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Investigation and prevention of intraosseous temperature rise in guided implant surgery: an ex-vivo study

Gözde Gökçe Uçkun^{1*} , Sina Saygılı², Metin Berk Kasapoğlu³, Mehmet Ali Erdem³ and Abdulkadir Burak Çankaya³

Abstract

Background This study evaluated temperature changes at implant preparation sites using a surgical guide, the effects of the cooling solution's temperature, and the impact of performing osteotomy at low speed without irrigation. The working hypothesis was that effective cooling with a low-temperature solution is essential to prevent excessive heat generation at the osteotomy site.

Methods A surgical guide was fabricated using stereolithographic technology. Temperature variations were recorded using a K-type thermocouple. On 40 sheep iliac bone specimens, four implant sites were prepared with a surgical guide as experimental groups: 2.9 mm × 8.5 mm and 2.9 mm × 13 mm representing narrow diameters, and 3.8 mm × 8.5 mm and 3.8 mm × 13 mm representing regular diameters. A 3.5 mm × 10 mm implant site prepared using the conventional method served as the control group.

Results A statistically significant temperature increase was observed in all groups as the bur diameter increased. The temperature rise in implant sites prepared with surgical guides at high speed under irrigation was significantly higher than that observed with the conventional technique. Furthermore, the temperature elevation in the group irrigated with solution cooled to 10 °C was significantly lower than in the group irrigated with solution at 24 °C and the group subjected to low-speed drilling without irrigation.

Conclusions Appropriately applied external irrigation, tailored to patient-specific conditions, can maintain intraosseous temperatures within safe thresholds. Moreover, refraining from low-speed drilling without irrigation and employing low-temperature cooling solutions in guided surgical systems represent more reliable strategies for controlling thermal increases.

Keywords Dental implant, Surgical guide, Guide design, Bone necrosis, Revolution, Thermal change

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Background

To ensure adequate osseointegration between a dental implant and bone, certain conditions must be met: the implant material must be biocompatible; the implant surface must consist of microstructures created by specialized surface treatments such as sandblasting and etching to promote bone cell proliferation and integration; and the osteoblastic cells surrounding the implant must exhibit sufficient cellular activity [1]. Thermal trauma inflicted on the bone during implant osteotomy preparation is a significant risk factor for early dental implant failure [2]. The heat generated during this process can impair regenerative processes and induce osteonecrosis. Research has established that, to preserve bone viability, the maximum temperature during implant site preparation should not exceed 47 °C, and drilling time should remain under one minute to avoid adverse effects [3].

Clinicians have advocated the use of surgical guides in dental implant surgery over the conventional approach due to their advantages in restorative-driven implant placement, improved consistency between treatment planning and surgical execution, increased efficiency, and reduced surgical errors [3]. However, this technique limits direct contact between the irrigation fluid, burs, and implant site. Consequently, bone temperature may rise during implant site preparation, potentially compromising osseointegration [4].

Several studies have examined temperature changes in implant preparation sites using surgical guides with high- and low-speed drilling, as well as the effect of irrigation solution temperature [3, 5–9]. However, to our knowledge, no study has evaluated all these parameters collectively in bone tissue with density precisely determined by CBCT. This gap has limited the comprehensive understanding of temperature variations during implant site preparation. The working hypothesis was that effective cooling with a low-temperature solution is essential to prevent excessive heat generation at the osteotomy site.

This study compared the temperature changes at implant preparation sites using a surgical guide versus the conventional method on sheep iliac crest bones, simulating D3 bone density under *in vitro* conditions. Additionally, the study evaluated the impact of the irrigation solution's temperature and the effects of low-speed osteotomy without irrigation on the temperature changes in bone tissue.

Within the limitations of our study, the primary finding is that the temperature increases at implant sites prepared under irrigation with a surgical guide remain within safe limits, consistent with dos Santos et al. [10] and Migliorati et al. [8]. A secondary outcome of our study is that controlling temperature increases can be effectively achieved by using low-speed drilling with irrigation solutions at low temperatures. Our results align

with those of Barrak et al. [5], who demonstrated that cooling the irrigation solution to 10 °C prevents significant temperature increases, regardless of implant site diameter.

