ABSTRACT

Purpose: In this study, we aimed to evaluate the degree of heat generation when a novel drill design with an irrigation slot was used with metal sleeve-free (MF) and metal sleeve-incorporated (MI) surgical guides in an environment similar to that of the actual oral cavity.

Methods: A typodont with a missing mandibular right first molar and 21 bovine rib blocks were used. Three-dimensional-printed MF and MI surgical guides, designed for the placement of internal tapered implant fixtures, were used with slot and non-slot drills. The following groups were compared: group 1, MI surgical guide with slot drill; group 2, MI surgical guide with a non-slot drill; and group 3, MF surgical guide with a slot drill. A constant-temperature water bath at 36°C was used. The drilling was performed in 6 stages, and the initial, highest, and lowest temperatures of the cortical bone were measured at each stage using a non-contact infrared thermometer.

Results: There were no temperature increases above the initial temperature in any drilling procedure. The only significant difference between the non-slot and slot groups was observed with the use of the first drill in the MI group, with a higher temperature in the non-slot group ($P=0.012$). When the heat generation during the first and the second drilling was compared in the non-slot group, the heat generation during the first drilling was significantly higher ($P<0.001$), and there was no significant difference in heat generation between the drills in the slot group.

Conclusions: Within the limitations of this study, implant-site preparation with the surgical guide showed no critical increase in the temperature of the cortical bone, regardless of whether there was a slot in the drill. In particular, the slotted drill had a cooling effect during the initial drilling.

Keywords: Cortical bone; Dental implants; In vitro techniques; Osteonecrosis; Thermometers
Heat generation due to drilling under guided surgery

Conflict of Interest
No potential conflict of interest relevant to this article was reported.

Author Contributions
Conceptualization: Dong-Woon Lee; Data curation: Yoon-Sil Choi; Formal analysis: Young Lee; Investigation: Jae-Woon Oh; Methodology: Dong-Woon Lee; Software: Young Lee; Validation: Jae-Woon Oh; Writing - original draft: Yoon-Sil Choi and Jae-Woon Oh; Writing - review & editing: Dong-Woon Lee.

Recent studies on different types of surgical guides have compared the advantages and disadvantages of metal sleeve-free (MF) and metal sleeve-incorporated (MI) surgical guides. The degree of angular deviation, which is a measure of the attrition of the inner part of the sleeves, was lower when using MF surgical guides than when using MI surgical guides [6]. Although the accuracy of implant placement with an MI surgical guide is higher than that with an MF surgical guide, the generation of frictional heat between the metal sleeve and the drill and the decrease in the cooling effect were reported to be sufficient risk factors for heat generation [7]. The frictional heat generated during surgery can cause the death of differentiated and undifferentiated cells, thereby acting as a major risk factor for the failure of osseointegration [5]. Another study showed that greater damage occurred when heat at 53°C was generated for 1 minute [8]. Permanent cessation of blood flow at temperatures above 60°C has been proven to cause necrosis of the bone [9]. In previous studies, the use of a surgical guide led to higher heat generation; however, the highest recorded temperature was below the bone necrosis threshold [10]. Therefore, it is thought that the guide can safely be used in actual clinical practice.

Several studies have focused on irrigation due to the higher heat generated while using a surgical guide [5,11,12]. Irrigation plays a direct and important role during bone preparation by cooling the contact surface between the drill and bone. In a study on temperature change according to the number of irrigations and the depth reached during drilling, it was reported that without irrigation, the maximum temperature could increase to 50.9°C in the superficial part of the bone [13]. Considering these factors, it can be assumed that irrigating the bone preparation site during drilling using a surgical guide plays an important role in preventing osteonecrosis. Various efforts have been made to achieve effective irrigation while using a surgical guide, including modification of the sleeve design. In a study on heat generation according to the sleeve design (cylindrical, open C-shaped, and modified cylindrical), the open C-shaped and modified cylindrical sleeves showed better drill diameters and measurement depths and led to a significantly lower temperature increase regardless of the irrigation temperature [9].

Accordingly, a drill modified to allow the irrigation fluid to directly reach the bone preparation site by creating a passage in the center of the drill has been proposed as an ideal method to prevent osteonecrosis due to heat generation [14]. Although surgical guides are widely used for implant surgery, most studies on heat generation associated with surgical guide use have been conducted in an environment significantly different (in terms of the type of surgical guide, initial temperature, and measurement method, among other factors) from that of an actual oral environment.

