05	8.08	13.95**	11.70
		5	25.05*	8.00	8.13	14.26**	12.10
		6	22.87*	7.62	8.53	10.38**	14.72
		7	12.16*	12.74	3.59	1.37**	10.57
	Internal	1	6.55*	7.17	8.95	3.26**	2.87
		2	10.67*	8.26	7.88	3.67**	6.42
		3	11.34*	8.40	7.74	2.85**	8.49
		4	10.05*	9.22	6.88	1.85**	8.15
		5	10.43*	8.42	7.67	1.93**	8.57
		6	9.34*	8.09	8.10	0.96**	8.38
		7	7.00*	8.76	7.34	0.46**	6.35
	Combined	1	1.52*	6.04	9.94	1.17	0.44
		2	4.30*	5.34	10.56	2.17**	2.58
		3	6.69*	6.95	9.18	1.66**	5.26
		4	6.66*	8.39	7.70	1.16**	5.61
		5	7.48*	8.81	7.30	1.41**	6.20
		6	7.66*	8.83	7.21	1.16**	6.57
		7	5.93*	12.80	3.39	0.44**	5.63

Recorded by a thermoprobe with seven sensors located at predefined measurement depths (channels [Ch] 1, 2, 3, 4, 5, 6, and 7; Ch 1 at 2 mm, Ch 2 at 4 mm, Ch 3 at 8 mm, Ch 4 at 10 mm, Ch 5 at 11 mm, Ch 6 at 13 mm, Ch 7 at 16 mm). Shading indicates channel with highest temperature increase.
#Highest temperature increase during drilling and withdrawing.
†Time after reaching 10 mm drilling depth when Max. ΔT was measured.
‡Location of surgical drill when Max. ΔT was measured.
§Temperature increase measured on reaching 10 mm drilling depth.
¶Difference between Max. ΔT and ΔT at Peak.
*Statistically significant difference Max ΔT of 2 mm diameter compared to 3.5 mm diameter ($P \leq 0.05$).
**Statistically significant difference Max ΔT compared to ΔT at Peak ($P \leq 0.05$).

saline irrigation, 2.77 seconds after reaching the final drilling depth with the implant drill situated at 7.38 mm (Table 1).

Internal saline irrigation was the most efficient cooling method (2.50°C) compared with combined irrigation (4.22°C, $p < .02$) and then external coolants (5.79°C, $p < .01$).

Twist implant drills always revealed significantly higher temperature changes ($p < .01$) compared with conical implant drills in superficial cortical and in deeper cancellous bone areas for all irrigation methods studied. In contrast, without irrigation conical implant drills showed a significantly higher temperature rise ($p < .03$) than twist implant drills (Table 1).

16-mm Drilling Osteotomies. For the 16-mm drilling osteotomies, the highest temperature changes were mainly observed at 8 mm sensor depth (Ch 3) when irrigation was applied and at 4 mm sensor depth (Ch 2) without any irrigation supply (Table 2).

Twist drills. The greatest temperature increase (45.95°C) was determined with external irrigation at 8 mm sensor depth (Ch 3), 8.01 seconds after reaching the final depth of 16 mm with the surgical drill located at 8.12 mm from the starting position during withdrawal.

The lowest temperature change (14.25°C) could be observed with combined saline irrigation at 16 mm sensor depth (Ch 7), 15.49 seconds after reaching 16 mm drilling depth with the conical implant drill located at 0.85 mm (Table 2).

Within this experimental assembly, no significant differences could be observed regarding the maximum temperature changes between the various irrigation methods.

Conical implant drills. With the use of 3.5 mm conical implant drills, the maximum temperature increase of 44.48°C was recorded at 4 mm sensor depth (Ch 2) without any saline irrigation being used, 5.83 seconds after reaching the final depth with the drill located at 10.23 mm from the starting position during the process of withdrawing.

The smallest temperature rise of 1.52°C was observed with combined irrigation at 2 mm sensor depth (Ch 1), 6.04 seconds after reaching the maximum drilling depths with the drill located at 9.94 mm (Table 2).