Materials and methods

Forty iliac crest bone specimens were obtained from 20 sheep for this study. The bones were collected from a local butcher, and the animals were not sacrificed specifically for research purposes. The specimens were not frozen and were used on the same day they were collected. The sample size was determined to be eight per group based on power analysis conducted using G*Power version 3.1.9.6 (Heinrich Heine University, Düsseldorf). With a 95% confidence interval ($1-\alpha$), 95% test power ($1-\beta$), and an effect size of $f=1.376$, the required number of samples was calculated as eight per group. The bone density of all specimens was evaluated using cone beam computed tomography (CBCT) imaging (Planmeca ProMax 3D, Planmeca Oy, Helsinki, Finland). Hounsfield Unit (HU) values were obtained by analyzing the CBCT images using the Romexis software (Planmeca Oy, Helsinki, Finland). The mean HU value across all specimens was 696 HU (range: 638–848 HU). To ensure standardization and minimize potential variability arising from differences in CBCT acquisition parameters and software algorithms, all scans were performed using the same CBCT device and software under consistent settings for all samples. This approach was selected based on previous studies reporting that HU values from CBCT can show inter-device and inter-software variability due to factors such as patient age, sex, imaging protocols, and analysis software used [11–13]. For this reason, using a single CBCT device and uniform imaging parameters was considered essential for ensuring homogeneity across measurements. Although CBCT is not the gold standard for absolute bone mineral density measurement, it is commonly used in preclinical and *ex vivo* studies for relative bone density classification [12–14]. Following these evaluations, all specimens were classified as D3 bone type according to the Misch bone density classification [15]. (Fig. 1).

Preparation of surgical guide

All digital data obtained from the CBCT images of the specimens and the guiding prosthesis prepared for implant placement planning were merged using Real Guide 5.0 software (3Diemme Bioimaging Technologies, Biomec, Italy). The surgical guide was designed using stereolithographic technology (Fig. 2). The metal cylindrical sleeves embedded in the surgical guide were stock products which are exactly compatible with the burs from the Oxy Guided Surgery set (Biomec, Italy), which is registered within the Real Guide 5.0 software. The finalized

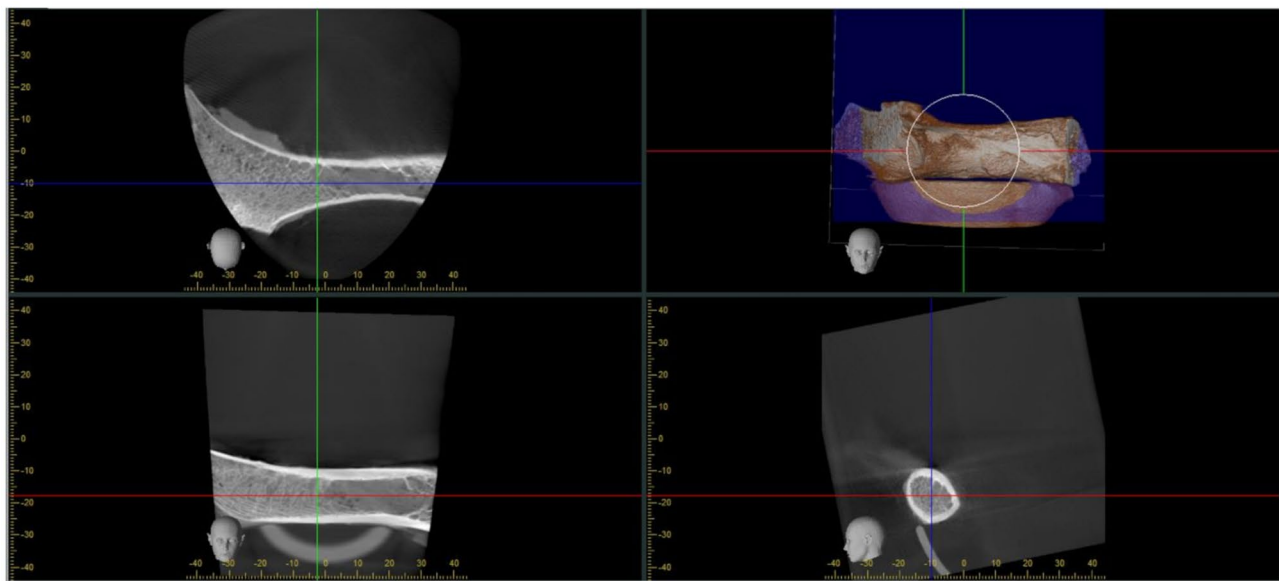


Fig. 1 Composite CBCT images of bone specimens used for determining bone density (D3) via Hounsfield Units

