Research Square

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Thermal effects of zirconia drills during guided versus conventional preparation: a standardized in vitro study

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Research Article

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Abstract

Background

Thermal injury during implant osteotomy remains a clinically relevant concern, as guided workflows may alter frictional conditions and limit effective irrigation. This study evaluated temperature development during guided implant site preparation with alumina-toughened zirconia drills versus conventional guide-free drilling in a standardized in vitro bone model.

Methods

Implant osteotomies were prepared in standardized bovine bone using ceramic drills (2.0, 2.8, and 3.5 mm) under guided and conventional conditions. Drilling depth (10/12 mm) and irrigation (none/external) were varied. A total of 240 preparations were performed using an automated drilling system. Intraosseous temperature was recorded 1 and 2 mm from the osteotomy wall using type-K thermocouples. The primary outcome was maximum temperature increase (ΔT_max), and the secondary outcome was the intrabony location of peak temperature. Data were analyzed using linear mixed-effects modeling.

Results

Guided surgical preparation did not affect ΔT_max ($p > 0.05$). Drill diameter, drilling depth, and irrigation significantly influenced temperature development, with an interaction between drill diameter, irrigation, and drilling depth ($p = 0.0007$). The highest temperature increases occurred during pilot drilling (2.0 mm). External irrigation substantially reduced temperature rise and shifted peak temperatures in deeper layers of bone.

Conclusions

Within the limitations of this in vitro study, guided preparation with alumina-toughened zirconia drills did not increase thermal exposure versus conventional drilling. External irrigation remains essential, particularly during pilot drilling and at greater depths.

Trial registration:

Not applicable.

Background

After decades of experience gained from various dental implant solutions, implants have become an indispensable cornerstone of modern dental restorations. Meta-analyses of 20-year implant survival reveal survival rates of approximately 80%, with factors such as lower bone quality in the maxilla and smoking habit being particularly associated with implant loss [1]. Although titanium implants remain the gold standard in dental implantology due to well-documented success rates and highly established long-term clinical outcomes [2, 3], an expanding body of promising clinical data supports the use of zirconia dental implants [4, 5]. Favorable material-based characteristics of zirconia include high biomechanical stability [6, 7] and favorable cellular-level biocompatibility [8]. In addition to reports on metal-based allergies [9] and esthetic considerations as possible indications for ceramic applications in dentistry [10], zirconia implants may also represent an alternative for patients with specific restorative preferences [11].

Since implant success is a multifactorial process over time, the implant bed preparation technique may also influence the future outcome of implant therapy. For example, in vivo results have demonstrated a decrease of primary and secondary stability with increased drill usage during bone preparation, suggesting direct effects of instrument-related parameters on the future osseointegration process [12]. At a cellular level, recent clinical evidence has revealed differences in osteoblastic activity and osteogenic potential of harvested autogenous particles depending on the preparation technique in a split-mouth investigation [13]. Excessive surgical trauma during bone preparation has long been associated with early implant loss and may be attributed to thermal injury when bone temperatures exceed 44–47°C for more than 1 minute [14]. In this context, several contributing factors substantially influence heat generation during osteotomy, including irrigation [15], guided surgical applications [16], and drill material and design [17]. However, these determinants have often been studied in isolation. Previous investigations have examined either the influence of surgical guidance or the influence of drill material on thermal development during implant osteotomy, whereas the interaction of both factors has remained insufficiently characterized under standardized conditions.

This limitation is particularly relevant in in vitro thermal research, where differences in specimen type, sensor positioning, drilling kinematics, and irrigation protocols substantially impair direct between-study comparability.

In the search for optimal material for surgical instruments, high-performance mixed ceramics composed of zirconium and aluminum oxide may offer promising physical properties, such as high flexural strength and fracture toughness combined with favorable drill sharpness and biocompatibility [18]. As metal particle contamination following osteotomy preparation with martensitic surgical steel has been observed using SEM-EDX analysis in vitro [19], the use of high-performance ceramic drill materials could prove advantageous. Furthermore, metal wear during drilling may contribute to the release of titanium particles from the implant surface, potentially linking to higher particle concentrations in peri-implantitis sites [20]. Ceramic surgical instruments may therefore represent a viable alternative to stainless steel, provided that novel drills meet all required physical material properties for clinical application. However, original research and systematic reviews focusing on the performance of ceramic drill materials have yielded inconclusive results to date [21–23]. Previous work, including studies from our group [17], has addressed the thermal behavior of ceramic drills under conventional preparation conditions. These data, however, do not answer whether the use of surgical guidance modifies thermal development when alumina-toughened zirconia drills are applied. To address this question meaningfully, the present study deliberately retains a validated experimental platform and varies the clinically relevant exposure of interest rather than introducing additional methodological heterogeneity.