Therefore, in this study, we aimed to overcome the limitations of earlier ex vivo experiments by closely imitating the oral environment. Finally, this study aimed to evaluate whether the drill size or MF and MI surgical guides affect the degree of heat generation.
MATERIALS AND METHODS

Model and drill preparation
A typodont (D85S-TRM.406, Nissin Dental Products Inc., Kyoto, Japan) with a missing mandibular right first molar and cryopreserved bovine ribs were used. A block of the bovine rib was cut to a size of 8 mm × 8 mm × 10 mm (mean cortical outer-layer thickness: 2.63±0.55 mm) and placed in the region of the right first molar on the mandibular typodont (Figure 1). The rib block was trimmed to the same size as the model implant site, and due to the difference in hardness between the rib block and implant site, we were able to obtain fixation by using a mallet.

Standard Tessellation Language and Digital Imaging and Communications in Medicine files were obtained using an intraoral scanner (Medit i500, Medit Corp., Seoul, Korea) and CBCT imaging (KaVo, 3D eXam instrument, Imaging Sciences International LLC, Hatfield, PA, USA; voxel size, 0.30 mm; exposure time, 8.9 s; 120 kVp, 18.54 mAs), respectively. An implant fixture (Ø 5.0 mm × 8 mm, Dentis, Daegu, Korea) was designed to fabricate a surgical guide for implant placement using a guide software (Dentiq Guide, Dentis). An MF surgical guide and an MI surgical guide with a metal sleeve (Ø 5.35 mm, height 3.5 mm) were designed as well.

A window with a 2-mm height and 3-mm width was made on the buccal aspect of the guide for measurement. A roof (14 mm × 10 mm) was made above the window to prevent water inflow (Figure 2). The designed guide was printed using a 3D printer (Zenith L, Dentis), washed with alcohol for 10 minutes, and post-cured for 10 minutes.

A newly designed slot drill, which had 3 slots (depth: 1.4 mm, width: 3.4 mm) was placed in the barrel area of the drill in the longitudinal direction, and a non-slot drill sealed with...
utility wax was used (Figure 3). During drilling and all preparatory steps, the irrigation fluid temperature was set to room temperature.

Study design
Twenty-one bovine rib models were used in this study during guided surgery. The models were divided into 3 groups according to the presence or absence of a metal sleeve and slot design as follows:

Group 1 (MI + slot, n=7): MI surgical guide with a slot drill
Group 2 (MI + non-slot, n=7): MI surgical guide with a non-slot drill
Group 3 (MF + slot, n=7): MF surgical guide with a slot drill
The sample size was calculated using G*Power version 3.1.9.4 with analysis of variance (ANOVA). Repeated measures and within-between interactions were calculated to detect an effect size of 0.25 (power: 80%, two-sided α: 0.05, correlation between repeated measures: 0.7 and non-sphericity correction ε: 1). Because we obtained 6 repeated measures of temperature, 6 blocks had to be included in each group, and to account for the possible loss of samples, we used 7 blocks in each group.

A non-contact infrared thermometer (Fluke VT04A, Fluke Corporation, Everett, WA, USA) was used to measure the cortical bone temperature through the window of the surgical guide by placing the bovine rib model in a constant-temperature bath (C-WBA2, Changshin Science, Seoul, South Korea) at 36°C to reproduce the normal body temperature in human beings [15,16]. The thermometer was set to an emissivity of 0.96, and the temperature was measured through the window of the surgical guide from a distance of 20 cm. The initial temperature was measured for each block in each group. The planned implant in the right mandibular first molar was prepared according to the manufacturer’s recommendations. Drills of the following sizes were used: Ø 2.2 mm × 6 mm (first), Ø 2.2 mm × 8 mm (second), Ø 3.5 mm × 8 mm (third), Ø 4.0 mm × 8 mm (fourth), Ø 4.5 mm × 8 mm (fifth), and Ø 5.0 mm × 8 mm (final). All drilling was performed using a surgical implant micromotor (Osseo System, XO Dentalcare, Horsholm, Denmark) and handpiece (WS-75 E/KM, W&H Dentalwerk, Burmoos, Austria) at a speed of 800 rpm and torque of 55 N-cm at 25°C. The procedure was performed by a periodontist (D.W.L.). The temperature at the start of the drill and the highest or lowest temperature during drilling were recorded for each group (Figure 4).

