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Intra-osseous heat generation during implant bed preparation with static navigation: Multi-factor *in vitro* study

Running head (abbreviated title)

Intra-osseous heat generation during bone drilling

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O.S-C: Data collection, drafting of the article, approval of the submitted and final versions.
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Abstract

Objectives: To compare the intra-osseous temperature reached during bone drilling for dental implant placement using open versus closed static surgical guides and evaluate the influence of bone density, osteotomy drilling depth, and irrigation fluid temperature.

Material and methods: 960 osteotomies were performed with 2 mm pilot drills in 16 solid rigid polyurethane foam blocks. Two main variables were considered: the guide type (open or closed guide) and bone density (hard (D1) or soft (D4). The blocks were divided into four groups according to the type of surgical template and bone density as follows: group one: closed guide and hard bone; group two: open guide and hard bone; group three: closed guide and soft bone; and group four: open guide and soft bone. A combination of different experimental conditions was used, including different bone osteotomy depths (6 or 13 mm) and irrigation fluid temperatures (5 ºC or 21 ºC).

Results: The highest mean temperature was found in group one (28.29±4.02 ºC). In the soft bone groups (three and four), the mean maximum temperature decreased compared to groups one and two (dense bone) and was always higher with closed guides (23.38±1.92 ºC) compared to open guides (21.97±1.22 ºC) ($p<0.001$). The osteotomy depth and irrigation fluid temperature also significantly influenced the bone temperature ($p<0.001$), especially in hard bone.

Conclusions: The greatest heat generation was observed in high-density bone. The final intra-bone temperature was about 1 ºC higher with a closed static surgical guide than with an open guide. The heat generation in osteotomy sites was substantially reduced by cooling the irrigation fluid to 5 ºC.

Keywords: Computer-aided surgery, Computer-assisted surgery, Dental implants, Osteotomy, Bone tissue.

Introduction

Adequate three-dimensional (3D) positioning of dental implants has been revealed as a key factor for aesthetic outcomes, easy maintenance, stability of peri-implant soft and hard tissues, and long-term success (Buser, Martin, & Belser, 2004; D'Haese, Ackhurst, Wismeijer, De Bruyn, & Tahmaseb, 2017; Linkevicius, Puisys, Vindasiute, Linkeviciene, & Apse, 2013; Tarnow, Cho, & Wallace, 2000). Guided surgery has been widely applied to achieve ideal 3D implant positioning (Bover-Ramos, Viña-Almunia, Cervera-Ballester, Peñarrocha-Diago, & García-Mira, 2018; Colombo et al., 2017; Moraschini, Velloso, Luz, & Barboza, 2015; Raico Gallardo et al., 2017; Schneider, Marquardt, Zwahlen, & Jung, 2009) as it can reduce human error (Amorfini, Migliorati, Drago, & Silvestrini-Biavati, 2017). Freehand implant surgery is less accurate in transferring 3D pre-surgical planning to the patient than guided surgery (Farley, Kennedy, McGlumphy, & Clelland, 2013; Pozzi, Tallarico, Marchetti, Scarfò, & Esposito, 2014; Vercruyssen et al., 2015; Younes et al., 2018). The application of static surgical templates for bone drilling and implant placement is a popular implant surgery navigation system. Closed or open static implant guides are currently available. The open guide has an open access located on the buccal side of the template that allows a buccal view of the surgical field and better contact of the irrigation fluid with the implant drill. However, this open design may affect the stent stability during drilling (Fauroux, De Boutray, Malthiéry, & Torres, 2018). In contrast, closed guides tend to cover the entire surgical field and do not allow for direct visualization of the surrounding soft and hard tissues. In addition, closed guides limit irrigation, which is usually used to cool down the temperature of the drill. Consequently, it has been shown that the use of a closed surgical guide for implant site preparation instead of a surgical template generates more heat (Liu, Wu, Zhang, Peng, & Liao, 2018; Misir, Sumer, Yenisey, & Ergioglu, 2009).