With the widespread availability of digital preplanning techniques and three-dimensional applications in dentistry, global research interest in guided implantology continues to rise [24]. Fully guided protocols are currently regarded as the gold standard regarding the accuracy of implant placement [25]. However, recent systematic review and meta-analysis comparing guided and conventional guide-free surgery have documented significantly higher temperature generation during guided procedures, particularly in greater osteotomy depths [26]. While guided versus conventional implant bed preparation has already been investigated in standardized in vitro settings using stainless steel drills [27, 28], these findings cannot be directly extrapolated to ceramic instruments because drill material, thermal conductivity, wear behavior, and cutting characteristics may alter heat generation patterns. Accordingly, evaluation of guided surgery with ceramic drills requires direct study within the same validated thermal model to permit meaningful material-specific comparison.

To date, no standardized experimental investigation has examined temperature development during guided implant site preparation using alumina-toughened zirconia drills. Previous studies have addressed either ceramic drills under guide-free conditions or guided preparation with stainless steel drills, but the combination of guided surgery and ceramic drill material has remained untested under invariant experimental conditions. Therefore, the present controlled in vitro study aimed to investigate temperature development during guided implant site preparation using alumina-toughened zirconia drills compared with conventional guide-free drilling in a standardized bovine bone model.

Methods

Materials

The present study extends a standardized comparative in vitro testing platform by evaluating alumina-toughened zirconia drills (diameters 2.0, 2.8, and 3.5 mm; Komet Ceradrill™, Komet®, Gebr. Brasseler, Lemgo, Germany) (Fig. 1) under guided and conventional conditions.

Standardized commercially available bovine bone samples (BoneSim™, Newaygo, MI, USA), consisting of constant cortical and cancellous bone layers, corresponding to human mandibular bone density (type II) [29] and exhibiting thermal conductivity comparable to human bone ($0.35\ W\ m^{-1}\ K^{-1}$) [30], were used (Fig. 2A). This model has previously been validated for preclinical thermal testing of surgical instruments [17, 27, 28, 31–36]. To improve simulation of the anatomical properties of the alveolar process, the bone discs were cut into a rectangular shape prior to testing by using a belt saw (BAS 261 Precision™, Metabo GmbH, Nürtingen, Germany). Constant sample dimensions (5.6 x 1.8 x 1.0 cm; width tolerance ± 0.05 mm; total number of samples: 48) were verified using a digital caliper. Samples exhibiting material defects or dimensional deviations greater than ± 0.05 mm were excluded. As only artificially manufactured bone specimens were used, no ethical approval was required.

A customized material testing apparatus was used to execute standardized automated drilling sequences. The surgical handpiece (WS-75 E/KM 20:1, W&H, Bürmoos, Austria) was rigidly mounted to the vertically moving crosshead, while the bone specimen was fixed in a vise to prevent movement artifacts. Crosshead motion was controlled by dedicated software, allowing predefined intermittent drilling and withdrawal cycles with constant feed rates, dwell time, and depth control. Two preparation depths were investigated (10 mm and 12 mm), resulting in total preparation times of 32.0 s and 38.9 s, respectively, as previously described [17, 27, 28, 34–37]. Drilling in cortical and subcortical bone was performed with a feed rate of 2 mm/s, whereas drilling in deeper cancellous layers and drill withdrawal was performed at 1 mm/s. Axial force was recorded continuously using an external load cell, and drilling depth was monitored by a draw-wire

encoder. The system further included a surgical motor unit (Implantmed SI-923, W&H, Bürmoos, Austria). During irrigated experiments, room-temperature saline was delivered through a standard irrigation tubing at a constant flow rate of 50 mL/min. For temperature measurement, type-K thermocouples (RS PRO Type K Thermocouple, RS Components Ltd, Corby, UK) were connected to a multifunction data acquisition module and recording software. Continuous real-time temperature measurement at multiple depths was achieved by fixing the sensors to a custom 3D-printed sensor array with a defined vertical spacing of 3 mm between adjacent sensors (Fig. 3).

Methods

The present experiment was conducted within the same validated thermal testing platform used in previous comparative in vitro studies from our group [27, 28]. Core experimental parameters were intentionally retained to ensure direct comparability across studies, while the investigated exposure of interest in the present study was the use of alumina-toughened zirconia drills under guided versus conventional preparation.

The experimental design comprised:

- surgical technique: conventional surgery (CS) vs. guided preparation (GP)
- drill diameter: 2.0, 2.8, 3.5 mm
- drilling depth: 10, 12 mm
- irrigation mode: no irrigation, external irrigation

This resulted in 240 preparations in total (2 x 3 x 2 x 2 x 10 repetitions), all performed under controlled ambient temperature conditions (21.0 ± 1.0°C).

Conventional surgery served as the control group. To reduce the impact of possible specimen-specific factors, multiple osteotomies were performed within each bone specimen using different experimental conditions; the assignment of conditions to osteotomies within each sample was randomized. No data points were excluded from the analysis. Experimental procedures were paused if ambient temperature exceeded 22.0°C. A drilling speed of 800 rpm was selected, consistent with established atraumatic preparation protocols [17, 27, 28, 34–40]. To eliminate confounding due to drill wear, new unused drills were employed for each individual preparation.