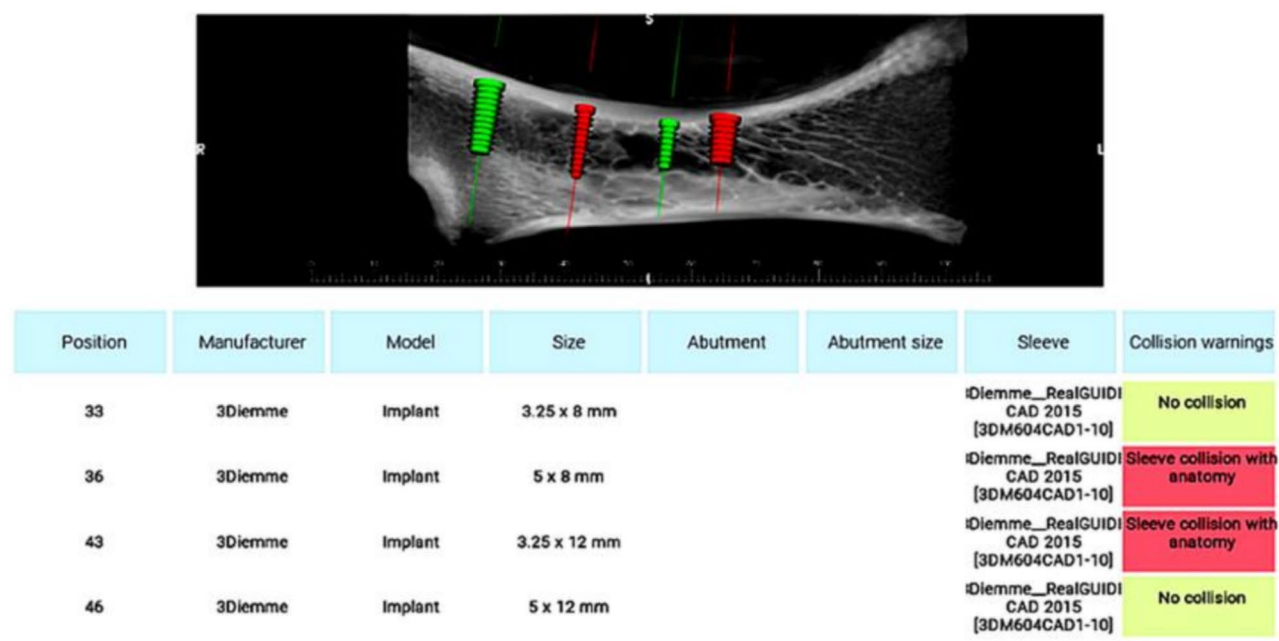


Fig. 2 Digital design of the stereolithographic surgical guide based on CBCT data

surgical guide was fabricated using a Free Shape 120 3D printer (Accuretta, Taiwan) (Fig. 3).

The bone surface morphology of each specimen was segmented directly from the CBCT datasets using Real Guide 5.0 software (3Diemme Bioimaging Technologies, Biomec, Italy). The segmentation process allowed the creation of a precise three-dimensional model of the bone surface, which was then used as the reference for surgical guide design. This ensured accurate adaptation of the guide to the bone contour during experimental

procedures. The segmentation was performed manually by an experienced operator to minimize errors and improve anatomical accuracy. Previous studies have shown that CBCT-based segmentation, when performed with appropriate software and user calibration, can reliably reflect external bone surface morphology for ex vivo surgical planning purposes [16, 17].



Fig. 3 Finalized stereolithographic surgical guide used for guided implant site preparation

Implant site preparation and temperature change observation

The experiments were conducted by the same researcher, an oral surgery specialist experienced in dental implant procedures, in a room maintained at a constant temperature of 24 °C. The bone specimens were stored in a 24 °C saline solution, matching the ambient temperature to ensure uniform initial conditions. The surgical guide was secured to the iliac crest using four mini-screws. A 2 mm diameter K-type thermocouple (Ser Resistans, Turkey) and a single-channel temperature control unit (Red-box TCS 01), with a sampling interval of 100 ms, were used to record temperature changes during implant site preparation. The thermocouple was insulated with silicone impression material. For thermocouple placement, sockets were prepared in the bone using a 2 mm diameter pilot drill, located 1 mm away from the designated implant site. The specimens were fixed to the workbench using two vices (Fig. 4).

Four implant sites were prepared as experimental groups on the same bone specimen using a surgical guide: 2.9 mm × 8.5 mm and 2.9 mm × 13 mm representing narrow diameters, and 3.8 mm × 8.5 mm and 3.8 mm × 13 mm representing regular diameters. A 3.5 mm × 10 mm implant site was prepared as a control group using the conventional method (Table 1).

Experimental groups in the study were determined as follows;

Group A Implant sites with narrow and regular diameters in varying lengths were prepared using a surgical

guide and the conventional method, with external irrigation at high speed (900 rpm).

Group B Implant sites with narrow and regular diameters in varying lengths were prepared using a surgical guide and the conventional method at low speed (300–600 rpm) without irrigation.

Group C Implant sites with narrow and regular diameters in varying lengths were prepared using a surgical guide and the conventional method at high speed (900 rpm), with external irrigation using solutions at both high (24 °C) and low (10 °C) temperatures.

Continuous external irrigation was provided via the surgical unit using irrigation fluid at 24 °C for Group A and 10 °C for Group C. The irrigation flow rate was maintained at a constant 100 ml/min. According to the manufacturer's instructions, implant sites were prepared in two stages using an up-and-down drilling motion, retracting the bur halfway through its length during each pass in all groups. After the initial pilot drilling, the working length of the implant site was prepared using a 2.3 mm diameter bur, followed by the use of the final bur. For each implant site, the baseline temperature at the deepest point of the corresponding working length, the temperature after using the 2.3 mm diameter bur, and the temperature after using the final bur were recorded.