Thermal changes during bone drilling can cause bone alterations such as osteonecrosis (ON), which is defined as the *in situ* loss of a bone segment and is characterized by avascular necrosis of the bone (Bolland, Hood, Bastin, King, & Grey, 2004). Thermally induced osteonecrosis is a traumatic type of necrosis caused by high temperatures that can result in micro-damage to the osteocytes with cell apoptosis, followed by osteoclast activation and bone resorption (Augustin et al., 2012; Jeong et al., 2014; Noble, 2003). Therefore, bone temperature monitoring during osteotomy drilling using thermocouple methods has been used to prevent implant integration complications (Delgado-Ruiz et al., 2018; Gehrke et al., 2018; Jeong et al., 2014; Liu et al., 2018; Misir et al., 2009; Möhlhenrich, Modabber, Steiner, Mitchell, & Hölzle, 2015; Sumer, Keskiner, Mercan, Misir, & Cankaya, 2014).

In summary, static navigation for implant bed preparation appears to generate greater internal bone heat than using a freehand technique. Open static surgical guides seem to reduce heat generation compared to closed guides because there is more contact between the irrigation fluid and drill. Consequently, the influence of surgical guide designs and other factors such as bone density, irrigation fluid temperature, and osteotomy depth must be considered when planning guided implant surgery procedures (Raico Gallardo et al., 2017; Younes et al., 2018)

This *in vitro* study aimed to evaluate the maximum bone temperature reached during implant bed preparation using two different types of surgical guides (open and closed) and assess the influence of bone density, osteotomy drilling depth, and irrigation fluid temperature on the bone thermal changes.

Material and methods

Study design

The present *in vitro* study was carried out on eight solid rigid polyurethane foam blocks measuring 130 x 160 x 200 mm in size and distributed into four blocks simulating type I bone (D1) and four blocks simulating type IV bone (D4) according to the bone density classification of Misch and Degidi (Misch & Degidi, 2003) (Sawbones, Pacific Research Laboratories, USA). Each bone block was then cut into ten smaller pieces, resulting in 40 smaller blocks of D1 and D4 density, respectively, measuring 130 x 16 x 200 mm in size. To allow for more osteotomies, each block was drilled on both sides. The D1 and D4 foam blocks' characteristics were a density, compressive strength, and compressive modulus of 0.08 g/cm^3 and 0.48 g/cm^3; 0.6 MPa and 18 MPa; and 16 MPa and 445 MPa, respectively. This study was approved by the Research Ethics Committee of the Universitat Internacional de Catalunya (Ref. CIR-ELM-2017-02).

In partially edentulous patients, canine, premolar, and molar acrylic resin teeth were inserted in the blocks and fixed with triad gel (TriadGel® Dentsply Sirona, USA) to simulate the remaining teeth for better guiding stabilization. A space was left between the inserted simulated teeth to allow for six osteotomies per block, resulting in a total of 960 osteotomies.

The blocks were divided into four groups according to the type of surgical template (open or closed guide) and bone density: group one: closed guide and hard bone (D1); group two: open guide and hard bone (D1); group three: closed guide and soft bone (D4); and group four: open guide and soft bone (D4).

The closed guide (Figure 1) covered the entire surgical field and did not allow for the visualization of the simulated bone during the drilling sequence. In contrast, the open guide (Figure 2) had an open access located on the buccal side of the template that offered buccal visibility of the surgical field, direct visual control of the bone drilling, and better contact with the irrigation fluid.

The blocks in each group were subjected to four different experimental conditions, combining two factors with two magnitudes each: 1) the depth of the bone osteotomy (6 or 13 mm), and 2) the temperature of the irrigation fluid (fridge temperature 5 ºC or room temperature 21 ºC).

Figure 3 shows the distribution of the samples, specifying the number of blocks (n), number of osteotomies (m), and number of temperature measurements (k).

Surgical templates

The solid blocks with the inserted acrylic resin teeth were digitally scanned (REV 100, Optical Reveng Dental, 3DBiotech®, Spain). The scanned image of each block was reconstructed with built-in software and analyzed on a desktop computer with specialized implant planning software (Limaguide V01.2, Innovación Dental®, Spain). The surgical templates were designed and finally printed with a 3D printer (M300, Zortrax®, Poland) according to the design involved (open or closed). Each surgical template provided six osteotomy drilling sites, prepared with six open or closed plastic sleeves to allocate 2 mm diameter drills.

Drilling procedure

A specially designed machine with an attached implant motor that could produce a continuous drilling movement with a predetermined position and load was used. The device was coupled to a 20:1 reduction speed handpiece with a predetermined load of 2 kg (SurgicPro, NSK Nakanishi Inc., Japan). A thermometer with two thermocouples (DEM 106, Velleman®, Belgium) was added to the block to register the maximum temperature reached during the osteotomies (Figure 4).