To reproduce a clinical guided workflow under standardized laboratory conditions, digital planning procedures were adopted [41]. Prior to testing, all samples underwent optical surface scanning (iTero; Align Technology Inc., San Jose, CA, USA) and multislice computed tomography. Implant planning was performed using coDiagnostiX® software (coDiagnostiX® Version 10.9.1; DentalWings Inc., Montréal, Canada) for five osteotomies per sample according to the respective drill diameters and preparation depths (Fig. 4).

Lateral channels for temperature measurement (1 mm diameter) and fixed sleeves for template stabilization pins were digitally designed (Fig. 2B-C). Planning was conducted by G.D.S. before experimental testing. Surgical guides were exported and fabricated using a custom rapid-prototyping system at the Center for Medical Physics and Biomedical Engineering, Medical University of Vienna, Austria.

Temperature measurement preparation included predrilling of lateral channels and fixation holes using depth-controlled multi twist drills and newly fabricated templates for each drilling cycle. Temperature measurements were performed at constant distances of 1 mm and 2 mm to the osteotomy wall. For drills with diameters of 2.8 and 3.5 mm, sequential graduated drilling was performed according to manufacturer recommendations. A thermal transfer compound was applied to sensor channels prior to thermocouple insertion to improve thermal contact [17, 27, 28, 34–37, 39, 42].

Conventional surgery was performed without surgical guide. For guided preparation, titanium guide sleeves were used for pilot drilling (steco-system-technik GmbH & Co KG, Hamburg, Germany), and corresponding drill-handle cylinders (Straumann®, Basel, Switzerland) were used for larger drill diameters (Fig. 5).

Samples were fixed in a vise to the testing machine to prevent movement artifacts. Surgical suction was applied continuously during irrigated procedures in a constant distance of 2 cm from the preparation site. All experiments were conducted between 2024 and 2025. Operators D.T., Z.T and G.D.S., were not blinded to group allocation. Outcome assessors and statisticians (M.M., E.U., K.G.) were likewise aware of the group assignment during analysis.

Statistical analysis

For each preparation, the following parameters were recorded:

- temperature (°C) at 1 mm and 2 mm distance from the osteotomy wall (sampling interval: 0.01 s)
- drilling depth (mm)
- axial force (V equivalent signal)

Recording commenced 20 s prior to drilling and continued for 60 s after completion (Fig. 6).

Temperature increase was calculated as: $\Delta T(°C) = T_x - T_0$, where T_0 represents baseline temperature prior to drilling and T_x the temperature at time point x [17, 27, 28, 31, 34–37, 39, 42, 43].

Primary outcome: maximum temperature increase (ΔT_max).

Secondary outcome: intrabony location of maximum temperature increase.

Temperature changes were normally distributed and are presented as means ± standard deviation. Median, minimum and maximum values were used to describe depth locations of peak temperatures. A linear mixed-effects model was fitted including drill diameter, drilling depth, irrigation mode, and surgical technique, as well as all interaction terms up to four-way interaction. Kenward–Roger adjustment was applied to correct degrees of freedom for unequal variances. Normality of residuals was assessed graphically. Pairwise comparisons between surgical techniques were performed for exploratory purposes using unequal t-tests when appropriate. Statistical analysis was conducted using SAS® software (version 9.4, SAS Institute Inc., Cary, NC, USA). All tests were two-sided, and $p \leq 0.05$ was considered statistically significant.

Results

This investigation comprised a total of 240 experimental implant site preparations, including conventional implant surgery (CS) and guided implant preparation (GP). The effects of three drill diameters (2.0, 2.8, 3.5 mm), two drilling depths (10 and 12 mm), and two irrigation modes (no irrigation and external irrigation) on temperature development were evaluated.

Highest temperature increase

Highest temperature increase (ΔT_max) was determined across all five temperature sensors and both measurement distances (1 and 2 mm) for each preparation. For each experimental condition, 10 identical repetitions were performed. The corresponding mean values and standard deviations [ΔT_max, mean (SD), °C] are summarized in Table 1 and illustrated in Fig. 7.

Table 1
Maximum temperature increase (ΔT_max) by surgical technique, drill diameter, drilling depth, and irrigation mode across five temperature sensors and both measurement distances; values are mean ± standard deviation [ΔT (°C), mean (SD)]; subgroup p-values between guided implant preparation (GP) and conventional implant surgery (CS) exploratory and provided for descriptive interpretation only

Drilling depth		**10 mm**		**12 mm**	
Diameter	**Method / p-value**	**No irrigation**	**External irrigation**	**No irrigation**	**External irrigation**
2.0 mm	**GP**	18.24 (3.50)	15.24 (6.22)	20.76 (5.46)	20.45 (4.46)
	CS	16.94 (7.03)	14.69 (7.05)	27.50 (8.46)	16.82 (8.54)
	p-value	0.6075	0.8568	0.0510	0.2549
2.8 mm	**GP**	13.83 (3.00)	4.98 (1.46)	12.90 (1.70)	13.72 (6.86)
	CS	12.47 (1.84)	6.81 (3.85)	14.96 (2.17)	16.57 (9.69)
	p-value	0.2411	0.1859	0.0301	0.4590
3.5 mm	**GP**	14.41 (1.86)	5.34 (2.17)	17.44 (1.91)	6.71 (1.30)
	CS	17.16 (3.23)	4.95 (1.63)	17.64 (2.71)	6.00 (2.79)
	p-value	0.0349	0.6557	0.8544	0.4777