Statistical analysis

Descriptive data are presented as median (minimum–maximum). The Kolmogorov–Smirnov and Shapiro–Wilk tests were used to assess the normality of the data

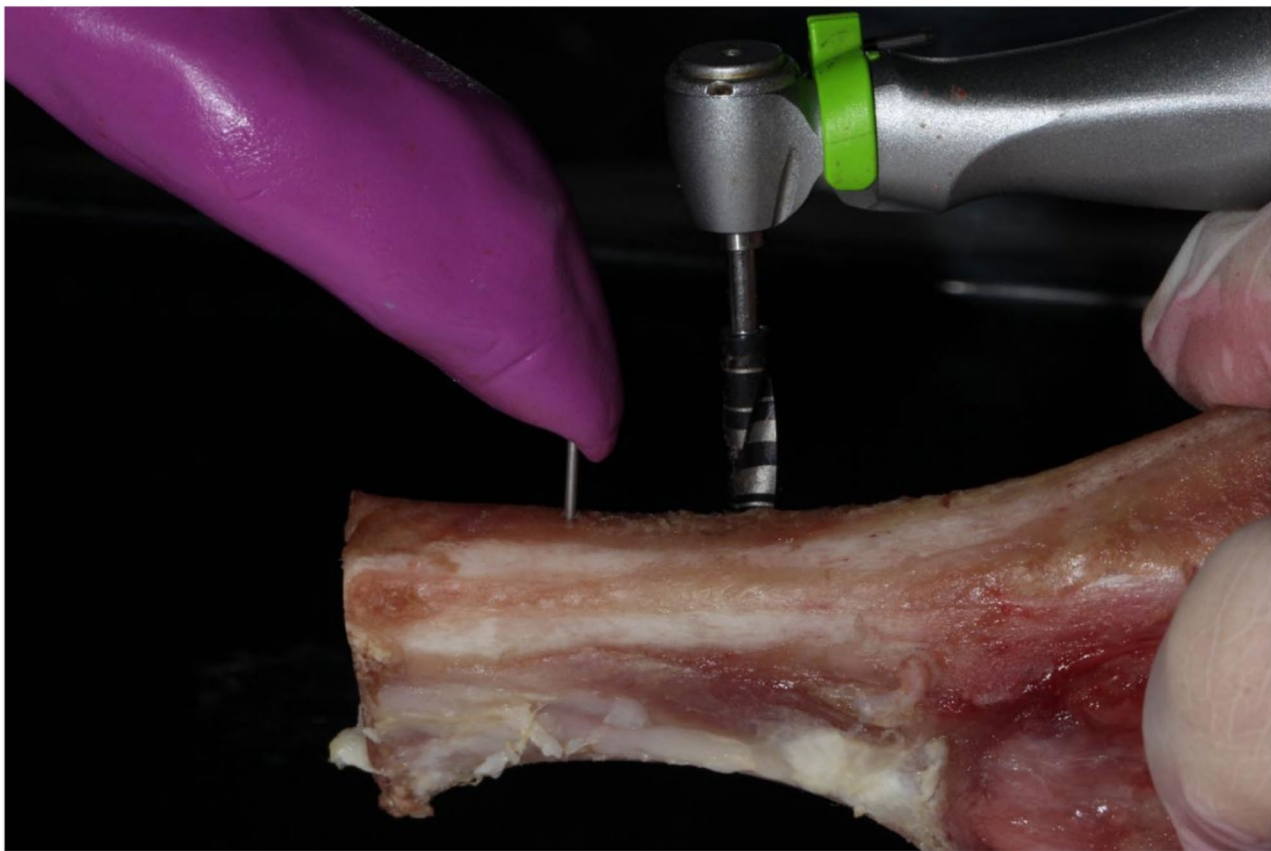


Fig. 4 Experimental setup with thermocouple placement in the iliac crest bone for intraosseous temperature measurement

Table 1 Division of experimental groups

Group A		Group B		Group C	
900 rpm		300 rpm		600 rpm	
Study Groups	ControlGroup	Study Groups	Control Group	Study Groups	Control Group
2.9 mm x 8.5 mm	3.5 mm x 10 mm	2.9 mm x 8.5 mm	3.5 mm x 10 mm	2.9 mm x 8.5 mm	3.5 mm x 10 mm
2.9 mm x 13 mm		2.9 mm x 13 mm		2.9 mm x 13 mm	
3.8 mm x 8.5 mm		3.8 mm x 8.5 mm		3.8 mm x 8.5 mm	
3.8 mm x 13 mm		3.8 mm x 13 mm		3.8 mm x 13 mm	

distribution. The Mann–Whitney U test was applied for comparisons between two groups, while the Kruskal–Wallis test was used for comparisons among three or more groups. For post-hoc analysis, the Mann–Whitney U test with Bonferroni correction was employed. The Wilcoxon signed-rank test was used to evaluate temperature changes for the 2.3 mm and 2.9/3.8 mm burs relative to baseline temperature values. The mixed ANOVA with Greenhouse–Geisser correction was applied to assess differences in temperature changes across experimental conditions, specifically in the group where implant sites were prepared using a surgical guide without saline irrigation at low speed. A $p < 0.05$ was considered statistically