Statistical analysis
All data are reported as the mean ± standard deviation. The 2-sample t-test was used to evaluate the effectiveness of the slot and the metal sleeve on the temperature at each drill size. Repeated-measures ANOVA and post hoc tests using the Bonferroni correction were used to evaluate the temperature differences according to the group and drill size in each metal sleeve group and slot group. The Mauchly test was used to test for the assumption of sphericity, whereas the Greenhouse–Geisser correction was used to correct for sphericity violations. Statistical significance was set at P<0.05. All the analyses were conducted using R software, version 4.0.1 (R Foundation for Statistical Computing, Vienna, Austria; http://www.R-project.org).

Figure 4. Drilling and measurement. (A) Drilling with external irrigation in a constant-temperature bath. (B) Non-contact infrared thermometer.
Ethical approval of studies and informed consent
Not applicable, because this article does not contain any studies with human or animal subjects.

RESULTS

Temperature observations
Compared to the initial temperature, there was no further increase in the temperature in any of the groups and during any of the drilling steps (Table 1). However, there was a significant difference in the temperature between group 1 (MI + Slot) and group 2 (MI + non-slot) with use of the first drill ($P=0.023$).

Slot–drill size interaction in the MI group
Repeated-measures ANOVA performed in the metal sleeve group revealed a significant slot × drill size interaction ($F_{1.72,20.63}=9.00$, $P=0.002$), and a significant main effect of the drill size ($F_{1.72,20.63}=16.66$, $P<0.001$) on the temperature, although no significant main effects of the slot ($F_{1.12}=1.92$, $P=0.191$) were observed. A significant slot × drill size interaction means that the effect of the slot on temperature was different, depending on the drill size. In other words, the effect of drill size on the temperature depends on the slot. Therefore, post hoc analysis of the drill size and the slot was performed with the slot and drill size fixed, respectively.

The only significant difference between the non-slot and slot groups was observed with the first (Ø 2.2 mm × 6 mm) drill. The temperature was higher in the non-slot group (i.e., cooling was effective in the slot group). Near-significant differences were observed between the non-slot and slot groups when using the second (Ø 2.2 mm × 8 mm) drill ($P=0.066$) and the third drill ($P=0.098$) (Figure 5).

The post hoc comparisons did not reveal any significant temperature differences according to the drill size in the slot group. In the non-slot group, the temperature decreased as the drill size increased. However, the highest temperature at the time of drilling was significantly different between the first and second drills ($P<0.001$) and between the fifth and final drills ($P=0.031$); there was a near-significant difference in this temperature between the third and fourth drills ($P=0.051$) (Figure 6).

Metal sleeve and drill size in the slot group
Repeated-measures ANOVA performed in the slot group showed a significant main effect of the drill size ($F_{4,60}=6.28$, $P<0.001$) on the temperature; however, statistical significance was not found for the metal sleeve × drill size interaction ($F_{4,60}=0.88$, $P=0.503$) or main effect of

Table 1. Mean temperature (°C) according to the group and drill size

| Drill           | Group 1 (MI + Slot) (n=7) | Group 2 (MI + non-slot) (n=7) | Group 3 (MF + slot) (n=7) | Group 1 vs. 2 P-value | Group 1 vs. 3 P-value |
|-----------------|---------------------------|-----------------------------|--------------------------|----------------------|----------------------|
| Initial temperature | 36.23±0.24               | 36.03±0.38                  | 36.27±0.16               | 0.265                | 0.704                |
| 1st (Ø 2.2 mm × 6 mm) | 33.13±0.30               | 34.76±1.43                  | 33.07±0.25               | 0.023*               | 0.704                |
| 2nd (Ø 2.2 mm × 8 mm) | 32.86±0.31               | 33.76±1.14                  | 32.71±0.43               | 0.084                | 0.489                |
| 3rd (Ø 3.5 mm × 8 mm) | 32.70±0.24               | 33.59±1.28                  | 32.41±0.37               | 0.119                | 0.112                |
| 4th (Ø 4.0 mm × 8 mm) | 32.84±0.26               | 32.97±0.77                  | 32.41±0.59               | 0.687                | 0.102                |
| 5th (Ø 4.5 mm × 8 mm) | 32.83±0.46               | 32.66±0.96                  | 32.31±0.45               | 0.678                | 0.054                |
| Final (Ø 5.0 mm × 8 mm) | 32.63±0.45               | 32.30±0.79                  | 32.30±0.62               | 0.358                | 0.277                |

Values are presented as mean±standard deviation.
MI: Metal sleeve-incorporated surgical guide, MF: metal-sleeve-free surgical guide.
*P <0.05.
the metal sleeves \( F_{1,12}=4.22, P=0.062 \). Because the temperature depended only on the drill size, post hoc analysis of the drill size was conducted regardless of the metal sleeve in the slot group. The effect of the drill size on the temperature with the use of the second \((\Omega 2.2 \text{ mm } \times 8 \text{ mm})\) and first \((\Omega 2.2 \text{ mm } \times 6 \text{ mm})\) drills was only slightly outside the range of significance \( P=0.091 \).
DISCUSSION