Preparations at 10-mm drilling depth

For non-irrigated preparations using 2.0-mm drills, mean ΔT_max values were 18.24 (3.50) °C for GP and 16.94 (7.03) °C for CS. For 2.8-mm drills, mean values were 13.83 (3.00) °C for GP and 12.47 (1.84) °C for CS, and for 3.5-mm drills 14.41 (1.86) °C for GP and 17.16 (3.23) °C for CS (Table 1).

Under external irrigation, mean ΔT_max values at 10 mm were 15.24 (6.22) °C for GP and 14.69 (7.05) °C for CS with 2.0-mm drills, 4.98 (1.46) °C for GP and 6.81 (3.85) °C for CS with 2.8-mm drills, and 5.34 (2.17) °C for GP and 4.95 (1.63) °C for CS with 3.5-mm drills (Table 1).

Preparations at 12-mm drilling depth

For non-irrigated preparations using 2.0-mm drills, mean ΔT_max values were 20.76 (5.46) °C for GP and 27.50 (8.46) °C for CS. For 2.8-mm drills, mean values were 12.90 (1.70) °C for GP and 14.96 (2.17) °C for CS, and for 3.5-mm drills 17.44 (1.91) °C for GP and 17.64 (2.71) °C for CS (Table 1).

Under external irrigation, mean ΔT_max values at 12 mm were 20.45 (4.46) °C for GP and 16.82 (8.54) °C for CS with 2.0-mm drills, 13.72 (6.86) °C for GP and 16.57 (9.69) °C for CS with 2.8-mm drills, and 6.71 (1.30) °C for GP and 6.00 (2.79) °C for CS with 3.5-mm drills (Table 1).

Temperature increase and surgical preparation technique

The effect of surgical preparation technique (CS vs. GP) on ΔT_max was evaluated in a linear mixed-effects regression model adjusted for diameter, drilling depth, irrigation mode, and their interactions. A significant interaction was observed between drill diameter, irrigation mode, and drilling depth ($p = 0.0007$). However, surgical technique showed no statistically significant main effect on temperature increase and did not significantly interact with any other factor.

Accordingly, no overall statistically significant differences in temperature development between guided and conventional preparation were detected under the investigated conditions. Subgroup comparisons shown in Table 1 and Fig. 7 are exploratory and intended for descriptive purposes; p-values should therefore be interpreted cautiously.

Intrabony location of maximum temperature increase

The spatial distribution of peak temperature changes within the bone specimen was assessed by identifying the sensor channel depth (3, 6, 9, 12, or 15 mm) at which ΔT_max occurred, at both measurement distances (1 mm and 2 mm) for all experimental conditions (Table 2).

Drill diameter 2.0 mm

For both 10-mm and 12-mm drilling depths, maximum temperature increases during non-irrigated preparations were observed predominantly between sensor depths of 3 and 6 mm. Under external irrigation, peak temperatures occurred mainly between 6 and 9 mm (Table 2).

Drill diameter 2.8 mm

At a drilling depth of 10 mm, maximum temperature increases occurred between 4.5 and 6 mm under non-irrigated conditions and between 7.5 and 9 mm with external irrigation (Table 2). At 12 mm drilling depth, peak temperature locations were observed between 6 and 9 mm without irrigation and consistently at 9 mm under external irrigation (Table 2).

Drill diameter 3.5 mm

For 10-mm preparations, maximum temperature changes occurred between 3 and 6 mm without irrigation and between 6 and 9 mm with external irrigation (Table 2). For 12-mm preparations, peak temperatures were detected between 4.5 and 6 mm in non-irrigated conditions and between 9 and 12 mm when external irrigation was applied (Table 2).

Table 2

Intrabony location of maximum temperature increase; sensor channel depths (3, 6, 9, 12, and 15 mm) reported as median, minimum, and maximum values for measurement distances of 1 mm and 2 mm, for both drilling depths, three drill diameters, and two irrigation modes; GP = guided implant preparation; CS = conventional implant surgery

Drilling depth			**10 mm**						**12 mm**					
Irrigation			**No irrigation**			**External irrigation**			**No irrigation**			**External irrigation**		
Sensor channel depth (mm)			**Median**	**Min**	**Max**	**Median**	**Min**	**Max**	**Median**	**Min**	**Max**	**Median**	**Min**	**Max**
Diameter	**Method**	**Distance**												
2.0 mm	**GP**	**1 mm**	3	3	6	6	3	9	3	3	9	9	6	12
		2 mm	3	3	3	6	6	6	3	3	6	6	6	9
	CS	**1 mm**	6	3	6	9	6	9	6	6	9	9	6	12
		2 mm	6	3	6	9	6	9	6	3	9	9	6	12
2.8 mm	**GP**	**1 mm**	6	3	6	9	6	9	9	6	9	9	6	12
		2 mm	6	3	6	7.5	6	9	6	3	6	9	6	12
	CS	**1 mm**	6	3	6	9	6	15	6	6	9	9	9	12
		2 mm	4.5	3	6	9	6	15	6	3	9	9	9	12
3.5 mm	**GP**	**1 mm**	6	6	6	7.5	6	9	6	3	9	11	9	12
		2 mm	6	3	6	6	6	9	6	3	6	9	6	12
	CS	**1 mm**	6	3	6	9	9	9	6	3	9	12	9	12
		2 mm	3	3	6	9	6	15	4.5	3	6	9	9	12