Regarding efficiency of coolants, combined irrigation showed the lowest maximum temperature change (7.66°C) compared to internal (11.34°C, $p = .12$) and finally followed by external irrigation (28.49°C, $p < .01$).

When using coolants, twist implant drills of 2 mm diameter showed a significantly higher temperature increase compared with conical implant drills of 3.5 mm diameter ($p < .03$) in superficial cortical and in deeper cancellous bone areas. No significant differences could be observed without any irrigation regarding the different geometry of implant drills (Table 2).

DISCUSSION

Previously published studies primarily focused on the source of heat generation and on factors contributing to heat generation during drilling, such as different drill parameters, drilling methods, and coolant delivery,[1,8] without taking into consideration the topographic distribution of temperature changes and their real-time progression during the implant osteotomies. This often could not be carried out because osteotomies were performed with handheld equipment or using single thermocouples or superficial infrared thermography.[1,8,14,20,21,25,28] Consequently, to overcome these limitations, the present study used a fully automated intermittent drilling procedure with a multichannel measurement system and a precalibrated linear motion potentiometer was deployed to control the drilling depth per time during each osteotomy and to localize the advancement of the drill tip and its actual position. To our knowledge, this study is the first one to investigate real-time temperature changes, focusing not only on the drilling procedure of the surgical instrument but also on its withdrawal movement.

In the present investigation, the maximum temperature changes were always observed during the process of withdrawing, regardless of the coolant method used, the drilling depth, or the drill geometry. Significantly lower values could be observed on reaching the maximum drilling depth of 10 or 16 mm, confirming our hypothesis that – contrary to assumptions – the highest temperature increase is not to be expected during the drilling process but much rather during the retraction of the surgical drill in the course of the withdrawal procedure. In addition, the recording of the advancement of the surgical implant drill revealed that the greatest temperature changes occurred after reaching the maximum drilling depths of 10 and 16 mm with the surgical bur mostly located in superficial cancellous or even cortical bone areas. Previous investigations could not provide comparable results, because they either did not focus on this consideration or did not collect any further details on the time frame of measurements. It can be assumed that these investigations recorded and evaluated temperature changes only during the shearing process of the surgical instruments without including the withdrawing aspect.[1,8]

An explanation for the significantly higher temperature changes during withdrawal could be the fact that heat generation, as a result of the shearing energy and the mechanical friction of the surgical drill, is directly proportional to the time of exposure to frictional forces between the contact area of the drill and the surrounding bone. It should be noted that mechanical friction is produced during the whole osteotomy, including drilling and withdrawing, in contrast to shearing energy, which is a product of the cutting edges of the surgical instrument and therefore mainly released during the drilling procedure.[1,14,27,29] The correlation between temperature rise and prolonged duration of the contact area can also be explained by the results of Lee and colleagues[15] indicating that the mechanical and physical properties of the surgical instrument, especially its significantly higher thermal conductivity compared with bone, leads to a rapid rise of temperature on the drill bit and therefore to an extended heat transfer to the surrounding bone, due to the existing thermal gradient from the hotter heat source to the cooler specimen.[1]

Based on the fact that shearing and frictional forces are principally located at the cutting tip of the surgical instrument, previous studies suggested that the greatest heat generation could be expected in the area of the drilling cavity base.[14,30] In contrast, our measurements illustrated that the maximum detected temperature increase was at 4 mm sensor depth for the 10-mm drilling osteotomies, and for the 16-mm osteotomies, at 4 mm sensor depth without coolant supply and at 8 mm sensor depth when irrigation was applied. These results are consistent with recently published findings that could identify greater intrabony heat generation during implant osteotomies in deeper cancellous layers than in superficial cortical bone areas.[4,20,25,31,32]

The deployment of the multichannel temperature sensors, allowing accurate measurement of temperature at predefined depths, revealed higher temperature changes during 16-mm drilling depth osteotomies compared with 10-mm drilling depth osteotomies, regardless of the drill diameter or the irrigation method applied. This observation confirms that drilling depth is a predominant factor for heat generation during implant site preparation, as also indicated by other studies.[1,8,9,20,23]