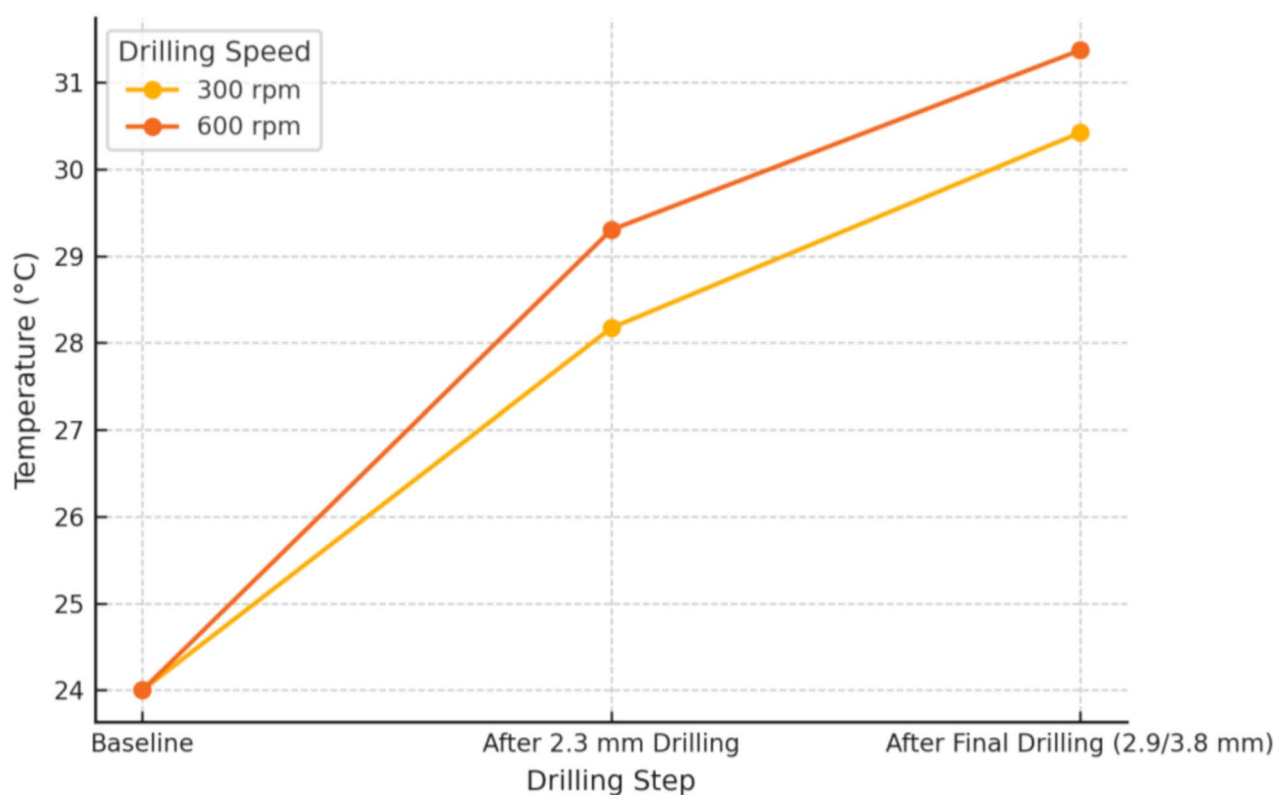
significant. Data analyses were performed using SPSS version 16.0.

Results

In this study, 192 implant sites with varying lengths and diameters were prepared. In all study groups and at all implant sites, the initial temperature was recorded as 24 °C. In each group, the temperature values for both narrow and regular diameter implants were significantly higher than the initial baseline temperature ($p = 0.001$ for both comparisons). The mean temperature values were 30.5 ± 4 °C in Group A, 31 ± 5 °C in Group B (Table 2), and 28 ± 3 °C in Group C.

Table 2 Comparison of temperature values after intermediate (2.3 mm) and final (2.9/3.8 mm) drilling steps at 600 rpm and 300 rpm in group B

	Starting Temperature	Diameter 2.3 mm	Diameter 2.9 mm/3.8 mm	p value
		Median $\pm$ Standard Deviation		
600 rpm	24.0 $\pm$ 0	29.30 $\pm$ 2.42	31.37 $\pm$ 2.46	0.058
300 rpm	24.0 $\pm$ 0	28.17 $\pm$ 2.34	30.42 $\pm$ 2.52	
Total	24.0 $\pm$ 0	28.73 $\pm$ 2.43	30.90 $\pm$ 2.52	

**Table 3** Temperature values in study groups

Study Group	Diameter 2.3 mm (°C) (Median(min-max))	Diameter 2.9 mm/3.8 mm (°C) (Median(min-max))	p value
Group A (n=80)	28 °C (25–31 °C)	30.5 °C (25–33 °C)	0.001
Group B (n=80)	29 °C (24–33 °C)	31 °C (26–36 °C)	0.001
Group C (n=36)	26 °C (23–28 °C)	27 °C (25–31 °C)	0.001

A statistically significant increase in temperature was observed with increasing implant diameter across all study groups ($p=0.001$ for each group, Table 3).