Two different 2 mm diameter drills (Limaguide V01.2, Innovación Dental®, Spain), with mechanical stoppers at 6 mm and 13 mm, respectively, were used to perform the osteotomies through the surgical guide to ensure the correct depth and minimize any human errors (LimaGuide system, Barcelona, Spain). The drill speed was kept at 900 rpm constantly. Each set of drills was only used for five osteotomies to prevent drill wear from influencing the results.

Saline solution (Braun, GmbH, Germany) was continually used at 50 ml/min, at two different temperatures: room temperature (21 ºC) and cooled in the fridge (5 ºC). The saline solution’s temperature was recorded every 5 min and was replaced if the temperature changed by 1 ºC.

Data retrieval

For the temperature measurements, two type K thermocouple devices were coupled to a digital thermometer with an accuracy of 0.1 °C and inserted into two holes placed at each side of the osteotomy, 1 mm lateral to the osteotomy level (6 and 13 mm, respectively). The maximum temperature obtained (in °C) in each perforation drilling procedure in the two positions (buccal and lingual) was the primary variable of the study. The temperatures were recorded in a Microsoft Excel Office® 2011 spreadsheet (Microsoft Corporation, Redmond, USA). We waited until the temperature had returned to baseline (21 ºC) before commencing the next drilling procedure after each bone perforation.

Statistical analysis

The statistical analysis was performed using Statgraphics®Plus version 5.1 (Statpoint Technologies, Inc. Virginia, USA). A descriptive analysis of the different variables was made. The Kolmogorov-Smirnov test showed that the temperature data exhibited a non-normal distribution. However, the large sample size meant that a parametric approach could be used. Regarding the inferential analysis, linear models of the generalized estimation equations (GEE) were used, based on the hierarchical design of the observations (two measurements per bed and six beds per block). The dependent variable was always the maximum temperature reached, and the mean was compared for different levels of the independent factors. The chi-squared statistic of Wald was considered for the significance of the factors, with a significance level of 5% ($\alpha = 0.05$). Multiple comparisons were corrected according to Bonferroni's criteria.

Results

Bone temperature assessment

The maximum drilling temperature was reached in group one, with a mean value of 28.29±4.02 ºC, approximately 1 ºC above the value recorded in group one (27.16±3.39 ºC). The mean maximum temperature was lower in the soft bone groups (groups three and four) than in the hard bone groups (groups one and two). Furthermore, the mean maximum temperature was always higher with a closed guide than with an open guide (23.38±1.92 ºC vs. 21.97±1.22 ºC). Table 1 details the temperatures reached in each group. The mean maximum temperature was not equal in the four groups ($p<0.001$). Bonferroni's multiple comparison test showed that there were significant differences between any two of the groups. The detailed results are listed in Table 2.

Influence of bone density

Bone density was found to introduce great variability in heat generation, as seen in Figure 5. The effect of bone type on temperature was the same regardless of whether a closed or open guide was used. Linear models of GEE were established. First, in hard bone (D1), the temperature was significantly higher ($p<0.001$). Second, the temperature was significantly higher with a closed guide ($p<0.001$). Third, the effect of bone type did not appear to be influenced by the type of template ($p = 0.436$). Fourth, the effect of the type of guide did not appear to be influenced by the type of bone density ($p = 0.436$). However, the chi-squared statistic was much greater for the bone factor than the guide factor, implying that the observed variability was mostly due to bone density. The detailed results are presented in Table 2.

The maximum threshold temperature of ≥ 47 ºC, as described by Eriksson and Albrektsson (1983, 1984), was only reached in the hard bone groups. In contrast, the 47 ºC threshold was never reached in the soft bone groups.

Influence of osteotomy drilling depth and cooling irrigation

Apart from the observation that the combination of hard bone (D1) and closed guide yielded the highest temperatures ($p < 0.001$), the 13 mm drilling depth in groups one and two (dense bone) was associated with higher mean temperatures than with a 6 mm drilling depth. In contrast, in group three, the mean temperature at a depth of 6 mm was higher than at 13 mm. Besides, in group four, no difference was observed in the mean temperature between osteotomy depths (Tables 1 and 2).