Discussion

The present study evaluated the thermal performance of ceramic drills during guided versus conventional implant site preparation in a standardized experimental setting. Across all investigated drill diameters, drilling depths, and irrigation modes, no statistically significant effect of surgical technique on temperature increase was detected. Accordingly, the null hypothesis could not be rejected, as guided and conventional preparation did not differ with respect to maximum temperature increase (ΔT_max).

These findings are consistent with previous experimental investigations suggesting that guided preparation does not inevitably result in higher intrabony temperatures compared with freehand drilling [16, 27]. Although early evidence reported increased heat generation during guided procedures [44], subsequent studies have demonstrated a more differentiated pattern. From a physical perspective, additional friction between rotating drills and guiding sleeves may contribute to heat generation, and irrigation efficiency may be reduced by the shielding effect of the surgical template, particularly in deeper osteotomy regions [45]. However, experimental investigations of irrigation flow and intrabony temperature development in different template designs have shown that, despite reduced coolant delivery in fully guided systems, this does not necessarily translate into clinically relevant temperature elevations [46].

In the present investigation, surgical guides with closed designs were deliberately used to reflect conditions in which irrigation may be more restricted. Although significant temperature differences were observed between irrigation modes, drill diameters, and drilling depths, no systematic temperature increase attributable to guided surgery was detected. These results corroborate the findings of Waltenberger et al. and Abuhajar et al., who reported only minor or clinically negligible thermal differences between limiting and non-limiting guides [46, 47]. Moreover, the guiding systems applied in this study, including metal sleeves for pilot drilling and drill handle cylinders for larger diameters, appear to exert minimal additional thermal influence. This interpretation is supported by numerical and experimental data demonstrating that frictional heat generated at the drill–guide interface is largely independent of tool diameter [45].

To the authors' knowledge, this study represents the first standardized investigation assessing thermal development during guided implant site preparation using alumina-toughened zirconia drills. Consequently, the results must be interpreted in relation to existing data on ceramic drills under guide-free conditions. Previous studies have reported favorable biological and mechanical properties of mixed zirconia drills, including enhanced bone formation in healing models [48], high wear resistance [49], and low thermal conductivity [50]. Nevertheless, systematic reviews have concluded that the available evidence regarding their thermal behavior remains inconclusive, largely due to methodological heterogeneity and varying experimental conditions [22].

The present study should be interpreted as the missing comparative step within a standardized thermal research platform. Earlier investigations addressed either the effect of drill material under conventional guide-free conditions or the effect of guided versus conventional preparation using stainless steel drills [27, 28]. In contrast, the present study specifically examined the previously untested intersection of these two variables, namely guided implant osteotomy using alumina-toughened zirconia drills. The intentional retention of specimen geometry, drilling kinematics, temperature measurement, and irrigation conditions was methodologically necessary to enable direct between-study comparison and to isolate the influence of the variable of interest without introducing additional experimental heterogeneity.

Within this framework, the close agreement of conventional temperature values with those reported in earlier guide-free investigations supports the internal consistency of the platform and strengthens the interpretation of the present guided ceramic data. The validated standardized bovine bone model therefore allowed direct comparison with previous thermal performance studies [17, 27, 31, 32, 36] and supports the robustness of the present findings. As temperature values obtained for conventional surgery in this study closely match those reported in earlier guide-free investigations using the same model [17], the validity of the guided preparation data appears robust. Notably, although ceramic drills produced higher peak temperatures than stainless steel drills reported previously in the same experimental setup [17, 27], the use of surgical guidance itself did not further increase thermal exposure.

Consistent with prior investigations, the highest temperatures were recorded during pilot drilling with 2.0-mm instruments [16, 34]. Beyond peak temperature values, exposure duration to elevated temperatures is clinically relevant, as bone necrosis has been reported when temperatures exceed 47°C for more than one minute [14]. Recent in vivo and ex vivo data indicate that sequential graduated drilling protocols may prolong thermal exposure times compared with simplified approaches [51]. This aspect is particularly relevant for ceramic drills, as previous work from the present research group demonstrated that the combination of increased peak temperatures and prolonged exposure times may pose a biological risk in guide-free preparation [36]. Therefore, although guided surgery does not appear to exacerbate thermal load, careful attention to irrigation efficiency and drilling protocols remains essential when ceramic drills are used.