The differences in temperature increase between Groups A and C, and between Groups B and C, were statistically significant ($p=0.001$). However, the difference between Groups A and B was not statistically significant and approached the threshold of significance.

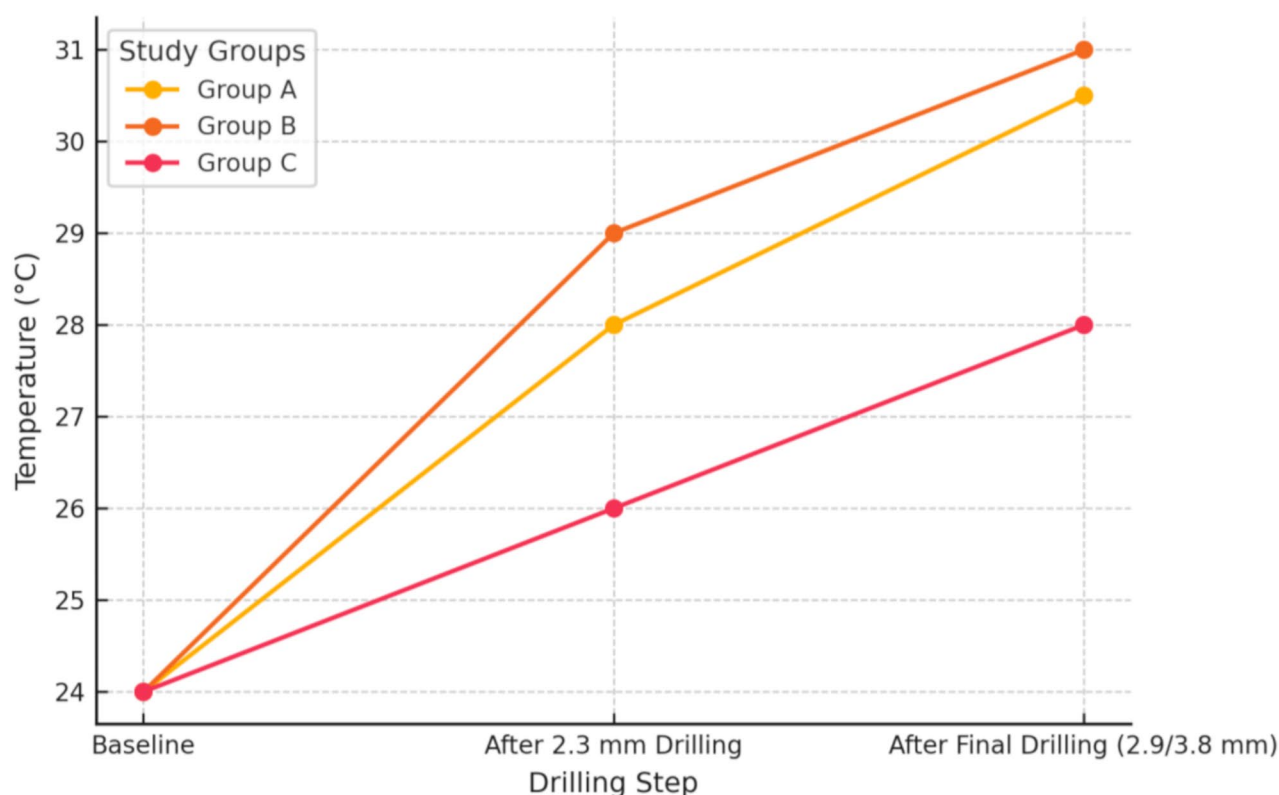
Temperature increases in Groups A and B were higher than those observed in Group C (Table 4). Furthermore, temperature increases in both Groups A and B were significantly greater than in the control groups.

As shown in Table 2, temperature values after both intermediate (2.3 mm) and final (2.9/3.8 mm) drilling steps were higher in the 600 rpm subgroup than in the 300 rpm subgroup of Group B, although the difference was not statistically significant ($p=0.058$). This trend suggests a progressive increase in bone temperature with drilling speed, even in the absence of irrigation.

The comparative data for all study groups are summarized in Table 4, which clearly demonstrates that temperature values in Groups A and B were notably higher than those recorded in Group C. This supports the role of cooled irrigation in effectively reducing intraosseous temperature rise during guided implant osteotomy.