Lastly, the irrigation fluid temperature also significantly influenced the heat generated during bone drilling ($p < 0.001$). Chilled fluid at 5 ºC reduced the temperature peaks for all groups to similar degrees, which was not the case with room temperature irrigation (Table 1). For the 6 mm drilling depth, the reduction of the bone temperature in relation to bone density and irrigation fluid temperature proved to be more linear across the four groups (Figure 6). The detailed results are shown in Table 2.

Most importantly, maximum temperatures above the threshold of 47 ºC (Eriksson & Albrektsson, 1983; Eriksson & Albrektsson, 1984) were only observed in the high-density bone groups when room temperature irrigation was used. The maximum temperatures never reached the 47 ºC threshold when chilled irrigation fluid was used.

Discussion

Our findings indicate that high-density bone and closed surgical guides contribute to increased intra-osseous temperature during bone drilling compared to low-density bone and open guides. Furthermore, high-density bone and greater drilling depths lead to increased heat generation. Using chilled irrigation fluid helps to reduce heat generation and avoid bone temperatures above the 47 ºC threshold.

Several factors have been reported to influence bone temperature during bone drilling, including bone density, cortical bone thickness, aspects related to bone drilling parameters, different surgical guides, and irrigation fluid temperature (Augustin et al., 2012; Boa et al., 2016; Bolland et al., 2004; Delgado-Ruiz et al., 2018; Jeong et al., 2014; Lee, Gozen, & Ozdoganlar, 2012).

Bone density has been previously reported as the primary influencing factor behind increased temperature variability (Karaca, Aksakal, & Kom, 2011). It has been argued that the duration of bone drilling depends on the hardness of cortical bone, which correlates to bone mineral density, and these parameters are closely related to increased bone temperature (Karaca et al., 2011). Furthermore, the present study found that the depth of the bone preparation was seen to significantly influence the bone temperature reached in hard density bone, in agreement with Misir et al. (Misir et al., 2009). They recorded an increase in heat generation associated with deeper osteotomy drillings (3, 6, and 9 mm). However, they did not take bone density into account. Our study did not find a significant increase in the intra-bone temperature associated with deeper osteotomies in soft bone. Interestingly, the mean bone temperature was higher at a depth of 6 mm than at 13 mm. This may be due to the short duration of the shallow drilling procedure in soft bone and the lesser effect of the irrigation fluid over this short period.

The use of surgical templates to achieve better results in implant positioning has several shortcomings. Surgical templates can reduce the surgeon's visibility and prevent the irrigation fluid from cooling the drill during bone preparation, thereby generating more heat than with freehand implant placement surgery (Fauroux et al., 2018; Misir et al., 2009). However, not all surgical template designs have the same effect in terms of bone temperature changes (Amorfini et al., 2017; Farley et al., 2013; Pozzi et al., 2014; Younes et al., 2018). An open guide design enhances surgical visibility and allows for the proper irrigation of the drills while transferring the pre-surgical implant positioning planning to the surgical sites (Fauroux et al., 2018). In the present study, open surgical guides reduced the bone temperature during drilling by approximately 1 ºC compared to closed guides in hard and soft density bone. Nevertheless, this degree of difference did not imply a variation that exceeded the recommended temperature limit.

The mean temperature reached in our study was far from the temperature threshold of 47 ºC reported by Eriksson and Albrektsson in 1983 and 1984 (Eriksson & Albrektsson, 1983; Eriksson & Albrektsson, 1984), and is in agreement with the observations of Di Fiore, Sivolella, Stocco, Favero and Stellini (2018).

Nonetheless, this study revealed that bone temperatures above 47º C during implant bed preparation might be reached in high-density bone when room temperature irrigation fluid is used. This finding highlights the importance of using a chilled irrigation fluid to avoid excess intra-bone temperatures. Irrigation during bone drilling has two main functions, that is, to reduce the bone temperature (Liu et al., 2018) and enhance the removal of bone debris (Augustin et al., 2012). Boa et al. found that external irrigation during flapless guided surgery could reduce 50% of the bone temperature generated compared to non-irrigation (Boa et al., 2015). Interestingly, studies involving implant static navigation surgery have reported no differences in terms of the bone temperature reached between continuous and intermittent drilling (Di Fiore et al., 2018) or between flapless and flap surgery (Jeong et al., 2014). Furthermore, according to the results of Boa et al. (2016) and Di Fiore et al. (2018), the use of pre-cooled irrigation fluid (10 ºC and 6 ºC, respectively) is recommended to control bone temperature, especially when using a closed guide. This is in agreement with our findings, where chilled irrigation fluid (5 ºC) reduced the intra-bone temperature compared to room temperature irrigation fluid (21 ºC) and prevented intra-bone temperatures from rising above 47º C during implant bed preparations in high-density bone.