The temperature measurement methodology applied in this study, using intrabony thermocouples positioned at defined distances from the osteotomy site, allows precise real-time assessment of thermal changes and has been validated in multiple prior investigations [17, 27, 31, 46]. Infrared thermography was deliberately excluded, as it only provides indirect surface temperature estimation. The use of an automated drilling system further ensured reproducibility and eliminated operator-dependent variability. Additionally, drill wear was excluded as a confounding factor by using new instruments for each preparation.

From a clinical perspective, the present findings suggest that guided implant surgery using ceramic drills does not impose an additional thermal risk compared with guide-free preparation, provided adequate irrigation is applied. The beneficial effect of irrigation was confirmed across all drill diameters and drilling depths, consistent with previous reports demonstrating that the presence of irrigation significantly reduces temperature rise during osteotomy procedures [15]. Consequently, particular caution appears warranted during pilot drilling, especially in deeper osteotomies and when irrigation is insufficient. Furthermore, evaluation of sensor channel data revealed that maximum temperature increases occurred at greater intrabony depths under irrigated conditions compared with non-irrigated preparations. This finding indicates that external irrigation effectively limits heat accumulation in superficial bone layers, thereby shifting the location of residual thermal maxima toward deeper regions of the osteotomy.

Several limitations must be considered. First, this was an in vitro investigation and may fully reproduce the biological environment of living bone, including perfusion, metabolic heat dissipation, and physiological baseline temperature. Nevertheless, the thermal conductivity of the employed bone model closely approximates that of human bone [30], and comparable temperature patterns have been reported between bovine bone and in vivo models [51]. Because baseline temperature in our in vitro model was room temperature, the results should be interpreted as relative differences in thermal exposure between conditions rather than as direct evidence of exceeding in vivo temperature thresholds. Second, only a widely used surgical guide with a closed design was evaluated, and other guide geometries or irrigation-enhanced templates may yield different results [52]. Third, only room-temperature irrigation was applied for comparison of testing results, whereas cooled irrigation fluids have been shown to further reduce intrabony temperatures [53].

Future research could aim to validate these findings under in vivo conditions and to investigate the biological consequences of thermal exposure associated with ceramic drills, including bone-to-implant contact, marginal bone remodeling, and osteocyte viability. Additionally, cellular responses to ceramic drill wear particles warrant investigation, particularly in comparison with metallic debris. Finally, different ceramic compositions may exhibit varying thermal properties, offering the potential to optimize drill design for improved thermal-mechanical performance.

Conclusion

The present controlled in vitro experimental study compared the thermal performance of ceramic drills during guided and conventional implant site preparation using automated drilling in a standardized bovine bone model. No statistically significant difference in temperature development was observed between guided and conventional drilling when alumina-toughened zirconia drills were used. However, significant temperature differences were detected with respect to drill diameter, drilling depth, and irrigation mode. The highest temperature increases consistently occurred during pilot drilling with 2.0-mm instruments, irrespective of the surgical technique. External irrigation substantially reduced temperature rise across all experimental conditions.

Within the limitations of this in vitro model, these findings suggest that guided implant surgery using ceramic drills does not impose additional thermal risk compared with conventional preparation, provided that adequate irrigation protocols are applied.

Abbreviations

ΔT_max
maximum temperature increase
SEM-EDX
scanning electron microscopy–energy dispersive X-ray spectroscopy
3D
three-dimensional
CS
conventional surgery
GP
guided preparation
T_x
recorded absolute temperature at time point x
T_0
recorded initial baseline temperature
SD
standard deviation

Declarations

Ethics approval

For this in vitro investigation using artificially manufactured testing samples, ethics approval was not required.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Author Contribution

D.T. design/concept, led experimental investigation and writing of manuscriptZ.T. involved in experimental investigation K.G. revised manuscript critically E.U. design/concept, technical support M.M. statistical analysis of obtained data G.D.S. conceived ideas, revised manuscript critically and secured investigation funding

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Availability of data and materials

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Figures

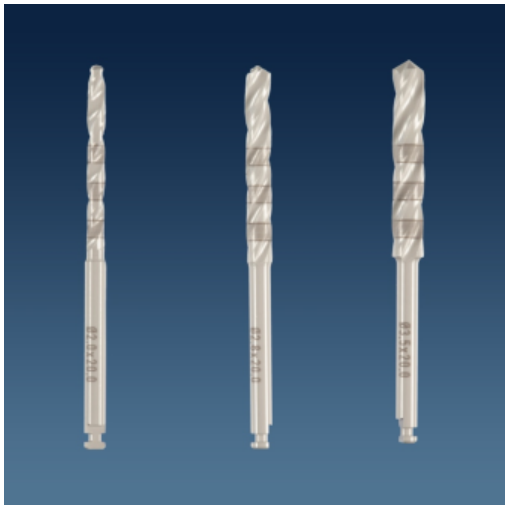


Figure 1

Investigated ceramic implant twist drills (diameters 2.0, 2.8, and 3.5 mm; Komet Ceradrill™, Komet®, Gebr. Brasseler, Lemgo, Germany)