According to previous findings, temperature rise with osteotomy depth is also depending on the geometry of the surgical instrument indicating that drill design is an influencing factor for heat generation.[22,23,28,33,34] In the present evaluation, the twist drill of 2 mm revealed significantly higher temperature changes than the conical implant drill of 3.5 mm when a saline irrigation was applied. This also confirms the consideration of other authors who recommended a graduated, predrilling osteotomy instead of a one-step drilling procedure for ensuring atraumatic surgical drilling.[1,2,8,17,34,35] Being a crucial part of the generally accepted osseointegration technique, a graduated osteotomy widens the implant site by removal of a smaller quantity of cortical and cancellous bone, as the preceding surgical drill has already initially processed the osteotomy site, thus providing for reduced frictional forces for the subsequent drills of sequential diameter. Apart from the recommendation for a graduated surgical preparation, in this study simulating a clinical osteotomy, an intermittent drilling approach was conducted to avoid the traumatic continuous procedure. It is known that continuous drilling is responsible for higher frictional forces due to the clogging effects of the bone debris and is invariably associated with a greater heat generation because of insufficient cooling infiltration.[1,8,22,23]

Instead, the principal idea of intermittent drilling is to incrementally enlarge the drilling diameter and to decrease friction by application of a saline irrigation, assuring the continuous removal of cutting debris and the cooling effect on the bone and thus enhancing the dissipation of heat. This study clearly demonstrates that sufficient irrigation is mandatory even when a graduated and intermittent surgical drilling is performed, revealing significantly higher temperature changes without coolant supply as compared with situations in which an external, internal, or combined irrigation was applied during drilling and withdrawing.

Similar to previous studies, the results of our multichannel thermoprobe measurements revealed that for the twist implant drills during 10-mm osteotomies external irrigation showed significant lower temperature changes compared with an internal or combined irrigation, proving that the efficacy of this irrigation is more beneficial in superficial tissue areas.[1,8,20,25,36,37] Furthermore, it could be demonstrated that with greater osteotomy depths of 16 mm, twist implant drills were invariably associated with temperature changes above the harmful threshold of 47°C, regardless of whether an irrigation was deployed or not. The fact that the design and the flute geometry of the twist drill are responsible for higher frictional forces due to insufficient removal, plugging of formed bone debris and possible clogging of the internal capillary tube implies the need of further technical modifications concerning drill parameters, especially during deeper implant site preparations.[15,17,23,33,34]

As regards conical surgical drills, it could be confirmed, that for both drilling depths of 10 and 16 mm, all tested irrigation methods provided sufficient reduction in temperature changes during the drilling and withdrawing process. Comparing the efficiency of various irrigation methods, internal and combined saline irrigation were found to be superior to the commonly used external irrigation, showing significantly lower temperature values. These results confirm recently published findings indicating that internal and combined irrigation have more favorable cooling effects than external irrigation during bone osteotomies.[1,8,20,25,38]

In contrast to other surveys investigating temperature changes, the present study was the first to observe and evaluate the entire drilling procedure, including the shearing and the withdrawing movement of the surgical drill. From the perspective of the investigated material it could be demonstrated that the time of occurrence of the maximum temperature increase was always during the withdrawing process and not, as previously assumed, during the drilling procedure itself. Although high implant survival and osseointegration rates can be observed in clinical use, these new insights about temperature changes during osteotomies could be an interesting clinical factor for future investigations focusing on the effects of different irrigation modes during various implant drilling techniques, such as conventional rotatory versus osteotome/ultrasonic/laser instrumentation or surgical template–guided implant dentistry.

In this respect, future studies should consider that the time frame of temperature recordings must include the process of withdrawing in order to gain supplementary data, which will accomplish an improvement of implant osteotomies.