This study has several limitations. Polyurethane foam blocks (Möhlhenrich et al., 2015) may differ from living bone in quality and elasticity. However, they have been found to have physical and mechanical characteristics similar to cortical and cancellous bone and are easy to standardize to different bone densities. Nevertheless, the results obtained could differ from those recorded in clinical practice due to differences between patients (Vilani, Ruellas, Mattos, Fernandes, & Elias, 2015). Additionally, to standardize this study, the drilling speed and drill diameter were not modified throughout the investigation, and only external irrigation was employed. The use of other conditions could have yielded different results. Drilling parameters such as the drill design (e.g., helix angle, chisel edges, helical or straight flutes), drill diameter, and the type of material have all been shown to influence bone temperature during drilling (Matthews & Hirsch, 1972). Moreover, drill wear and sterilization cycles leading to drill dullness also contribute to heat production (Matthews & Hirsch, 1972; Möhlhenrich et al., 2015). Additionally, drilling speed, the torque applied, and the depth of the preparation have all been shown to modify bone temperature during bone drilling (Cordioli & Majzoub, 1997; Matthews & Hirsch, 1972). Delgado-Ruiz et al. (Delgado-Ruiz et al., 2018) reported significantly lower temperatures when drilling at a slow-speed (50 rpm; 22.11 ± 0.8 °C) compared to the drilling speeds of 150 rpm (24.75 ± 1.1 °C) and 300 rpm (25.977 ± 1.2 °C). Furthermore, the bone temperatures in cortical bone were found to be significantly higher while working at higher speeds. No irrigation with lower speeds was revealed to avoid excessive heat generation (Salomó-Coll et al., 2020). Salomó-Coll et al. (2020) also revealed that the mean temperatures attained when using 2 or 3.5 mm diameter drills were similar, indicating little variability with different drill diameters under similar conditions (Salomó-Coll et al., 2020). This contrasts with other studies that showed that a decrease in drill diameter is related to an elevation in bone temperature due to increased energy transfer to the bone (Boa et al., 2016; Matthews & Hirsch, 1972).

Furthermore, internal or double irrigation systems were not used. However, their benefits remain controversial. Boa et al. (2016) described that double irrigation during osteotomies could reduce the heat generated in the bone. Misir et al. (2009) observed no differences in bone heat generation with external or external and internal irrigation during implant osteotomies with surgical guides. For standardization purposes, external irrigation was selected in the present study to achieve clear results and more specific clinical guidance for this commonly used irrigation system.

Further studies should involve an upgraded mechanism to assess the intra-bone temperature during implant bed preparations. For example, a device that does not require the insertion of thermocouple electrodes inside the apical zone of the bone preparations would be preferable.

When interpreting the results of this study, it is important to recognize that the mean maximum temperature reached the 47 ºC threshold in none of the tested scenarios. However, when looking at the maximum values measured in each group, a bone temperature of >47 ºC was reached in several samples when irrigating with room temperature fluid in dense bone sites. Using a chilled irrigation fluid (5º C) was found to be effective in maintaining the intra-bone temperature below the 47 ºC threshold.

Conclusions

Within the limitations of this *in vitro* study, it can be concluded that in high-density bone (D1), a closed guide for a deep ostectomy will lead to the highest intra-bone temperatures. With a closed static surgical guide, the final intra-bone temperature was about 1 ºC higher than with an open guide. The osteotomy depth significantly affected the maximum temperature reached in high-density bone samples, especially when room temperature irrigation fluid was used. This study also confirmed the value of using chilled irrigation fluid (~5 ºC) to avoid heat generation above 47 ºC in dense bone.

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Tables legends

Table 1. The temperature recorded (ºC) according to each group, osteotomy drilling depth, and irrigation fluid.