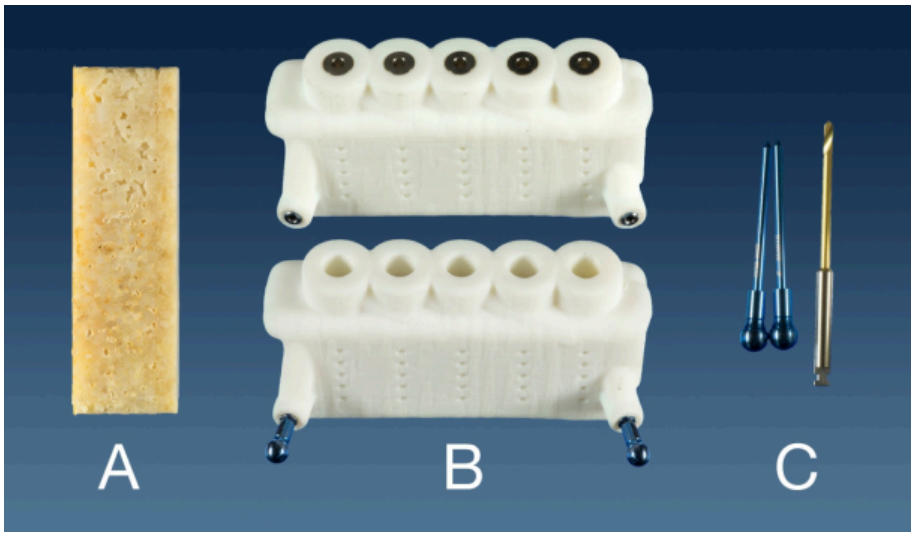


Figure 2

(A) Standardized bovine bone specimen; (B) Surgical guide with inserted guiding sleeves for 2.0-mm diameter pilot drilling and surgical guide with inserted template fixation pins for drill-handle-based guided preparations using 2.8- and 3.5-mm drills; (C) Template fixation pin and corresponding drill

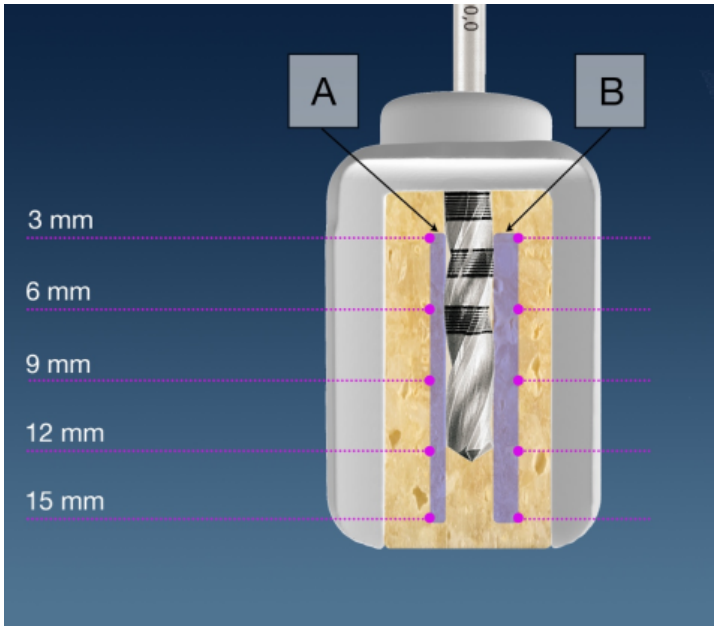


Figure 3

Illustration of the real-time temperature measurement setup during guided implant preparation; temperature sensor locations at 1-mm distance (A) and 2-mm distance (B) from the osteotomy site

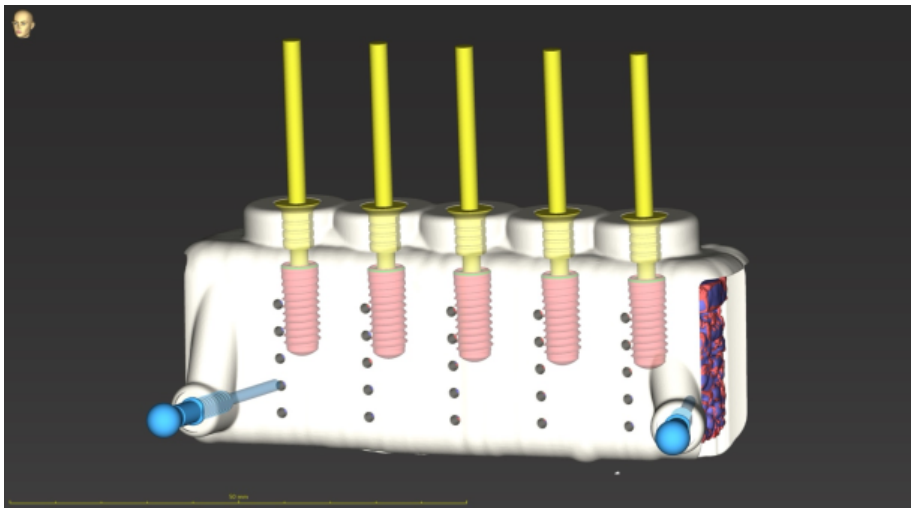


Figure 4

Digital planning workflow for guided implant site preparation showing the superimposed surgical guide, standardized bovine testing specimen, and five virtually planned 10-mm implant positions to illustrate the predefined drilling trajectories used for the guided experimental protocol