Table 4 Comparison of intraosseous temperature values among groups A, B, and C after intermediate and final drilling steps

	Starting Temperature	Diameter 2.3 mm	Diameter 2.9 mm/3.8 mm	p value
	Median $\pm$ Standard Deviation			
Group A	24.0 $\pm$ 0	27.98 $\pm$ 1.61	30.12 $\pm$ 2.03	0.001
Group B	24.0 $\pm$ 0	28.73 $\pm$ 2.43	30.09 $\pm$ 2.52	
Group C	24.0 $\pm$ 0	26.0 $\pm$ 1.19	27.84 $\pm$ 1.77	
Total	24.0 $\pm$ 0	27.96 $\pm$ 2.15	30.06 $\pm$ 2.44	



Discussion

This study evaluated temperature changes at implant preparation sites using a surgical guide, the effects of the cooling solution temperature, and the impact of performing osteotomy at low speed without irrigation. The measurements confirmed that effective cooling with a low-temperature solution is essential for preventing excessive heat generation at the osteotomy site, thereby validating the working hypothesis.

In similar studies, most bone samples analyzed consisted solely of cortical bone with D1 density, while studies involving both cortical and cancellous bone layers often failed to specify their respective densities. In contrast, our study utilized iliac crest bone specimens from sheep, which closely resemble human jawbone in terms of morphology, density, and cortical-to-cancellous bone ratio. This model allowed us to simulate the thermal conduction behavior of human mandibular bone more accurately. Bone densities were quantitatively confirmed via

Hounsfield Unit (HU) values, ensuring comparability to human mandibular conditions.

A statistically significant temperature increase was observed across all study conditions as bur diameter increased. Thus, it is recommended that clinicians use smaller-diameter burs and ensure effective irrigation to reduce heat generation and prevent bone damage during guided implant surgery.

It was further observed that implant sites prepared using guided surgery with high-speed drilling under 24 °C irrigation exhibited significantly greater temperature increases than those prepared using the conventional freehand technique. This outcome is likely due to insufficient irrigation caused by the physical barrier imposed by surgical guides. Nevertheless, the temperature increase remained within the safe limit of under 10 °C. Consistent with prior literature, our findings support the safety of guided surgery when external irrigation is effectively applied with careful technique.

Low-speed osteotomy without irrigation has been proposed as an alternative to conventional methods [18]. Reported benefits include the potential to collect autogenous bone grafts without saliva contamination [19], as well as enhanced surgical control and improved visibility in the absence of irrigation [20]. However, our study found no statistically significant difference in temperature increase between implant sites prepared with guided surgery at low speed without irrigation and those prepared at high speed with 24 °C irrigation. These findings indicate that low-speed osteotomy without irrigation offers no thermal advantage under guided conditions.

Temperature increases at implant sites prepared using a surgical guide at 600 rpm without irrigation were significantly greater than those observed in freehand drilling. Moreover, temperature differences became more pronounced as drilling depth increased. Similarly, the temperature increase observed at 600 rpm was significantly higher than at 300 rpm, although the difference was not statistically significant.

Several factors beyond irrigation are known to influence intraosseous temperature rise during implant preparation, including drilling speed, bur design and sharpness, cortical bone thickness, and drilling depth [21]. One study reported that higher drilling speeds reduced temperature increases in cortical bone; however, in our study, no significant temperature reduction was observed in cancellous bone at higher drilling speeds [22]. In fact, when irrigation was not used, temperature increases exceeded 10 °C with rising drilling speed, surpassing the threshold for thermal injury.

In contrast to Oh et al. [9], our study revealed that eight specimens surpassed the critical 10 °C threshold during guided surgery at 600 rpm without irrigation, and five specimens exceeded this threshold at 300 rpm under the same conditions. Based on these findings, we conclude that guided implant site preparation at low speed without irrigation does not provide a thermal advantage and may increase the risk of bone damage. Further research is required to confirm these results, particularly *in vivo*.

The lowest temperature increases were observed in implant sites prepared with guided surgery under high-speed drilling and 10 °C irrigation. The findings illustrated in Table 4 reinforce the conclusion that guided implant surgery under high-speed drilling combined with 10 °C irrigation results in the lowest intraosseous temperature rise. In contrast, the lack of irrigation or the use of standard-temperature irrigation (24 °C) led to significantly higher temperature increases. At this low temperature, sites drilled to 8.5 mm depth exhibited significantly less temperature rise compared to those drilled to 13 mm. Even with narrow-diameter burs, increased depth significantly elevated intraosseous temperature. However, under 10 °C irrigation, increased bur

diameter did not result in statistically significant temperature changes at 8.5 mm depth. These findings support the use of 10 °C cooling solutions to effectively mitigate temperature rise during guided surgery.

Besides irrigation and drilling speed, implant diameter also had a significant effect on intraosseous temperature. Narrow-diameter implant sites consistently exhibited lower temperature increases compared to wider sites under identical conditions. This can be attributed to the greater surface area and resistance encountered when preparing wider sites, which increases friction and heat generation. Therefore, clinicians should exercise additional caution when preparing wider implant sites, ensuring adequate irrigation and temperature monitoring to prevent exceeding thermal thresholds. These results highlight the importance of adapting surgical protocols based on implant diameter, especially when using guided techniques with limited irrigation access.