Table 2. Beta coefficients (mean temperature differences) and 95% CI for different effects from GEE models. Corrected p-values of Wald´s Chi^2 test using Bonferroni's criteria (*p<0.05; **p<0.01; ***p<0.001)

Figure legends

Figure 1. Closed implant guide.

Figure 2. Open implant guide.

Figure 3. Flowchart distribution of the study sample.

Figure 4. Handpiece, thermometer, and thermocouple.

Figure 5. Boxplot of bone temperature distribution according to each group.

Figure 6. Mean maximum temperature (ºC) according to each group, osteotomy drilling depth, and irrigation fluid.

Table 1

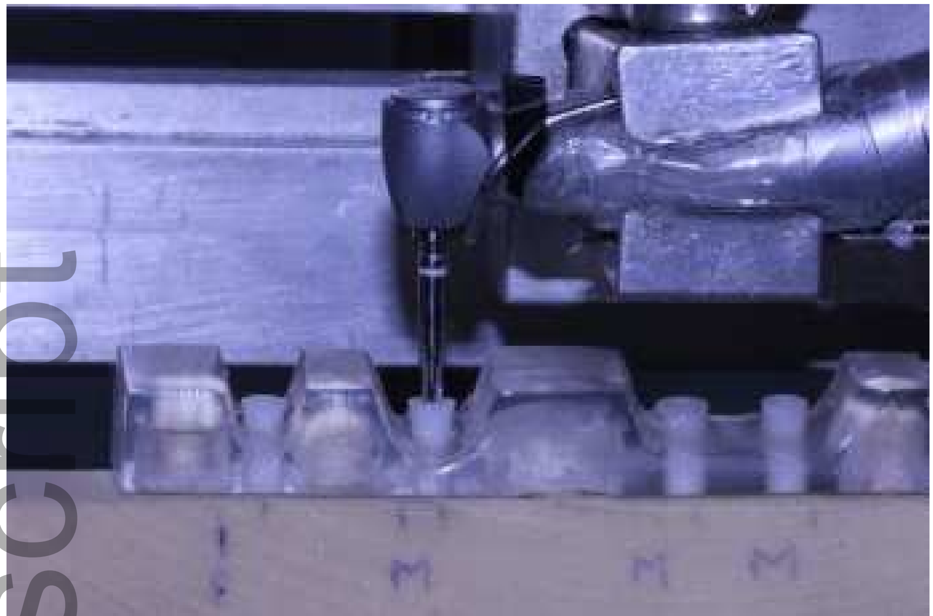
GROUP	DRILLING DEPTH (mm)	IRRIGATION FLUID (ºC)	N	MEAN	SD	MINIMUM	MAXIMUM	MEDIAN
1	6	5	120	27,58	3,85	21,60	37,90	26,30
		21	120	28,17	5,26	22,30	50,00	26,50
	13	5	120	28,26	3,26	22,00	35,60	27,55
		21	120	29,17	3,25	23,20	35,40	28,70
2	6	5	120	26,05	1,81	21,80	32,10	25,95
		21	120	27,10	4,31	22,00	47,80	26,55
	13	5	120	27,14	2,90	22,30	35,60	26,90
		21	120	28,34	3,64	22,30	36,70	28,00
3	6	5	120	23,95	1,39	19,80	27,30	24,05
		21	120	24,77	2,33	21,10	30,10	24,20
	13	5	120	22,04	,98	20,30	27,10	22,00
		21	120	22,77	1,43	20,10	26,80	22,45
4	6	5	120	21,28	,85	19,50	23,20	21,30
		21	120	22,82	1,24	20,10	26,20	22,70
	13	5	120	21,48	,91	19,70	23,70	21,50
		21	120	22,29	1,16	20,10	26,40	22,10

Table 1. Temperature recorded (ºC) according to group, drilling depth and irrigation fluid.