CONCLUSIONS

From a clinical point of view, our results suggest that implant drilling with sufficient irrigation supply is mandatory not only during the shearing process of the surgical instrument but especially during its withdrawal, which is associated with the maximum temperature accumulation.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

1. Augustin G, Zigman T, Davila S, et al. Cortical bone drilling and thermal osteonecrosis. Clin Biomech 2012; 27:313–325.
2. Brånemark PI, Hansson BO, Adell R, et al. Osseointegrated implants in the treatment of the edentulous jaw. Experience from a 10-year period. Scand J Plast Reconstr Surg 1977; 16 (Suppl):1–132.
3. Eriksson RA, Albrektsson T. The effect of heat on bone regeneration: an experimental study in the rabbit using the bone growth chamber. J Oral Maxillofac Surg 1984; 42: 705–711.
4. Mišić T, Marković A, Todorović A, Čolić S, Šćepanović M, Miličić B. An in vitro study of temperature changes in type 4 bone during implant placement: bone condensing versus bone drilling. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2011; 112:28–33.
5. Albrektsson T, Branemark PI, Hansson HA, Lindstrom J. Osseointegrated titanium implants. Requirements for

ensuring a long-lasting, direct bone-to-implant anchorage in man. Acta Orthop Scand 1981; 52:155–170.
6. Eriksson AR, Albrektsson T. Temperature threshold levels for heat-induced bone tissue injury: a vital-microscopic study in the rabbit. J Prosthet Dent 1983; 50:101–107.
7. Iyer S, Weiss C, Mehta A. Effects of drill speed on heat production and the rate and quality of bone formation in dental implant osteotomies. Part II: relationship between drill speed and healing. Int J Prosthodont 1997; 10:536–540.
8. Tehemar SH. Factors affecting heat generation during implant site preparation: a review of biologic observations and future considerations. Int J Oral Maxillofac Implants 1999; 14:127–136.
9. Oliveira N, Alaejos-Algarra F, Mareque-Bueno J, Ferres-Padro E, Hernandez-Alfaro F. Thermal changes and drill wear in bovine bone during implant site preparation. A comparative in vitro study: twisted stainless steel and ceramic drills. Clin Oral Implants Res 2012; 23:963–969.
10. Yoshida K, Uoshima K, Oda K, Maeda T. Influence of heat stress to matrix on bone formation. Clin Oral Implants Res 2009; 20:782–790.
11. Marković A, Mišić T, Miličić B, Calvo-Guirado JL, Aleksić Z, Dinić A. Heat generation during implant placement in low-density bone: effect of surgical technique, insertion torque and implant macro design. Clin Oral Implants Res 2012. doi:10.1111/j.1600-0501.2012.02460.x
12. Abouzgia MB, James DF. Measurements of shaft speed while drilling through bone. J Oral Maxillofac Surg 1995; 53:1308–1315.
13. Davidson SR, James DF. Drilling in bone: modeling heat generation and temperature distribution. J Biomech Eng 2003; 125:305–314.
14. Sener BC, Dergin G, Gursoy B, Kelesoglu E, Slih I. Effects of irrigation temperature on heat control in vitro at different drilling depths. Clin Oral Implants Res 2009; 20:294–298.
15. Lee J, Ozdoganlar OB, Rabin Y. An experimental investigation on thermal exposure during bone drilling. Med Eng Phys 2012; 34:1510–1520.
16. Lekholm U, Zarb GA. Patient selection and preparation. In: Branemark PI, Zarb GA, Albrektsson T, eds. Tissue-integrated prostheses: osseointegration in clinical dentistry. Chicago, IL: Quintessence, 1985:199–210.
17. Strbac GD, Giannis K, Unger E, Mittlböck M, Watzek G, Zechner W. A novel standardized bone model for thermal evaluation of bone osteotomies with various irrigation methods. Clin Oral Implants Res 2013. doi:10.1111/clr.12090