Within the limitations of our study, the primary finding is that guided implant surgery is a safe technique that does not cause thermal damage, provided that effective external cooling is applied. Consistent with this result, dos Santos et al. [10] and Migliorati et al. [8] found that temperature increases at implant sites prepared under irrigation using a surgical guide remained within safe limits in all study groups. Another significant finding of our study is the increased temperature rise associated with larger bur diameters. These results align with those of Frösch et al. [23], who reported that greater bur diameters used in surgical guide-assisted implant site preparation are associated with significantly increased temperatures and that, during 4.2 mm osteotomies, the critical temperature of 47 °C was exceeded for more than one minute.

The secondary outcome is that avoiding low-speed drilling without irrigation and using low-temperature irrigation solutions in guided surgical systems are effective strategies to control thermal increase. In a study by Oh et al. [9], temperature changes in implant sites prepared at 50 rpm with a surgical guide were reported to remain well below the critical threshold, suggesting the method's safety. However, unlike the results reported by Oh et al., our study observed that several subjects reached or exceeded the critical temperature threshold. Based on these findings, we suggest that performing implant site preparation at low speed without irrigation does not offer an advantage when using a surgical guide. In this study, we observed a significantly lower temperature increase when the irrigation solution was cooled to 10 °C. Barrak et al. [5] compared the effects of irrigation solutions at varying temperatures (10 °C, 15 °C, and 20 °C) on intraosseous temperature increase during guided surgery. Their study reported that the average temperature change did not exceed 1 °C when irrigation

solution cooled to 10 °C was used, regardless of implant site diameter. However, irrigation fluid cooled to 15 °C did not result in a significant reduction in temperature change. Based on these findings, we conclude that irrigation with a solution cooled to 10 °C is effective in controlling intraosseous temperature increases during guided implant surgery.

This study has several limitations due to its in vitro design. The specimens lacked physiological characteristics such as vascularity and natural body temperature, which may have affected thermal measurements. To minimize variability, specimens with similar anatomical features and D3 bone density (confirmed via CBCT) were selected. However, it was not possible to standardize cortical and cancellous bone thicknesses or to use identically designed surgical guides for each sample, which may have introduced variability. One of the limitations of CBCT-based HU measurements is the lack of standardization across different devices and software platforms, which may lead to variations in reported bone density values. Several studies have shown that differences in patient age, sex, imaging parameters, software algorithms, and implant site distribution can influence HU measurements [11–13]. De Oliveira et al. [16] demonstrated that different software packages can produce varying bone density results even from the same CBCT dataset. To minimize this source of bias, all CBCT scans in our study were performed using the same device and software, under identical imaging parameters. While CBCT cannot provide absolute bone mineral density values comparable to those obtained from medical CT, its application for relative density classification in ex vivo models is well-documented and widely accepted in the literature [12, 13, 15]. Therefore, our use of CBCT-derived HU values for specimen classification into the D3 bone density group is considered methodologically appropriate for this in vitro study setting. Although thermocouple placement was carefully measured, the potential for human error exists. Thus, while our study provides valuable insights, clinical extrapolation is limited. Future investigations should prioritize in vivo studies to validate and expand upon these findings.

Conclusions

Within the limitations of the present study, it can be concluded that in guided dental implant surgery, external irrigation —when effectively applied and tailored to patient-specific conditions— can maintain intraosseous temperature within safe limits. Avoiding low-speed drilling without irrigation and utilizing low-temperature irrigation solutions during guided surgical procedures represents a more reliable strategy for controlling thermal increase.

Although the use of surgical guides results in a greater intraosseous temperature rise compared to the conventional method, the observed increase is not sufficient to compromise bone vitality, indicating that guided surgery remains a safe technique. Therefore, advantages such as restorative-driven implant placement, improved consistency between treatment planning and surgical execution, increased time efficiency, and reduced surgical errors further support the preference for the guided surgical approach.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s12903-025-06620-z>.

Supplementary Material 1

Supplementary Material 2

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Not applicable.

Author contributions

Gözde Gökçe Uçkun; Methodology, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Visualization, Project administration. Sina Saygılı; Methodology, Software, Validation, Visualization, Supervision. Metin Berk Kasapoğlu; Formal analysis, Data Curation, Visualization. Mehmet Ali Erdem; Conceptualization, Methodology, Validation, Writing - Review & Editing, Supervision. Abdulkadir Burak Çankaya; Conceptualization, Methodology, Validation, Writing - Review & Editing, Supervision.

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Data availability

Data is provided within the supplementary information files. The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Because iliac crest bones were obtained from dead animals and the animals were not sacrificed for use in the study, this study is not subject to ethics committee approval.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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