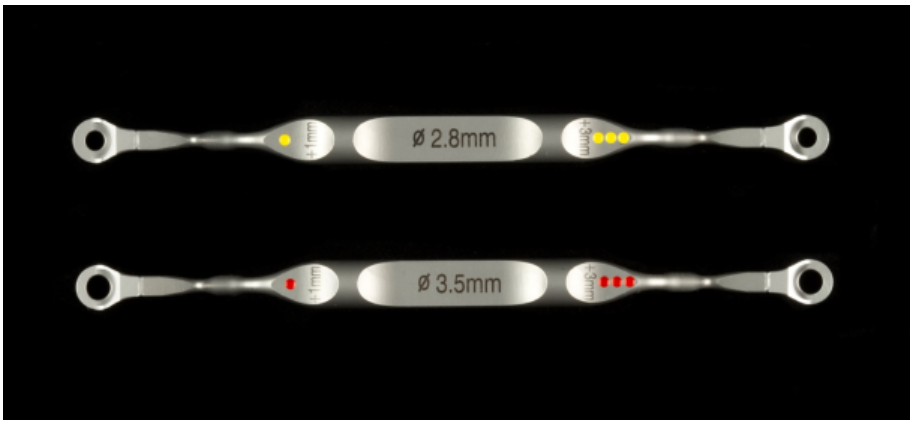


Figure 5

Surgical drill-handle cylinders used for guided preparations with 2.8- and 3.5-mm drill diameters

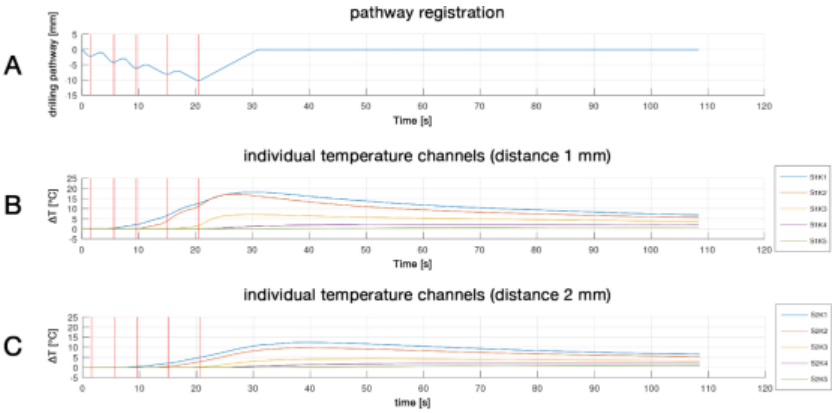


Figure 6

Exemplary illustration of (A) drilling pathway registration using an external linear motion potentiometer and real-time recording of temperature changes (ΔT) at (B) 1-mm distance and (C) 2-mm distance from the osteotomy site

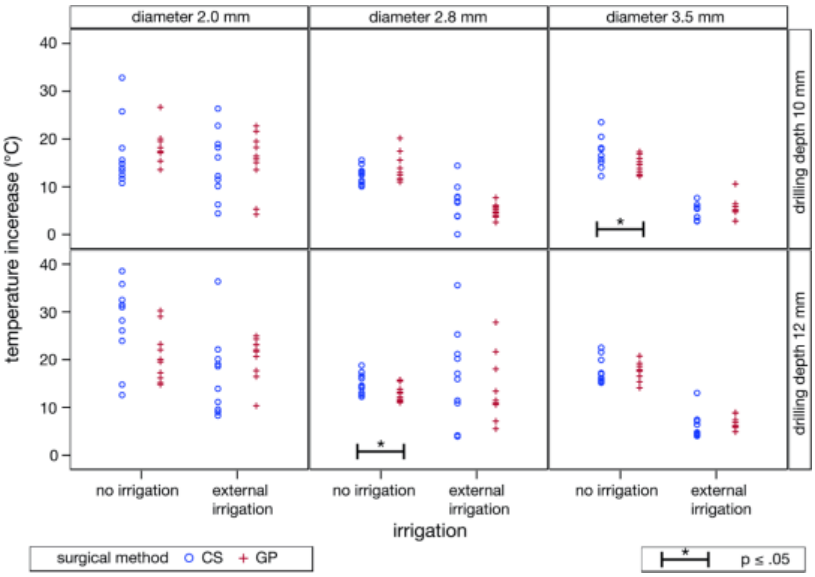


Figure 7

Recorded temperature increases during conventional implant surgery (CS) and guided implant preparation (GP) for three drill diameters (2.0, 2.8, and 3.5 mm), two irrigation modes (no irrigation and external irrigation), and two drilling depths (10 and 12 mm)

Supplementary Files

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