Table 2

Comparison between GROUPS	MEAN TEMPERATURE DIFFERENCE (º C)	95% CI	p-value
1 - 2	1.13	0.51 – 1.77	0.003**
1 - 3	4.91	4.31 – 5.51	<0.001***
1 - 4	6.33	5.74 – 6.91	<0.001***
2 - 3	3.78	3.28 – 4.27	<0.001***
2 - 4	5.19	4.66 – 5.72	<0.001***
3 - 4	1.42	1.18 – 1.66	<0.001***
D1 – D4	4.90	4.30 – 5.50	<0.001***
Closed – Open guide	1.42	1.18 – 1.66	<0.001***
in D1: Closed - Open	1.14	0.51 – 1.77	0.003**
in D4: Closed - Open	1.42	1.18 – 1.66	<0.001***
in Closed: D1 – D4	4.91	4.31 – 5.51	<0.001***
in Open: D1 – D4	5.19	4.66 – 5.72	<0.001***
Fluid temp: 5 – 21º	0.96	0.62 – 1.29	<0.001***
Depth: 6 – 13 mm	-0.03	-0.19 – 0.13	0.717
In Group 1: Depth 6 – 13mm	-0.83	-1.29 - -0.37	0.010*
In Group 2: Depth 6 – 13mm	-1.16	-1.96 - -0.36	0.124
In Group 3: Depth 6 – 13mm	1.95	1.47 – 2.43	<0.001***
In Group 4: Depth 6 – 13mm	0.16	0.03 – 0.29	0.455

Table 2. Beta coefficients (mean temperature differences) and 95% CI for different effects from GEE models. Corrected p-values of Wald´s Chi^2 test using Bonferroni´s criteria (*p<0.05; **p<0.01; ***p<0.001).



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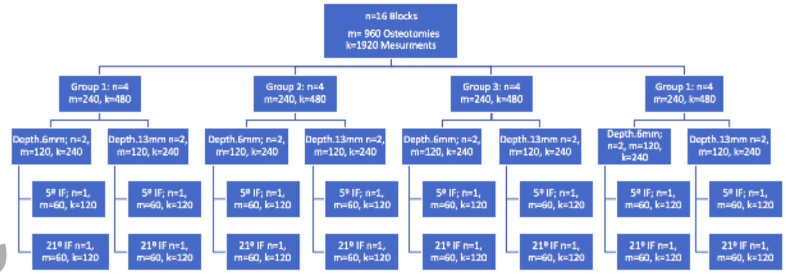

n: blocks; m: osteotomies; k: temperature measurements; IF: irrigation fluid.

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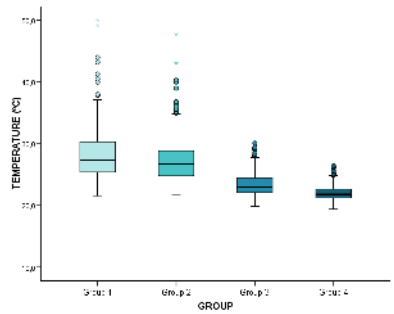

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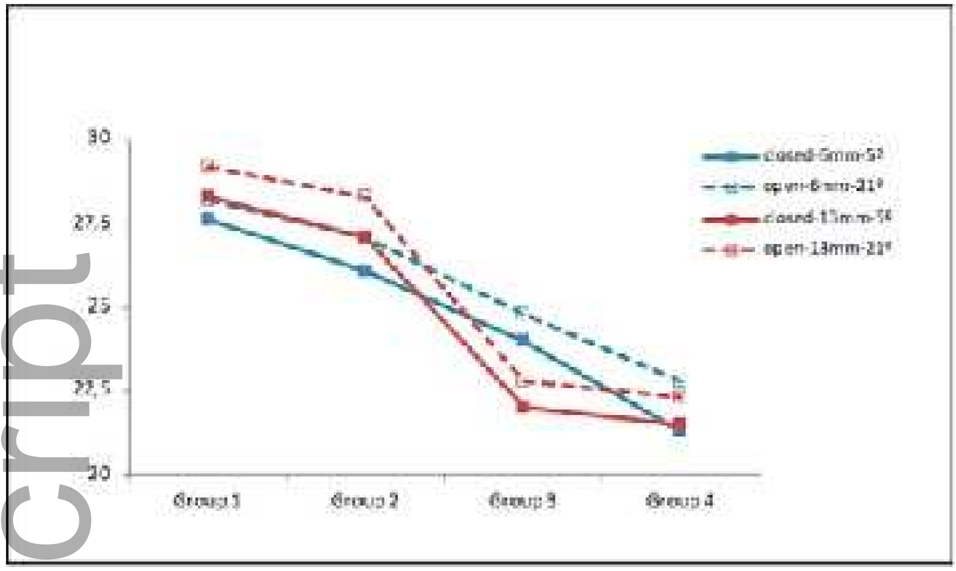

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