18. Clattenburg R, Cohen J, Conner S, Cook N. Thermal properties of cancellous bone. J Biomed Mater Res 1975; 9:169–182.
19. Davidson SR, James DF. Measurement of thermal conductivity of bovine cortical bone. Med Eng Phys 2000; 22:741–747.
20. Strbac GD, Unger E, Donner R, Bijak M, Watzek G, Zechner W. Thermal effects of a combined irrigation method during implant site drilling. A standardized in vitro study using a bovine rib model. Clin Oral Implants Res 2012. doi:10.1111/clr.12032
21. Benington IC, Biagioni PA, Briggs J, Sheridan S, Lamey PJ. Thermal changes observed at implant sites during internal and external irrigation. Clin Oral Implants Res 2002; 13:293–297.
22. Ercoli C, Funkenbusch PD, Lee HJ, Moss ME, Graser GN. The influence of drill wear on cutting efficiency and heat production during osteotomy preparation for dental implants: a study of drill durability. Int J Oral Maxillofac Implants 2004; 19:335–349.
23. Cordioli G, Majzoub Z. Heat generation during implant site preparation: an in vitro study. Int J Oral Maxillofac Implants 1997; 12:186–193.
24. Allsobrook OF, Leichter J, Holborrow D, Swain M. Descriptive study of the longevity of dental implant surgery drills. Clin Implant Dent Relat Res 2011; 13:244–254.
25. Harder S, Egert C, Wenz HJ, Jochens A, Kern M. Influence of the drill material and method of cooling on the development of intrabony temperature during preparation of the site of an implant. Br J Oral Maxillofac Surg 2013; 51:74–78.
26. Jochum RM, Reichart PA. Influence of multiple use of Timedur-titanium cannon drills: thermal response and scanning electron microscopic findings. Clin Oral Implants Res 2000; 11:139–143.
27. Rashad A, Kaiser A, Prochnow N, Schmitz I, Hoffmann E, Maurer P. Heat production during different ultrasonic and conventional osteotomy preparations for dental implants. Clin Oral Implants Res 2011; 22:1361–1365.
28. Scarano A, Piattelli A, Assenza B, et al. Infrared thermographic evaluation of temperature modifications induced during implant site preparation with cylindrical versus conical drills. Clin Implant Dent Relat Res 2011; 13:319–323.
29. Lee J, Rabin Y, Ozdoganlar OB. A new thermal model for bone drilling with applications to orthopaedic surgery. Med Eng Phys 2011; 33:1234–1244.
30. Krar F, Oswald JW, St Amand JE. Technology of machine tools. New York: McGraw-Hill, 1977:122–123.
31. Misir AF, Sumer M, Yenisey M, Ergioglu E. Effect of surgical drill guide on heat generated from implant drilling. J Oral Maxillofac Surg 2009; 67:2663–2668.
32. Sumer M, Misir AF, Telcioglu NT, Guler AU, Yenisey M. Comparison of heat generation during implant drilling using stainless steel and ceramic drills. J Oral Maxillofac Surg 2011; 69:1350–1354.
33. Chacon GE, Bower DL, Larsen PE, McGlumphy EA, Beck FM. Heat production by 3 implant drill systems after repeated drilling and sterilization. J Oral Maxillofac Surg 2006; 64:265–269.

34. Oh HJ, Wikesjo UM, Kang HS, Ku Y, Eom TG, Koo KT. Effect of implant drill characteristics on heat generation in osteotomy sites: a pilot study. Clin Oral Implants Res 2011; 22:722–726.
35. Eriksson RA, Adell R. Temperatures during drilling for the placement of implants using the osseointegration technique. J Oral Maxillofac Surg 1986; 44:4–7.
36. Lavelle C, Wedgwood D. Effect of internal irrigation on frictional heat generated from bone drilling. J Oral Surg 1980; 38:499–503.
37. Haider R, Watzek G, Plenk H. Effects of drill cooling and bone structure on IMZ implant fixation. Int J Oral Maxillofac Implants 1993; 8:83–91.
38. Augustin G, Davila S, Udilljak T, Staroveski T, Brezak D, Babic S. Temperature changes during cortical bone drilling with a newly designed step drill and an internally cooled drill. Int Orthop 2012; 36:1449–1456.