The most remarkable finding in this study was that the amount of heat generated during bone preparation around the cortical bone was not significant when using the surgical guide in conditions similar to those of the actual oral environment; further, the temperature during all drilling steps was lower than the initial temperature. Regardless of the use of a digital surgical guide, various factors are involved in heat generation during bone preparation for implant placement, such as bone quality, cortical bone thickness, drill shape, irrigation method, drilling speed, pressure, and time [17].

This study attempted to reproduce the oral environment using a dead bone block, which might have led to differences in temperature measurements due to differences in emissivity. However, unlike previous studies, efforts were made to create an environment with a temperature similar to the body temperature using a constant-temperature water bath at 36°C. Although a dead bone block is a thermal conductor, the cancellous area was kept in contact with the water to keep it from becoming too dry while maintaining the temperature. Additionally, a bovine rib was used in this study, as it exhibits bone quality and cortical bone conductivity most similar to that of a human mandible [18-20]. Although type II and III densities are most commonly used in various studies [21,22], as in this study model, it is necessary to consider that more heat may be generated with type I density [23].

The geometry of the drill plays an important role in heat generation, as a lack of drill angle or a small angle of clearance can result in a temperature rise [24,25]. To complement this, a newly designed drill with a propeller inserted into a titanium tube was compared with an existing external irrigation drill. It was observed that the newly designed drill enabled direct irrigation of the preparation site and had a cooling effect [24]. The results of this study showed that temperature during the initial drilling was reduced more effectively in the slot group. This cooling effect resulted from sufficient direct irrigation of the bone preparation site by using the novel drill, which was developed by adding 3 slots to an existing external irrigation drill. Conversely, the drill without such a slot (non-slot group) might have allowed relatively difficult access to external irrigation during the drilling rotation. It may be considered that the influence of these slots is small compared to the speed of drilling. However, in most clinical cases, a pumping motion is conducted during implant site preparation. From this point of view, the slot around the drill—that is, the space around it—can be considered more effective for cooling above the cortical foramen at the initial stage. In addition, the step-by-step drilling may explain why the temperature change during the later drilling was smaller than the temperature change during the initial drilling. This might have been caused by the prolonged application of frictional force to the superficial level of the bone and its temperature being higher than that of the deeper part owing to the high coefficient of friction of the cortical bone. In step-by-step drilling, the bone is prepared using a small-diameter drill, whereas a large-diameter drill requires only a small amount of cortical bone preparation, resulting in less heat generation [26]. Therefore, performing additional irrigation during the initial drilling is judged to be useful in a clinical scenario [27,28].

Previous studies have reported the advantages of using a low-temperature irrigation fluid [7,13,29,30]. However, this study showed no critical heat generation with a room-temperature fluid, as in previous studies [5,28].

The temperature was measured using an infrared thermometer. Previous studies have shown that the temperature of wet surfaces cannot be measured appropriately using this method.
To combat this problem, we designed a surgical guide with a roof added to prevent water inflow. In addition, the method using an infrared thermometer has multiple advantages over the thermocouple method described in previous studies [17,31]. According to the manufacturer, an infrared thermometer is relatively economical, easier to use, and more accurate than thermocouples (the precision of the one used here was in the range of ±1% at temperatures between 20°C and 300°C). An added advantage was that there was no need to place a thermocouple probe, and the temperature was measured without directly contacting the bone surface. Several studies have been conducted on MI and MF surgical guides. The MF surgical guide is distorted during the manufacturing process, causing deformation of the inner surface area of the sleeve and the accumulation of resin residues at the surgical site [6,32,33].

The MI surgical guide has a high tolerance and exhibits greater resistance to the removal (cutting) force exerted by the rotating drill [25]. These characteristics are thought to affect the stability and accuracy of implant placement [6]. A limitation of this study is that the stability and accuracy of the MF and MI surgical guides were not evaluated. However, no significant difference was observed between the MI and MF surgical guides in the relationship between heat generation and step-by-step drilling in the related post hoc analysis results. Furthermore, the pressure and duration of drilling were standardized by a single periodontal/implant specialist.

In conclusion, implant-site preparation with the surgical guide yielded no critical increase in the temperature of the cortical bone, regardless of whether there was a slot in the drill. In particular, the slotted drill had a cooling effect during the initial drilling.

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